STUDIES OF PRACTICAL DAYLIGHT SIMULATORS FOR INDUSTRIAL COLOUR QUALITY CONTROL

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Thesis Redaction Requirements

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Abstract

Daylight simulators are widely used in industries for visual assessments and internal light sources of colour measuring instruments. As the CIE defined its standard daylight illuminants based on a combination of various measurement results, the precise realisation of CIE daylight illuminants is virtually impossible. Daylight simulators have therefore been developed to simulate the CIE daylight illuminants only approximately. The variety of daylight simulators used in practice caused a big concern on the quality of daylight simulators for industrial colour quality control. This study aims to investigate the variations of practical daylight simulators and the performances of standard methods including the BS950 band value method, CIE metamerism index method and CIE colour rendering index method for evaluating daylight simulators. The study also aims to reveal the discrepancies between various standards for specifying daylight simulators and to highlight the influence of these discrepancies on industrial colour quality control.

An industrial survey on viewing cabinets was first carried out. The variations of D65 and D50 simulators accumulated were analysed in terms of colorimetric and spectral results. The results show that the D65 simulators generally performed better than the D50 simulators with higher CIE metamerism index and colour rendering ratings. The filtered tungsten lamps exhibit the best quality while the three-band fluorescent lamps show the worst quality. It was also found that both the CIE and ISO might not give appropriate specifications for the chromaticities of daylight simulators, i.e. too lenient for the former and too strict for the latter.

A psychophysical experiment using real metameric pairs was conducted for evaluating the quality of six D65 daylight simulators. It was found that in general, all the simulators studied agreed well with each other in terms of the visual results, except for the three-band fluorescent lamp. The results show that BS 950 band value method and CIE metamerism index method are equally reliable for evaluating the quality of daylight simulators. It was also revealed that a simulator having band-value deviations well below the BS 950 tolerance corresponds to a high CIE metamerism index rating and therefore is judged as good quality.

Seven metamer sets were generated based on different principles. These metamer sets were used to compare various metamerism indices for quantifying metamerism as well as to evaluate two methods, goodness-of-fit of SPD and CIE metamerism index for assessing daylight simulators. The results show that the measure of goodness-of-fit of SPD does not agree well with the CIE metamerism index method. It was proved that the CIE metamers are representatives of real metamers, however, the CIE metamer set gives smaller colour differences for the test simulators because it exhibits lower metamerism degree comparing to the generated metamer sets. It was also found that a limited number of metamers could be selected from a range of real metamers to perform as effective as the CIE set for evaluating daylight simulators.

The CIE colour rendering index method for evaluating daylight simulators was investigated using the CIE test colours and new sets of test colours. It was found that the CIE test colour sets agreed better with the paint sample sets than with the textile or thread sample sets. The four colour difference formulae, CIELAB, CMC, CIE94 and CIEDE2000, exhibit a similar performance for calculating CIE colour rendering index, and they all outperform CIEU*V*W*. No significant difference was found for the performance between two chromatic adaptation transforms, von Kries and CMCCAT2000. The results also show that it might be more appropriate to adopt the total CIE test colours instead of the first eight colours for calculating CIE colour rendering index. A new set of test colours, selected from the CIE and other test colours for showing medium to large colour inconstancy as well as covering a large colour gamut, was proved to have a better performance than the CIE test colours.

Finally, a method was developed for optimising the spectral power distributions of daylight simulators. Significant improvements in quality were achieved for the test lamps after the optimisation. A guideline for viewing cabinet design was also proposed based on the relevant standards and information accumulated from the industrial survey on viewing cabinets.

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CHAPTER 1
INTRODUCTION

1.1 Background

The colour of a physical sample depends primarily on the composition of the light reflected from it which enters the observer's eyes. This is governed by two factors, the reflectance characteristics of the sample and the composition of the light falling on it. In the textile industry, for instance, a dyer determines the reflectance characteristics by his choice of dyes but he has no control over the composition of the lights under which the textile will be viewed. Natural daylight itself varies in composition, from the reddish light of sunrise and sunset to the bluish light of cloudless northern sky. Furthermore, natural daylight is not available either at night or in many interior rooms. These limitations have motivated a long search for ways to simulate natural daylight, usually by choosing lamps and developing filters to modify their spectral power distributions. Before daylight could be simulated, it was necessary to characterise it by measurement, to decide which phase to use, and to standardise it.

Based upon the measured spectral power distributions (SPDs) of real daylight, in 1963, the CIE (COMMISION INTERNATIONALE DE L'ÉCLAIRAGE) recommended a standard daylight illuminant with correlated colour temperature (CCT) at 6500K to represent average daylight across both visible and UV regions commencing at 300 nm. (Note that the majority of this research work was closely associated with CIE, which is a world organisation for standardising methods for measuring colour and light.) The CIE then recommended a numerical procedure to determine the relative SPD of standard daylight illuminants with CCT ranging from 4000K to 25000K. A series of daylight illuminants with CCT at 5000K, 5500K, 6500K and 7500K, denoted as D50, D55, D65, D75 respectively, were particularly recommended by the CIE to represent daylight of different phases (CIE 1986). The way in which the CIE defined its standard daylight illuminants however caused the theoretical nature of these illuminants and made it virtually impossible to realise them precisely (Hunt

1992). Artificial daylight sources (also termed as daylight simulators) have therefore been developed to simulate the CIE daylight illuminants only approximately.

The development of daylight simulators dates back to early this century, when artificial daylight was needed to test photographic materials, so filters made of coloured liquids, dyed gelatine, blue glass, or combinations of these were developed to convert the light of an acetylene flame or other sources to daylight. Since the specifications of CIE standard daylight illuminants, the lighting industry has made great efforts to develop qualified daylight simulators for various applications. The three major types of daylight simulators developed are filtered tungsten lamps, filtered xenon lamps and fluorescent lamps (Wyszecki 1970). The filtered lamps, are designed to have a closer simulation of SPD to a CIE daylight illuminant, however, there lie the drawbacks of low energy efficiency and high manufacturing cost. The fluorescent lamps have the advantage of high energy efficiency and low manufacturing cost, but show larger discrepancies in SPD relative to the CIE daylight illuminant.

As daylight is preferably used for visual assessment of colours, there is an increasing demand from the industries for qualified daylight simulators. Surface colour industries (e.g. textiles, paints and paper) and the graphic-arts industry (e.g. press and printing) carry out a large number of visual assessments under the illumination of artificial daylight. For colour measuring instruments such as spectrophotometers, daylight simulators, e.g. filtered flash or continuous short-arc xenon lamps, are usually employed as the internal light sources. The SPDs of daylight simulators are also used in the colorant formulation process.

Due to the wide range of applications and variety of daylight simulators in practice, the quality of daylight simulators is a big concern for manufacturers and users. For industrial colour quality control, it is frequently found that daylight simulators having different SPDs may significantly affect the visual results on colour matching and colour appraisal, resulting in large discrepancies between the visual and instrumental results (Lam and Xin 2002, Kuo and Luo 1996a&b). The quality of daylight simulators and lighting devices accommodating the simulators, such as viewing cabinets, plays a key role in causing these discrepancies.

1.2 Assessing the Quality of Daylight Simulators

The quality of daylight simulators is a main concern of this study. A high quality simulator should be close to the standardised colour in terms of x, y or u', v' co-ordinates and also its

SPD. Assessment of daylight simulators generally falls into two categories. In the first category, we are concerned with a single sample and the question of whether the sample looks the correct colour. If not, we often blame the source rather than the sample, and say that the light source has poor colour rendering properties. In the second category, we consider two samples, one of which is intended to be a match to the other. Hopefully the samples will match under all light sources, but for metameric pairs, the match holds for one source, not for another. If the match must hold for daylight, then the simulator needs to be a good approximation to daylight. If not, a good match viewed under daylight may appear to be unsatisfactory in the viewing cabinet (and vice versa).

A colour rendering index is used to assess the degree of colour appearance change for a single test colour when the illuminant is changed. It falls to the first of these two categories. A metamerism index is a measure applied for both categories. It is used to assess the excess colour shift of difference in rendering between the two samples of a metameric pair under a test simulator (Rich 2004). The two indices must be related somehow. For instance, if a simulator has more or less the correct energy distributions, both indices must be high. Similarly if some colours are not rendered correctly, incorrect results may be retained for some metameric pairs (one sample may be rendered correctly and the other one not), causing a poor metamerism index rating. However, a simulator having a good metamerism index rating may not necessarily have a good colour rendering index rating. This is because a pair of metameric samples which are not rendered correctly may exhibit similar colour shifts in terms of direction and magnitude.

Standardisation of daylight simulators is important for industrial quality control where colour products need to be reproduced consistently and faithfully. Various national and international standards have so far been established to serve this purpose. These include:

- AATCC EP9 (1999) Visual Assessment of Color Difference of Textiles
- ANSI PH2.31 (1969) Direct Viewing of Photographic Color Transparancies
- ASTM D4086 (1992) Standard Practice for Visual Evaluation of Metamerism
- ASTM D1729 (1996) Standard Practice for Visual Evaluation of Color and Color Difference of Diffusely Illuminated Opaque Materials
- British Standard BS 950 (1967) Specification for Artificial Daylight for the Assessment of Colour, Part 1: Illuminant for Colour Matching and Colour Appraisal, Part 2: Viewing Conditions for the Graphic Arts Industry.

- CIE publication 13.3 (1995) Method of Measuring and Specifying Colour Rendering Properties of Light Sources
- CIE publication 51 (1981) A method for Assessing the Quality of Daylight Simulators for Colorimetry
- CIE publication 51.2 (1999) A Method for Assessing the Quality of Daylight Simulators for Colorimetry
- Japanese Industrial Standard JIS Z 8716 (1991) Fluorescent Lamp as a Simulator of CIE Standard Illuminant D65 for a Visual Comparison of Surface Colours-Type and Characteristics
- ISO 3664 (2000) Viewing Conditions for Graphic Technology and Photography
- ISO 3668 (2001) Paints and Varnishes - Visual Comparison of the Colour of Paints

Amongst the standards listed above, the British, US and ISO standards were established mainly for specifying standard viewing conditions for specific applications. As daylight illumination is one of the most important factors of viewing conditions in practice, in these standards, CIE daylight illuminants were chosen as standard sources and the required quality of daylight simulators were specified. Colorimetric results such as chromaticity co-ordinates, correlated colour temperature (CCT), CIE metamerism index and colour rendering index are generally considered with respect to the quality of daylight simulators. The British standard BS 950 particularly specified the tolerance of spectral disagreement between the standard and test simulator.

1.3 Aims and Approaches of the Study

There are four aims of this study. The first two aims are to analyse the variations of daylight simulators (including viewing cabinets) in practice and to investigate standard methods such as the BS 950 band value method, the CIE metamerism index and colour rendering index methods for evaluating daylight simulators. Both the band value method and the CIE methods were recommended decades ago and their performances need to be further tested following the modern developments of daylight simulators and advances in colour science. The CIE metamerism index method uses a limited number of virtual metamers. It is important to know whether these CIE metamers are good representatives of real metamers in practice. The CIE colour rendering index method was originally developed for evaluating a wide range of light sources. It employs a limited number of test colour samples selected from the Munsell Color Order system and uses the von Kries chromatic adaptation transform and CIEU*V*W* colour difference formula for calculating colour rendering index. The effectiveness of the test colour samples, chromatic adaptation transform and colour difference formula, are thus a big concern with respect to the validity of the CIE colour rendering index method.

The third aim of this study is to reveal the discrepancies between various standards for specifying daylight simulators and to highlight the influence of these discrepancies on industrial colour quality control, e.g. visual assessments for colour differences, metamerism and colour appearance. The final aim of this study is to develop methods for improving the quality of daylight simulators and to propose guidelines for viewing cabinet design. It is hoped that the total outcomes of this study could be used to improve the reproducibility of visual assessments as well as the agreement between instrumental and visual assessments. This research work was divided into three stages according to many different tasks, including:

Stage 1 Data Acquisition, Processing and Analysis

A large quantity of spectroradiometric data for D65 and D50 simulators was accumulated from the UK textile industry and the US graphic-arts industry respectively. Data processing was carried out to calculate colorimetric results for the daylight simulators (e.g. chromaticity co-ordinates, luminance, CCT, CIE colour rendering index, CIE metamerism index, etc.) and surface colours (e.g. tristimulus values, colour difference, special metamerism index, colour inconstancy index, etc.). Data analysis was also conducted to investigate the variations of viewing cabinets and D65 and D50 simulators in terms of colorimetric and spectral results.

Stage 2 Visual Assessment

Psychophysical experiments were conducted for evaluating six D65 simulators. Statistical measures were employed to examine the reliability of visual results and the correlation between the visual results and predicted results obtained using standard methods such as the BS 950 band value method and CIE metamerism index method. The performances of four colour difference formulae were also tested for calculating the CIE metamerism index.

Stage 3 Testing Existing Methods and Deriving News Methods

In addition to the experimental approach, a theoretical approach was employed to investigate the CIE metamerism index and colour rendering index methods for evaluating daylight simulators. New sets of metamers and test colours were generated to test the effectiveness of the CIE metamers and test colours for calculating the CIE metamerism index and colour rendering index respectively. A limited number of metamers were selected from a range of real metamers to perform as effectively as the CIE set for evaluating daylight simulators. New test colours were developed to replace the current CIE test colours for improving the colour rendering index method. A method to optimise the SPD of a daylight simulator was proposed to achieve a better quality simulator. A guideline for viewing cabinet design was also proposed.

1.4 Current Standard Activities

The present study investigated daylight simulators with focus on their industrial applications, variations, quality assessment and possible improvement. Research in metamerism, colour rendering, chromatic adaptation transform, colour difference and colour inconstancy, are all relevant to this study. The study was conducted in conjunction with the activities of six CIE Technical Committees and one ASTM subcommittee, including:

- CIE TC1-33, Colour Rendering, Chaired by Janos D. Schanda.
- CIE TC1-44, Practical daylight sources for colorimetry, Chaired by Robert Hirschler.
- CIE TC1-45, Revision of CIE publication 51 to include D50 simulators, Chaired by Calvin S. McCamy.
- CIE TC1-52, Chromatic Adaptation Transform, Chaired by M. R. Luo.
- CIE TC1-53, A Standard Method of Assessing the Quality of Daylight Simulators, Chaired by C. S. McCamy.
- ASTM Subcommittee E12.11, New standard practice for selecting and calibrating sources for the visual assessment of object colors and new standard test method for assessing the quality of sources for the visual assessment of object colors.

1.5 Thesis Outlines

This thesis describes the approaches used to fulfil the aims of the current study. The introduction given in this chapter addresses the importance of understanding the problems facing industries in using daylight simulators. The following is a preview of chapters to come:

Chapter 2 *Literature Survey* reviews previous work relevant to this subject, which is a prerequisite for implementing and completing the study. The information presented includes important concepts of photometry, a wide scope of colorimetry, types and application of daylight simulators, national and international standards for specifying daylight simulators and design of viewing cabinets, and methods for evaluating and improving the quality of daylight simulators.

Chapter 3 *Variations of Practical D65 and D50 Simulators* introduces an industrial survey of viewing cabinets. The qualities of the viewing cabinets investigated are reported. The variations of D65 and D50 simulators accumulated are analysed in terms of colorimetric and spectral results. The qualities of these investigated simulators are evaluated based on various standards.

Chapter 4 *Experimental Assessment on the Quality of D65 Simulators* describes a psychophysical experiment for the evaluation of six D65 test simulators using real metameric pairs. The performances of the BS 950 band value method and the CIE metamerism index method are tested using the visual assessment results.

Chapter 5 *Generating New Sets of Metamers for Evaluating D65 Simulators* describes the process in generating seven new metamer sets. The metameric properties of these generated metamers are analysed. The qualities of 15 D65 simulators are tested using different metamer sets including the CIE metamers. A limited number of metamers are selected from a range of real metamers to perform as effective as the CIE set for evaluating daylight simulators.

Chapter 6 *Investigating the CIE Colour Rendering Index Method for Evaluating D65 Simulators* investigates the CIE colour rendering index method using new test colours in addition to the CIE test colours for evaluating 15 D65 test simulators. The performances of the chromatic adaptation transform and colour difference formula adopted in the CIE method are also evaluated. A set of new test colours is developed to replace the current CIE test colours for improving the method performances.

Chapter 7 *Improving the Quality of D65 and D50 Simulators* introduces software designed to optimise the SPDs of test simulators for improving the lamps' qualities.

Chapter 8 *Conclusions* summaries all the findings from this study and describes the future work. A guideline for viewing cabinet design is also proposed.

During this PhD study, three papers have been published, which are:

1. H. Xu, M. R. Luo and B. Rigg, Evaluation of Daylight Simulators. Part I: Colorimetric and Spectral Variations. Coloration Technology, 119, p.59-69, 2003.
2. H. Xu, M. R. Luo and B. Rigg, Evaluation of Daylight Simulators. Part II: Assessing the Quality of Daylight Simulators Using Real Metameric Pairs. Coloration Technology, 119, p.253-263, 2003.
3. H. Xu, M. R. Luo and B. Rigg, Evaluating the Quality of Daylight Simulators Using Metameric Samples, The 9th Congress of the International Colour Association (AIC Color 01), p.697-700, Rochester, USA, 2001.

Further papers are to be submitted for publishing following the completion of this PhD thesis.

CHAPTER 2
LITERATURE SUVEY

2.1 Introduction

This chapter provides the background information related to this study. Section 2.2 briefly introduces photometry and its basic concepts and units are described. Section 2.3 covers a wide scope of colorimetry, including CIE colour specification, CIE standard illuminants, colour difference formulae, colour order systems, chromatic adaptation transforms, colour inconstancy indices, colour rendering, metamerism, colorant formulation and colour measuring instruments. Section 2.4 gives a comprehensive review on the development and applications of daylight simulators. Section 2.5 introduces various national and international standards for specifying daylight simulators. Section 2.6 provides outlines for viewing cabinet design. Section 2.7 reviews several methods for evaluating daylight simulators, and Section 2.8 evaluates the CIE method for assessing daylight simulators. Section 2.9 introduces some approaches for making daylight simulators of good quality and Section 2.10 summaries the previous work relevant to the author's study. Sections 2.4 to 2.9 are the main contribution of this literature survey to the author's study, and cover almost all the aspects with regard to the quality of daylight simulators for industrial colour quality control.

2.2 Photometry

Photometry concerns the measurement of light. If there is no light, no colour can be perceived. It forms the basis for colour science. The basic concepts and units for photometry are described below (CIE 1987).

Radiant and Luminous Flux

Flux is the basic unit of optical power, expressed in watts (for radiant flux) or lumens (for luminous flux). The term 'luminous' is used when radiant flux is weighted with the luminosity function $V(\lambda)$, also named as the photopic luminous efficiency function, defined by the CIE in 1924 (CIE 1986). **Lumen** is the unit for luminous flux. One lumen is defined as the luminous flux emitted through unit solid angle (one **steradian**) from a directional unit point source of one candela. It is equivalent to the luminous flux of monochromatic radiant energy with radiant flux of ($\frac{1}{683}$ W) at a frequency of 540 x 10^{12} Hz (approximately a wavelength of 555 nm).

Radiant and Luminous Intensity

Radiant and luminous intensity refer to the radiant and luminous flux emitted per unit solid angle, respectively. **Candela (cd)** is the unit for luminous intensity. One candela is the luminous intensity in a given direction, of a source emitting a monochromatic radiation at a frequency of 540 x 10^{12} Hz, the radiant intensity of which in that direction is $\frac{1}{683}$ watt per steradian.

Irradiance and Illuminance

Irradiance and Illuminance refer to the radiant or luminous flux per unit area incident on a surface, respectively. **Foot-candle** (lumen per square foot) is a measure of illuminance produced by a luminous flux of 1 lumen uniformly distributed over a surface area of one square foot. **Lux (lx)** is the unit for illuminance. It equals to the illuminance produced by a luminous flux of 1 lumen uniformly distributed over a surface of area of 1 square metre.

Radiance and Luminance

Radiance and Luminance refer to in a given direction, at a point in the path of a beam, the radiant and luminous intensity per unit projected area, respectively. The basic unit for luminance is candela per square meter **(cd/m²)**.

Luminous Efficacy of Lamps

Luminous efficacy has two meanings. For a light source, it means the ratio of luminous flux emitted to power consumed, an indicator for energy saving. For radiation, it means the ratio of luminous flux to radiant flux, expressed as K in Equation 2.2.1.

$$K = \frac{\int P(\lambda)V(\lambda)d\lambda}{\int P(\lambda)d\lambda} \qquad 2.2.1$$

where $P(\lambda)$ is the radiant power, $V(\lambda)$ is the photopic luminosity function and λ varies from 380 nm to 780 nm. The theoretical maximum value of luminous efficacy is 683 lumen per watt when a light source emits radiation only at 555 nm ($V(\lambda) = 1$). The values of luminous efficacy for all the commercial lamps range from 10 to 150 (Hunt 1998, p.97). For instance, tungsten lamps have low luminous efficacy with values normally under 20, while high-pressure or low-pressure sodium lamps have the highest luminous efficacy amongst all the commercial lamps with values above 100.

2.3 Colorimetry

The term colorimetry usually refers to the measurement of colour. The CIE colorimetry system (CIE 1986) is a well-established system which provides measures to quantify colours. The CIE system considers three essential components, light sources, objects and observers, which determine the colour perception. It is a well known phenomenon that different light sources may affect the colour appearance of an object quite significantly. To standardise the light sources in practice, the CIE defined standard illuminants and artificial light sources representative of these illuminants. (A source is a physical emitter of light, e.g. sunlight, a candle or a lamp, while an illuminant normally refers to theoretical data on relative energy at each of visible as well as near UV range of light, e.g. CIE illuminants.)

The CIE also recommended two sets of colour matching functions, namely the CIE 1931 Standard Colorimetric Observer (known as 2° Observer) and the CIE 1964 Supplementary Standard Colorimetric Observer (known as 10° Observer). Both CIE 1931 and 1964 Observers represent averaged colour vision of a group of observers, with the former to be used for viewing field between 1° and 4° of angular subtence and the latter for viewing field greater than 4° of angular subtence. The CIE colorimetry system also specifies the geometry for measuring colours and providing the measures to correlate with human colour perception.

2.3.1 CIE Colour Specifications

The CIE tristimulus values X, Y and Z of a colour are obtained by multiplying together the relative SPD (S_λ) of a CIE standard illuminant, the reflectance factor R_λ (or the transmittance T_λ) of an object, and the CIE 1931 (or CIE 1964) Standard Colorimetric Observer $\bar{x}_\lambda$, $\bar{y}_\lambda$ and $\bar{z}_\lambda$. The products are summed and normalised across the visible spectrum, resulting in CIE tristimulus values, as shown in Equation 2.3.1.

$$X = k\sum_{\lambda} S_{\lambda} R_{\lambda} \bar{x}_{\lambda} \Delta\lambda$$
$$Y = k\sum_{\lambda} S_{\lambda} R_{\lambda} \bar{y}_{\lambda} \Delta\lambda$$
$$Z = k\sum_{\lambda} S_{\lambda} R_{\lambda} \bar{z}_{\lambda} \Delta\lambda$$
$$k = \frac{100}{\sum_{\lambda} S_{\lambda} \bar{y}_{\lambda} \Delta\lambda} \qquad 2.3.1$$

The above equation is applicable for light sources by setting R_{λ} to 1.0 across the whole spectrum. The absolute luminance of a light source is calculated by using S_{λ} as the absolute spectral radiance and setting k to 683 (CIE 1986). The chromaticity coordinates (x, y and z) are calculated from the XYZ tristimulus values by Equation 2.3.2.

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z} \qquad 2.3.2$$

$$where \ x+y+z=1$$

The CIE XYZ colour space is very useful for quantifying a colour, however, it has the limitation of non-uniformity with respect to colour change. Equal changes in x, y, Y or (X, Y, Z) do not correspond to equal perceived differences. In 1976 the CIE recommended the CIE 1976 Uniform Chromaticity Scales (UCS) diagram (chromaticity coordinates denoted as u', v'), which gives a more perceptually uniform colour distribution than that of the x, y diagram. The transform from x, y chromaticity to u', v' chromaticity is shown in Equation 2.3.3. The CIE tristimulus values and chromaticity coordinates calculated using 10° Observer are denoted by adding the subscript 10 for each term, e.g. X_{10}, Y_{10}, Z_{10}.

$$u' = \frac{4x}{-2x+12y+3}, \quad v' = \frac{9y}{-2x+12y+3} \qquad 2.3.3$$

2.3.2 Colour Temperature and Correlated Colour Temperature

Colour temperature and correlated colour temperature (CCT) are used to describe certain properties of light sources. The former is applied to radiation, such as electric discharge lamps, when the light of this radiator has the same (or nearly the same) chromaticity coordinates as a blackbody radiator at a certain temperature. This temperature is then called the colour temperature of the selective radiator (Wyszecki 1982, p.224). The term CCT is introduced when the chromaticity of selective radiator (e.g. a fluorescent lamp) is not exactly equal to any of the chromaticities of blackbody radiators. According to the CIE (1986), the CCT of an illuminant is defined by the temperature corresponding to the point on the Planckian locus which is nearest to the point representing the CIE 1960 u, v chromaticity of the illuminant, when based on the CIE 1931 Standard Observer.

The colour temperature T_c is sometimes expressed using a reciprocal scale ($10^6/T_c$), which is the reciprocal megakelvin and denoted as MK^{-1} (10^6 K^{-1}). Judd (1936) first proposed so-called isotemperature lines for the evaluation of CCT for some radiators. Kelly (1963) calculated the isotemperature lines and plotted them in the CIE 1960 (u, v) chromaticity diagram (u=u', v=3/2v'), as shown in Figure 2.3.1. A numerical method was proposed by Robertson (1968) to calculate the CCT from the knowledge of the spectral power distribution (SPD) of the source. The method uses Kelly's isotemperature lines and allows a good interpolation between two adjacent members of a set of isotemperature lines. Other methods for calculating CCT were given by Schanda (1978), Krystek (1984), Qiu (1987) and McCamy (1992). Although Robertson's method requires a large amount data to be stored for computation, it is most frequently used for calculating CCT (Berns 2000, p.4).

Figure 2.3.1 The Planckian locus with the normals to it (lines of constant CCT at each 10 microreciprocal degree) (reproduced from Kelly 1963)

2.3.3 CIE Standard Illuminants

The character of a light source is fully determined by its SPD, the way in which the amount of energy distributes through the spectrum. A light source can be more simply defined in terms of colour temperature. CIE standard illuminants were defined by the CIE with specific SPDs to represent different types of light sources.

2.3.3.1 CIE Illuminants A, B, C and D

In 1931, CIE recommended three standard illuminants, A, B and C (CIE 1986). CIE standard illuminant A is defined as an illuminant having the same relative SPD as that of a Planckian radiator at a temperature of 2856K. It is used as a representative of tungsten light sources. CIE illuminant A can be realised by a standard source (source A), which is a gas-filled tungsten filament lamp operating at a CCT of 2856K. However, a standard illuminant representing daylight is difficult to define, as natural daylight can vary quite considerably in SPD due to factors such as latitude, weather conditions, time, etc. Figure 2.3.2 shows the SPDs of five phases of daylight in arbitrary units.

Figure 2.3.2 The SPDs of 5 phases of daylight: '1' for direct daylight, '2' for illuminated horizontal plane by sun through clear sky; '3' overcast skylight; '4' north skylight on 45 plane; '5' zenith skylight (reproduced from Choudhury 2000, p.9).

CIE illuminants B and C were recommended to represent different phases of daylight, and can be realised by combining source A and liquid filters containing solutions of different chemicals. Illuminants B and C are now obsolete. Both CIE B and C illuminants are deficient in ultra-violet region compared with real daylight. Hence in 1963, CIE recommended a new standard illuminant (D65) with a CCT at 6500K to represent average daylight across both visible and UV regions commencing at 300 nm. The CIE then recommended a numerical procedure to determine the relative SPD of standard daylight illuminants with CCT ranging from 4000K to 25000K. The method is based upon the SPD of real daylight measured at three different global locations: Teddington (UK), Rochester (USA) and Ottawa (Canada). A series of standard daylight illuminants with CCT at 5000K, 5500K, 6500K and 7500K, denoted as D50, D55, D65, D75 respectively, were particularly recommended by the CIE to represent daylight of different phases.

The CIE method to calculate the SPD of a standard daylight illuminant can be described using three stages. Firstly, the CIE 1931 chromaticity coordinates (x_D, y_D) of the daylight illuminant are calculated from its CCT (T_c), as shown in Equations 2.3.4 to 2.3.6. Secondly, two factors M_1 and M_2 are computed from the chromaticity coordinates defined using Equation 2.3.7. Finally, the relative SPD of the daylight illuminant is calculated using Equation 2.3.8.

For daylight with CCT from approximately 4000K to 7000K:

$$x_D = -4.6070\frac{10^9}{T_c^3} + 2.9678\frac{10^6}{T_c^2} + 0.09911\frac{10^3}{T_c} + 0.244063 \qquad 2.3.4$$

For daylight with CCT from 7000K to approximately 25000K

$$x_D = -2.0064\frac{10^9}{T_c^3} + 1.9018\frac{10^6}{T_c^2} + 0.24748\frac{10^3}{T_c} + 0.237040 \qquad 2.3.5$$

$$y_D = -3.000x_D^2 + 2.870x_D - 0.275 \qquad 2.3.6$$

$$M_1 = \frac{-1.3515 - 1.7703x_D + 5.9114y_D}{0.0241 + 0.2562x_D - 0.7341y_D}$$

$$M_2 = \frac{0.0300 - 31.4424x_D + 30.0717y_D}{0.0241 + 0.2562x_D - 0.7341y_D} \qquad 2.3.7$$

where M_1 and M_2 are factors depending on the chromaticity co-ordinates of the particular phase of a daylight illuminant.

$$S(\lambda) = S_0(\lambda) + M_1 S_1(\lambda) + M_2 S_2(\lambda) \qquad 2.3.8$$

where the values for $S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ were originally tabulated at 10 nm intervals from 300 nm to 830 nm (partly by extrapolating from the measured values). As pointed by Hunt (1992), the 10 nm data were later transformed by a linear interpolation technique to the intermediate 5 nm and 1 nm values. The interpolation process however generated abrupt discontinuities of the rate of change of power throughout the spectrum, these changes being so large in some parts of the spectrum as to result in a saw-tooth distribution of power. Hence, attempts were made by Schanda (1996, 1999) and Kránicz to achieve smoother SPDs for the CIE daylight illuminants, in which they proposed the use of different interpolation techniques such as Lagrange interpolation.

Figure 2.3.3 shows the SPDs of CIE illuminants A, B, C and D65, and Figure 2.3.4 shows the SPDs of CIE illuminants C, D65 and D50. The CIE 1931 and 1964 chromaticity co-ordinates for the CIE illuminants are listed in Table 2.3.1.

Figure 2.3.3 The SPDs of CIE illuminants A, B, C and D65 (reproduced from Wyzsecki 1982, p.144)

Figure 2.3.4 The SPDs of CIE illuminants C, D65 and D50 (reproduced from Berns 2000, p.6)

Table 2.3.1 The CIE 1931 (x, y) and 1976 (u', v') chromaticity co-ordinates for CIE illuminants A, C and D under CIE 2° and 10° Observers (Hunt 1998, p.264)

Chromaticity co-ordinates (based on 5 nm intervals from 380 to 780 nm)							
	X	Y	Z	x	y	u'	v'
A	109.85	100.00	35.58	0.4476	0.4074	0.2560	0.5243
C	98.07	100.00	118.23	0.3101	0.3162	0.2009	0.4609
D_{50}	96.42	100.00	82.49	0.3457	0.3585	0.2092	0.4881
D_{55}	95.68	100.00	92.14	0.3324	0.3474	0.2044	0.4807
D_{65}	95.04	100.00	108.89	0.3127	0.3290	0.1978	0.4683
D_{75}	94.96	100.00	122.61	0.2990	0.3149	0.1935	0.4585
	X_{10}	Y_{10}	Z_{10}	x_{10}	y_{10}	u'_{10}	v'_{10}
A	111.15	100.00	35.20	0.4512	0.4059	0.2590	0.5242
C	97.28	100.00	116.14	0.3104	0.3191	0.2000	0.4626
D_{50}	96.72	100.00	81.41	0.3478	0.3595	0.2102	0.4889
D_{55}	95.79	100.00	90.93	0.3341	0.3488	0.2051	0.4816
D_{65}	94.81	100.00	107.33	0.3138	0.3310	0.1979	0.4695
D_{75}	94.41	100.00	120.63	0.2997	0.3174	0.1930	0.4601

2.3.3.2 CIE F Illuminants

Fluorescent lamps are widely used for store, office and works lighting. There is a wide range of fluorescent lamps due to the use of different phosphor types and formulations. The CIE recommended the SPDs for twelve types of fluorescent lamps, designated as F1 to F12 (CIE 1986). These distributions do not constitute CIE standard illuminants, but they were compiled by the CIE as representative distributions for practical purposes (Hunt 1998, p.265). According to the CIE, these F-illuminants are categorised into three groups: normal (F1 to F6), broad-band (F7 to F9) and three-band (F10 to F12). Illuminants F2, F7 and F11 are recommended by the CIE to represent each group, respectively.

Each of the distributions in the normal group consists of two semi-broad band emissions of antimony and manganese activation in calcium halophosphate phosphor. The illuminants in this group have a reasonably high luminous efficacy. Their colour rendering (see Section 2.3.6) is adequate for many purposes but it is not very good for reddish colours, because of some deficiency in emission at the long wavelength end of the spectrum (Hunt 1998, p.79). The cool white fluorescent lamp (CWF) is represented by illuminant F2 in this group (Berns 2000, p.6).

The lamps represented by the F illuminant in the broad-band group usually use multiple phosphors. This results in their SPDs being flatter and having a wider range in the visible spectrum. The illuminants in this group have very good colour rendering, and their emission at the long wavelength end of the spectrum is appreciably greater than in the case of the normal group; however, their efficacy is lower (Hunt 1998, p.80). Illuminants F7 and F8 are often used to simulate CIE D65 and D50 illuminants, respectively (Berns 2000, p.7).

As the name implies, the emissions of the F illuminants in the three-band group tend to be concentrated in three bands of the spectrum, and these bands are quite narrow, and are designed to occur around wavelengths of approximately 610, 545 and 435 nm. Lamps in this group tend to have relatively high luminous efficacies and reasonably good colour rendering. They tend to increase the saturation of most colours, and this makes them attractive for some purposes, such as lighting goods in stores, but the appearance of some colours can be somewhat distorted, so that they are less suitable for critical evaluation of colours in general (Hunt 1998, p.80). The so-called fluorescent lamp TL84 is represented by illuminant F11 in this group.

Figure 2.3.5 shows the SPDs of some frequently used CIE F illuminants, with F2 and F11 in (a) and F7 and F8 in (b). Note that all have appreciable amount of energy concentrated at a few wavelengths. This means that their SPDs are quite different from any of the CIE standard illuminants. The problems investigated in this thesis largely arise from these differences. The CIE 1931 and 1976 chromaticity coordinates (x, y) and (u', v'), CCT and colour rendering index for these F illuminants are listed in Table 2.3.2. Figure 2.3.6 shows the CIE 1976 chromaticity coordinates (u', v') for CIE illuminants A, B, C, D and some fluorescent lamps together with those of Planckian radiators of similar CCT.

Figure 2.3.5 The SPDs of four CIE F illuminants, F2 and F11 in (a) and F7 and F8 in (b) (reproduced from Berns 2000, p.7)

Table 2.3.2 The CIE 1931 (x, y) and CIE 1976 (u', v') chromaticity co-ordinates, CCT and colour rendering index for the CIE F illuminants (Hunt 1998, p.265)

Group	Lamp	Chromaticity co-ordinates (based on 5 nm intervals from380 to780 nm)				Corre-lated colour tempe-rature	Colour rend-ering index
		x	y	u'	v'	K	R_a
Normal	F1	0.3131	0.3371	0.1951	0.4726	6430	76
	*F2	0.3721	0.3751	0.2203	0.4996	4230	64
	F3	0.4091	0.3941	0.2368	0.5132	3450	57
	F4	0.4402	0.4031	0.2531	0.5215	2940	51
	F5	0.3138	0.3452	0.1927	0.4769	6350	72
	F6	0.3779	0.3882	0.2190	0.5062	4150	59
Broad-band	*F7	0.3129	0.3292	0.1979	0.4685	6500	90
	F8	0.3458	0.3586	0.2092	0.4881	5000	95
	F9	0.3741	0.3727	0.2225	0.4988	4150	90
Three-band	F10	0.3458	0.3588	0.2091	0.4882	5000	81
	*F11	0.3805	0.3769	0.2251	0.5017	4000	83
	F12	0.4370	0.4042	0.2506	0.5214	3000	83

Figure 2.3.6 The CIE 1976 chromaticity coordinates (u', v') for some CIE illuminants A (S_A), B (S_B), C (S_C) and D together with those of Planckian radiators of similar CCT. Fluorescent lamps are indicated as: WWF (warm white), WF (white), CWF (cool white), ADF (artificial daylight). The series D_{40} to D_{100} refers to the CIE standard D illuminants having CCT from 4000 K to 10,000 K (reproduced from Hunt 1995, p.217)

2.3.4 CIELAB and CIELUV Colour Spaces

It has been long realised that one of the greatest disadvantages of the CIE tristimulus or chromaticity systems is that they are far from equally visually spaced. In response to this, the CIE recommended two colour spaces, CIELUV and CIELAB (CIE 1986). Both spaces provide perceptual attributes such as lightness, chroma and hue, and are more perceptually uniform than the CIE XYZ space with respect to colour perception. CIELUV space also provides the attribute of saturation. A three dimensional representation of the CIELUV space is shown in Figure 2.3.7.

Figure 2.3.7 A three dimensional representation of the CIE LUV space. The CIE LAB space is similar, except that there is no representation of saturation (s) (reproduced from Hunt 1998, p.64).

The same lightness scale (L*) is used for both colour spaces, as given in Equation 2.3.9. Note that the subscript n in the following formulae indicates the individual value for the reference white.

$$L^* = 116(Y/Y_n)^{1/3} - 16 \quad \text{for} \quad Y/Y_n > 0.008856$$
$$L^* = 903.3(Y/Y_n) \quad \text{for} \quad Y/Y_n \leq 0.008856 \qquad 2.3.9$$

The red-green scale (a*), yellow-blue scale (b*), chroma (C*) and hue (h_{ab}) for CIELAB space are:

$$a^* = 500[f(X/X_n) - f(Y/Y_n)]$$
$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)] \qquad 2.3.10$$

where $f(I) = I^{1/3}$ for $I > 0.008956$,

otherwise $f(I) = 7.787I + 16/116$

here I is *X/Xn, Y/Yn* or *Z/Zn*, as the case may be.

$$C^*_{ab} = (a^{*2} + b^{*2})^{1/2} \qquad 2.3.11$$
$$h_{ab} = \arctan(b^*/a^*) \qquad 2.3.12$$

The red-green scale (u*), yellow-blue scale (v*), chroma (C^*_{uv}), saturation (s_{uv}) and hue (h_{uv}) for CIELUV space are:

$$u^* = 13L^*(u' - u'_n), \qquad v^* = 13L^*(v' - v'_n) \qquad 2.3.13$$

$$C^*_{uv} = (u^{*2} + v^{*2})^{1/2} \qquad 2.3.14$$

$$s_{uv} = 13[(u' - u'_n)^2 + (v' - v'_n)^2]^{\frac{1}{2}} \qquad 2.3.15$$

$$h_{uv} = \arctan(v^* / u^*) \qquad 2.3.16$$

where u' and v' are calculated from Equation 2.3.3, and subscript n indicates a specified white object.

2.3.5 Colour Difference Formulae

The quality of a colour is often quantified in terms of colour difference between the colour reproduced and the one desired. The requirement that measures of colour difference should correspond to the perceptual colour difference led to the development of uniform colour spaces and colour difference formulae. So far, many colour difference formulae have been developed based upon various visual data sets. The CIEU*V*W* is an early colour difference formula recommended by the CIE in 1964 (CIE 1986), and is also used for calculating the CIE colour rendering index (see Section 2.5.4.1). The CIELAB and CIELUV formulae (CIE 1986), recommended by the CIE in 1976, are two most widely used formulae serving as a basis for the structure of many modern formulae. The colour differences specified by CIELAB and CIELUV are measured as the Euclidean distance between the coordinates of two stimuli. In recent formulae such as CMC (l:c) (Clarke 1984), Bradford (l:c) (Luo 1987a & b), CIE94 (CIE 1995b), LCD (Kim 1997), CIEDE2000 (CIE 2001), modifications were made for the three axes (lightness, chroma and hue) in the CIELAB space to improve its perceptual uniformity for dealing with small size colour differences used by industry. Comprehensive reviews on the development of colour difference formulae are given by Luo (1986b), Smith (McDonald 1997, p.140), Cui (2000) and Berns (2000, p.107).

2.3.5.1 CIEU*V*W* Colour Difference Formula

To calculate CIEU*V*W* colour difference, the CIE 1960 UCS co-ordinates (u, v) and tristimulus Y should be transformed into CIE 1964 Uniform Space co-ordinates (U*V*W*) for the two stimuli compared. The CIEU*V*W* colour difference is the Euclidean distance between the coordinates of two stimuli, as expressed in Equation 2.3.17.

$$\Delta E = [\Delta U^{*2} + \Delta V^{*2} + \Delta W^{*2}]^{\frac{1}{2}} \qquad 2.3.17$$

where

$$W^* = 25(Y)^{1/3} - 17$$
$$U^* = 13W^*(u - u_n)$$
$$V^* = 13W^*(v - v_n)$$
$$\text{and} \quad u = \frac{4x}{-2x + 12y + 3}, \quad v = \frac{6y}{-2x + 12y + 3}$$

The subscript *n* in the above equations indicates a specified white object.

2.3.5.2 CIELAB and CIELUV Colour Difference Formulae

The CIELAB and CIELUV colour difference formulae (CIE 1986) are two basic but important formulae recommended by the CIE in1976 for calculating the colour difference between two stimuli in the CIELAB and CIELUV colour space, respectively. The two formulae calculate the colour difference using the Euclidean distance between the coordinates of two stimuli, as expressed in Equations 2.3.18 and 2.3.19, respectively.

$$\Delta E^*_{ab} = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} = (\Delta L^{*2} + \Delta C_{ab}^{*2} + \Delta H_{ab}^{*2})^{1/2} \qquad 2.3.18$$
$$\Delta E^*_{uv} = (\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2})^{1/2} = (\Delta L^{*2} + \Delta C_{uv}^{*2} + \Delta H_{uv}^{*2})^{1/2} \qquad 2.3.19$$

where the three coordinates in CIELAB and CIELUV spaces are calculated using Equations 2.3.9, 2.3.10 and 2.3.13 for the two stimuli compared. The ΔH_{ab}^* value can also be calculated using Equation 2.3.20 (Sève 1991).

$$\Delta H^*_{ab} = 2(C_1^* C_2^*)^{1/2} \sin(\Delta h_{ab}^*) \qquad 2.3.20$$

where C_1* and C_2* are the chroma values (see Equation 2.3.11) for the two stimuli in comparison and Δh_{ab}* is the difference in hue angle (see Equation 2.3.12) between the two stimuli in comparison.

2.3.5.3 CMC Colour Difference Formula

The CMC (l:c) colour difference formula (Clarke 1984) is a more advanced formulae with improved performances, particularly for the lightness and chroma scales. The formula was developed by members of the Colour Measurement Committee (CMC) of the Society of the Dyers and Colourists (SDC) in 1984. It is used both as the British (BS 6923) and American standards (AATCC 173) for calculating small colour differences for textiles, and in 1995 it became the ISO standard (ISO 105-J03) for the textile industry.

The colour difference using the formula is calculated as expressed in Equation 2.3.21.

$$\Delta E_{CMC(l:c)} = \sqrt{\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{cS_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{S_H}\right)^2} \qquad 2.3.21$$

where

$$S_L = \begin{cases} \dfrac{0.040975L^*_S}{1+0.01765L^*_S} & L^*_S \geq 16 \\ 0.511 & L^*_S < 16 \end{cases}$$

$$S_C = \frac{0.0638C^*_{ab,S}}{1+0.0131C^*_{ab,S}} + 0.638$$

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

$$f = \sqrt{\frac{{C^*_{ab,S}}^4}{{C^*_{ab,S}}^4 + 1900}}$$

$$T = \begin{cases} 0.36 + |0.4\cos(h_{ab,S} + 35)| & h_{ab,S} < 164^\circ \text{ or } h_{ab,S} > 345^\circ \\ 0.56 + |0.2\cos(h_{ab,S} + 168)| & 164^\circ \leq h_{ab,S} \leq 345^\circ \end{cases}$$

where L^*_S, $C^*_{ab,S}$ and $h^*_{ab,S}$ represent the standard from which the colour difference is determined and ΔL^*, ΔH^*_{ab} and ΔC^*_{ab} are calculated using the CIELAB colour difference formula. The CMC formula corrects the major deficiencies in the CIELAB formula by adjusting lightness differences using a weighting function (S_L), chroma differences using a weighting function (S_C) and hue differences using a weighting function (S_H). The perceptibility and acceptability of colour differences are calculated when the ratio (l:c) is set to (1:1) and (2:1), respectively.

2.3.5.4 CIE94 Colour Difference Formula

The CIE94 colour difference formula (CIE 1995b) is another advanced formula proposed by the CIE in 1994. It calculates the colour difference between two stimuli as in Equation 2.3.22.

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2} \quad 2.3.22$$

where

$$S_L = 1$$
$$S_C = 1 + 0.045 C^*_{ab}$$
$$S_H = 1 + 0.015 C^*_{ab}$$
$$k_L = k_C = k_H = 1 \quad \text{for reference conditions}$$
$$C^*_{ab} = C^*_{ab,Standard} \quad \text{or} \quad \sqrt{C^*_{ab,1} C^*_{ab,2}}$$

where S_C and S_H are calculated using the C^*_{ab} value of the standard. If neither sample can be logically deemed as the standard, the geometric mean of the chroma values is used for calculating S_C and S_H.

2.3.5.5 CIEDE2000 Colour Difference Formula

The CIEDE2000 colour difference formula (CIE 2001) is a more advanced formula proposed by the CIE in 2000. The formula includes not only lightness, chroma and hue weighting functions, but also an interactive term between chroma and hue differences for improving the performance for blue colours and a scaling factor for the CIELAB a^* scale for improving the performance for grey colours. The calculation for CIEDE2000 colour difference involves four steps, and the final colour difference is expressed in Equation 2.3.23.

Step 1. Calculate the CIELAB L^*, a^*, b^*, and C^* as usual

$$L^* = 116 f(Y/Y_n) - 16$$
$$a^* = 500[f(X/X_n) - f(Y/Y_n)]$$
$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$$
$$C^*_{ab} = \sqrt{a^{*2} + b^{*2}}$$

where

$$f(I) = \begin{cases} I^{1/3} & \text{for } I > 0.008856 \\ f(I) = 7.7871 + 16/116 & \text{Otherwise} \end{cases}$$

Step 2. Calculate a', C' and h'

$$L' = L^*$$
$$a' = (1+G)a^*$$
$$b' = b^*$$
$$C'_{ab} = \sqrt{a'^2 + b'^2}$$
$$h'_{ab} = \tan^{-1}(b'/a')$$

where

$$G = 0.5\left(1 - \sqrt{\frac{\overline{C^*_{ab}}^7}{\overline{C^*_{ab}}^7 + 25^7}}\right)$$

where $\overline{C^*_{ab}}$ is the arithmetic mean of the C^*_{ab} values for a pair of samples. Note that h'_{ab} should be a value between 0° and 360° depending on a' and b' values.

Step 3. Calculate $\Delta L'$, $\Delta C'$ and $\Delta H'$

$$\Delta L' = L'_b - L'_s$$
$$\Delta C'_{ab} = C'_{ab,b} - C'_{ab,s}$$
$$\Delta H'_{ab} = 2\sqrt{C'_{ab,b} C'_{ab,s}} \sin\left(\frac{\Delta h'_{ab}}{2}\right)$$

where $\Delta h'_{ab} = h'_{ab,b} - h'_{ab,s}$

Step 4. Calculate CIEDE2000 ΔE_{00}

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H'_{ab}}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'_{ab}}{k_C S_C}\right)\left(\frac{\Delta H'_{ab}}{k_H S_H}\right)} \quad 2.3.23$$

where

$$S_L = 1 + \frac{0.015\left(\overline{L'} - 50\right)^2}{\sqrt{20 + \left(\overline{L'} - 50\right)^2}}$$

and

$$S_C = 1 + 0.045\,\overline{C'_{ab}}$$

and

$$S_H = 1 + 0.015\,\overline{C'_{ab}}\,T$$

where

$$T = 1 - 0.17\cos\left(\overline{h'_{ab}} - 30^\circ\right) + 0.24\cos\left(2\overline{h'_{ab}}\right) + 0.32\cos\left(3\overline{h'_{ab}} + 6^\circ\right) - 0.20\cos\left(4\overline{h'_{ab}} - 63^\circ\right)$$

and

$$R_T = -\sin(2\Delta\theta)R_C$$

where

$$\Delta\theta = 30\exp\left\{-\left[\left(\overline{h'_{ab}} - 275^\circ\right)/25\right]^2\right\}$$

and $$R_C = 2\sqrt{\frac{\overline{C'_{ab}}^7}{\overline{C'_{ab}}^7 + 25^7}}$$

where $\overline{L'}$, $\overline{C'_{ab}}$, and $\overline{h'_{ab}}$ are the arithmetic means of the L', C'_{ab} and h'_{ab} values for a pair of samples.

The CIEDE2000 formula is obviously far more complicated than the other formulae. However, a computing program can carry out all the calculations almost instantaneously.

2.3.6 Colour Order Systems

In addition to the CIE colour specification, a colour order system is another approach to describe a colour quantitatively. By definition, a colour order system is a conceptual system of organized colour perceptions. For practical purpose, a colour order system is usually depicted by a physical system consisting a large number of ordered colour patches. Various colour order systems have so far been established based upon different principles. These include the Munsell color system, Natural colour system (NCS), Ostwald system, DIN system, OSA uniform colour scale system, etc. Reviews on colour order systems are given by Berns (2000, p.36) and Choudhury (1996b). The current study used the measured reflectance data for the colour samples of three colour order systems, Munsell, NCS and DIN, as test-colour samples. Details about these three colour systems are also described by Hunt (1998, p.134).

2.3.6.1 Munsell System

The Munsell system is a widely used colour order system, originated by the American artist A. H. Munsell in 1905 (Munsell 1905), and extended and refined in various ways since. The system divides the colour space into three dimensions, Munsell hue, Munsell value and Munsell chroma, as shown in Figure 2.3.8.

Figure 2.3.8 Arrangement of colours in Munsell color order system. Hues are represented along the circumference of a circle divided into five principal hues, Red (R), Yellow (Y), Green (G), Blue (B) and Purple (P), and subdivided into five intermediate hues (YR, GY, BG, PB and RP). The 10 portions are then subdivided into 10 divisions to give a total of 100 hues. The figures in parentheses reflect hue expressed on a continuous scale between 1 and 100. Munsell value, represented vertically along the axis of the circle, is divided into 10 equal steps from black (0) to white (10). Munsell chroma is represented by the distance from the centre (neutral) to a maximum of 17 (reproduced from Choudhury 1996b).

An important feature of the Munsell system is that the colours are arranged so that, for each perceptual attribute used, as nearly as possible the perceptual difference between any two neighboring samples is constant. Munsell Book of Colour Glossy and Matte Editions are representative exemplifications of the system.

2.3.6.2 NCS System

The NCS system was developed in Sweden (Johansson 1937). The guiding principle of the system is defining a colour by its resemblance to Hering's six elementary colours, black (B), white (W), yellow (Y), red (R), blue (B), and green (G), expressed as percentages. The elementary colours are usually shown as a three-dimensional colour space resulting in NCS hue, NCS blackness (or NCS whiteness), and NCS chromaticness, as shown in Figure 2.3.9.

Figure 2.3.9 The NCS constant hue triangle and hue circle (see right hand diagram). Colours are scaled according to their degree of resemblance to the six elementary colours. Hue is the resemblance to the nearest chromatic elementary colour (e.g. Y30R indicates 30% resemblance to red and 70% to yellow). Chromaticness is the resemblance to the colour of the same hue of maximum possible chromatic content and blackness or whiteness is the resemblance of the colour to the perfect black or white (see left hand diagram). The sum of the chromaticness, blackness and whiteness must be 100 (reproduced from Choudhury 1996b).

2.3.6.3 DIN System

The DIN system was developed by Richter and his co-workers in Germany (Richter 1952). The three perceptual variables used are hue (T), saturation (S) and darkness (D), as shown in Figure 2.3.10. Colours of constant dominant (or complementary) wavelength are regarded as being of constant hue. The system specifies 24 principal hues for the whole colour space, having values of T=1 for a yellow, proceeding via reds, purples, blues and greens, to a yellow-green of T=24, and back to T=25=1. The 24 principle hues were chosen to represent equal hue differences between adjacent pairs, all round the hue circle.

The second of the three variables, saturation, S, is a function of distance from the point representing the reference white on a chromaticity diagram, and for colours of the same luminance factor (not the same darkness) equal saturation represents equal perceptual differences from the grey of the same luminance factor. In the colour solid of the DIN system, as show in Figure 2.3.10, the saturation S, is represented by angular distance out from the grey scale axis, evaluated from the black point. The maximum value of S is different for different hues, so that the edge of the top surface is not circular.

The third variable, darkness, D, is related to darkness rather than to lightness, and is not related in a simple manner to luminance factor. In this respect it is similar to blackness in the NCS. The colour solid in Figure 2.3.10 is formed by having the grey scale as a vertical axis, with white at the top, for which D=0, and black at the bottom, for which D=10. An important feature of this system is that the equality of visual spacing is maintained locally and not globally in all three dimensions. An atlas for the DIN system is available, known as the DIN Colour Chart.

Figure 2.3.10 DIN colour solid with three variables, hue (T), saturation (S), and darkness (D) (reproduced from Choudhury 1996b).

2.3.7 Chromatic Adaptation Transforms

Chromatic adaptation is one of the most important characteristics of human visual system. It describes the process of favorable or useful adjustment of the sensory process to compensate for changes in the spectral quality of light source in order to keep visual perception of colour approximately constant. Light sources differ greatly in their SPDs (see Figures 2.3.3 to 2.3.5). Hence, tristimulus values calculated from Equation 2.3.1 for the same sample also differ greatly under different light sources. Table 2.3.1 gives examples for theoretical samples reflecting 100% of the light at each wavelength. Note that the huge change in Z between different illuminants in the table. Really good whites (e.g. MgO or $BaSO_4$ powder) reflect about 98% of light at all wavelengths in the visible region, and the values in Table 2.3.1 are therefore close to those which would be obtained for such surfaces.

A typical example of chromatic adaptation phenomenon is that a piece of white paper will appear white whether it is seen outdoors in daylight or indoors under an artificial light. A chromatic adaptation transform (CAT) refers to a mathematical model, which is capable of accurately predicting the corresponding colours, i.e. two sets of tristimulus values corresponding to the same colour appearance for an observer fully adapted under a test and a reference illuminant. As indicated above, the tristimulus values for corresponding colours may be very different. In contrast, L*, a* and b* values change relatively little as the illuminant changes. (They are constant for samples which reflect the same percentage of light at all wavelengths, but this is not true for other samples.) A chromatic adaptation transform is a very important part for quantifying colour inconstancy (see Section 2.3.8) and colour rendering (see Section 2.3.9) properties of light sources. Both phenomena will be investigated in Chapter 6.

Numerous CATs have so far been derived to fit different visual data sets. According to Luo (2003), these CATs can be divided into two groups in terms of their performances: CIELAB (CIE 1986), RLAB (Fairchild 1996, p.338) and von Kries (1911), and CIECAT94LAB (Nayatani 1999), CMCCAT97 (Luo 1998), CMCCAT2000 (Li 2002) and CAT02 (Moroney 2002). Luo's study also showed that the latter group performed significantly better than the former. In this study, one representative CAT was chosen from each of the two groups (von Kries from the first group and CMCCAT2000 from the second one) for the evaluation of colour rendering properties of daylight simulators. The von Kries was chosen because it is an earliest, fundamental and widely used CAT, and it was also adopted by the CIE for calculating the CIE colour rendering index (see Section 2.5.4.1). The CMCCAT2000 was chosen because it is a recent and more elaborate CAT and was proved to have a better performance than the old ones in fitting the experimental data (Luo 2003). The detailed calculation procedures for these two CATs are described below.

Note that CAT02 is the latest developed CAT. It is a modification of CMCCAT2000 and is incorporated in the new CIE colour appearance model, CIECAM02 (Moroney 2002). CAT02 has a better compatibility to CMCCON97 and the coefficients were optimised by removing one experimental data set, McCann data set, which was performed under a set of quite chromatic and low illumination conditions. However, during the work of this study, CAT02 was not published so CMCCAT2000 was implemented as the representative of advanced CATs for the calculation of colour rendering index and colour inconstancy index (see Section 2.3.8). The results are thought to be very similar by using either CMCCAT2000 or CAT02 for this study.

Comprehensive reviews on the phenomenon of chromatic adaptation and CATs are given by Bartleson (1977-8), Fairchild (1998, p.175) and Luo (2000b). Bartleson commented that it was difficult to point to a successful CAT based on his study. Despite the wide use of the oldest CAT, von Kries CAT, a more advanced and realistic model is in demand. Luo's study revealed that there are large differences between different CATs in terms of predicted colour shifts, and CMCCAT2000 performs the best amongst all available CATs, especially for the data sets accumulated from the use of surface colours.

2.3.7.1 von Kries

In 1904, von Kries (1911) studied chromatic adaptation following the Young-Helmholz theory, which assumes that, although the responses of the three cone types (RGB) are affected differently by chromatic adaptation, the relative sensitivities of each of the three cone mechanisms remain unchanged. Hence chromatic adaptation can be considered as a reduction in sensitivity by a constant factor for each of the three cone mechanisms. The magnitude of each factor depends upon the colour of the stimulus to which the observer is adapted. The relationship, given in Equation 2.3.24, is known as the von Kries coefficient law.

$$R_c = \alpha R = (\frac{R_{rw}}{R_w})R \qquad 2.3.24$$

$$G_c = \beta G = (\frac{G_{rw}}{G_w})G$$

$$B_c = \gamma B = (\frac{B_{rw}}{B_w})B$$

$$where \quad \frac{R}{R_w} = \frac{R_c}{R_{rw}}; \quad \frac{G}{G_w} = \frac{G_c}{G_{rw}}; \quad \frac{B}{B_w} = \frac{B_c}{B_{rw}}$$

and R_c, G_c, B_c and R, G, B are the cone response of the same observer, but viewed under test and reference illuminant respectively, R_{rw}, G_{rw}, B_{rw} and R_w, G_w, B_w are the cone response for the reference white under the reference and test illuminant respectively. The terms α, β and γ are the von Kries coefficents corresponding to the reduction in sensitivity of the three cone mechanisms due to chromatic adaptation.

In 1974, the CIE technical committee on colour rendering (CIE 1974) adopted a version of the von Kries model derived by Helson and co-workers. It is still in use for making small adjustments to account for differences in colours in illuminants to be compared for colour-rendering properties. This procedure is given below.

Step 1. Calculation of R, G, B; R_{rw}, G_{rw}, B_{rw}; and R_w, G_w, B_w using Judd's cone transformation in Equation 2.3.25.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.000 & 1.000 & 0.000 \\ -0.460 & 1.360 & 0.100 \\ 0.000 & 0.000 & 1.000 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad 2.3.25$$

Step 2. Calculation of the α, β and γ von Kries coefficients and the R_c, G_c, B_c values using Equation 2.3.24.

Step 3. Calculation of corresponding tristimulus X_c, Y_c, Z_c using Equation 2.3.26.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \begin{bmatrix} 2.954 & -2.174 & 0.220 \\ 1.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 1.000 \end{bmatrix} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \qquad 2.3.26$$

2.3.7.2 CMCCAT2000

Chromatic adaptation transform CMCCAT2000 (Li 2002) originates from CMCCAT97 (Luo 1998). It is much simpler than CMCCAT97 in the calculation and also fits the available data sets better. The full steps in using the CMCCAT2000 are given below.

Step 1. For the sample, calculate

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M \begin{bmatrix} X/Y \\ Y/Y \\ Z/Y \end{bmatrix} \qquad 2.3.27$$

$$where \quad M = \begin{bmatrix} 0.7982 & 0.3389 & -0.1371 \\ -0.5918 & 1.5512 & 0.0406 \\ 0.0008 & 0.0239 & 0.9753 \end{bmatrix}$$

Similarly calculate R_w, G_w, B_w from x_w, y_w, Y_w and R_{wr}, G_{wr}, B_{wr} from x_{wr}, y_{wr}, Y_{wr}.

Step 2. Calculate the degree of adaptation, D.

$$D = F\{0.08\log_{10}[\{L_{A1} + L_{A2})/2] + 0.76 - 0.45(L_{A1} - L_{A2})/(L_{A1} + L_{A2})\} \qquad 2.3.28$$

where F equals one for average viewing condition and F equals 0.8 for dim and dark-surround (project image) conditions, and where L_{A1} and L_{A2} are the luminances of the test and reference adapting fields respectively. If D is greater than one or less than zero, set it to one or zero respectively.

Step 3. Calculate R_c, G_c, B_c from R, G, B (similarly R_{wc}, G_{wc}, B_{wc} from R_w, G_w, B_w).

$$R_c = [D(R_{wr}/R_w) + 1 - D]R \qquad 2.3.29$$
$$G_c = [D(G_{wr}/G_w) + 1 - D]G$$
$$B_c = [D(B_{wr}/B_w) + 1 - D]B$$

Step 4. Calculate for the reference illuminant the corresponding tristimulus values for the sample, X_c, Y_c, Z_c and for the adopted white, X_{wc}, Y_{wc}, Z_{wc}.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = M^{-1} \begin{bmatrix} R_cY \\ G_cY \\ B_cY \end{bmatrix} \qquad 2.3.30$$

2.3.8 Colour Inconstancy Index

As the human visual system is very good at compensating for changes in the level and colour of illuminants, there is a tendency for the appearance of colours to remain approximately constant over a wide range of conditions. This phenomenon is known as colour constancy (Hunt 1998, p.123). However, in most situations, some changes in colour appearance do occur, and then there is a departure from colour contancy, referred to as colour incontancy. The degree of colour inconstancy for a sample can be measured by an index, which calculates the colour difference between the corresponding colour of a sample (when transformed, by means of chromatic adaptation transform, from a test to a reference illuminant) and the actual colour of that sample measured or computed in the reference illuminant.

A colour inconstancy index, namely CMCCON02, was recently developed by Luo et al (2003) as part of the work of the Colour Measurement Committee (CMC) of the Society of Dyers and Colourists, with a view to its possible subsequent adoption as a British Standard and as an International Standard. However, during the work of this study, CMCCON02 was not published so an earlier version named CMCCON00 (Luo 2000a) was implemented. The main difference between these two versions is that CMCCON00 uses the CMCCAT2000 while CMCCON02 uses the CAT02 chromatic adaptation transform (see Section 2.3.7). The three steps in calculating CMCCON00 are described below:

Step 1. The tristimulus values, X, Y, Z of a sample in a test illuminant are measured or computed, and the values X_r, Y_r, Z_r of the sample in a reference illuminant are measured or computed similarly.

Step 2. Using the CMCCAT00 Chromatic Adaptation Transform (see Section 2.3.7.2) with the factor D set equal to 1.0, the tristimulus values, X, Y, Z are used to compute the tristimulus values, X_c, Y_c, Z_c for the corresponding colour in the reference illuminant.

Step 3. Using a suitable colour difference formula, the colour difference, ΔE, defined by the difference between X_c, Y_c, Z_c and X_r, Y_r, Z_r is computed. This difference, ΔE, provides the colour inconstancy index, CMCCON00.

2.3.9 Colour Rendering

Colour rendering by definition is the effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance against a reference illuminant (CIE 1987). As early as 1896, Peterson (1896) demonstrated the change of the spots of an imitated leopard skin from brown under daylight to olive green under a gas, an oil and an electric lamp individually. Colour rendering property is a very important criterion with respect to the quality of light sources. Poor colour rendering causes severe colour distortion and affects critical colour judgement. Wright (1967) found that the use of tungsten lamps may create problem in medical diagnosis. For instance, cyanosis exhibits a bluish hue of certain part of the human body such as lips, finger nails, ear lobes etc. due to low oxygen content of blood. This is difficult to assess under a tungsten light source as the infected parts appear to be darker and not bluer.

To find a precise measure to quantify the colour rendering property of a light source has been a challenge for colour scientists for many decades, particularly since the widespread use of fluorescent lights. The difficulty lies in the fact that colour rendering is a phenomenon associated with many factors, i.e. the SPD of the light source, state of chromatic adaptation, the choice of reference illuminant, viewing condition, etc. Early attempts in evaluating colour rendering can be traced in literature published by Jerome (1953, 1976), Barnes (1957), Nickerson (1958, 1960, 1962, 1965), Crawford (1959, 1963), Wyszecki (1959), Azuma (1960), Hennicke (1960), Münch (1960, 1963), Ouweltjes (1960, 1969), Nayatani (1972b & c), and Halstead (1977). Recent studies on colour rendering are given by Schanda (1981, 2002), Mori (1982), Seim (1985), Boynton (1990), Embrechts (1992), Xu (1993, 1995), Hashimoto (1997), Fuchida (1997), Yaguchi (1999) and Trigt (1999).

The measures proposed by the above researchers for quantifying colour rendering fall into two categories. One is an objective measure of colour rendering and the other is the test colour method. Objective measure is a sample independent method which only concerns whether there is any excess or deficiency of emission in any part of the spectrum of a light source in comparison with a reference illuminant. The band value method (see Section 2.5.1) proposed by Bouma (1937) and Crawford (1963) is an example of this objective measure. The test colour method is a subjective method, which is based on the principle for assessing the magnitude of shift in chromaticity of an object colour illuminated in turn by a test and a reference light source. The CIE method to calculate a colour rendering index (CIE 1974, CIE 1995a) is an example of this approach (see Section 2.5.4.1).

The advantage of the test colour method is that it is based on viewing samples under light sources as occurs in practice. Correction for chromatic adaptation can be incorporated and extra test colours be included. Colour rendering property can be expressed by a single number (e.g. CIE general colour rendering index). However, because different reference illuminants are specified for light sources with different CCT, an equal value of the index for two light sources does not necessarily mean the two sources have equal colour rendering property. In addition, the test colours, e.g. the CIE test colours used for calculating the CIE colour rendering index, may not be representative of samples in general. The index also does not indicate the direction of the colour shift.

2.3.10 Metamerism

A number of definitions have been proposed for metamerism. According to Judd and Wyszecki (1963), metameric object colours are a pair of colours that when illuminated by a given reference illuminant, reflect stimuli of different SPDs that produce a good match under the same viewing conditions. This phenomenon is called metamerism. Metamerism is a serious problem for colourists. In most colorant processes a standard colour of unknown composition is matched by using a mixture of different colorants. A colourist may be happy with his matched sample under a particular light, but when the user observes the standard and sample under a different light, he may be surprised to see a distinct colour difference between them. Metamerism may be caused not only by change of illuminant, but also by change of observer, viewing geometry, field size, etc. Illuminant metamerism is the most important type of metamerism and is closely associated with the present study. Unless specifically indicated, metamerism usually refers to illuminant metamerism only (Choudhury 2000, p.295).

Many researchers have conducted studies on metamerism, and reviews given by Moridian (1976) and Choudhury (1992, 1996a). Moridian evaluated different types of metamerism indices and recommended one index which uses the lightness index instead of reflectance (see Section 2.3.9.2) having the best correlation with the visual results. Choudhury also studied various metamerism indices and concluded that the illuminant-dependent special indices give better performances than the general metamerism indices. He recommended that further metamerism indices be developed by incorporating an advanced chromatic adaptation transform.

2.3.10.1 Wavelength Intersections

For an object pair to be metameric, the reflectance curves of its members must be non-identical and must intersect at multiple wavelengths throughout the visible range. Stiles and Wyszecki (1977) verified on a theoretical basis that two stimuli to be metameric, must cross at least three times. Kuehni (1978) noticed that for coloured textile samples more pairs were observed with four to six crossovers than with just three crossovers. In recent years, there have been many debates on the locations of spectral intersections of the metamers of metameric pairs. Thornton (1974) observed that if metameric reflectances cross at three specific wavelengths, then a three narrow band lamp emitting principally at these wavelengths should render the specimens identical in appearance. He then revealed that spectral intersection often occurs at three wavelengths which are the sensitivity peaks of the human visual system. He named these wavelengths (458, 541 and 611 nm) as the prime wavelengths and demonstrated their importance in light source design (Thornton 1986).

Doubts arose on Thornton's prime wavelength proposal. Kuehni and Berns (1994) considered that Thornton's conclusion was coincidental. Robertson (1994) commented that the location of intersections depends on the nature of metameric SPD and he did not think fundamental significance existed for the location of intersections. Ohta (1987), however, claimed that strongly metameric pairs show intersection convergent at three wavelengths, 450, 540 and 610 nm, which are close to those proposed by Thornton. Berns and Kuehni (1990) reported the crossover locations depend on the spectral properties of the metameric stimuli. They concluded that for object colours, crossover could occur in almost any region of the visible spectrum depending on the colorant absorption bandwidths.

2.3.10.2 Metamerism Indices

A metamerism index is a measure of metamerism based on the spectrophotometric properties of metameric pairs. Ideally it should represent the extent of mismatch under various illuminants. Various metamerism indices have been proposed for quantifying the degree of metamerism. These include the CIE Special Index of Metamerism (CIE 1986) and other general indices of metamerism proposed by Bridgeman (1969), Nimeroff and Yurow (1965), Moradian *et al* (1977), Berns (1983), etc. Note that the closer the pair is to a perfect match under a reference illuminant, the less critical is the choice of method for calculating metamerism indices.

CIE Special Index of Metamerism

A metamer means the two samples of a pair show different reflectance spectra but have identical tristimulus values under a reference illuminant, e.g. CIE D65 (CIE 1987). The CIE Special Index of Metamerism (CIE 1986) calculates the colour difference (CIELAB or other colour difference formula as appropriate) between the two samples of a metamer when they are illuminated under the test illuminant. For cases where a colour difference already exists under the reference illuminant (a phenomenon termed as paramerism), the CIE advised that suitable accounts should be made for this difference. Multiplicative or additive approaches to correct the inequalities of tristimulus values were introduced by Brockes (1970).

Note that this index can be used for different purposes. Given one pair of metameric samples, the index can be calculated for each of a range of light sources (e.g. CIE illuminant A and various CIE F illuminants) for a pair which matches under CIE illuminant D65. The maximum (or mean) of the values gives an overall indication of the quality of the match. For a particular light source (e.g. a daylight simulator), the index can be calculated for a number of typical pairs of metameric samples and the mean used to assess the quality of the source. The index used for evaluating daylight simulators was specifically termed by the CIE as CIE metamerism index (see Section 2.5.4.2).

General Indices of Metamerism

The CIE Special Index of Metamerism is illuminant specific. It needs one reference and at least one test illuminant. The test illuminant can be varied and a number of indices may be calculated. To make the index illuminant independent and to specify the degree of metamerism of a pair of specimens by a single number, a number of general indices of metamerism have been proposed. They are based on spectral difference between standard and trial, which is inevitable for metamers. Accordingly Bridgeman (1969) developed the following index:

$$MI = [\sum (R_{1\lambda} - R_{2\lambda})^2]^{1/2} \qquad 2.3.31$$

where R represents the reflectances of the colour surfaces investigated at each reported wavelengths, subscripts 1 and 2 denote the two samples of a pair.

Bridgemen's index does not take into account the variation of the eyes' sensitivity to different spectral lights. For instance, differences in R for wavelengths around 400 nm and 700 nm are obviously less important than those for intermediate wavelengths.

Nimeroff and Yurow (1965) weighted the spectral differences with colour matching functions, a linear transformation of the spectral sensitivity functions of the three cone primaries, and they proposed an index as below:

$$MI = [\sum_{\lambda}\{\bar{x}_{\lambda}(\Delta R_{\lambda})\}^2 + \sum_{\lambda}\{\bar{y}_{\lambda}(\Delta R_{\lambda})\}^2 + \sum_{\lambda}\{\bar{z}_{\lambda}(\Delta R_{\lambda})\}^2]^{1/2} \qquad 2.3.32$$

Or

$$MI = [\sum_{\lambda}\{\bar{u}_{\lambda}(\Delta R_{\lambda})\}^2 + \sum_{\lambda}\{\bar{v}_{\lambda}(\Delta R_{\lambda})\}^2 + \sum_{\lambda}\{\bar{w}_{\lambda}(\Delta R_{\lambda})\}^2]^{1/2} \qquad 2.3.33$$

$$where \quad \bar{u}(\lambda) = 2\bar{x}(\lambda)/3, \quad \bar{v}(\lambda) = \bar{y}(\lambda), \quad \bar{w}(\lambda) = [3\bar{y}(\lambda) - \bar{x}(\lambda) + \bar{z}(\lambda)]/2$$

Moradian *et al* (1977) suggested the use of the lightness index proposed by Wyszecki ($L_{\lambda}=25(R_{\lambda})^{1/3}-17$), instead of reflectance and the index becomes:

$$MI = [\sum_{\lambda}\{\bar{x}_{\lambda}(\Delta L_{\lambda})\}^2 + \sum_{\lambda}\{\bar{y}_{\lambda}(\Delta L_{\lambda})\}^2 + \sum_{\lambda}\{\bar{z}_{\lambda}(\Delta L_{\lambda})\}^2]^{1/2} \qquad 2.3.34$$

This index allows for the fact that differences in R for low R values (e.g. R=10 to R=20) are much more important than the same differences for high R values (e.g. R=80 to R=90).

Viggiano (2001) proposed a metric for comparison of radiance ratio (e.g. reflectance) spectra, which is called as a perception-referenced metamerism index (also termed as Spectral Comparison Index) based on colorimetric principles. The metric provides a single-valued result, which is the maximum colour difference to be encountered under practical viewing conditions. It is a linear approximation to the sum of a series of ΔE^*_{ab} values wherein the two spectra differ only within a single narrow wavelength band, as expressed in Equation 2.3.35.

$$M_V = \sum_{\lambda} w(\lambda) \cdot \|\Delta\beta(\lambda)\| \qquad 2.3.35$$

where $\Delta\beta(\lambda)$ is the difference between the two radiance ratio spectra, and

$$w(\lambda)=\sqrt{(\frac{dL^*}{d\beta(\lambda)})^2+(\frac{da^*}{d\beta(\lambda)})^2+(\frac{db^*}{d\beta(\lambda)})^2} \qquad 2.3.36$$

The derivatives of L*, a*, and b* with respect to β(λ) are computed via the chain rule:

$$\frac{dL^*}{d\beta(\lambda)}=116\cdot k\cdot s(\lambda)\cdot \bar{y}(\lambda)\cdot\frac{d}{dY}f(\frac{Y}{Y_n}) \qquad 2.3.37$$

$$\frac{da^*}{d\beta(\lambda)}=500\cdot k\cdot s(\lambda)\cdot\left[\bar{x}(\lambda)\frac{d}{dX}f(\frac{X}{X_n})-\bar{y}(\lambda)\frac{d}{dY}f(\frac{Y}{Y_n})\right]$$

$$\frac{db^*}{d\beta(\lambda)}=200\cdot k\cdot s(\lambda)\cdot\left[\bar{y}(\lambda)\frac{d}{dY}f(\frac{Y}{Y_n})-\bar{z}(\lambda)\frac{d}{dZ}f(\frac{Z}{Z_n})\right]$$

and, further:

$$\frac{d}{du}f(\frac{u}{u_n})=\frac{1}{3u}\cdot f(\frac{u}{u_n}),\quad \text{if } \frac{u}{u_n}>0.008856 \qquad 2.3.38$$

or

$$\frac{d}{du}f(\frac{u}{u_n})=\frac{7.787}{u_n},\quad \text{if } \frac{u}{u_n}\le 0.008856$$

where u is replaced by, in turn, X, Y, Z and u_n by the corresponding tristimulus value of the specified white object, s(λ) is the spectral power distribution of the reference illuminant (say CIE D65).

2.3.10.3 Metameric Correction Using Parameric Decomposition

The calculation of the CIE Special Metamerism Index requires the metameric pair to be a perfect match under the reference illuminant. Unfortunately, for most real samples, this condition is not satisfied. Simple additive and multiplicative approaches were proposed by Brokes (1970) to correct the inequalities of tristimulus values of a metameric pair under the reference illuminant. Fairman (1987) suggested spectral correction of one of the specimen using the Cohen-Kappauf decomposition technique (Cohen 1982, 1985). Cohen and Kappauf derived a square symmetrical matrix R from a weight set (e.g. ASTM weights) represented by matrix A, expressed as:

$$R = A(A'A)^{-1}A' \quad \text{where} \quad A = \begin{bmatrix} w_{X,1} & w_{Y,1} & w_{Z,1} \\ w_{X,2} & w_{Y,2} & w_{Z,2} \\ \vdots & \vdots & \vdots \\ w_{X,n} & w_{Y,n} & w_{Z,n} \end{bmatrix} \qquad 2.3.39$$

and A' is the transpose of matrix A. The operations of matrix R are based on Wyszecki's hypothesis (Wyszecki 1953) that the colour processing mechanism preserves only part of the colour stimulus, the fundamental, evoking a single colour sensation, and ejects the residual, with no effect on the colour sensation. Hence, any reflectance spectra can be decomposed into two components called fundamental stimulus and residual stimulus (also termed as metameric black) using matrix R. If the matrix R is multiplied by the reflectance spectrum N (n by 1 matrix), the fundamental stimulus N^* ($N^* = RN$) is obtained. The residual stimulus B is given by subtracting fundamental stimulus from reflectance spectra ($B = N-N^*$).

The general procedure for parameric correction is to decompose both the standard and trial of a parameric pair of stimuli into their component fundamental stimuli and metameric blacks. Then the metameric black of the trial is added to the fundamental stimulus of the standard. The result is a corrected spectral distribution, as expressed below:

$$N_c = N_s^* + B_t = RN_s + (I - R)N_t \qquad 2.3.40$$

where I is an identity matrix, N_s is the reflectance spectra of the standard and N_t the reflectance spectra of the trial.

2.3.11 Colorant Formulation

Colorant formulation is the commercial application of computer methods to recipe formulation (McDonald 1997, p.209). The Kubelka-Munk (KM) optical theory is widely used in commercial formulation systems, in which the concentration of a selected set of colorants required to match a target shade are predicted by computer software. The method was used in this study to generate metamers from a set of dyes. The light scattering and absorption in a colorant layer can be approximated by the KM theory. For opaque materials, the KM function can be expressed in a simplified form as:

$$\frac{K}{S}=\frac{(1-R_{\infty})^{2}}{2R_{\infty}} \qquad 2.3.41$$

where K is the absorption coefficient, S is the scattering coefficient and R_{∞} is the reflectance of light of a given wavelength by a sample of infinite thickness. The ratio (K/S) is commonly known as 'K over S' (Berns 2000, p.164).

The advantage of the KM theory is to convert the reflectance into the K and S values, which are additive for a particular colouring system. For example, for typical paint and plastic materials, the resultant K/S from a three-colorant formulation can be expressed by:

$$\frac{K}{S}=\frac{K_{s}+c_{1}K_{1}+c_{2}K_{2}+c_{3}K_{3}}{S_{s}+c_{1}S_{1}+c_{2}S_{2}+c_{3}S_{3}} \qquad 2.3.42$$

where c is the concentration coefficient, subscript s and 1 to 3 represent the substrate, and colorants 1 to 3 respectively. For textile and dyed paper colouring system, the scattering power is mainly contributed by the substrate, i.e. undyed fabric or paper. Hence, equation 2.3.42 can be rewritten as:

$$\frac{K}{S}=(\frac{K}{S})_{s}+c_{1}(\frac{K}{S})_{1}+c_{2}(\frac{K}{S})_{2}+c_{3}(\frac{K}{S})_{3} \qquad 2.3.43$$

Equation 2.3.43 can be expressed in matrix notation:

$$G = AC, \text{ and } C = A^{-1}G \qquad 2.3.44$$

$$\textit{where } G = \begin{bmatrix} (\frac{K}{S})_{\lambda_1} - (\frac{K}{S})_{s,\lambda_1} \\ (\frac{K}{S})_{\lambda_2} - (\frac{K}{S})_{s,\lambda_2} \\ \vdots \\ (\frac{K}{S})_{\lambda_k} - (\frac{K}{S})_{s,\lambda_k} \end{bmatrix}, \; A = \begin{bmatrix} (\frac{K}{S})_{1,\lambda_1} & (\frac{K}{S})_{2,\lambda_1} & (\frac{K}{S})_{3,\lambda_1} \\ (\frac{K}{S})_{1,\lambda_2} & (\frac{K}{S})_{2,\lambda_2} & (\frac{K}{S})_{3,\lambda_2} \\ \vdots & & \\ (\frac{K}{S})_{1,\lambda_k} & (\frac{K}{S})_{2,\lambda_k} & (\frac{K}{S})_{3,\lambda_k} \end{bmatrix}, \; C = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix}$$

Equation 2.3.44 only gives the initial formulation. To achieve a satisfactory colorimetric match, the final formulation usually involves an iterative loop. A general workflow of colorant formulation is introduced by McDonald (1997, p.218), as shown in Figure 2.3.11. Stage 7 in Figure 2.3.11 is the most intriguing section. Equation 2.3.45 is a matrix widely used for calculating the correct recipe (McDonald 1997, p.221).

$$\begin{bmatrix} \Delta c_1 \\ \Delta c_2 \\ \Delta c_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial c_1}{\partial X} & \frac{\partial c_1}{\partial Y} & \frac{\partial c_1}{\partial Z} \\ \frac{\partial c_2}{\partial X} & \frac{\partial c_2}{\partial Y} & \frac{\partial c_2}{\partial Z} \\ \frac{\partial c_3}{\partial X} & \frac{\partial c_3}{\partial Y} & \frac{\partial c_3}{\partial Z} \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \qquad 2.3.45$$

At the end of each loop in the iteration procedure, the above correction matrix is calculated. If the ΔX, ΔY and ΔZ differences from standard are not within tolerance, they are inserted into the correction matrix to compute the changes in dye concentration required to bring the recipe nearer to the target.

Figure 2.3.11 Flow chart showing the basis of most computer match-predication systems (reproduced from McDonald 1997, p.218)

2.3.12 Colour Measuring Instruments

Colour measuring instruments play an important role in colorimetry. The goal of most colour measurement is to provide a numerical specification of the colour of a sample. There is a wide range of colour measuring instruments, e.g. colorimeters, spectrophotometers, spectroradiometers, tele-spectroradiometers, etc., made by different manufacturers with different design and specifications. Berns (2000, p.82) described colour measuring instruments in great detail. The current study used a spectrophotometer and a tele-spectroradiometer for measuring surface colours and light sources, respectively. These are introduced below.

2.3.12.1 Spectrophotometers

Spectrophotometers are instruments that measure the percentage (or fractional) reflectance from, or the transmittance through, materials as a function of wavelength. They can be connected to a computer and the reflectances of a measured surface, including the calculated CIE data such as X, Y, Z, L*, a*, b*, etc. are displayed on the computer. For colour measurement, spectrophotometers only measure the visible spectrum, usually from 380 nm to 780 nm with a 10 nm or 20 nm interval. The main components of a spectrophotometer include a light source, an optical system for defining the geometric conditions of measurement, some means of dispersing light, and a detector and signal processing system that converts light into signals suitable for analysis. Four standard geometries (illumination/viewing) were defined by the CIE (1986) for reflectance measurement, denoted as Diffuse/Normal, Normal/Diffuse, 45/Normal and Normal/45, respectively.

The spectrophotometer used in this study is a GretagMacbeth ColorEye 7000A, as shown in Figure 2.3.12. The instrument is configured with true dual-beam optical design and has the capacity to measure both reflectance and transmittance. The measurement geometry is diffuse illumination and 8° viewing with specular component included or excluded. The instrument uses a single flash pulsed xenon lamp (a D65 simulator) as the light source, together with automated UV calibration and control. The measured wavelength ranges from 360 nm to 750 nm with 10 nm interval. The photometric range of the instrument is 0 to 200%. According to the manufacturer's certificate, the inter-instrument agreement is 0.08 average ΔE^*_{ab} and repeatability (for a white) is less than 0.01 RMS (root of mean square) ΔE^*_{ab}.

Figure 2.3.12 Image of GretagMacbeth ColorEye 7000A spectrophotometer (downloaded from the company web site)

2.3.12.2 Spectroradiometers

Spectroradiometers are designed to measure radiometric quantities: irradiance (W/m^2) or radiance ($W/m^2 \cdot sr$). The radiometric energy is measured over the visible spectrum with a fixed interval such as 5 nm, 10 nm or 20 nm. The colorimetric values are expressed by luminance (cd/m^2) and illuminance (lx) for radiance and irradiance respectively. The tele-spectroradiometer (TSR) is the most frequently used instrument in this category. The key components of a TSR comprise a telescope, a monochromator and a detector. No internal light source is required as a TSR is used to measure light sources or self-luminous colours (e.g. CRT colours) at a distance.

In this study, a Minolta CS-1000 Tele-spectroradiometer, as shown in Figure 2.3.13, was used to measure light sources. The instrument is configured with a SLR (single lens reflex) optical system for targeting an object and a high-resolution photodiode array for capturing the signal, the wavelength ranging from 380 nm to 780 nm with 5 nm bandwidth. The instrument features a high signal to noise ratio and low polarisation error (below 5%). According to the manufacturer, the instrument is traceable to a NPL standard, with measurement accuracy expressed as: ±2%±1digit, ±0.0015 and ±0.0010 for luminance, chromaticities x and y, respectively for a working standard (tungsten light). The instrument can work in three modes: auto, internal and external, and manual. Auto mode is designed for measuring a stationary light, for which a sensor detects the target stimulus and then automatically sets a suitable integration time for the measurement.

Figure 2.3.13 Image of Minolta CS 1000 tele-spectroradiometer (downloaded from the company web site)

2.4 Development and Applications of Daylight Simulators

The SPD of a physical or real light source depends on several factors. For instance, the energy distribution of an artificial lamp depends on its make, age, applied voltage etc. For the CIE daylight illuminants, their SPDs were defined based on the combinations of different measurement results on daylight and was originally tabulated at 10 nm interval (see Section 2.3.3.1). As Hunt (1992) pointed out, the 10 nm data were later interpolated to 5 nm and 1 nm interval values, and the theoretical nature of the CIE daylight illuminants made it virtually impossible to realise these illuminants precisely. Real daylight sources (here termed as daylight simulators) have therefore been developed to simulate the standard daylight illuminants only approximately.

2.4.1 Different Types of Daylight Simulators

Wyszecki (1970) conducted a study on daylight simulators and he categorised three major types of daylight simulators: Xe-sources, T-sources and F-sources. The Xe-Sources are high-pressure short-arc xenon lamps. He concluded that suitably filtered xenon-arc lamps provided promising candidates as daylight simulators. The agreement between the SPDs of the Xe-sources and that of the CIE D65 illuminant appears quite good throughout the spectral range from 300 to 800 nm except for a considerable excess of irradiance around 470 nm and above 700 nm. Filter correction incorporated in the Xe-sources seems insufficient for these spectral bands. The T-sources are either tungsten-halogen or tungsten-iodine lamps combined with one or more coloured glass filters used as spectrum modulators. The agreement between the SPDs of the T-sources and those of the CIE daylight iluminants is generally quite good in the visible region of the spectrum. However, in the ultraviolet region (λ<380 nm), the T-sources exhibit serious deficiencies and the use of spectrum modulators, which consist of conventional absorption filters, is insufficient. The F-sources are fluorescent lamps. The discrepancies between the SPDs of the F-sources and those of the CIE daylight illuminants are generally quite severe at the wavelengths of the emission lines. Another discrepancy that is characteristic of fluorescent sources occurs in the wavelength region above 600 nm, where these sources show a rapid decrease of spectral irradiance relative to the corresponding CIE daylight illuminant.

2.4.1.1 Filtered Tungsten Lamps

For filtered tungsten lamp, the technology has been around since electric gas-filled tungsten incandescent lamps became commercially available over 80 years ago. The best known method of making a good daylight simulator is to use an incandescent tungsten lamp with a special blue glass filter. The most critical procedure in developing filtered tungsten lamps is the design of filters. A good design of filters ensures a close simulation of SPD of the lamp with respect to the CIE daylight illuminant. The main drawback of filtered tungsten lamps is the insufficiency of power in the UV range, low energy efficiency and high manufacturing cost.

Research has been conducted to develop a good quality daylight simulator using filtered tungsten lamp. Rich and Jalijali (1990) reported a simulator having a CIE metamerism index category of 'AA' (see Section 2.5.4.2). This simulator used a filtered tungsten-halogen lamp, to provide visible flux, with a miniature fluorescent lamp, to provide ultraviolet flux, and is used in integrating-sphere instruments such as the Hunter D54P, the ACS SpectroSensor II, and the ChromaSensor CS-5. Liu and Berns (1991) proposed an optimisation algorithm for designing coloured glass filters to simulate CIE illuminant D65. The colour filters they used were arranged either side-by-side, or side-by-side in series. The optimised D65 simulators achieved high colour rendering index, relatively high luminous efficacy and CIE metamerism index category 'B' for the visible range. Corrons (1987) and Pons used quartz-halogen incandescent lamps as daylight simulators and also achieved a high colour rendering index and good CIE metamerism index category 'BB' for both visible and ultraviolet wavelength regions.

According to the CIE TC1-44 progress report (Hirschler 1997), the GretagMacbeth light booth (SpectraLight) uses filtered tungsten lamp as a daylight simulator and the lamp is a good simulation of CIE D65 illuminant with metamerism index category 'A' for visible range and 'D' for the UV range. Tailored Lighting Inc. (TLI) also uses a tungsten filament lamp plus filter combination in its ColorView booth with an interesting feature: the colour temperature of the illumination is continuously changeable from 2856K to over 6500K. Both TLI and Color Savvy announced the marketing of new types of daylight simulators based on tungsten filament lamps.

2.4.1.2 Filtered Xenon Lamps

In addition to filtered tungsten lamps, filtered xenon lamps can also realise an excellent daylight simulation. These two kinds of lamps are widely used as daylight simulators in colour measuring instrument such as spectrophotometers. Terstiege (1991) analysed the advantage in using filtered xenon lamps as instrumental light sources. He stated that because the filtered tungsten lamps are insufficient in the SPDs for the UV range, filtered xenon lamps are preferred. Xenon lamps normally have an excess of radiation between 300 nm and 400 nm compared with CIE illuminant D65. However, this radiation can easily be absorbed by filters. The most accurate daylight simulator using filtered xenon-arc lamps was built by Gundlach (1978, 1980) at the German Federal Institute of Material Science and Testing (BAM) for colour measurement purposes. The simulator used a complex filter system, employing 15 components, and achieved 'AA' for the CIE metamerism index category. The applications of filtered xenon sources as daylight simulators were reported by McCamy (1994).

Hirschler (1997) categorised the filtered xenon lamps into three groups: filtered xenon short arc lamps, filtered xenon flash lamps, and combination of filtered and unfiltered xenon flash lamps. Filters need to be well designed for both visible and UV ranges to achieve a good daylight simulation as well as to improve the lamps with respect to ageing and control of the UV-visible ratio. The reported CIE metamerism index category (see Section 2.5.4.2) for filtered xenon flash lamps can be as good as 'AB', 'BA' or 'BB'. Murakami Color Research Laboratory used filtered xenon short-arc lamp in its Model NL500 (Natural Light Standard White Light Source). Ushio Inc. and Toshiba manufacture xenon lamps with filters.

2.4.1.3 Fluorescent Lamps

Fluorescent light sources are commonly found in office buildings, factories, stores and homes. Cool White Fluorescent (CWF) at 4150K is a common wide-band fluorescent light source used for US office or store lighting. TL84 Fluorescent at 4100K is a commercial narrow-band fluorescent widely used in Europe. Ultralume 30 (U30) at 3000K is a commercial narrow-band fluorescent used in the US (Macbeth 1996). Fluorescent lamps are by far the most widely used daylight simulators, with much improved colour rendering properties thanks to recently developed seven-phosphor technologies. They are widely used in luminaires and in light booths, their popularity being due primarily to low cost and simple operation and maintenance as compared to those based on filtered tungsten or xenon lamps (Hirschler 1997).

A detailed description of fluorescent lamps was given by Choudhury (2000, p.11). He stated that fluorescent lamps had been available since the late 1930s. They are usually long tubes, the inside of which is coated with phosphors and with electrodes at the two ends. The tubes are filled with a rare gas that carries the electric discharge until the drop of liquid mercury in the tube has been vaporized. These lamps utilize mercury vapors which radiate light in the visible and ultraviolet wavelength regions. Some of the visible light is transmitted through the translucent coating of the fluorescent powder on the inside of the glass tube. Ultraviolet light, mainly at 253.7 nm, emitted by mercury vapour excites the fluorescent coating to generate additional and spectrally more continuous light in the visible range of wavelengths.

The phosphors are inorganic compounds of high chemical purity and sometimes some metals are added as activators to increase their efficiency. The most important phosphors are halophosphates which emit radiation particularly in the most sensitive green-yellow region of the spectrum creating "white" light. Red emission was poor until lamps like de luxe Warm White lamp which utilizes blends of phosphor were introduced. Other phosphors include metal tungstates, silicates, borates and arsenates. For daylight fluorescent lamps, magnesium tungstate is used as phosphor which emits light at 480 nm. Calcium halophosphate as phosphor and antimony/manganese as activator are used in cool-white fluorescent lamps lacking red light and in modified redder warm-white fluorescent lamps.

Thornton (1971) showed that instead of attempts to duplicate continuous spectrum in fluorescent lamps to match daylight, it is better to match with prime colour lights namely red, green and blue spectral lights. This gives better lamp efficacy (see Section 2.2) and colour rendering. He calculated that the ideal wavelengths for these lines are 450 nm (blue), 540 nm (green) and 610 nm (red). Newer types of phosphors (mostly made of rare earths) emitting lights of narrower bands were developed to produce the 3-line prime lamp (also termed as the 3-band lamp). For instance, Westinghouse in the USA developed the

Ultralume lamps, Philips marketed the TL84 lamp in the UK and Toshiba marketed the D65 3-band lamp. However, none of these lamps are real 3-line prime lamps. The Ultralume has broad green and blue bands and the TL84 actually emits light at six wavelengths. The 3-line prime lamps also show some deficiencies such as a poor metamerism index and poor brightness for materials treated with optical brightening agents.

There is a wide range of different types of fluorescent lamp, according to the types of phosphors used; these vary form those having high efficiency but poor colour rendering, to those having lower efficiency but good colour rendering. The typical luminous efficiencies for fluorescent lamps range from 45 to 95 lm/W (Hunt 1998, p.79). The CIE metamerism indices for fluorescent lamps vary considerably. Mori *et al* (1983) concluded that it was practical to produce a fluorescent lamp with 'BB' category by a relatively simple combination of fluorescent materials. The Japanese standard 8716-1991 reported a new Toshiba fluorescent lamp with the 'BB' category.

The CIE also recommended 12 F illuminants to represent different types of fluorescent lamps (see Section 2.3.3.2). The SPDs of these F illuminants represent those of real fluorescent lamps, available when the CIE recommendation was made. The CIE colour rendering indices for the CIE F illuminants range from 51 to 95 (Hunt 1998, p.265).

2.4.2 Applications of Daylight Simulators in Colorimetry

Because natural daylight can vary quite considerably in SPD due to changeable weather conditions, it is important to develop good daylight simulators for various applications. McCamy (1990) summarised the applications of daylight simulators. He pointed out that artificial illumination, especially artificial daylight illumination, is a critical factor for visual assessment, colour measurement and colorant formulation, etc.

Surface colour industries such as textile, paints, plastics, use a large number of visual assessments in colour matching and colour appraisal. Daylight simulators are widely used for metamerism studies (Mori 1983, Kuo 1996a and 1996b, Schlüpfer 1999, Lester 1999), for testing for ultraviolet-excited fluorescence (Chong 1981, Rich 1990) and for standardization of viewing conditions (ASTM 1992 & 1996, ISO 2000). Daylight simulators are also used for evaluating human visual performance and clarity (Dain 1998a & b, Vrabel 1998).

For colour measuring instruments such as spectrophotometer, daylight simulators, e.g. filtered flash or continuous short-arc xenon lamps, are usually employed as the light sources within the instrument. Details on using daylight simulators for colour measuring instruments were reported by Hirschler (1997).

Colorant formulation is one of the main tasks of modern industrial colour science, aiming to predict the colorant formulation of pigments or dyes for matching a given colour. Spectrophotometers and associated computers with elaborate computational schemes solve this kind of problem in laboratories, formulation plants, and even in retail paint stores. To minimise mismatches due to metamerism, such systems compute the optimum formulation for viewing under the various illuminations that are likely to be encountered in practice. CIE D65 illuminant is generally used to represent daylight in recipe predication (McDonald 1997, p.209). As the CIE standard illuminants exist only theoretically, while the simulated sources in a viewing cabinet actually exists and are usually the contractual basis for acceptable matches, Salzman suggested that the formulation computations be based on the actual SPD of the illumination to be used to judge the match. This logical approach is being accepted by increasing numbers of colourists. To facilitate the colorimetric computations, Macbeth has computed colorimetric weighting factors for the simulations of CIE illuminants D65 and D75 used in Macbeth viewing booths and these weighting factors are supplied in the computer programs used with Macbeth spectrophotometers (McCamy 1990).

2.4.3 Industrial Applications of Different Daylight Simulators

The CIE recommended a series of standard daylight illuminants to represent daylights with CCT at 5000, 5500, 6500 and 7500 K. Daylight simulators with varied CCT are required by various industrial applications. North Sky Daylight at 7500K (D75) is the light produced from a moderately overcast sky as one faces north in the northern hemisphere (south in the southern hemisphere). It is normally used for visual evaluation of opaque materials as outlined in ASTM D1729-96.

Average North Sky Daylight at 6500K (D65) conforms to international standards in Europe, the Far East, and South America. It is generally regarded as the preferred standard source for the surface colour industries such as textiles, paints, plastics, etc. For recipe formulation, CIE D65 illuminant is used as a standard source in recipe prediction and it is also used to provide correlation with instrumental measurements. The Detroit Colour Council, in conjunction with the SAE (Society of Automotive Engineers), adopted the use of D65 for visual evaluation of automotive interiors and exteriors.

Noon Sky Daylight at 5000K (D50) is the desired light source for performing colour quality and uniformity evaluation in the graphic arts industry, as specified in ANSI PH 2.32 and ISO 3664 (see Section 2.5.5.1). The reason lies in the fact that graphic arts products such as transparencies or prints are generally viewed not only under daylight but also under yellower tungsten or fluorescent light. D50 illuminant was therefore chosen as it is less different from tungsten and low CCT fluorescent lights than D65 illuminant (Johnson 1998, p.37).

Horizon Daylight at 2300K is provided by using a tungsten halogen lamp operated at half power. It provides the light quality that is found in early morning sunrise or late afternoon sunset. If an acceptable colour match can be achieved under Horizon Daylight (when the sky is the reddest) and North Sky Daylight (when the sky is the bluest), probably a good match would be possible in any phase of daylight (Macbeth 1996).

2.5 Standards for Specifying Daylight Simulators

The variety of daylight simulators causes concerns for lamp manufacturers and users, as daylight simulators having different SPDs may significantly affect the visual results on colour matching and colour appraisal. At about the same time of the author's study, Lam *et al* (2000-1) conducted an investigation into the influence of various D65 simulators on colour matching. In their study, fifty observers were asked to determine the visual match point using the D&H colour rule under three D65 simulators. The results show that D65 simulators with differing SPDs considerably affect the visual colour matching judgements.

Standardisation of daylight simulators is important for industrial quality control where colour products need to be reproduced consistently and faithfully. So far, various national and international standards have been developed to serve this purpose. These standards include the British standard BS 950, the American standards ANSI PH 2.31, ASTM D1729-96, the Japanese standard JIS Z 8716, 8720, 8726, 9112, CIE publication 13.3, 51, 51.2, and ISO 3664, 3668. The British, American and ISO standards were established mainly for specifying standard viewing conditions for certain applications. As daylight illumination is one of the most important viewing conditions in practice, CIE daylight illuminants were chosen as standard sources in these standards. The specifications for daylight simulators are thus the key contents of the standards. Colorimetric features such as chromaticity coordinates, colour temperature, colour rendering index, metamerism index are generally considered for evaluating the quality of daylight simulators. The British standard particularly specified the tolerance of spectral disagreement between the test simulator and standard illuminant. The Japanese standard provided the relative SPD for a representative D65 fluorescent lamp (Toshiba). Further details for each of the standards including CIE recommendations are described below.

2.5.1 British Standard

British Standard BS950-1967 *Specification for Artificial Daylight for the Assessment of Colour* is one of the earliest standards for specifying a daylight simulator. The standard includes two parts, Part 1 is entitled *Illuminant for Colour Matching and Colour Appraisal*, and Part 2 *Viewing Conditions for the Graphic Arts Industry*. The CIE D65 and D50 illuminants were chosen as the standard sources for Part 1 and Part 2, respectively. For D65 simulators, the chromaticity tolerance was given in the form of a 12-sided polygon with the standard chromaticity (x = 0.3127, y = 0.3291) of CIE D65 illuminant as its centre, see Table 2.5.1. For D50 simulators, only the standard chromaticity was given. For both D65 and D50 simulators, the difference between the SPD of a test simulator and that of the CIE illuminant should also lie within certain limits, namely the tolerance of band value. Band value, also termed as band luminance, is the integration result between the SPD of a light source and CIE standard photometric observer V(λ) for each specified band. The band value approach used in this standard is primarily based on Crawford's study on colour rendering (Crawford 1963). The essence of the method is to simplify the SPD of a light source by dividing the spectrum into a relative small number of bands. This method was later adopted as the British standard for specifying the quality of daylight simulators. In this standard, a set of standard band values was specified for the CIE D65 and D50 illuminants, respectively. Each set includes values for six visible bands and two ultraviolet bands.

When evaluating the quality of daylight simulator using the BS950 method, the SPD of the simulator is first multiplied by the V(λ) function and a luminous power value is generated. Subsequently, the luminous power value for each wavelength is summed for each band as defined in Table 2.5.2. Note that for dealing with the border wavelength between two bands, the luminous power value is divided by two and then used in each band. The band values are then normalised so that the sum of the six visible bands equals 100 lumen in flux. The normalised value in each band is finally compared with those listed in Table 2.5.2. For a test simulator, the deviation of its SPD with respect to that of the CIE illuminant is quantified as the difference of band values. The tolerance of band value was also specified in the standard, which is ±15% for the six visible bands and ±30% for the two ultraviolet bands. For D50 simulators, it was stated that if two contiguous bands deviate in the same sense the mean deviation of the two bands should not exceed 7.5%.

Table 2.5.2 lists all the band compositions and values for both D65 and D50 simulators. The band values specified in this standard provide a clear indication for judging whether the SPD of a daylight simulator is close to that of the CIE illuminant. According to the standard, a daylight simulator having band value well inside the tolerance specified is regarded to be of good quality. A worked example is given in Appendix A for calculating the band values of CIE illuminants D65 and D50.

Table 2.5.1 Chromaticity tolerance specified in BS 950 for D65 simulators

x	y
0.3185	0.3383
0.3192	0.3361
0.3182	0.3320
0.3157	0.3272
0.3125	0.3228
0.3092	0.3202
0.3069	0.3199
0.3062	0.3221
0.3072	0.3262
0.3097	0.3310
0.3129	0.3354
0.3162	0.3380

Table 2.5.2 Band value and band value tolerance in percentage specified in BS 950

Spectral band	Wavelength range (nm)	Band value for 100 lumen flux (mW for two UV bands)		Band value tolerance in percentage (%)
		CIE D65	CIE D50	CIE D65 & CIE D50
U.V.A	300-340	11.2	4.70	±30
U.V.B	340-400	43.2	22.40	±30
Visible 1	400-455	0.79	0.573	±15
Visible 2	455-510	11.2	9.6	±15
Visible 3	510-540	23.1	21.8	±15
Visible 4	540-590	43.7	44.2	±15
Visible 5	590-620	14.4	15.8	±15
Visible 6	620-760	6.8	8.01	±15

2.5.2 American Standard

ANSI PH 2.31-1969 *Direct Viewing of Photographic Color Transparancies* is one of the earliest standards developed in the USA for viewing photographic materials. It is stated in the standard that the chromaticity and SPD of the illumination should approximate those for the CIE D50 illuminant. Tolerances are specified in terms of chromaticity, colour temperature and CIE colour rendering index. The standard was later consolidated in 1989. Another American standard ASTM D1729-96 *Standard Practice for Visual Evaluation of Colors and Color Differences of Diffusely-Illuminated Opaque Materials* gives specifications for several light sources used in the visual assessment of opaque materials. The ASTM standard chose CIE D65 illuminant as the standard source for daylight illumination and recommendations were given for the use of D65 simulators, e.g. CIE metamerism index category as 'BC' or better (see Section 2.5.4.2). This method was later adopted by the American Association of Textile Chemists and Colorists (AATCC 1999) for assessing colour differences for textile materials.

2.5.3 Japanese Standard

The Japanese standard JIS Z 8716-1991 *Fluoresecent Lamp as a Simulator of CIE Standard Illuminant D65 for a Visual Comparison of Surface Colours - Types and Characteristics* only considers fluorescent lamps as D65 simulators and describes principles for specifying the quality of D65 fluorescent lamps. For instance, the chromaticity of D65 fluorescent lamps should be located on the side or inside of a quadrilateral enclosed by 4 coordinate points on the CIE 1931 chromaticity diagram. The CIE metamerism index category should be 'BC' or above. The CIE general colour rendering index (R_a) should be 95 or above and CIE special colour rendering index (R_i) be 85 or above. The relative SPD for a representative lamp, made by Toshiba, was also given in the standard.

2.5.4 CIE Recommendations

2.5.4.1 CIE Colour Rendering Index

The CIE method to calculate a colour rendering index was first recommended by the CIE in 1965 and was later updated (CIE 1995a). This method calculates the resultant colour shifts for 14 test-colour samples (the reflectance values of these samples are supplied in the CIE publication). The resultant colour shift is quantified by calculating the colour differences (CIE 1964 U*V*W*) for each test-colour sample illuminated under the reference illuminant and test simulator with correction for chromatic adaptation. The calculated colour difference is then converted to an index, namely CIE special colour rendering index (R_i), via linear transformation for each test-colour sample. Eight of the 14 test-colour samples were chosen from the Munsell colour-order system, covering the hue circle with moderate saturation and approximately equal lightness. The CIE general colour rendering index (R_a), which is the average special colour rendering indices for the 8 test-colour samples, is defined to indicate the colour rendering property of a test light source. The other six test-colour samples, representing four highly saturated primary colours (R, Y, G, B) as well as complexion and foliage colours, were added in this method to indicate the colour rendering property of a test light source under extreme conditions. The CIE also specified that the reference illuminant for light sources with CCT below 5000K shall be a Planckian radiator and above 5000K one phase of CIE D illuminants (see Section 2.3.3.1). The reference illuminant should have the closest distance to the test light source in the CIE 1960 (u, v) chromaticity diagram (Hunt 1998, p.96). For special cases, CIE or other specific standard illuminants may serve as reference illuminants. The chromaticity tolerance for a test lamp relative to its reference illuminant is set to be 0.0054 in Δuv unit. The detailed steps for calculating the CIE colour rendering index are given below.

Step 1. Determine the CIE 1931 tristimulus values of the test simulator (X_k, Y_k, Z_k), reference illuminant (X_r, Y_r, Z_r) and the test-colour sample under the test simulator ($X_{k,i}$, $Y_{k,i}$, $Z_{k,i}$) and under the reference illuminant ($X_{r,i}$, $Y_{r,i}$, $Z_{r,i}$). Note that subscript *k* and *r* refers to the test simulator and reference illuminant, respectively, and subscript *i* indicates number *i* of the 14 test-colour samples.

Step 2. Transform the CIE 1931 tristimulus values obtained from Step 1 to the CIE 1960 UCS co-ordinates, (u_k, v_k) for the test simulator, (u_r, v_r) for the reference illuminant, ($u_{k,i}$, $v_{k,i}$) and ($u_{r,i}$, $v_{r,i}$) for the test-colour sample under the test simulator and the reference illuminant, respectively.

Step 3. Calculate the new co-ordinates ($u'_{k,i}$, $v'_{k,i}$) for the test-colour sample under the test simulator after taking into account the adaptive colour shift caused by the different state of chromatic adaptation under the test simulator and the reference illuminant.

$$u'_{k,i} = \frac{10.872 + 0.404\frac{c_r}{c_k}c_{k,i} - 4\frac{d_r}{d_k}d_{k,i}}{16.518 + 1.481\frac{c_r}{c_k}c_{k,i} - 4\frac{d_r}{d_k}d_{k,i}}$$

$$v'_{k,i} = \frac{5.520}{16.518 + 1.481\frac{c_r}{c_k}c_{k,i} - 4\frac{d_r}{d_k}d_{k,i}} \qquad 2.5.1$$

Functions c and d in the above equation are calculated for the test simulator (giving c_k, d_k), for the reference illuminant (giving c_r, d_r) and for the test-colour sample (giving $c_{k,i}$, $d_{k,i}$), using Equation 2.5.2.

$$c = \frac{1}{v}(4 - u - 10v)$$

$$d = \frac{1}{v}(1.708v + 0.404 - 1.481u) \qquad 2.5.2$$

Step 4. Transform the CIE 1960 UCS co-ordinates (u, v) into CIE 1964 Uniform Space co-ordinates (U*V*W*) for the test-colour sample under the reference illuminant and test simulator.

$$W^*_{r,i} = 25(Y_{r,i})^{1/3} - 17; \qquad W^*_{k,i} = 25(Y_{k,i})^{1/3} - 17$$

$$U^*_{r,i} = 13W^*_{r,i}(u_{r,i} - u_r); \qquad U^*_{k,i} = 13W^*_{k,i}(u'_{k,i} - u'_k)$$

$$V^*_{r,i} = 13W^*_{r,i}(v_{r,i} - v_r); \qquad V^*_{k,i} = 13W^*_{k,i}(v'_{k,i} - v'_k) \qquad 2.5.3$$

The values $u'_k = u_r$, $v'_k = v_r$ are the chromaticity co-ordinates of the light source to be tested after consideration of the adaptive colour shift. The values $Y_{r,i}$ and $Y_{k,i}$ must be normalised so that $Y_r = Y_k = 100$.

Step 5. Calculate the colour difference (CIE 1964 Colour-Difference Formula) for the test-colour sample under the test simulator (after chromatic adaptation) and reference illuminant.

$$\Delta E_i = \sqrt{(U^*_{r,i} - U^*_{k,i})^2 + (V^*_{r,i} - V^*_{k,i})^2 + (W^*_{r,i} - W^*_{k,i})^2}$$

$$= \sqrt{(\Delta U^*_i)^2 + (\Delta V^*_i)^2 + (\Delta W^*_i)^2} \qquad 2.5.4$$

Step 6. Calculate CIE special colour rendering indices (R_i) for each test-colour sample and CIE general colour rendering index (R_a) using the CIE test-colour sample from 1 to 8.

$$R_i = 100 - 4.6\Delta E_i \qquad 2.5.5$$

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i \qquad 2.5.6$$

The general colour rendering index for a CIE standard daylight illuminant is 100, which is the maximum value of the colour rendering index, representing the perfect colour rendering property for a light source investigated. Although CIE did not recommend a grade for colour rendering index to classify the quality of daylight simulators, daylight simulators with high colour rendering index (e.g. R_a above 95 and R_i all above 85) are regarded as of good quality in terms of colour rendering (JIS 1991).

2.5.4.2 CIE Metamerism Index

The CIE metamerism index method was first recommended by the CIE in its Publication 51 (CIE 1981) and was later updated (CIE 1999). The essence of the method is the use of a limited number of pairs of virtual metamers, each perfectly matching under the CIE daylight illuminant but a mismatch under a test simulator designed to simulate the CIE illuminant approximately in SPD. The development of the method dates back to the earlier research conducted by Berger (1973, 1975) and Strocka, Richter (1972), Nayatani *et al* (1972a, 1977), Ganz (1977), etc. The original version of this method only provided metamers for evaluating daylight simulators for D55, D65 and D75. For each of the CIE daylight illuminants, a set of eight metamers was provided as part of the CIE method, five for the visible range (400 nm to 700 nm) and three for UV range (300 nm to 400 nm). The updated version includes a new set of metamers for evaluating D50 simulators. Colour differences (CIELAB or CIELUV) are calculated for each metamer under the CIE illuminant and the test simulator using the CIE 1964 Supplementary Colorimetric Observer. The CIE metamerism index, which is the average colour differences of the metamers, is defined for both visible and UV ranges (denoted as MI_{vis} and MI_{uv} respectively). The test simulator is categorized into 'A' to 'E' category based on its metamerism index value, as shown in Table 2.5.3. The steps for calculating the CIE metamerism index are given below.

Step 1. Normalise the SPD of the test simulator

$$S_n(\lambda) = 100\, S(\lambda) / \sum_{380}^{780} S(\lambda)\bar{y}_{10}(\lambda)\Delta\lambda \qquad 2.5.7$$

Step 2. Calculate of the spectral radiance factor β(λ). For non-fluorescent samples, β(λ) is tabulated in the CIE publication. For fluorescent samples, β(λ) is calculated using Equation 2.5.8.

$$\beta(\lambda) = \beta_S(\lambda) + \beta_L(\lambda)$$
$$\beta_L(\lambda) = N * F(\lambda) / S_n(\lambda)$$
$$N = \sum_{\lambda'=300}^{460} S_n(\lambda')Q(\lambda')\Delta\lambda' \qquad 2.5.8$$

where

$S_n(\lambda)$: Normalized SPD of the test simulator
$S_n(\lambda')$: $S_n(\lambda)$ over the range 300 to 460 nm
$\beta_S(\lambda)$: Spectral reflection radiance factor (tabulated in the CIE publication)
$\beta_L(\lambda)$: Fluorescence radiance factor
F(λ): Relative spectral distribution of radiance emitted by fluorescence
Q(λ'): Spectral external radiant efficiency
N: Effective excitation
λ: wavelengths of reflection and emission (380-780 nm)
λ': wavelengths of excitation (300-460 nm)

Step 3. Calculate tristimulus values of the test simulator and each sample for the 8 virtual metamers using Equation 2.5.9.

$$X_n = \sum_{380}^{780} S_n(\lambda)\bar{x}_{10}(\lambda)\Delta\lambda, \qquad X = \sum_{380}^{780} \beta(\lambda)S_n(\lambda)\bar{x}_{10}(\lambda)\Delta\lambda$$
$$Y_n = \sum_{380}^{780} S_n(\lambda)\bar{y}_{10}(\lambda)\Delta\lambda, \qquad Y = \sum_{380}^{780} \beta(\lambda)S_n(\lambda)\bar{y}_{10}(\lambda)\Delta\lambda$$
$$Z_n = \sum_{380}^{780} S_n(\lambda)\bar{z}_{10}(\lambda)\Delta\lambda, \qquad Z = \sum_{380}^{780} \beta(\lambda)S_n(\lambda)\bar{z}_{10}(\lambda)\Delta\lambda \qquad 2.5.9$$

Step 4. Calculate colour difference ΔE (CIELAB or CIELUV) for each metamer and Metamerism Index for both visible range (MI_{vis}) and UV range (MI_{uv}) using Equation 2.5.10.

$$MI_{vis} = \sum_{i=1}^{5} \Delta E_i / 5, \quad MI_{uv} = \sum_{i=1}^{3} \Delta E_i / 3 \qquad 2.5.10$$

Table 2.5.3 CIE specifications on metamerism index category

Colour Difference		CIE Metamerism Index
CIELAB	CIELUV	Category
<0.25	<0.32	A
0.25 to 0.5	0.32 to 0.65	B
0.5 to 1.0	0.65 to 1.3	C
1.0 to 2.0	1.3 to 2.6	D
>2.0	>2.6	E

The final metamerism index result is expressed by the index for MI_{vis} followed by that for MI_{uv} such as 'AB'. A daylight simulator with MI_{vis} of 'A' means the simulator gives almost the same performance as the CIE illuminant in revealing metameric effects for the visible range. On the other hand, a simulator with MI_{vis} of 'E' means it shows a considerable discrepancy from the CIE illuminant in revealing these effects. The metamerism index for the UV range (MI_{uv}) is important for assessing fluorescent samples. A high quality daylight simulator should have high metamerism index rating for both visible and ultraviolet regions. The ASTM standard D1729 (1996) and Japanese standard JIS Z 8716 (1991) stated that the CIE metamerism index should be 'BC' or above for a high quality daylight simulator. It is also specified in this method that the chromaticity of a daylight simulator should lie within a radius of 0.015 $u'_{10}v'_{10}$ units from the appropriate CIE daylight illuminant in CIE 1976 Uniform Chromaticity Scale (UCS) diagram.

Figure 2.5.1 shows the reflectance curves of the 5 CIE metamers for evaluating D65 simulators for the visible range. The distribution of these metamers in CIE a* b* space is shown in Figure 2.5.2. A careful examination on Figure 2.5.1 reveals that each metamer has different number of crossovers at different wavelengths. Figure 2.5.2 shows that these metamers are located almost only in the first and fourth quadrants of CIE a* b* space, implying an insufficient coverage of colour gamut.

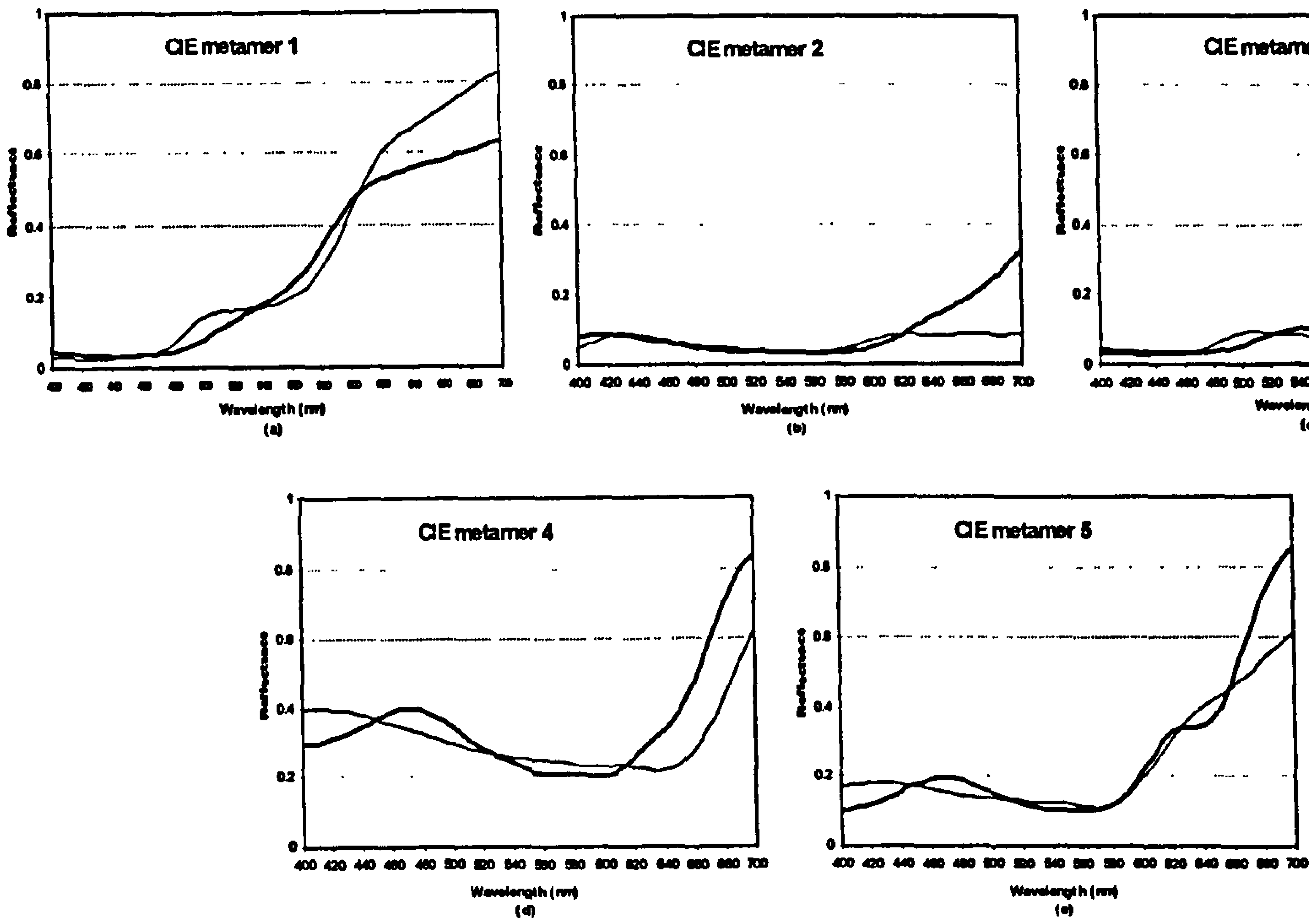


Figure 2.5.1 Reflectance curves of the 5 CIE metamers for the visible region

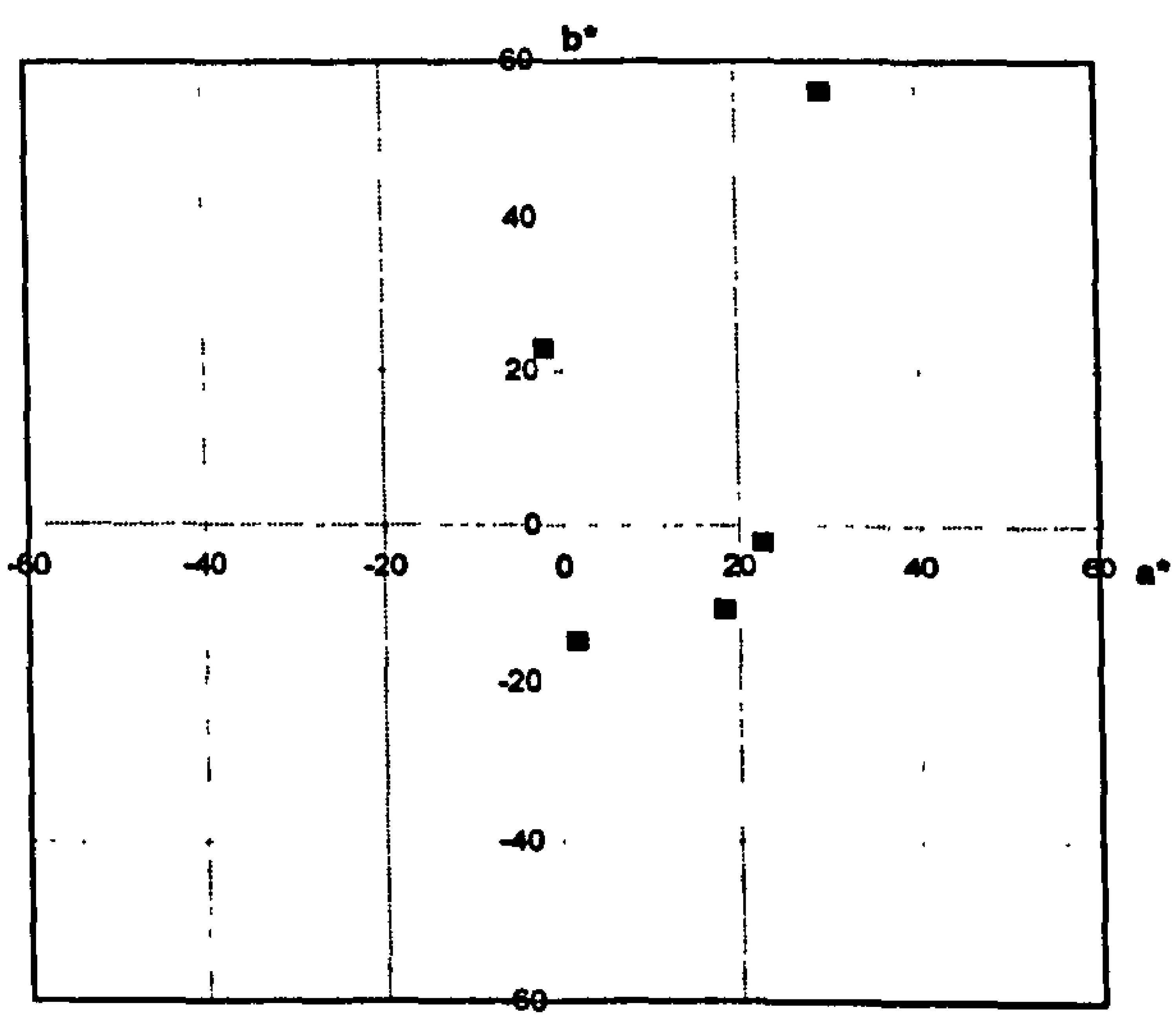


Figure 2.5.2 Sample distribution for the 5 CIE metamers for the visible region

2.5.5 ISO Standard

2.5.5.1 ISO 3664

ISO 3664-2000 *Viewing conditions for graphic technology and photography* is the international standard specifying viewing conditions for images on both reflective and transmissive media, such as prints (both photographic and photomechanical) and transparencies, as well as images displayed in isolation on colour displays. The standard specified four viewing conditions for: critical comparison of prints (P1), practical appraisal of prints (P2), direct viewing for transparencies (T1) and projection viewing for transparencies (T2). It is specified that the illumination at the viewing surface should approximate that of CIE D50 illuminant for appraising prints or transparencies. The illumination level are 2,000±500 lx (or 2,000±250 lx at the centre of the illuminated viewing surface area) and 500±125 lx for conditions P1 and P2 respectively, and 1,270±320 cd/m^2 (or 1,270±160 cd/m^2 at the centre of the illuminated viewing surface area) for conditions T1 and T2. For images displaying on colour monitors, the chromaticity of the monitor white should approximate that of the CIE D65 illuminant. For the former viewing condition, the chromaticity deviation for a simulator relative to CIE D50 illuminant should be within the radius of 0.005 u'_{10} v'_{10} units. For the white point of a CRT display, the chromaticity deviation relative to CIE D65 illuminant should be within the radius of 0.025 u'_{10} v'_{10} units. For luminance level,

The standard adopts the CIE colour rendering index and the CIE metamerism index as the criteria for specifying daylight simulators for prints and transparencies. The CIE colour rendering index is set to 90 or above for the general colour rendering index (R_a) and 80 or above for the special colour rendering index (R_i) respectively, referring only to test samples 1 to 8. The CIE metamerism index category is specified as 'C' or above for the visible range (MI_{vis}), and for the UV range, MI_{uv} should be less than 4 ΔE^*_{ab} units. The tolerance for the CIE metamerism index is thought to be not tight, as colour products from graphic arts industry generally do not present as large metameric effects as those from the surface colour industries. The standard also specifies that the illumination uniformity, calculated in terms of the ratio between the minimum and maximum illumination, be larger than 0.75 for normal viewing conditions.

2.5.5.2 ISO 3668

ISO 3668-2001 *Paints and varnishes – Visual comparison of the colour of paints* is one of a series of standards dealing with the sampling and testing of paints, varnishes and related products. It specifies a method for the visual comparison of the colour of films of paints or related products against a standard (either a reference standard or a freshly prepared standard) using either natural daylight or artificial light sources in a standard booth. For natural daylight illumination, it is recommended that diffuse daylight should be used. The diffuse daylight is preferably from a partially cloudy north sky in the northern hemisphere and a partially cloudy south sky in the southern hemisphere, and the light should not be reflected from any strongly coloured object such as a red brick wall or green tree. Illumination should be uniform over the viewing area and have a level of at least 2,000 lx. For artificial illumination, the lighting booth should be an enclosure from which external light is excluded. The light sources should give SPDs approximating to those of CIE illuminant D65 and CIE illuminant A. The quality of simulation of daylight should be assessed by the method described in CIE Publication 51. The SPD of the daylight simulator shall be in the category BC (CIELAB) or better. The illumination level at the colour-matching position shall be between 1,000 lx and 4,000 lx, a figure towards the upper end of the range being desirable for dark colours. The interior of the colour-matching booth for general use shall be painted a matt neutral grey (the absolute values of a^* and b^* be less than 1.0) with a lightness L^* of about 45 to 55. This may be set as high as 65 for matching light and near-white colours, or as low as 25 for matching dark colours.

2.6 Standards for Viewing Cabinet Design

Viewing cabinets (also termed as lighting booths) configured with daylight sources and other selected light sources such as tungsten-filament, TL84, UV, etc., are commonly used for visual assessments. Currently, there is a quite considerable variety of viewing cabinets, made by different manufacturers and based on different principles. The quality of viewing cabinets is generally considered in terms of the quality of light source, illuminance level, uniformity, viewing area, interior colour, etc. These factors all have impact on industrial colour control. Hence, it is important to standardise the viewing cabinet design.

2.6.1 General Guidelines

The general guidelines for viewing cabinet design were described by Sinclair (1997). He listed some important criteria for visual assessments using a modern viewing cabinet, including:

- Nature and intensity of the light source
- Angle of illumination and viewing of the sample
- Colour of viewing cabinet interior and sample background
- Size and distance apart of the samples
- State of adaptation of the observer
- Observer's colour vision characteristics
- An agreement on the methods for calculating colour difference or colour appearance

The first three factors should be taken into account for the design of all sorts of viewing cabinets, whilst recommendations can also be laid down for standardising the state of adaptation of the observers for checking their colour vision characteristics.

2.6.1.1 Light Sources

Most viewing cabinets provide a selection of light sources, with press-button accessibility (Sinclair 1997). Typical sources that might be available include:

- An artificial daylight source (normally D65 or D50, D55, D75 simulator)
- A tungsten-filament source
- A three-band fluorescent source (TL84)
- A UV source (for enhancing fluorescent whites)
- Optional source (CWF, U30, Horizon, etc.)

Artificial daylight sources can be filtered tungsten-filament lamps but in the UK are more likely to be fluorescent tubes conforming to BS950: Part 1: 1967 (see Section 2.5.1). Such lamps have a specified UV content which is useful for assessing fluorescent whitening agents on textiles, paper and plastics. Users of a viewing cabinet should be aware of the SPDs of the lamps provided, as many different combinations of sources are marketed. Provision of other sources, such as the tungsten-filament and the TL84 lamps, allows for the checks of the colour constancy of samples and metamerism of sample pairs. The latter is assessed by the extent of the change in the quality of colour match when the illuminant is changed (from daylight to tungsten-filament lamp, for example).

2.6.1.2 Illuminance Levels

The illuminance levels are usually specified and can range from 700 lx to over 3000 lx, the latter value being preferred when matching dark colours. The illuminance level should be checked routinely and the lamps replaced when the output drops by a specified value, or after sources have been run for a specified number of hours (Sinclair 1997). With artificial daylight sources it is usually the UV content that declines most rapidly. It is necessary to conduct a check on the 'colour balance' characteristics, i.e. a test for illuminance level or a test for the maintenance of the SPDs within acceptable limits, etc.

2.6.1.3 Construction and Geometry

In a typical viewing cabinet, the lamps are placed in a recess directly above the matching surface, preferably behind a frosted glass cover and/or filter glass, which provides reasonably diffuse illumination, see Figure 2.6.1. Some cabinets have a directional light source for assessing gloss, but the assessment of surface gloss requires a cabinet of specific design. The cabinet should be placed at a height such that the viewing angle for the observer of average stature is approximately 45° (Sinclair 1997).

2.6.1.4 Interior Colour

According to Sinclair (1997), the matching surface and the interior of a matching cabinet should be painted a light to medium grey (about 30% reflectance, corresponding to CIE L* of around 62).

Figure 2.6.1 The sketch of an artificial daylight booth (reproduced from Sinclair 1997)

2.6.2 Australian Standard

Australian Standard AS 4004 (1992) *Lighting booths for visual assessment of colour and colour matching*, is one of the few standards available in specifying viewing cabinets. The general features specified in the standard include:

- Viewing area
- Quality of daylight simulator and incandescent light source
- Illuminance level of daylight simulator and incandescent light source
- Uniformity of daylight simulator and incandescent light source
- Interior colour
- Maintenance

2.6.2.1 Viewing Area

The viewing area should be expressed as an area in the horizontal plane, specified with reference to the walls of the booth or other convenient landmarks, and in the vertical plane, expressed as the distance below the diffuser of the luminaires or other convenient landmark. The dimensions of the viewing area shall be not less than 300 by 200 mm.

2.6.2.2 Daylight Simulator

The quality of daylight simulator used in a booth should be assessed in terms of category according to the requirements of CIE Publication 51 (see Section 2.5.4.2). A simulator with CIE metamerism index category 'E' is regarded as unqualified. Daylight simulators may include a variety of sources, such as filtered tungsten, special fluorescent or xenon lamps. The minimum illuminance level in the viewing area shall be not less than 1000 lx and the maximum level not more than 5000 lx. The preferred illuminance level is 1500 to 2500 lx. When measured at 50 mm intervals over the viewing area identified by the manufacturer, using a cosine-corrected detector of area not great than 1000 mm^2, the ratio of the highest to lowest illuminance over the viewing area shall not be greater than 1.25.

2.6.2.3 Incandescent Source

The incandescent light source should have a colour temperature of not less than 2200K and not more than 2900K. The mean illuminance over the viewing area shall be not less than 0.7 times and not more than 1.3 times the mean illuminance over the viewing area provided by the daylight simulator. The tolerance for uniformity of illuminance is as same as that for the daylight simulator.

2.6.2.4 Additional UV Source

The booth may be fitted with additional UV lamps to alter the ultraviolet (UV) light content or to simulate specific lighting conditions.

2.6.2.5 Interior Colour

The colour of the walls and base below the viewing area shall be a neutral gray, having a lightness value of CIE L* not less than 50 and not greater than 75, and a chroma value of C^*_{ab} not greater than 4.0. This approximates Munsell N5 (CIE L* about 50) to N7 (CIE L* about 70) with a Munsell Chroma not greater than 0.5.

2.6.2.6 Maintenance and Other Features

The booth shall be inspected after each 100 hour of operation to ensure that the reflectors, bulbs, filters and diffusing glass are kept clean, and the electric lamp is replaced at intervals nominated by the light booth manufacturer, or when the illuminance falls below a specified level.

The standard also included specifications for electrical safety, recommended life of sources and heat generation and dissipation. In addition, the standard provided a table to classify the degree of colour matching and required booth category. In this study, a guideline for viewing cabinet design was proposed based on international standards and this standard (see Appendix G).

2.7 Methods for Evaluating Daylight Simulators

McCamy (1994) raised three questions related to the different kinds of criteria in assessing a daylight simulator: (1) Do objects look the same as they do in daylight? (2) Do pairs of objects match as they do in daylight? (3) Do selected objects have colours we prefer to those seen in daylight? For colour appraisal, the first is of interest; for colour matching, the second. The third is considered for general illumination, and sometimes termed as colour preference. In Section 2.5, various standards were described for specifying daylight simulators. These standards generally consider two aspects of a daylight simulator with respect to its quality, one is the SPD and the other is colorimetric features, such as chromaticity, CCT, colour rendering index, metamerism index. It should be noted that although chromaticity and CCT are often cited by the lighting industry (McCamy 1999) as the essential specifications for daylight simulators, they have the drawback of ambiguity. For a given CCT, there is an infinite variety of possible chromaticities, and for every chromaticity, there is an infinite variety of possible SPDs. Hence, methods for evaluating the quality of daylight simulators more or less examine their SPDs. These methods include the goodness-of-fit in SPD, band-value method, colour rendering approach, degree of metameric match, etc., which are described below. Some industries, such as the textile and paper industries, make a wide use of fluorescent dyes, pigments and in particular brightening agents, so it is important to evaluate the quality of a daylight simulator not only for the visible range, but also for the ultraviolet wavelength region.

2.7.1 Goodness-of-fit of SPD

Wyszecki (1970) first suggested the goodness-of-fit measure for quantifying the quality of daylight simulators. The measure calculates the spectral disagreement between the target illuminant and the test simulator. It might purely count the spectral goodness-of-fit, such as the square root of the mean-square deviation (abbreviated as Index *d*) and the mean absolute deviation (abbreviated as Index *e*). Or, it could test the spectral goodness-of-fit with colorimetric principles being taken into account, such as the one suggested by Nimeroff (1965), abbreviated as Index σ_N in Wyszecki's study.

Index *d* is expressed in Equation 2.7.1.

$$d = \left(\frac{1}{n}\sum_{\lambda=\lambda1}^{\lambda2}(S_D(\lambda) - f_1 S(\lambda))^2\right)^{1/2} \qquad (2.7.1)$$

where $S(\lambda)$ is the relative spectral irradiance of the test source and $S_D(\lambda)$ the relative spectral irradiance of the target CIE daylight illuminant at wavelength λ, n is the number of wavelength at which $S(\lambda)$ and $S_D(\lambda)$ are specified in the range $\lambda_1 \leq \lambda \leq \lambda_2$, and f_1 is a scaling factor.

The introduction of a scaling factor is justified and desirable because both $S(\lambda)$ and $S_D(\lambda)$ are relative functions and initially have usually been normalized arbitrarily so as to have the value 100.0 at λ=560 nm. For the calculation of the mean-square deviation we could choose for f_1 any value greater than zero, but a more appropriate choice is the value that makes d a minimum. This occurs when f_1 is set to:

$$f_1 = \sum_{\lambda=\lambda1}^{\lambda2} S(\lambda)S_D(\lambda) / \sum_{\lambda=\lambda1}^{\lambda2} S^2(\lambda) \qquad (2.7.2)$$

The Index e is expressed in Equation 2.7.3.

$$e = \frac{1}{n}\sum_{\lambda=\lambda 1}^{\lambda 2} \left| S_D(\lambda) - f_2 S(\lambda) \right| \tag{2.7.3}$$

To make Index e a minimum the scaling factor, f_2 is set equal to the median of the values $S_D(\lambda)/S(\lambda)$ each of which is taken to occur $S(\lambda)$ times.

The Index σ_N is expressed in Equation 2.7.4.

$$\sigma_N = (\sigma_u^{\ 2} + \sigma_v^{\ 2} + \sigma_w^{\ 2})^{1/2} \tag{2.7.4}$$

where

$$\sigma_u^{\ 2} = \frac{1}{n}\sum_{\lambda=\lambda 1}^{\lambda 2} ((f_3 S(\lambda) - S_D(\lambda))\,\bar{u}(\lambda))^2$$

$$\sigma_v^{\ 2} = \frac{1}{n}\sum_{\lambda=\lambda 1}^{\lambda 2} ((f_3 S(\lambda) - S_D(\lambda))\,\bar{v}(\lambda))^2$$

$$\sigma_w^{\ 2} = \frac{1}{n}\sum_{\lambda=\lambda 1}^{\lambda 2} ((f_3 S(\lambda) - S_D(\lambda))\,\bar{w}(\lambda))^2$$

and

$$\bar{u}(\lambda) = \frac{2}{3}\bar{x}(\lambda)$$

$$\bar{v}(\lambda) = \bar{y}(\lambda)$$

$$\bar{w}(\lambda) = \frac{1}{2}(-\bar{x}(\lambda) + 3\bar{y}(\lambda) + \bar{z}(\lambda))$$

The scaling factor f_3 can be chosen so as to make σ_N a minimum, that is:

$$f_3 = \frac{\sum_{\lambda=\lambda 1}^{\lambda 2} S(\lambda) S_D(\lambda)(\bar{u}^2(\lambda) + \bar{v}^2(\lambda) + \bar{w}^2(\lambda))}{\sum_{\lambda=\lambda 1}^{\lambda 2} S^2(\lambda)(\bar{u}^2(\lambda) + \bar{v}^2(\lambda) + \bar{w}^2(\lambda))} \tag{2.7.5}$$

Index σ_N is limited to testing the goodness-of-fit between $S(\lambda)$ and $S_D(\lambda)$ for the visible spectrum only, while Index e and d could be used as a measure for testing both visible and ultraviolet regions of the spectrum.

2.7.2 Band Value Method

This band value method was first proposed by Bouma (1937) and later modified by Crawford (1963). The main approach in this method is to divide the whole spectrum, including both visible and ultraviolet wavelength regions, into several bands. For each investigated band, the method compares the band luminance value of a simulator to that of a target illuminant. The method was adopted in British Standard BS 950-1967 (see Section 2.5.1).

2.7.3 Colour Rendering Approach

The colour rendering approach looks at the colour rendering property (see Section 2.3.9) of a daylight simulator, which is generally regarded by the lighting industry as a very important criterion with respect to its quality (McCamy 1994). The CIE colour rendering index (see Section 2.5.4.1) is a standard approach widely used for quantifying the colour rendering property of daylight simulators.

2.7.4 Degree of Metameric Match

This method usually adopts some pairs of metameric specimens, which are designed to perfectly match under a CIE daylight illuminant. These metameric pairs exhibit some degree of colour differences under a daylight simulator. The larger the colour differences, the worse quality of the simulator. Nayatani and Takahama (1972a) first proposed this approach and used 12 metameric grays as testing pairs in their study. Berger and Strocka (1973) further investigated this approach using 68 metameric sample pairs. Unlike the theoretical metameric samples used by Nayatani and Takahama, Berger and Strocka used measured reflectance curves of actual metameric sample pairs. Their results revealed that it was appropriate to select a few metameric pairs for the evaluation of daylight simulators. The CIE metamerism index method (see Section 2.5.4.2) is representative of this approach.

2.7.5 Colour Difference Metric

Terstiege (1991) proposed a method which is similar to the goodness-of-fit method in some ways. His method first transformed the spectral deviation between the standard illuminant and test simulator into colorimetric errors, and then calculated the colour differences from the colorimetric error results. The method is expressed as below:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = K \sum_{\lambda=400}^{700} \left| c \cdot S(\lambda) - S_D(\lambda) \right| \begin{bmatrix} \bar{x}_{10}(\lambda) \\ \bar{y}_{10}(\lambda) \\ \bar{z}_{10}(\lambda) \end{bmatrix} \qquad 2.7.6$$

where

$$K = 100 / \sum_{\lambda=400}^{700} S_D(\lambda) \cdot \bar{y}_{10}(\lambda), \qquad c = \frac{\sum_{\lambda=400}^{700} S_D(\lambda)}{\sum_{\lambda=400}^{700} S(\lambda)}$$

The colorimetric errors in terms of F_x, F_y and F_z could be converted into CIELAB colour differences. Terstiege tested both CIE metamerism index method and the colour difference method for six D65 simulators and he found that the colour difference results could discriminate the quality difference of some simulators for which the CIE metamerism index results could not.

2.7.6 Evaluating Daylight Simulators for the Ultraviolet Region

The German Standard DIN 6173 proposed the effective excitation method for the ultraviolet assessment. This method was further investigated by Berger and Strocka (1975). Richter (1975) and Nayatani *et al* (1977) suggested an alternative. They used a number of metameric pairs, each of which consisted of fluorescent samples. Ganz (1977) adopted a slightly different approach from that of Richter and Nayatani. His method was based on the colorimetric error of a fluorescent sample resulting when the test simulator was used as an irradiating source on the samples instead of the appropriate standard daylight illuminant. The CIE metamerism index method adopted the modified Ganz method for evaluating the daylight simulators for the ultraviolet wavelength region (see in Section 2.5.4.2). Billmeyer (1980) and Chong (1981) tested the accuracy of various proposed methods for evaluating the quality of daylight simulators, mainly for the ultraviolet wavelength region, using fluorescent samples for visual assessment. They concluded that the methods based on colorimetric weighting correlated better to the visual results than those based on radiometric weighting. Rich (1990) demonstrated a practical approach for evaluating the quality of a daylight simulator using a light source with a sphere spectrophotometer. The simulator in his study was UV enhanced and its quality for the UV range was investigated by measuring fluorescent and non-fluorescent white samples using the instrument.

2.7.7 Measures of Fit

The methods described in Sections 2.7.1 to 2.7.6 provide theoretical measures for evaluating daylight simulators. The performances of these methods depend on how the predicted results agree with the visual assessment results. A statistical measure, Performance Factor (PF/3), can be used to indicate the agreement between two sets of data, e.g. colour difference ΔE_i and visual colour difference ΔV_i. The measure was originally developed by Luo *et al* (1987a) and has been extensively used by many researchers (Kuo 1996a, Cui 2000 and Lam 2002). It combines three different statistical measures, Coefficient of Variation (CV), Gamma Factor (γ) and (V_{ab}), with a suitable weight for each one. The smaller the PF/3 value, the better the agreement between two compared data sets. For a perfect agreement, PF/3 should be zero. The calculation for PF/3 is expressed as below:

$$PF/3 = 100\ (\gamma\text{-}1 + V_{AB} + CV/100\ )/3 \qquad 2.7.7$$

where Coefficient of Variation (CV) is a measure to indicate the departure from a linear relationship between two sets of data, e.g. ΔE_i and ΔV_i. It is the root mean square deviation of ΔE_i and ΔV_i (suitably scaled by a scaling factor f) as a percentage of the mean ΔE value, as given in Equation 2.7.8. If ΔE_i and ΔV_i follow a perfect linear relationship, CV should be zero. The larger the CV value, the larger disagreement between ΔE_i and ΔV_i.

$$CV = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta E_i - f\Delta V_i)^2}}{\overline{\Delta E}} * 100 \qquad 2.7.8$$

where

$$f = \frac{\sum_{i=1}^{N}(\Delta E_i \Delta V_i)}{\sum_{i=1}^{N}(\Delta V_i)^2}, \qquad \overline{\Delta E} = \frac{1}{N}\sum_{i=1}^{N}\Delta E_i$$

Gamma Factor (γ) is a measure to indicate the proportional relationship between two set of data, e.g. ΔE_i and ΔV_i. The logarithm of $\Delta E_i/\Delta V_i$ usually forms a normal distribution and the standard deviation of ln ($\Delta E_i/\Delta V_i$) is used as a measure of fit, expressed as in Equation 2.7.9.

$$\ln(\gamma) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\ln\left(\frac{\Delta E_i}{\Delta V_i}\right) - \overline{\ln\left(\frac{\Delta E_i}{\Delta V_i}\right)}\right]^2} \qquad 2.7.9$$

V_{ab} is expressed in Equation 2.7.10, where F is the scaling factor.

$$V_{AB} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(\Delta E_i - F\Delta V_i)^2}{\Delta E_i F \Delta V_i}} \qquad 2.7.10$$

where

$$F = \sqrt{\sum_{i=1}^{N}\frac{\Delta E_i}{\Delta V_i} \Big/ \sum_{i=1}^{N}\frac{\Delta V_i}{\Delta E_i}}$$

For perfect agreement, CV, V_{AB} and PF/3 should be zero and γ equal to 1. A PF/3 value of 30 means the disagreement is about 30% between two sets of data.

2.8 Evaluation of the CIE Methods for Assessing Daylight Simulators

The CIE methods for assessing daylight simulators include the CIE colour rendering index (see Section 2.5.4.1) and CIE metamerism index (see Section 2.5.4.2). The colour rendering index is used to estimate the degree to which a test light source renders a set of object colours correctly compared to their appearance under a reference illuminant. The method was designed to evaluate all light sources including daylight simulators. Although the CIE colour rendering index (CRI) has not been designed to evaluate daylight simulators, one can try to check how far the use of this method provides a description that correlates with visual observations. A simulator with a low CRI is obviously not very satisfactory. However, CIE illuminant A has a CRI of 100 and most tungsten lamps have very high CRI; none of them are good daylight simulators. The CIE metamerism index was therefore designed exclusively for assessing daylight simulators. The method estimates the colour differences of metameric pairs under a test illuminant. These metameric pairs are perfect matches under a reference daylight illuminant.

The CIE colour rendering index method and metamerism index method have been widely used by different industries as standard criteria for evaluating the quality of daylight simulators, and the performances of these two methods have been investigated by numerous researchers. Most of these studies revealed that, basically, the two CIE methods have worked satisfactorily for general applications. With the development of new light sources (e.g. daylight simulators) and advances in colour science, it is therefore possible that both the CIE methods could be updated. For instance, the CIE colour rendering index is calculated using the CIE 1964 U*V*W* colour difference formula, which is rarely used for any other applications.

2.8.1 Evaluation of the CIE Method for Assessing Colour Rendering

2.8.1.1 Advantages and Disadvantages in Using the CIE Method

Halstead (1977) published a review on colour rendering. She concluded that the major technical advantage of this method is that it is based on the principle of viewing coloured surfaces under different lamps, which is what happens in practice. A correction for chromatic adaptation is included and any extra sample, such as red meat or lettuce, can be used to produce a special index for that sample provided that details of the sample are specified.

However, one disadvantage of the method is that the colour rendering property is given by a single number, for non-technical people, equality of indices implies equality of fidelity of colour rendering, which is not always the case. The further the index is lower than 100 the more likely it is that two lamps which have the same CCT and R_a will have different colour rendering properties. Even equality of a special index R_i does not guarantee equality of colour rendering since the index does not indicate the direction of the colour shift. Another drawback is that it is essential to quote the CCT of the lamp as two lamps with very different CCTs can have almost the same colour rendering index R_a. For example, a high-efficiency daylight lamp at 6500K has a R_a of 77 whereas a de luxe Warm White at 3000K has a R_a of 80.

Terstiege (1991) analysed the CIE colour rendering index method for assessing the quality of daylight simulators. He pointed out that with the development of new daylight simulators, particularly such as the marketing of three-band type fluorescent lamps, the CIE colour rendering index showed deficiencies mainly due to the limited colour gamut covered by the eight unsaturated test-colour samples.

2.8.1.2 Early Visual Assessments

Halstead *et al* (1971) carried out experiments using simultaneous comparisons of lamps with similar chromaticities but different colour rendering properties. The experiment was designed to eliminate chromatic adaptation effects as much as possible. The test lamps irradiated the eight CIE test-colour samples and a number of observers judged the difference in terms of a four-category scale. It was found that a just-noticeable difference (JND) was equivalent to a difference of about 12 to 18 units of the special index R_i, according to the particular samples.

Kamble and Mori (1971) performed a similar experiment and found that about 7 units of the general index R_a, was equivalent to the average JND for CIE test-colour samples 1 to 8. However, their results also showed that the degree of correlation between the visual score and the special index varied according to the sample. Maitreya (1975) reported his results using a simultaneous binocular-viewing technique and he obtained a difference of 5 units in R_i corresponding to the minimum observed colour difference.

Eastman *et al* (1972) investigated a method of alternating timed viewing to study colour shifts on Munsell samples produced by eleven illuminants with very different chromaticities and colour rendering. The authors contended that the measured shifts in colour under these conditions are in accordance with those experienced in actual situations where the observers is thoroughly adapted to the visual conditions of the situation.

2.8.1.3 Evaluating the CIE Method Using Other Test-Colour Samples

Lester (1999) evaluated the CIE method using 61 D50 simulators. In her study, three CATs, including the von Kries transform, CIE transform (CIE 1994) and BFD transform, were tested in conjunction with two colour difference formulae, CIELAB and CIE94 (see Section 2.3.5). In addition to the CIE test-colour samples, two standard sample sets were used in the study. These are the SWOP data set used for graphic arts and the Kodak Q60 Ektachrome dye set used for photography. The SWOP set includes 928 colour patches and the Ektachrome includes 264 colour patches. Lester concluded that either the CIE test-colour sets or the real sample sets chosen from the graphic-arts industry showed the same trend in evaluating the quality of D50 daylight simulators.

2.8.1.4 To Achieve an Improved Method

The calculation of CIE colour rendering index involves two key stages, one is the chromatic adaptation and the other is the colour difference calculation. It is generally believed that the performances of the CIE method could be increased by improving the chromatic adaptation transform and the colour difference formula (Halstead 1977). It is also desirable to include some indications of the direction of the colour shifts in this method.

Halstead (1973a) and Henderson (1975) investigated the effects of chromatic adaptation on the colour rendering indices. Schanda (1981) also discussed the effects of chromatic adaptation on colour rendering. He pointed out that the CAT used by the current method is a von Kries transform with Judd PDT primaries, and it would be desirable to introduce a more modern CAT (see Section 2.3.7) to replace the von Kries transform.

The current CIE method uses the CIE 1964 U*V*W* colour difference formula, but there has been considerable discussion among colour scientists regarding the satisfaction of this equation. Maitreya (1975) obtained some subjective estimates of the colour differences produced when the CIE test-colour samples 1 to 14 were illuminated by different fluorescent lamps. He correlated the subjective scores with measures of the colour differences calculated using five different equations and concluded that the CIE 1964 colour difference formula was satisfactory.

Mori and Fuchida (1982) carried out an experimental study to evaluate which colour space is most suitable for the colour-rendering specification of light sources. Their study concluded that the CIELAB space is much better than the CIELUV and CIE U*V*W* spaces, and the changeover from the CIE U*V*W* to the CIELUV space hardly improves the CIE method of colour-rendering specification. It also showed that the terms $(X/X_n)^{1/3}$, $(Y/Y_n)^{1/3}$, and $(Z/Z_n)^{1/3}$ included in the CIELAB formula seemed to be a practical and appropriate correction for chromatic adaptation. Seim (1985) proposed a new colour difference formula named SVF. The formula was proved to describe data from several colour-scaling experiments better than both the CIELUV and CIELAB formulae. However, more recent work on colour difference assessments shows that formulae such as CIEDE2000 give even better performances (see Section 2.3.5).

2.8.1.5 Complementary Methods

The CIE colour rendering index method has the problem of explaining to people not familiar with colour technology the reason for choosing a series of reference standards. Many people still refer to natural daylight as the primary standard in spite of its variability and they also appreciate the changes which result from changing to incandescent light. It therefore seemed logical to develop other complementary methods capable of describing the colour rendering property of a light source (Halstead 1977).

Pracejus (1967) suggested that the area of the octagon formed by the UCS co-ordinates of the eight CIE test-colour samples was a possible measure of the acceptability of the colour rendering property of a lamp. He termed this area as 'gamut area', which he suggested could be used as an indicator for quantifying colour rendering property. He determined the area for an equal energy source. These ratios correlated reasonably well with subjective estimates of acceptability of the lamps in question. Thornton (1972) further interpreted the concept of 'gamut area' as a function of the discriminating power of a lamp, which was related to the colour rendering property. He postulated that the larger the area, the better the colour rendering. Halstead *et al* (1973b) developed a dual index using the CIE colour rendering index method but comparing the test lamp with both CIE D65 and A illuminants.

The relationship between colour discrimination and colour rendering was investigated by Boyce (1976-7) and Halstead (1977). Halstead concluded that a lamp cannot have good colour rendering without having good colour discrimination, however, the opposite may not be true. It is possible to distort the difference between two colours so that maximum discrimination is obtained but this does not mean that the colours are rendered well. Other concepts such as Colour Discrimination Index (CDI) and Colour Rendering Capacity (CRC) were proposed by Xu (1993).

2.8.2 Evaluation of the CIE Method for Assessing Metamerism

2.8.2.1 Evaluating the Virtual Metamers Used by the CIE Method

The CIE method uses a small number of virtual metamers for assessing the quality of daylight simulators. The performance of this method largely depends on whether these virtual metamers are representative and effective. Methods to evaluate these virtual metamers were introduced by McCamy (1999). The main approach for these methods is to perturb the ideal spectrum in a specified way and using the metamers to find the largest perturbation tolerated in a standard quality category. There are an infinite variety of ways in which the spectrum of a simulator may differ from the ideal spectrum. The perturbations proposed by McCamy include CCT perturbation, colorimetric perturbation, mercury-line perturbation, achromatic perturbation. These perturbations were designed to simulate defects known to occur in practice, and to challenge the ability of the metamers to reveal defects. They should also have no preference for a particular kind of simulator. Details on each of these perturbations are given below.

<u>CCT perturbation</u>

The SPD of a phase of daylight can be computed for any given CCT within a reasonable range. This perturbation is to vary the CCT of a daylight simulator, making its chromaticity to vary along the Planckian locus, and to calculate the appropriate SPD.

<u>Colorimetric perturbation</u>

A daylight simulator may not be on the Planckian locus even its CCT is right, its chromaticity may be on either the purple or green side of the Planckian locus. This chromaticity shift is normal to the Planckian locus, so the ideal spectrum can be perturbed along this normal direction by adding or subtracting specific amounts of the CIE colour matching function $\bar{y}(\lambda)$.

<u>Mercury line perturbation</u>

Fluorescent lamps are widely used for many applications. The spectrally continuous fluorescence emission is excited by the emission spectrum of mercury and some of the characteristic mercury lines are present in the total emission. The ratio of the radiant powers in the various lines and the ratio of line emission to continuous emission differ from one lamp type to another. Mercury line perturbation is to vary the radiant power of the mercury line spectrum relative to an ideal continuum.

<u>Achromatic perturbation</u>

Achromatic perturbation aims to introduce significant dissimilarities between the spectrum of a daylight simulator and that of the ideal. These dissimilarities should cause mismatches among pairs of specimens that match in daylight or vice versa. There are three forms of achromatic perturbations. The first one is termed 'broadband perturbation'. For this perturbation, the perturbed spectrum closely follows the general shape of the ideal curve. As the amplitude is increased, the dissimilarity increases. The perturbed spectral curve is displaced at several sections, and each retaining the shape of the ideal curve. This perturbation introduces a low degree of dissimilarity. The second form is termed 'primary perturbation'. Adding emission lines to the ideal spectrum introduces much great dissimilarity. The chosen wavelengths at 450, 520, and 650 nm are the wavelengths of three additive primaries which provide a large chromaticity gamut. The third form is termed 'complementary perturbation', which imposes the highest degree of dissimilarity by perturbing the spectrum of a daylight simulator at the two complementary wavelengths at 485 and 585 nm.

2.8.2.2 Testing the CIE Method Using Real Metamers

Schlüpfer *et al* (1999) conducted a study for assessing D50 daylight simulators. ISO 12642 colour patches were used as real metamers to generate metameric spectral reflectances under each of seven D50 simulators for eight imaging systems. The CIE metamerism index results (only based on the visible range) obtained from these simulators are compared with the metameric differences occurring under practical conditions when working with different imaging systems. It was found that the correlation between the CIE metarmerism index values and the metameric differences of the real metamers is such that the category classifications obtained with the metamerism index approximately match those obtained with the real metamers. The study concluded that the CIE metamerism index method might be regarded as a satisfactory measure for predicting the metamerism occuring with typical D50 daylight simulators used in the graphic arts industry.

Lam and Xin (2002) carried out a study in which psychophysical experiments were conducted to investigate the visual colour difference of 77 textile metamers using a grey-scale rating method under five D65 simulators. The quality of each of the D65 simulators was categorised according to the CIE metamerism index values for the visible range. The colour difference of each metameric pair was calculated using the SPDs of CIE D65 illuminant and D65 simulators investigated. The performance factor (PF/3) (see Section 2.7.8) was used to indicate the agreement between visual colour differences under five D65 simulators as well as between instrumental colour difference and visual colour difference. Their experimental results showed that the visual results were different depending on the qualities of the D65 simulators used, and visual data obtained from simulators with category A and B were in good agreement with the PF/3 measure and had no statistical difference in a pair comparison *t* test.

2.8.2.3 Other Investigations

Terstiege (1991) compared the CIE metamerism index metric and a colour difference metric he proposed using six D65 simulators. He concluded that his colour difference metric worked better than the CIE metamerism index results for daylight simulators (see Section 2.7.5). Lester (1999) also tested the CIE metamerism index results for 61 D65 simulators using two data sets, the SWOP data set for graphic-arts and the Kodak Q60 Ektachrome dye set for photography. She found that the use of the real SPD of the source as reference illuminant for colorimetric calculations may reduce the effect of illuminant metamerism.

2.9 To Achieve a Daylight Simulator of Good Quality

The quality of a daylight simulator in terms of colorimetric measures such as chromaticity, CCT, colour rendering index, metamerism index, etc. are determined by its SPD. It is known that a good simulation to the standard daylight illuminant is the key factor to guarantee the quality of a daylight simulator. The major three types of daylight simulators are filtered tungsten lamps, filtered xenon lamps and fluorescent lamps. The quality of filter type simulators depends on the filter technology (see Section 2.4.1.1). The best D65 simulator was developed by Gundlach (1980) in the BAM. This simulator used a xenon lamp with sophisticated filter combinations. It achieved a very close SPD relative to the CIE D65 illuminant, with a 'AA' category for the CIE metamerism index. The GretagMacbeth SpectraLight light booth has a D65 simulator using filtered tungsten lamp; its CIE metamerism index category for the visible range is 'A'. However, as the power irritated by tungsten lamps is insufficient in the ultraviolet range, filtered tungsten lamps have difficulty in achieving a good simulation to the CIE daylight illuminant. An additional UV lamp is usually supplied in the light booth for assessing fluorescent materials.

Fluorescent lamps have the advantage of low cost and relative high lamp efficiency. They have been widely used as daylight simulator in light booth and luminaries. The fluorescent lamps have the inherent spectral lines caused by mercury discharge, so that the discrepancies between the SPDs of the fluorescent lamps and those of the CIE daylight illuminants are generally quite severe at the wavelengths of the emission lines. Another discrepancy that is characteristic of fluorescent lamps occurs in the wavelength region above 660 nm where these lamps show a rapid decrease of spectral power relative to that of the corresponding CIE illuminant. However, the lamp manufacturers have made great efforts to develop high quality fluorescent lamps with a good colour rendering index and metamerism index. According the author's recent survey on viewing cabinets (Xu 2003), the best fluorescent lamp as D65 simulator achieved 'B' category of CIE metamerism index for the visible range and '98' for the CIE colour rendering index. Mori (1983) carried out a study of the feasibility of producing a good quality D65 simulator. He found that it is possible to develop a fluorescent lamp type simulator by a relatively simple combination of fluorescent materials. The lamp could achieve 'BB' category for the CIE metamerism index.

2.10 Summary

In this chapter, the previous work relevant to the author's study has been reviewed. The aim of this review is to provide comprehensive information of daylight simulators. A brief review was first given for basic concepts and units in photometry, which provides a basis for the measurement of daylight simulators. A detailed review of CIE colorimetry was provided, which includes relevant information such as CIE colour specifications, colour temperature, CIE standard illuminants, colour difference formulae, chromatic adaptation transforms, colour inconstancy index, colour rendering, metamerism, colorant formulation, etc. The review of CIE colorimetry is essential for understanding the CIE approaches in defining the qualities of daylight simulators. The development of daylight simulators was also reviewed in order to reflect the importance of developing qualified daylight simulators for different applications. Various standards for specifying daylight simulators were reviewed as they play an important role for industrial colour quality control in using daylight simulators. Methods for evaluating daylight simulators, such as the BS 950 band value method, CIE metamerism index and colour rendering index methods, goodness-of-fit of SPD, etc. were also reviewed to investigate the performances of these methods and to develop more effective methods. Finally, previous work in making good daylight simulators was reviewed as they provide clues for improving the quality of daylight simulators.

CHAPTER 3
VARIATIONS OF PRACTICAL D65 AND D50 SIMULATORS

3.1 Introduction

Daylight illumination is widely used for industrial quality control in respect of colour matching and colour appraisal. Natural daylight can vary quite considerably in spectral power distribution due to the changeable weather conditions, so in practice, artificial daylight sources are adopted for various industrial applications (see Section 2.4.3). To standardise the daylight sources used in practice, in the 1960s, CIE defined a method to specify standard daylight illuminant based on the SPD of real daylight measured at different global locations. A series of standard daylight illuminants was specially recommended by CIE to represent daylights with correlated colour temperature (CCT) at 5000K, 5500K, 6500K and 7500K, denoted as D50, D55, D65, D75 respectively (CIE 1986, see Section 2.3.3.1).

Among these recommended daylight illuminants, D65 and D50 are of particular importance. The D65 illuminant, representing average daylight throughout the visible spectrum and into the ultraviolet region as far as 300 nm, is generally regarded as the preferred standard source for surface colour industries such as textiles, paints, plastics. For recipe formulation, D65 illuminant is also used as a standard source. However, in graphic arts industries such as printing and publishing, transparencies or prints are generally viewed not only under daylight but also under much yellower tungsten or fluorescent lights. D50 illuminant was therefore chosen as a standard source as it is less different from tungsten and low CCT fluorescent lights than the D65 illuminant (Johnson 1998, p.37, see Section 2.4.3), and the fact that D50 illuminant having essentially equal amounts of energy in the red, green, and blue portions of the visible spectrum (see Figure 2.3.4) enables the viewer to easily detect small colour differences between two reflective images (SWOB booklet, p.31).

The CIE methods to define the standard daylight illuminants determine the theoretical nature of these CIE daylight illuminnants, which means it is impossible to physically realise them precisely (see Section 2.3.3.1). Artificial daylight simulators such as D65 and D50 simulators were developed to simulate the corresponding CIE illuminant only approximately. The three major types of daylight simulators are filtered tungsten lamps, filtered xenon lamps and fluorescent lamps (Wyszecki 1970, see Section 2.4.1). For surface colour and graphic arts industries, fluorescent lamps and filtered tungsten lamps are most widely used. The former has the advantage of high energy efficiency (CIE 1987, see Section 2.2) and low manufacturing cost, but shows large discrepancies in the SPD in comparison with the CIE daylight illuminants. The latter was designed to have a closer simulation of SPD to the CIE daylight illuminant, however, there lie the drawbacks of low energy efficiency and high manufacturing cost.

The variety of daylight simulators causes concerns for lamp manufacturers and users, as daylight simulators having different SPDs may significantly affect the visual results on colour matching and colour appraisal (Kuo 1995, Lam 2000-01). To understand the quality variation of practical daylight simulators, the author carried out an industrial survey on viewing cabinets. Viewing cabinets are important devices accommodating daylight sources as well as other important sources such as incandescent light source for visual assessments on colour matching and colour appraisal. The survey incorporates a general inspection on the viewing cabinet and spectroradiometric measurement for each source (except the UV) of the cabinet.

This chapter first describes the industrial survey on viewing cabinets. The quality of various viewing cabinets is analysed. The variation of the D65 and D50 lamps accumulated are then investigated for both colorimetric results and spectral results, and the quality of these lamps is evaluated based on various national or international standards (see Section 2.5). The majority of the results in this chapter was published by the author (Xu 2003a).

3.2 An Industrial Survey on Viewing Cabinets

On behalf of the Society and Dyers and Colourists (SDC), the author carried out an industrial survey on viewing cabinets. The aims of the survey were to investigate the quality variation of viewing cabinets used by the textile industry and to propose guidelines for viewing cabinet design (see Section 2.6). Field work was conducted and technical reports were produced for assessing the quality of the viewing cabinets investigated.

3.2.1 Field Work

3.2.1.1 Surveyed Sites

Ten viewing cabinets, located at four industrial sites and the Colour & Imaging Institute, were surveyed. The four industrial sites are: Penn Nyla (dye house), James H. Heal & Co. Ltd (textile testing machinery manufacturer), Roaches (textile testing machinery manufacturer) and Unilever Research. Each site had up to three viewing cabinets being surveyed. The manufacturers of these cabinets include GretagMacbeth (GM), VeriVide (VV), BYK-Gardner (BYK) and Roaches (RO), see Table 3.2.1 for the details.

Table 3.2.1 Details about the sites surveyed

No	Surveyed Site	Industry	Make	Quantity	Location
1	Penn Nyla (PN)	Dye house	GM SpectraLight III VV CAC 150 VV purpose-built	1 1 1	Laboratory Laboratory Production line
2	James H. Heal	Textile testing	VV CAC60	1	Laboratory
3	Roaches (RO)	Textile testing	Roaches Opti-Lite	1	Laboratory
4	Unilever Research (UN)	Textile testing	VV purpose-built VV DCAC 60 VV CAC 150	1 1 1	Laboratory Laboratory Laboratory
5	Colour & Imaging Institute (CII)	Education and Research	BYK byko spectra GM SpectraLight II	1 1	Laboratory Laboratory

3.2.1.2 Measurement Conditions

PTFE white tile

In the survey, the SPD of each light source situated in an investigated viewing cabinet was obtained by measuring the light reflected from a PTFE white tile across the visible region. The tile is made of diffusely reflecting plastics and has almost constant reflectance across the visible region from 380 nm to 780 nm (Gigahertz-Optik 1999). Figure 3.2.1 shows the reflectance of the tile measured by a GretagMacbeth ColorEye 7000A spectrophotometer (see Section 2.3.12.1). The measurement condition was set to large aperture, specular included and UV included. The instrument is a bench-top spectrophotometer configuring with an integrating sphere and true dual-beam system. The instrument is also under regular services from the manufacturer to maintain a good working order. The accuracy of the instrument was tested using 12 BCRA-NPL glossy tiles. The average/maximum colour differences (CMC (1:1)) under CIE D65 and CIE 10° Observer are 0.46/1.17 and 0.25/0.64

for specular included and excluded conditions respectively. The slight variations in reflectance of the tile were corrected for calculating the spectral radiance of the measured surface.

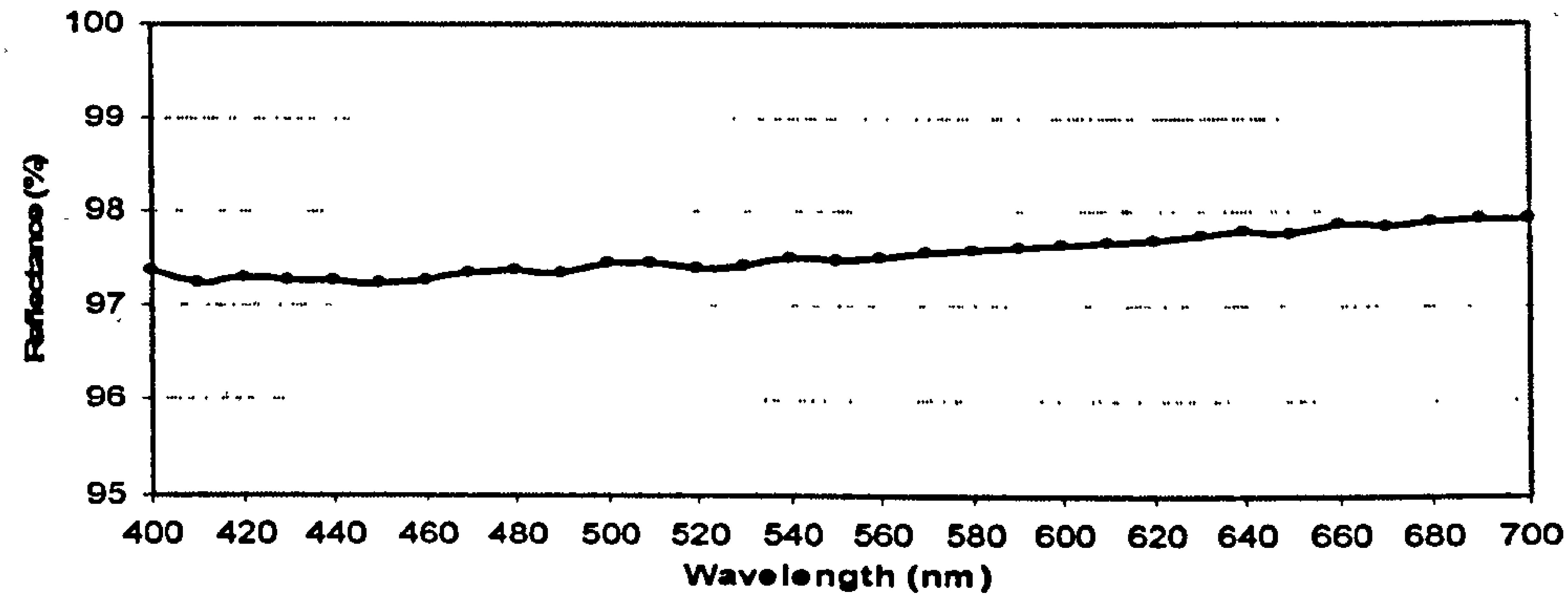


Figure 3.2.1 Measured spectral reflectance values for the PTFE white tile

Measurement geometry

The PFTE white tile was placed on the floor of the investigated cabinet and was measured at five positions, the centre and four corners. The distance from a corner to both horizontal and vertical edges was set approximately to a quarter of the normal distance between the edge and the centre, which ranged from 5 to 20 cm depending on the size of each individual cabinet. (Note that the quality of each light source within a cabinet is normal judged based on the measurement results from the centre position. However, due to the lamp position in the cabinet canopy, the measurement results from the four corner positions could be quite different from those in the centre position, resulting in poor uniformity of the cabinet, see more in Table 3.2.5.) The tile was measured at a 0/45 geometry with ambient lighting off. The warming-up time for each source was five minutes. The measurement setting up is shown in Figure 3.2.2.

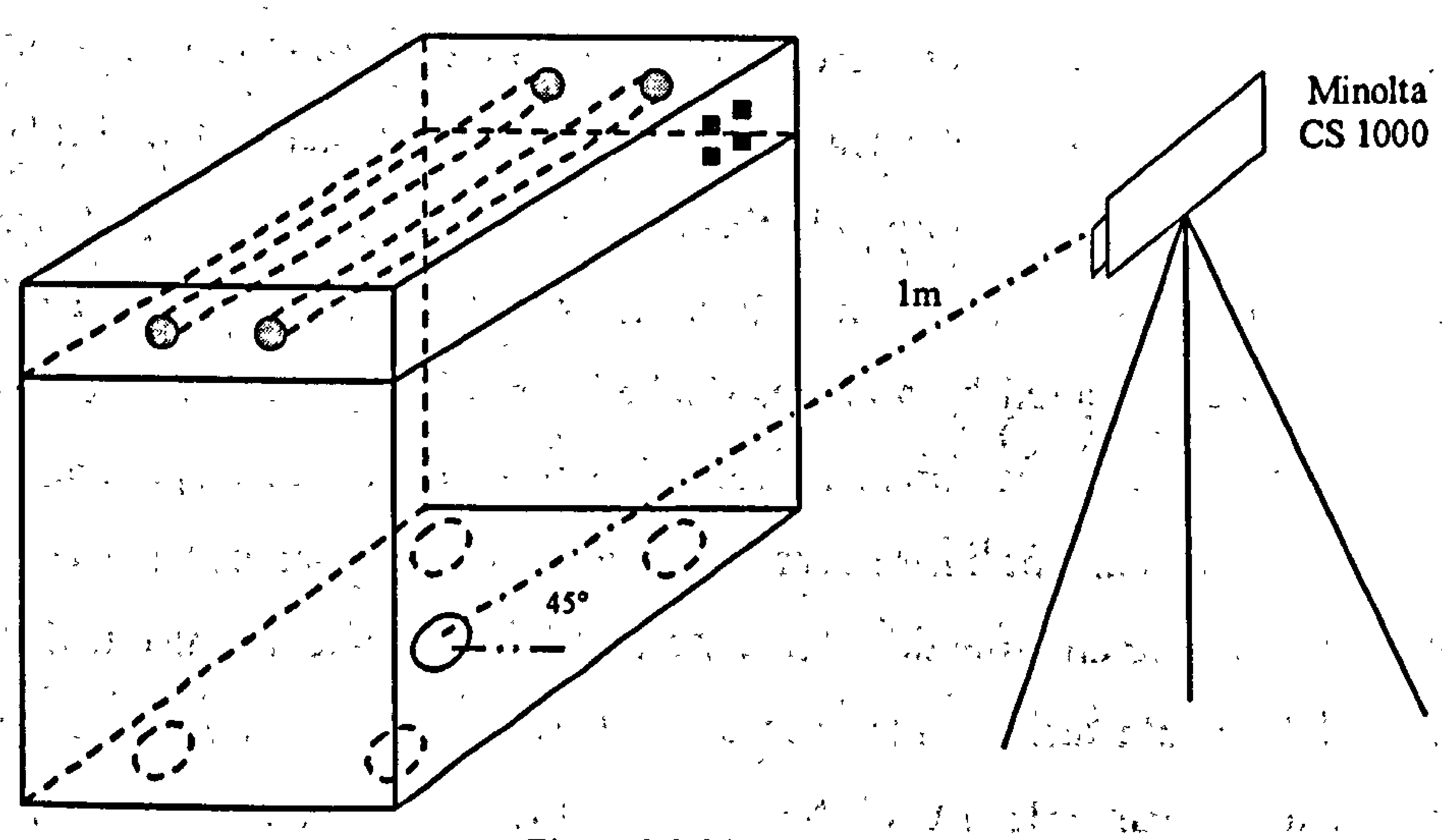


Figure 3.2.2 Measurement set up

<u>Measuring Instrument</u>

A tele-spectroradiometer, Minolta CS 1000, was used to measure the SPD of each light source within a viewing cabinet (see Section 2.3.12.2). The instrument is configured with SLR (single lens reflex) optical system to allow precise targeting and to minimise the stray light effect in measurement. The Auto mode, which is designed for measuring stationary lights, was adopted for the measurements. The advantage of using Auto mode is that a sensor fitted in the instrument detects the target stimulus and then automatically sets a suitable integration time for the measurement. The measured wavelength ranges from 380 nm to 780 nm with bandwidth and wavelength increment both set to 5 nm. The instrument has no capacity to measure the UV of the light sources.

Table 3.2.2 summaries the results for testing the instrument measurement performances. An incandescent lamp within a sphere (namely CII standard lamp) was measured. The lamp was warmed up for at least half an hour before the measurement was commenced. The instrument short-term repeatability was first tested by measuring the lamp twenty times at a 1-minute interval between two consecutive measurements. The chromaticities x, y for the 20 measurements did not change at all, only a very small change of about 0.02% was observed for luminance (cd/m^2). For long-term repeatability, the differences between two measurements at a 1-month interval are -0.17%, 0.0002 and 0.0001 for luminance (cd/m^2), chromaticities x and y respectively.

For instrument accuracy, the differences between the average of 20 readings measured by the CS 1000 and those certified by NPL for the CII standard lamp are –2.0%, 0.0035 and 0.0011 for luminance (cd/m^2), chromaticities x and y respectively. According to the instrument manual, the instrument was traced to a NPL standard with measurement uncertainty of ±2%±1digit, ±0.0015 and ±0.0010 for luminance (cd/m^2), chromaticities x and y respectively for a working standard (tungsten light). Hence, for the CII standard lamp, the differences between the instrument results and those certified by the NPL are out of the uncertainty range stated by the manufacturer, particularly in the case of x chromaticity. However, it should be noted that the working standard adopted by the instrument manufacturer for traceability to NPL might be quite different in luminance comparing to the CII standard lamp. In addition, the NPL certified results for the CII standard lamp have uncertainty of ±1.6%, ±0.0017 and ±0.003 for luminance (cd/m^2), chromaticities x and y respectively. These could all contribute to the chromaticity discrepancies between the instrument results and NPL results for the CII standard lamp.

As the luminance level encountered in this study (see Table 3.3.1) was much lower than that of the CII standard lamp, the instrument and viewing cabinet performances were also tested by measuring six D65 simulators. The results are reported in Table 3.2.3. These simulators will be used in Chapter 4 for a visual assessment of the quality of the lamps (see Section 4.2.1). Each of the six simulators was fitted in a viewing cabinet and had been fired for about 100 hours before the visual experiment was started. Each simulator was measured three times, before, during and after the experiment, at a 1-month interval between two consecutive measurements. The measurement geometry is shown in Figure 3.2.2. The warm-up time for each simulator was about five minutes before commencing the measurements. Only the centre position of the cabinet floor was measured. The ambient lighting was turned off during the measurement. For each simulator, the variations between the three measurement results were examined in terms of standard deviation and Maximum Difference (the difference between the average and the most deviated results). It was found the GE broad band fluorescent lamp had the worst measurement variations with Maximum Difference of 5.7%, 0.0012 and 0.0021 for luminance (cd/m^2), chromaticities x and y respectively. For most of the six simulators, the variations in terms of Maximum Difference are much larger than the instrument long-term repeatability (see Table 3.2.2). This suggests that some factors such as the change of lamp output due to working hour, fluctuation of power supply and change in measurement set-up might have a major impact on the measurement variation results.

Table 3.2.2 Testing the instrument (CS 1000) performances by measuring the CII standard lamp

		L (cd/m2)	x	y
	Measurement (1) (Ave. of 20 consecutive measurements)	6859	0.4528	0.4134
	Measurement (2) (one measurement after one month)	6847	0.4530	0.4135
Repeatability (long-term)	Diffference between (2) and (1)	-0.17%	0.0002	0.0001
	Certified by NPL	7002±1.6%	0.4493±0.0017	0.4123±0.0003
	Ave. of 20 measurements (CS 1000)	6859	0.4528	0.4134
Accuracy	Diffference between CS 1000 and NPL	-2.0%	0.0035	0.0011

Table 3.2.3 A summary of the instrument (CS 1000) and viewing cabinet performances

	L (cd/m²)	x	y	L (cd/m²)	x	y	L (cd/m²)	x	y
Simulators [a]	GM (FT)			VV (F7)			GM (F7)		
Before exp.	410.7	0.3127	0.3311	564.4	0.3083	0.3245	551.3	0.3155	0.3314
During exp.	404.2	0.3130	0.3317	547.3	0.3095	0.3264	537.6	0.3164	0.3322
After exp.	401.5	0.3126	0.3312	546.3	0.3090	0.3258	532.4	0.3167	0.3325
Ave.	405.5	0.3128	0.3313	552.7	0.3089	0.3256	540.4	0.3162	0.3320
Std.	4.7	0.0002	0.0003	10.2	0.0006	0.0010	9.7	0.0006	0.0006
Max Diff [b]	1.3%	0.0002	0.0004	2.1%	0.0006	0.0011	2.0%	0.0007	0.0006
Simulators	GE (F7)			TO (F7)			TO (3B)		
Before exp.	537.0	0.3155	0.3269	480.4	0.3191	0.3303	987.4	0.3134	0.3211
During exp.	494.4	0.3173	0.3302	486.0	0.3203	0.3320	939.1	0.3140	0.3221
After exp.	493.0	0.3172	0.3299	486.5	0.3202	0.3318	946.1	0.3143	0.3224
Ave.	508.1	0.3167	0.3290	484.3	0.3199	0.3314	957.5	0.3139	0.3219
Std.	25.0	0.0010	0.0018	3.4	0.0007	0.0009	26.1	0.0005	0.0007
Max Diff [b]	5.7%	0.0012	0.0021	0.8%	0.0008	0.0011	3.1%	0.0005	0.0008

a GM, VV and TO are the abbreviations for GretagMacbeth, VeriVide and Toshiba, respectively. FT and 3B are the abbreviations for filtered tungsten lamp and three-band fluorescent lamp respectively. F7 represents the broad band fluorescent lamps which have SPDs similar to CIE F7 illuminant.

b Max. Diff is the abbreviation for the difference between the average and the most deviated results.

3.2.2 General Information of the Viewing Cabinets Surveyed

3.2.2.1 Light Sources

Amongst the cabinets surveyed, two were made by GretagMacbeth, six were made by VeriVide, one by Roaches and one by BYK-Gardner. All the cabinets provide a selection of light sources, with press-button accessibility. All the viewing cabinets investigated are configured with four light sources, incandescent (A), average north sky daylight (D65), three-band fluorescent (TL84) and UV. Two additional sources, Cool White Fluorescent (CWF) and Horizon Daylight, are included in the GretagMacbeth SpectraLight cabinets. Light sources A and D65 are used to simulate CIE illuminants A and D65, respectively (see Section 2.3.3.1). The fluorescent source TL84 has a SPD close to that of the CIE F11 illuminant (see Section 2.3.3.2), with a CCT of 4100K. The fluorescent source CWF has a wide-band SPD close to that of CIE F2 or F6, with a CCT of 4150K, and falling in the 'normal' category of CIE F illuminants. TL84 lamps are mainly used in Europe while CWF lamps are used in the USA for office and store lighting. Horizon Daylight with a designed CCT of 2300K provides the light quality that is found in early morning sunrise or late afternoon sunset. This source is normally achieved by using a tungsten halogen lamp operated at half power (Macbeth 1996).

3.2.2.2 Cabinet Details

The details of each investigated cabinet are provided in Table 3.2.4, and their images are shown in Figures 3.2.3(a) to (f). It was found that except the light sources each viewing cabinet uses, these cabinets are different in the following aspects.

Working Environment

The working environment of each cabinet varies. Although most of the investigated cabinets are located in laboratories, the conditions in these laboratories were different. Some laboratories have strict control on ambient lighting (natural and artificial) and room temperature (denoted as 'L1' in Table 3.2.4), but some do not (denoted as 'L2' in Table 3.2.4). One VeriVide cabinet was located at a production line (denoted as 'P' in Table 3.2.4), so ambient lighting is unavoidable when using the cabinet for critical colour evaluation.

Age and Size

The cabinets were different in age, from almost new to seven years old. The GretagMacbeth SpectraLight III and BYK byko-spectra were almost brand new cabinets while one VeriVide CAC 150 and one VeriVide purpose-built cabinets had been used for over five years. The size of the cabinets varies greatly. For each dimension, the maximum size is about three times of the minimum one.

Interior Colour

The interior of all the cabinets were painted grey, but the lightness of the grey paint varied greatly. The BYK cabinet uses the lightest colour having L* of 79. The GretagMacbeth SpectraLight cabinets use a colour with lightness corresponding to Munsell Value N7 (see Section 2.3.6.1). The VeriVide cabinets and the Roaches cabinet use different colours as the interior paint, with lightness corresponding to either Munsell Value N5 or Smoky Pine. Note that the lightness (L*) in Table 3.2.4 were obtained by measuring the SPD of the cabinet floor and the PTFE white tile for the same position. The power ratio between the cabinet floor and the PTFE white tile (correction was made using the measured reflectance of the white tile) for each reported wavelength was taken approximately as the reflectance of the cabinet interior colour, given the fact that all the investigated cabinets were painted uniformly with a single grey colour. In Table 3.2.4, the variations of measured L* for the same supposed interior colour (say N5) reflect the fact that the interior paint is generally worn off to some extent with the age of the cabinet. The longer time the cabinet is used, the more worn is the interior paint. Inspections on the cabinets also show some cabinets had large scratches on the floor or wall.

Accessories and Electrical Controls

The cabinets of different make have different design for accessories and electrical controls. Some cabinets are configured with diffuser, dimmer control and elapsed-time meter, but some are not.

Table 3.2.4 Details of the viewing cabinets surveyed

No	Manuf.	Model	Location	Age (Year)	Viewing Dimension W x H x D (mm)	Source Included	Interior Colour	Diffuser
1	GM	SpectraLight II	CII (L1)[a]	2	900x640x580	D65, A, CWF, Horizon, UV	L^*=69 (N7)	With
2	GM	SpectraLight III	PN (L1)	0.5	890x660x600	D65, A, TL84, CWF, Horizon, UV	L^*=69 (N7)	With
3	VV	CAC 150	PN (L1)	7	1520x580x580	D65, A, TL84, UV	L^*=51 (SP)[c]	Without
4	VV	CAC 150	UN (L1)	2	1520x580x580	D65, A, TL84, UV	L^*=45 (N5)	Without
5	VV	CAC 60	JH (L2)[a]	2.5	670x360x380	D65, A, TL84, UV	L^*=50 (SP)	Without
6	VV	DCAC 60	UN (L1)	2	680x380x380	D65, A, TL84, UV	L^*=52 (SP)	Without
7	VV	Purpose-built	UN (L1)	2	1850x1050x1000	D65, A, TL84, UV	L^*=41 (N5)	Without
8	VV	Purpose-built	PN (P)[b]	5	660x420x370	D65, A, TL84, UV	L^*=51 (SP)	Without
9	RO	Opti-Lite	RO (L2)	1	680x360x380	D65, A, TL84, UV	L^*=48 (N5)	Without
10	BYK	Byko-spectra	CII (L1)	0	650x460x500	D65, A, TL84, UV	L^*=79	With

a L1 and L2 indicate that the cabinet is located in a laboratory with and without control on ambient lighting and room temperature, respectively.

b P indicates that the cabinet is located at production line.

c SP is an abbreviation for a grey paint called Smoky Pine.

Figure 3.2.3 Images of the surveyed viewing cabinets made by (a) GretagMacbeth SpectraLight, (b) VeriVide CAC 150, (c) VeriVide CAC 60 and DCAC 60, (d) VeriVide purpose-built, (e) Roaches Opti-Lite and (f) BYK byko-spectra.

3.2.3 Technical Report for Assessing a Viewing Cabinet

A technical report was produced for evaluating the quality of each viewing cabinet investigated. Each report consists of four sections (Sections A to D) and an Appendix. An exemplar report for one viewing cabinet (GretagMacbeth SpectraLight II) is given in Appendix B. In Appendix B, Section A provides the general information for a particular cabinet, i.e. the survey date, cabinet location, contact of survey site, etc. Section B gives a detailed description on the cabinet condition, and the information provided in this section includes the manufacturer and make of the cabinet, age, each light sources installed, viewing dimension, burn marks on the tubes, flickering, status of interior paint, diffuser, dimmer control, elapsed-time meter and working location.

Section C reports the colorimetric results for each light source, including chromaticity co-ordinates x, y and u', v', luminance and CCT. The uniformity of each light source was evaluated in term of Mean, Maximum Difference and CV for each type of colorimetric results. Mean refers to the average results for the five positions measured. Maximum Difference refers to the maximum difference between the mean results and the most deviate results from the five measurement positions. This metric is used to reveal the worst variation of a cabinet, as visual assessments are normally conducted within the central area of the cabinet and the four corners are thought to be the extreme positions for visual inspection. Coefficient of Variation (CV) is calculated by taking the standard deviation, dividing by the mean and multiplying by 100. This represents variation in percentage. Both the Maximum Difference and CV metrics can be used to examine the uniformity of each light source, the larger the two results, the worse the uniformity. It should be noted that some standards, e.g. ISO 3664 (see Section 2.5.5.1) and AS 4004 (see Section 2.6.2), calculate the illumination uniformity using the ratio between the minimum and maximum illumination across the view area and specify that ratio should be larger than 0.75 for normal viewing conditions.

In Section C, a target illuminant was also specified for each light source investigated, i.e. CIE illuminants D65, A, F11 and F6 for sources D65, A, TL84 and CWF, respectively. For each light source, the results from the centre position are regarded as typical of the cabinet. Chromaticity deviation in terms of Δu'v' was calculated between a source (centre position) and the target illuminant. CIE metamerism index results (see Section 2.5.4.2) for D65 sources were also reported. It should be noted that although some cabinets have dimmer controls, each light source was measured only at the maximum power capacity. Exception was made for the VeriVide DCAC 60 cabinet, which was measured at two illumination levels, maximum and a user defined level (less than 20% of the maximum) for the centre position, as requested by the cabinet user. The results for both illumination levels were reported for this cabinet.

Section D gives an overall comment on the quality of the viewing cabinet assessed. The last part of the technical report is an appendix, which includes an illustration for the measures used in the assessment results, reference and a plot of normalised SPDs for all the light sources investigated.

3.2.4 Summary Results for the Viewing Cabinets Investigated

The technical reports show that there is a large variety of viewing cabinets in use, differing in manufacturer, model, age, location, working environment, etc. For a particular source, say D65 source, its quality in terms of colour and illumination uniformity also varies with cabinets. The results from the technical reports for all the investigated viewing cabinets are summarised in Table 3.2.5, which includes the chromaticity co-ordinate (x, y) and (u', v'), chromaticity deviation ($\Delta u'v'$), luminance (cd/m^2), CCT (K) and CIE colour rendering index (CIE 1995a, see Section 2.5.4.1) for sources D65, A, TL84, CWF and Horizon respectively. The illumination uniformity of each investigated cabinet was also reported in terms of CV and the ratio between the minimum and maximum luminance values which were measured at the five positions of the cabinet floor. The luminance ratios for a source relative to the D65 source (AS 4004, 1992) are also included in the table. The CIE metamerism index (CIE 1999, see Section 2.5.4.2) for the visible range (MI_{vis}) is reported for the D65 sources. The CIELAB colour difference (ΔE^*_{ab}) was also reported for a reference white (perfect diffuser) illuminated under a source and a target illuminant.

All the colorimetric results in Table 3.2.5 were calculated using the measured SPD of each source (see Sections 2.3.1) at the centre position of the cabinet floor. These results are typical of the cabinet as visual assessments are mostly conducted within the central area of the cabinet floor. The variations of each type of result were also investigated in terms of average, range (difference between the maximum and minimum values), standard deviation and CV, with the maximum and minimum values of each result noted in bold with italic and underlined respectively. It worth noting that various standards and CIE recommendations are available for specifying the quality of daylight simulators (see Section 2.6), but not for the incandescent sources and other fluorescent sources such as TL84. The following analyses the quality of different viewing cabinets based on the results in Table 3.2.5.

Table 3.2.5 Summary results for each light source within the viewing cabinets investigated

Cabinet / Source	x	y	u'	v'	Δu'v'	L (cd/m²)	CCT (K)	ΔE*ab [a]	CV [b]	Ratio1 [b]	Ratio2 [c]	CRI	MIvis [d]
D65 (cabinet age in years)													
CIE D65	0.3127	0.3290	0.1978	0.4683			6504						
GM SpectraLight II (2)	0.3127	0.3311	0.1970	0.4694	0.0014	411	6491	1.34	8	0.86		96	A
GM SpectraLight III (0.5)	0.3131	0.3341	0.1962	0.4711	0.0032	387	6448	3.12	8	0.88		94	A
VV CAC 150 (7)	0.3203	0.3344	0.2011	0.4723	0.0052	369	6074	3.76	16	0.71		95	C
VV CAC 150 (2)	0.3147	0.3296	0.1990	0.4689	0.0013	263	6387	0.97	21	0.62		95	C
VV CAC 60 (2.5)	0.3096	0.3280	0.1960	0.4673	0.0021	483	6688	1.51	17	0.68		98	A
VV DCAC 60 (2)	0.3090	0.3250	0.1968	0.4656	0.0029	549	6741	2.26	19	0.67		98	B
VV Purpose-built (2)	0.3150	0.3307	0.1988	0.4695	0.0016	326	6366	1.15	18	0.69		96	C
VV Purpose-built (5)	0.3188	0.3361	0.1994	0.4730	0.0050	319	6141	3.92	14	0.73		96	B
RO Opti-Lite (1)	0.3153	0.3298	0.1993	0.4691	0.0017	591	6357	1.26	19	0.64		98	C
BYK byko-spectra (0)	0.3219	0.3419	0.1993	0.4764	0.0082	466	5978	6.91	13	0.73		94	C
AVE.	0.3150	0.3321	0.1983	0.4703	0.0033	417	6367	2.62	15	0.72		96	
RANGE	0.0129	0.0169	0.0051	0.0108	0.0069	328	763	5.94	15	0.26		4	
STD	0.0043	0.0047	0.0017	0.0031	0.0023	105	248	1.87	5	0.09		1.56	
CV	1	1	1	1	69	25	4	71	35	12		2	
A (cabinet age in years)													
CIE A	0.4476	0.4074	0.2560	0.5243			2856						
GM SpectraLight II (2)	0.4531	0.4122	0.2575	0.5269	0.0030	398	2801	3.89	9	0.80	0.97	99	
GM SpectraLight III (0.5)	0.4484	0.4115	0.2547	0.5260	0.0021	440	2865	2.49	8	0.88	1.14	99	
VV CAC 150 (7)	0.4681	0.4151	0.2658	0.5303	0.0115	306	2618	11.39	13	0.75	0.83	99	
VV CAC 150 (2)	0.4743	0.4184	0.2682	0.5325	0.0147	274	2563	15.35	14	0.73	1.04	98	
VV CAC 60 (2.5)	0.4707	0.4173	0.2665	0.5315	0.0127	401	2601	13.26	11	0.77	0.83	99	
VV DCAC 60 (2)	0.4706	0.4166	0.2667	0.5312	0.0127	484	2597	13.01	12	0.77	0.88	99	
VV Purpose-built (2)	0.4717	0.4163	0.2676	0.5313	0.0135	177	2579	13.47	17	0.68	0.54	99	
VV Purpose-built (5)	0.4893	0.4166	0.2788	0.5341	0.0248	301	2372	22.78	19	0.67	0.94	99	
RO Opti-Lite (1)	0.4704	0.4181	0.2659	0.5317	0.0124	370	2612	13.37	12	0.77	0.63	98	
BYK byko-spectra (0)	0.4660	0.4170	0.2636	0.5307	0.0099	431	2663	10.97	11	0.76	0.92	99	
AVE.	0.4683	0.4159	0.2655	0.5306	0.0117	358	2627	12.00	12	0.76	0.87	99	
RANGE	0.0409	0.0069	0.0241	0.0081	0.0227	307	493	20.28	13	0.21	0.60	1	
STD	0.0112	0.0023	0.0065	0.0024	0.0063	93	134	5.69	4	0.06	0.18	0.42	
CV	2	1	2	0	54	26	5	47	30	8	21	0	
TL84 (cabinet age in years)													
CIE F11	0.3805	0.3769	0.2251	0.5017			4000						
GM SpectraLight III (0.5)	0.3847	0.3808	0.2263	0.5040	0.0026	456	3903	2.47	9	0.81	1.18	85	
VV CAC 150 (7)	0.3874	0.3856	0.2261	0.5065	0.0049	716	3871	5.01	18	0.68	1.94	85	
VV CAC 150 (2)	0.3844	0.3822	0.2255	0.5045	0.0028	654	3923	3.00	23	0.62	2.48	85	
VV CAC 60 (2.5)	0.3827	0.3846	0.2235	0.5053	0.0039	760	3985	4.23	16	0.69	1.57	84	
VV DCAC 60 (2)	0.3832	0.3834	0.2243	0.5049	0.0033	984	3963	3.54	19	0.66	1.79	85	
VV Purpose-built (2)	0.3829	0.3822	0.2245	0.5043	0.0027	418	3963	2.89	19	0.67	1.28	85	
VV Purpose-built (5)	0.3959	0.3909	0.2296	0.5099	0.0094	505	3703	9.08	16	0.70	1.58	85	
RO Opti-Lite (1)	0.3845	0.3809	0.2261	0.5040	0.0025	868	3911	2.46	16	0.70	1.47	84	
BYK byko-spectra (0)	0.3884	0.3901	0.2250	0.5085	0.0068	485	3880	7.30	11	0.76	1.04	83	
AVE.	0.3860	0.3845	0.2257	0.5058	0.0043	650	3900	4.44	16	0.70	1.59	85	
RANGE	0.0132	0.0101	0.0061	0.0059	0.0068	567	281	6.62	14	0.19	1.44	2	
STD	0.0042	0.0037	0.0018	0.0021	0.0024	199	83	2.32	4	0.06	0.44	0.73	
CV	1	1	1	0	54	31	2	52	26	8	28	1	
CWF (cabinet age in years)													
CIE F6	0.3779	0.3882	0.2190	0.5062			4150						
GM SpectraLight II (2)	0.3797	0.3907	0.2192	0.5075	0.0013	345	4106	1.40	14	0.71	0.84	61	
GM SpectraLight III (0.5)	0.3767	0.3848	0.2195	0.5045	0.0018	392	4148	1.83	11	0.77	1.01	61	
Horizon (cabinet age in years)													
GM SpectraLight II (2)	0.5011	0.4172	0.2862	0.5361		282	N/A		9	0.80	0.69	99	
GM SpectraLight III (0.5)	0.4987	0.4176	0.2844	0.5359		351	N/A		5	0.89	0.91	99	

a. ΔE^*_{ab} refers to the CIELAB colour difference between a light source and the corresponding target illuminant for a reference white (perfect diffuser).

b. CV and Ratio1 are used to quantify the illumination uniformity. CV is calculated by taking the standard deviation, dividing by the mean and multiplying by 100. Ratio1 is the ratio between the minimum and maximum luminance values which were measured at the five positions (centre and four corners) of the cabinet floor.

c. Ratio2 is a luminance ratio (luminance measured at centre position) for a light source relative to the D65 source.

d. MI_{vis} represents the CIE metamerism index for the visible range. It is used specifically for D65 sources.

3.2.4.1 GretagMacbeth SpectraLight Viewing Cabinets

The two GretagMacbeth SpectraLight cabinets exhibit the best quality amongst all the viewing cabinets investigated. All the light sources with the cabinets, including D65, A, TL84, CWF, Horizon daylight, have almost the correct CCT and chromaticities in comparison with the target illuminants. The illumination uniformity of these two cabinets is generally very good in terms of CV and luminance ratio (see Ratio1 in Table 3.2.5) results. Only one CWF source is outside the ISO 3664 (see Section 2.5.5.1) tolerance of 0.75 for luminance ratio. The luminance ratio (see Ratio2 in Table 3.2.5) between a source and the D65 source is close to 1.0, indicating that each cabinet has similar illumination level for all light sources. For the D65 sources, both cabinets used filtered incandescent light sources as daylight simulators and achieved 'A' category for the CIE metamerism index. However, the two cabinets do not show good CIE colour rendering index (CRI) results for the CWF and TL84 sources, with CRI being only 61 for the CWF sources.

3.2.4.2 VeriVide Viewing Cabinets

The quality of the VeriVide viewing cabinets varies considerably. The illumination uniformity of the VeriVide cabinets is worse than the GretagMacbeth SpectraLight cabinets, partly due to the larger cabinet size. The luminance ratio results show that a few VeriVide cabinets do not meet the ISO 3664 tolerance of 0.75. For the quality of light sources, all the VeriVide cabinets show certain characteristics. For instance, the D65 sources exhibit relatively good quality with close chromaticities and CCT and good CRI in comparison with the CIE D65 illuminant (the chromaticity deviations for all the D65 sources are within the CIE tolerance of 0.015 in $\Delta u'_{10}v'_{10}$ unit). However, the quality of the incandescent sources is unsatisfactory, with considerably large deviations observed for chromaticity and CCT results. In particular, all the incandescent sources have CCT values lower than the specified one at 2856K. The worst one has CCT almost 500K lower than the specified one, resulting in the largest chromaticity deviation of 0.0248 in $\Delta u'v'$ unit. Despite this, the CRI results for the incandescent sources are still very good. The incandescent sources seem to correspond closely to black body radiators of lower colour temperature than CIE illuminant A and in one case close to horizon daylight (colour temperature of 2300K). The chromaticities of the TL84 sources are much closer to the target illuminant than those of the incandescent sources, but slightly worse than those of the D65 sources. The CRI results for the TL84 sources are much lower than other sources.

The CIE metamerism index category for the D65 sources ranges from 'A' to 'C' (detailed analysis is given in Section 3.3). The luminance results reveal that different VeriVide cabinets have different illumination levels. One purpose-built cabinet, which is the largest in size, has the lowest illumination level for almost all the light sources investigated. This reflects the difficulty in maintaining the illumination level for viewing cabinets of large size. The luminance ratio results reveal that different light sources have different illumination levels, with the TL84 sources having the highest levels and the incandescent sources having the lowest levels.

3.2.4.3 Roaches Viewing Cabinet

The quality of the cabinet is about average. The colours of the D65 and TL84 sources are quite close to the target ones, but that of the incandescent source is quite different. The D65 source only reaches the 'C' category for the CIE metamerism index. The illumination uniformity is good for the incandescent source, but not for the D65 and TL84 sources. The luminance ratio results for these two sources are outside the ISO 3664 tolerance of 0.75. The luminance ratio results reveal that the cabinet has different illumination levels for different sources, with the TL84 having the highest level and the incandescent having the lowest level.

3.2.4.4 BYK-Gardner Viewing Cabinet

The quality of the cabinet is regarded as unsatisfactory mainly because the colours of the three sources, D65, A and TL84, are considerably different from those of the target illuminants, particularly for the D65 and incandescent sources. The CIE metamerism index category for the D65 source is 'C'. The illumination uniformity of the cabinet is good for almost all the three sources, largely because of the use of a diffuser. The luminance ratio results reveal that the cabinet has a similar illumination level for the different sources.

3.2.5 Findings with Respect to the Quality of Viewing Cabinets

Some conclusions from this survey with respect to the quality of viewing cabinets are:

- For majority of the viewing cabinets investigated, the illumination uniformities are slightly varied for different light sources, e.g., the A sources generally give a better performance than the other sources such as D65 and TL84. In Table 3.2.5, the average results in terms of Ratio1 (the ratio between the minimum and maximum luminance values which were measured at the five positions of the cabinet floor) for the A sources are 0.76, which is within the ISO 3664 tolerance of 0.75, while those for the D65 and TL84 sources are out of the ISO 3664 tolerance. It was also found that the illumination uniformity of a viewing cabinet could be improved by the use of a diffuser. The three viewing cabinets, the two GretagMacbeth SpectraLight cabinets and the BYK cabinet, which use a diffuser, have much better illumination uniformity than the other cabinets which do not use a diffuser.

- Cabinets of large size have lower than average illumination levels. One VeriVide purpose-built cabinet, which is the largest amongst all the cabinets investigated, has the lowest illumination levels for both A and TL84 sources. For the D65 sources, the lowest level occurs on a VeriVide CAC 150 cabinet, which is also a large size cabinet.
- A large size cabinet is likely to have poor illumination uniformity. One VeriVide CAC 150 cabinet, a cabinet of large size, has the worst illumination uniformity with luminance ratio of only 0.62 for both D65 and TL84 sources, much lower than the ISO 3664 tolerance of 0.75.
- Not all the cabinet manufacturers consider the balance of illumination levels between different light sources, e.g. the GretagMacbeth SpectraLight cabinets and BYK cabinet have similar illumination levels for different light sources, but that is not the case for the VeriVide cabinets and Roaches cabinet.
- Ageing does not necessarily deteriorate the quality of viewing cabinets, while regular service is essential for maintaining the quality of viewing cabinets. For instance, the two GretagMacbeth SpectraLight cabinets and the two VeriVide CAC 150 cabinets, which are all regularly serviced, exhibit similar performances despite different ages.
- The A sources of the investigated cabinets except the GretagMacbeth SpectraLight ones show lower CCT than CIE A illuminant, but still give very good CRIs, presumably corresponding closely to black body radiators of the appropriate colour temperature. As normal domestic tungsten lamps can achieve CCT around 2800K (see Hunt 1998, p.96), the quality of these A sources in terms of colour temperature are thought to be unsatisfactory.

3.3 Variation of D50 and D65 simulators in Practice

Section 3.2 reveals that a considerable variation exists for the D65 sources within the viewing cabinets investigated. To quantify the variation of daylight simulators in practice, the measured SPDs of 15 D65 simulators and 58 D50 simulators, accumulated from UK and USA industrial laboratories respectively, were analysed. The lamp variations were examined in terms of colorimetric values and spectral results for different lamp types (i.e. fluorescent lamp or filtered tungsten lamp) and manufacturers. The quality of these investigated simulators was evaluated and compared to the CIE recommendations and ISO standards (see Section 2.5).

3.3.1 Data Acquisition

3.3.1.1 D65 Simulators

Lamp Details

Fifteen D65 simulators were measured by the author. Ten of them are the D65 sources of the viewing cabinets investigated in detail (see Section 3.2). The rest are fluorescent lamps made by different manufacturers. They were collected and measured in our laboratory. Each of these fluorescent lamps was evaluated in a purpose-built VeriVide viewing cabinet to accommodate the slight differences in lamp length. The size of the purpose-built cabinet is similar to that of VeriVide CAC 60 cabinet (see Table 3.2.4). The cabinet interior was painted with a grey colour having lightness of Munsell Value N5.

These D65 lamps were further divided into 8 groups (Groups A to H) according to different manufacturers and different types of lamps. Group A includes seven F7 lamps made by VeriVide (the SPDs of these lamps are similar to the CIE F7 illuminant (see Section 2.3.3.2). Groups B to F each include only one F7 lamp made by GE, GretagMacbeth (GM), Philips, BYK-Gardner (BYK) and Toshiba, respectively. Group G is a Toshiba three-band fluorescent lamp. (Although the CIE recommended F7 lamps to be used as D65 simulators with priority over other F-sources, three-band fluorescent lamps are still used as daylight simulators. Thus it was included for the variation analysis.) Group H includes 2 filtered tungsten lamps made by GretagMacbeth. All the D65 lamps had been used between 100 and 1000 hours when the measurement commenced. Some major lamp manufacturers such as Osram and National were not included due to the limited number of these lamps used in the UK textile industry.

Measurement Conditions

For measuring daylight simulators, the CIE recommended that the spectral irradiance at the sample surface should be measured. The effects of all wavelength selective modulators such as lenses, mirrors, diffusers, filters and booth walls are thus included in the measurement (CIE 1999). The same measurement condition was adopted for the 15 D65 simulators, as described in Section 3.2.1.2. Only the SPDs obtained from the centre position of the cabinet floor were used for this variation study. (Appendix C1 lists the measured SPDs for the 15 D65 simulators, corrected using the reflectance of the PTFE white tile.)

Although Billmeyer and Fairman (1987) mentioned that ideally a 2 nm interval is required for the SPD measurement of fluorescent lamps, the majority of commercial instruments adopt a 5 nm interval. Also, CIE only provides 5 nm data for calculating the CIE metamerism index (CIE 1999, see Section 2.5.4.2) and the CIE colour rendering index (CIE 1995a, see Section 2.5.4.1). Hence, an instrument with 5nm bandwidth and interval should be sufficient for the current study.

3.3.1.2 D50 Simulators

Lamp Details

The measured SPD data for 58 D50 simulators were supplied by Ms Audrey Lester at Eastman Kodak Co. USA. Lester (1999, see Sections 2.8.1.3 and 2.8.2.3) and co-workers completed a field study in 1997, in which more than 50 viewing cabinets, representing combinations of different viewing cabinets and D50 lamps used in the US printing industry, were measured. The results were used in her study for quantifying the illuminant metamerism of D50 simulators. However, no results have been published with respect to the lamp variations. Lester kindly provided her data to the author for further analysis.

Similar to the D65 lamps, the D50 lamps were also divided into 8 groups (Groups A to H) according to different lamp manufacturers and different type of lamps. Groups A to F each include 17, 12, 7, 7, 6 and 5 F8 lamps (the SPDs of these lamps are similar to the CIE F8 illuminant, see Section 2.3.2.2), made by GTI, MEGA, GE, Sylvania, GretagMacbeth and Philips, respectively. Group G includes 3 three-band fluorescent lamps made by Philips. Group H is a filtered tungsten lamp made by Solux. It should be noted that lamps from other major lamp manufacturers such as Toshiba, Osram were not included due to the limited number of these lamps available.

Measurement Conditions

A halon white plate was placed on the centre position of the cabinet floor and was measured at an approximate 0/45 geometry (The reflectance of the white plate was considered in calculating the spectral radiance on the measured surface). A Photo Research 703A tele-spectroradiometer was used for all the measurements. The measured wavelength ranged from 390 nm to 730 nm, with 5 nm for both bandwidth and interval. The ambient lighting was turned off during the measurements. (The measured SPDs for the 58 D50 simulators, corrected using the reflectance of the white tile, are listed in Appendix C2.)

3.3.2 Results and Discussion

3.3.2.1 Colorimetric Results

The performances of the D65 and D50 simulators are shown in Table 3.3.1. The reported results include luminance (cd/m^2), chromaticity coordinates (x, y and u'_{10}, v'_{10}), chromaticity deviation relative to the corresponding CIE daylight illuminant ($\Delta u'_{10}v'_{10}$), correlated colour temperature (CCT), general colour rendering index (R_a) and CIE metamerism index for the visible range (MI_{vis}). The CIELAB colour differences (ΔE^*_{ab}) for a reference white (perfect diffuser) illuminated under a simulator and the corresponding CIE daylight illuminant are also reported. The CIE metamerism index for the UV range (MI_{uv}) are not reported because the two tele-spectroradiometers used (Minolta CS 1000 for D65 simulators and Photo Research 703A for D50 simulators) do not have the capacity to measure the spectral power of the light sources for the UV range.

For the chromaticity deviation results, the CIE 1964 Supplementary Colorimetric Observer and CIE 1976 UCS Chromaticity were used, in accordance with the CIE specification (CIE 1999, see Section 2.5.4.2) and ISO standard (see Section 2.5.5.1). For groups having more than 3 lamps, only the maximum, minimum and average results are reported. (The colorimetric results for all the D65 and D50 simulators are reported in Appendix C3.) For each type of results in Table 3.3.1, the minimum and maximum values (for luminance, chromaticity, CCT and ΔE^*_{ab}) or best and worst results (for $\Delta u'_{10}v'_{10}$, R_a and MI_{vis}) are noted in bold with underlined and italic, respectively.

Table 3.3.1 Colorimetric results for the D65 and D50 simulators investigated, plus CIE D65 and D50 illuminants

Lamp	Quantity		L (cd/m^2)	x	y	u'_{10}	v'_{10}	$\Delta u'_{10}v'_{10}$	CCT (K)	ΔE^*_{ab} [a]	R_a	MI_{vis} [b]
CIE D65				0.3127	0.329	0.1979	0.4695	0.0000	6504	0.00	100	0.00 (A)
VeriVide (F7)	7	MAX	563	0.3203	0.3361	0.2015	0.4753	0.0062	*6751*	4.42	95	0.62 (C)
		MIN	263	0.3085	0.3247	0.1955	0.4689	0.0017	6058	1.24	98	0.25 (B)
		AVE	410	0.3137	0.3298	0.1981	0.4718	0.0035	6430	2.45	97	0.43 (B)
GE (F7)	1		535	0.3156	0.3272	0.2016	0.4694	0.0037	6326	1.92	93	0.82 (C)
GM (F7)	1		551	0.3158	0.3317	0.2000	0.4720	0.0033	6296	2.11	93	0.70 (C)
Philips (F7)	1		591	0.3153	0.3298	0.1990	0.4721	0.0028	6341	1.30	98	0.55 (C)
BYK (F7)	1		465	*0.3219*	*0.3419*	0.2001	*0.4791*	*0.0098*	5963	*7.35*	94	0.92 (C)
Toshiba (F7)	1		492	0.3198	0.3314	0.2012	0.4738	0.0054	6090	3.50	97	0.34 (B)
Toshiba (3B [c])	1		*985*	0.3135	0.3212	*0.2025*	0.4654	0.0062	6529	4.89	88	*2.31* (E)
GM (FT [c])	2	Lamp 1	387	0.3131	0.3341	0.1972	0.4718	0.0024	6440	3.15	94	0.23 (A)
		Lamp 2	411	0.3127	0.3311	0.1978	0.4701	0.0006	6486	1.37	96	0.18 (A)
Standard Deviation												
VeriVide (F7)	7		120	0.0048	0.0044	0.0023	0.0025	0.0019	283			
Rep. (F7) [d]	6		116	0.0029	0.0049	0.0010	0.0033	0.0028	164			
Overall (F7) [e]	12		111	0.0045	0.0048	0.0022	0.0030	0.0023	260			
CIED50				0.3457	0.3585	0.2102	0.4889	0.0000	5000	0.00	100	0.00 (A)
GTI (F8)	17	MAX	808	0.3553	*0.3739*	0.2157	0.4953	0.0072	4979	8.11	86	1.36 (D)
		MIN	217	0.3463	0.3578	0.2126	0.4877	0.0025	4709	0.39	91	1.09 (D)
		AVE	576	0.3503	0.3650	0.2135	0.4912	0.0044	4857	3.64	89	1.23 (D)
MEGA (F8)	12	MAX	*1022*	0.3565	0.3721	0.2156	*0.4954*	0.0085	4835	7.46	85	1.07 (D)
		MIN	320	0.3509	0.3644	0.2130	0.4916	0.0044	4677	3.31	90	0.92 (C)
		AVE	602	0.3524	0.3677	0.2137	0.4932	0.0056	4795	5.01	89	0.97 (C)
GE (F8)	7	MAX	678	0.3566	0.3722	0.2167	0.4950	0.0082	4895	7.29	87	1.09 (D)
		MIN	490	0.3490	0.3642	0.2128	0.4910	0.0033	4659	3.02	89	0.99 (C)
		AVE	583	0.3538	0.3679	0.2149	0.4933	0.0065	4746	5.36	88	1.04 (D)
Sylvania (F8)	7	MAX	730	0.3556	0.3706	0.2151	0.4948	0.0077	5044	6.68	87	1.06 (D)
		MIN	501	0.3450	0.3651	0.2094	0.4911	0.0023	4698	3.75	88	0.93 (C)
		AVE	611	0.3497	0.3684	0.2119	0.4931	0.0048	4892	5.54	88	1.00 (D)
GM (F8)	6	MAX	616	0.3532	0.3674	0.2144	0.4928	0.0057	*5131*	4.94	88	1.01 (D)
		MIN	207	0.3426	0.3642	0.2086	0.4901	0.0016	4766	4.29	90	0.92 (C)
		AVE	422	0.3455	0.3657	0.2102	0.4909	0.0025	5027	4.55	89	0.99 (C)
Philips (F8)	5	MAX	668	0.3526	0.3679	0.2136	0.4934	0.0056	4963	5.03	89	0.98 (C)
		MIN	305	0.3472	0.3636	0.2115	0.4907	0.0022	4792	2.77	91	0.91 (C)
		AVE	485	0.3503	0.3666	0.2126	0.4925	0.0043	4864	4.27	90	0.95 (C)
Philips (3B [c])	3	MAX	677	*0.3603*	0.3723	*0.2195*	0.4948	*0.0110*	4638	*8.30*	*80*	*2.74* (E)
		MIN	529	0.3574	0.3689	0.2183	0.4931	0.0092	4557	6.71	80	2.66 (E)
		AVE	612	0.3588	0.3704	0.2191	0.4937	0.0101	4600	7.24	80	2.71 (E)
Solux (FT [c])	1		11666 [f]	0.3485	0.3532	0.2136	0.4866	0.0041	4869	4.12	98	0.28 (B)
Standard Deviation												
GTI (F8)	17		155	0.0026	*0.0043*	0.0008	*0.0022*	0.0015	75			
MEGA (F8)	12		163	0.0016	0.0019	0.0007	0.0010	0.0011	45			
GE (F8)	7		67	0.0032	0.0029	0.0016	0.0015	*0.0020*	99			
Sylvania (F8)	7		96	*0.0039*	0.0019	*0.0021*	0.0013	0.0019	128			
GM (F8)	6		131	0.0038	0.0011	*0.0021*	0.0010	0.0016	*131*			
Philips (F8)	5		*175*	0.0021	0.0020	0.0009	0.0012	0.0014	67			
Rep. (F8) [d]	6		148	0.0033	0.0017	0.0019	0.0013	0.0017	111			
Overall (F8) [e]	54		148	0.0035	0.0032	0.0018	0.0018	0.0018	114			

a ΔE^*_{ab} is the CIELAB colour difference for a reference white (perfect diffuser) illuminated under a simulator and the corresponding CIE daylight illuminant.

b The letters in parentheses are the category of CIE metamerism index.

c 3B and FT are the abbreviations for three-band and filtered tungsten lamps respectively.

d Rep. is an abbreviated term for the representative F7 or F8 lamps, each chosen from different lamp groups.

e Overall refers to the overall F7 or F8 lamps.

f This filtered tungsten D50 lamp is a newly developed lamp and its luminance level seems exceptional.

The colorimetric results for the D65 simulators are summarised below.

Luminance

The luminance results in Tables 3.3.1 show that a considerable variation of illumination level at the viewing surface measured. The lowest level is 263 cd/m^2 and the highest level is 985 cd/m^2. However, the majority of the simulators have luminance levels between 400 and 600 cd/m^2, which implies that the luminance variation between the simulators is not large comparing with the large variation observed in natural daylight.

Chromaticity

For the chromaticity results, CIE 1931 chromaticity coordinate (x, y) and CIE 1976 UCS chromaticity coordinate (u'_{10}, v'_{10}) were used in the investigation. The results in Table 3.3.1 show that the chromaticity variation (difference between the maximum and minimum results) is 0.0130, 0.0210 for x and y respectively, and 0.0070, 0.0140 for u'_{10} and v'_{10} respectively.

The chromaticity deviation relative to the CIE illuminant was calculated in terms of $u'_{10}v'_{10}$ units. The results in show that one GretagMacbeth filtered tungsten lamp has the smallest deviation of 0.0006 while the BYK F7 lamp has the largest deviation of 0.0098, corresponding to 1.37 and 7.35 ΔE^*_{ab} units for a reference white, respectively. The chromaticity deviations for all the simulators investigated are well within the CIE specifications on chromaticity tolerance of 0.0150 (CIE 1999, see Section 2.5.4.2).

The distribution of chromaticity results (x, y) for all the 15 simulators is shown in Figure 3.3.1(a). The 12-sided polygon specified in the British standard BS 950 (see Section 2.5.1) for the chromaticity tolerance is also included in the diagram. It shows that for the lamps having chromaticity deviations less than 0.0050 in u'_{10} v'_{10} units, their x and y chromaticities are within the BS tolerance. Conversely, the lamps outside the BS 950 tolerance, such as the BYK F7 lamp, Toshiba F7 and three-band lamps and one VeriVide F7 lamp, have chromaticity deviations larger than 0.0050 in u'_{10} v'_{10} units. A transformation from x, y to u', v' chromaticities (not u'_{10}, v'_{10} chromaticities because BS 950 tolerance was defined only in x, y chromaticities) of the 12 points demonstrates the BS950 tolerance as an ellipse with a maximum radius of around 0.0060 in the CIE 1976 UCS Chromaticity Diagram, see Figure 3.3.1(c).

The chromaticity results in Figure 3.3.1(a) show that some of the lamps' deviations are away from the CIE daylight illuminant locus, indicating that these lamps have reddish or greenish colours in comparison with the CIE illuminants. Deviations along the locus are less important for the quality of the lamp, as they simply mean that the lamp corresponds to a different phase of daylight.

Correlated Colour Temperature (CCT)

There is a variation of about 800K between the lamp having the highest CCT and that having the lowest CCT. Almost all lamps are within 500K of CIE D65 illuminant.

CIE Colour Rendering Index

All the investigated simulators have general colour rendering index R_a well above 90 except for the three-band lamp having the lowest colour rendering index of 88.

CIE Metamerism Index

For the CIE metamerism index, the two GretagMacbeth filtered tungsten lamps have 'A' rating while the Toshiba three-band lamp has 'E' rating. This is expected due to the fact that filtered tungsten lamps have been designed to simulate the SPDs of the CIE daylight illuminants precisely while three-band lamps have energy concentrated at three wavelengths and hence exhibit large discrepancies in SPDs in comparison with the CIE illuminants. It is encouraging to find that some of the F7 lamps, e.g. a VeriVide F7 and the Toshiba F7 lamps, achieve a 'B' rating, indeed one is on the borderline for an 'A' rating.

The colorimetric results for the D50 simulators are summarised below.

Luminance

The luminance results in Tables 3.3.1 show that the luminance variation between the D50 simulators is of a similar degree to that between the D65 simulators. The lowest level is 207 cd/m^2 and the highest level is 1021 cd/m^2. The average luminance level is between 420 and 620 cd/m^2 for each lamp group, which are close to the ISO 3664 specification of 2000±250 lx for viewing conditions of critical comparison of prints. This degree of variation is considered to be insignificant comparing with the large variation observed in natural daylight.

Chromaticity

The chromaticity results in Table 3.3.1 show that the variation is 0.0180, 0.0210 for x and y respectively, and 0.0110, 0.0090 for u'_{10} and v'_{10} respectively. The chromaticity deviation relative to the CIE D50 illuminant was again examined in $u'_{10}v'_{10}$ units. One GretagMacbeth F8 lamp has the smallest deviation of 0.0016 while one Philips three-band lamp has the largest deviation of 0.0110, corresponding to 4.3 and 8.3 ΔE^*_{ab} units for a reference white, respectively. All the investigated simulators are satisfactory in terms of the CIE tolerance of 0.0150. However, many lamps are unsatisfactory in terms of the ISO tolerance of 0.0050 (ISO 3664, see Section 2.5.5.1), particularly the three-band lamps, which have the largest chromaticity deviations in comparison with other lamps.

Along with the distribution of chromaticity results (u'_{10}, v'_{10}) for all the 58 D50 simulators, see Figure 3.3.1(b), a circle with radius of 0.0050, representing the chromaticity tolerance specified by the ISO for D50 simulators, was also added to the diagram. It is clear that many F8 lamps, including all the three-band lamps, are outside the ISO tolerance, all in the lower CCT direction.

Correlated Colour Temperature (CCT)

The majority of the investigated lamps have slightly lower CCT than the specified one of 5000K, with the lowest at 4557K. The variation is about 600K between the lamp having the highest CCT and that having the lowest CCT.

CIE Colour Rendering Index

All the F8 lamps have general colour rendering index R_a between 85 and 91, with an average for each group of just under 90. The Solux filtered tungsten lamp has the highest colour rendering index of 98 while the Philips three-band lamps have the lowest colour rendering index of 80.

CIE Metamerism Index

The Solux filtered tungsten lamp has the best metamerism index rating of 'B' while the Philips three-band lamps have the worst rating of 'E'. All the Philips F8 lamps have rating of 'C' and all the GTI F8 lamps have rating of 'D'. The F8 lamps of other brand have rating of either 'C' or 'D'. None of the investigated lamps, including the Solux filtered tungsten lamp, achieved an 'A' rating.

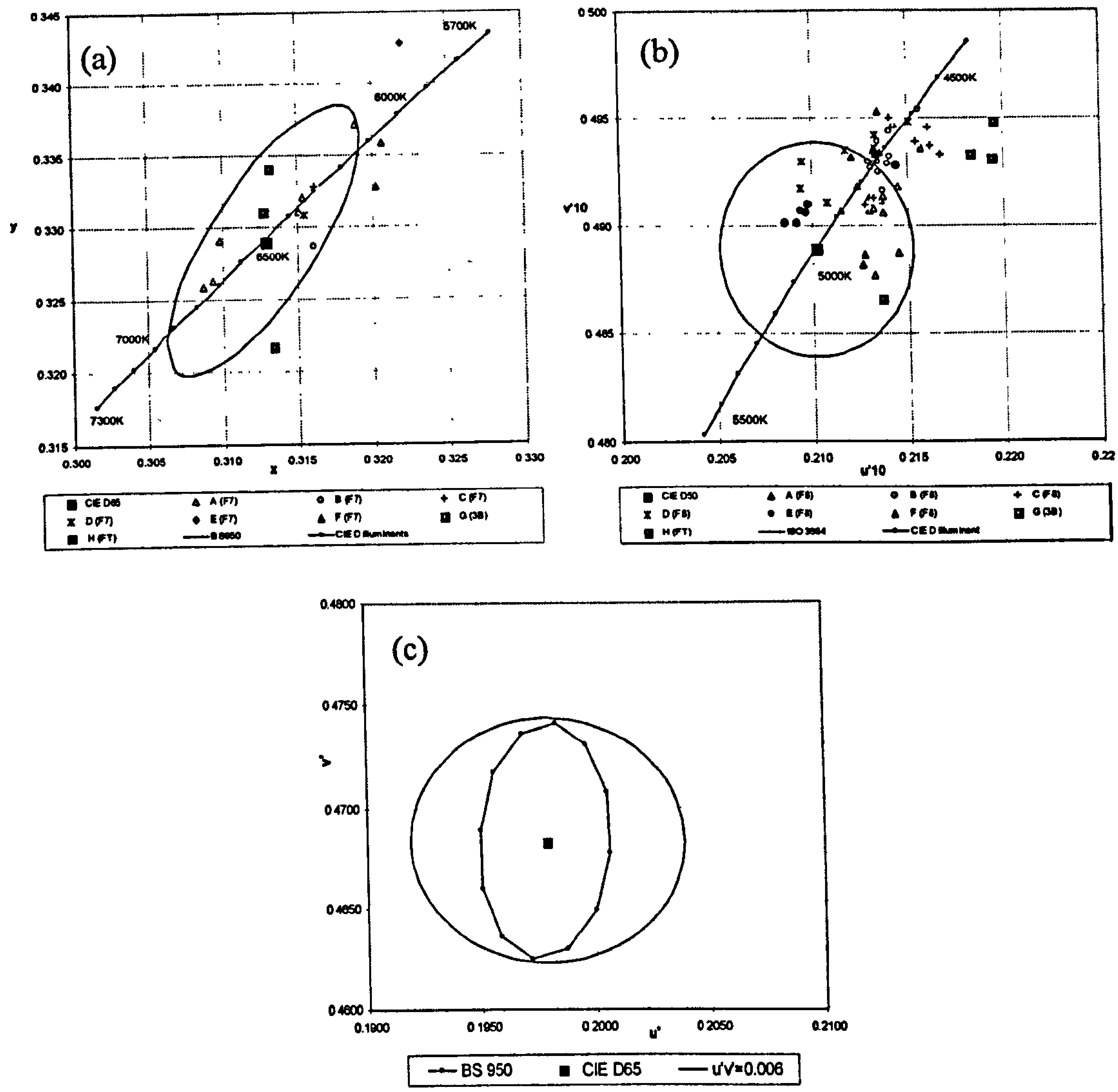


Figure 3.3.1 (a) Chromaticity coordinate (x, y) for D65 simulators, where A to F refer to broad band fluorescent lamps made by VeriVide, GE, GretagMacbeth, Philips, BYK and Toshiba, respectively, G refers to Toshiba three-band fluorescent lamps, H refers to GretagMacbeth filtered tungsten lamps. (b) Chromaticity coordinate (u'_{10}, v'_{10}) for D50 simulators, where A to F refer to broad band fluorescent lamps made by GTI, MEGA, GE, Sylvania, GretagMacbeth and Philips, respectively, G refers to Philips thee-band fluorescent lamps, G refers to Solux filtered tungsten lamps. (c) BS950 tolerance as an ellipse with a maximum of around 0.0060 u'v' units.

The relations between the CIE colour rendering index, metamerism index and chromaticity deviation results were also investigated for 8 selected D65 and D50 simulators, as shown in Figures 3.3.2(a) to (c) and (d) to (f) respectively. As CIE metamerism index is in ΔE^*_{ab} units, the average colour difference ΔE^*_{uvw} for the eight CIE test colours (see Section 2.5.4.1), which is a linear transformation of the CIE colour rendering index, was used in the comparison. The selected D65 (or D50) include six representative broad band fluorescent (F7 or F8) lamps, one filtered tungsten lamp and one three-band fluorescent lamp. The representative F7 or F8 lamps each represent one brand, and they were chosen from different lamp groups by having the closest chromaticities to the group mean. These representative lamps will also be used in the following spectral analysis for the F7 and F8 lamps.

Figure 3.3.2 show that for both D65 and D50 simulators, the three-band fluorescent lamp show the worst quality by having the worst colour rendering index and metamerism index results, and the filtered tungsten lamps show the best metamerism index results. However, for the 8 selected D65 and D50 simulators, which represent different types and makes of commercial lamps, no clear trend can be defined from Figures (a) and (d) with respect to the relations between CIE colour rendering index and metamerism index results, particularly in the case of broad band fluorescent lamps. It was also found the chromaticity deviation results are not in clear relations to either the CIE colour rendering index or metamerisn index results. Figure 3.3.2 reveals that different measures adopted by the CIE (e.g. CIE colour rendering index and metamerism index) for evaluating daylight simulators reflect different aspects of lamp quality and, there is no clear relationship between these measures.

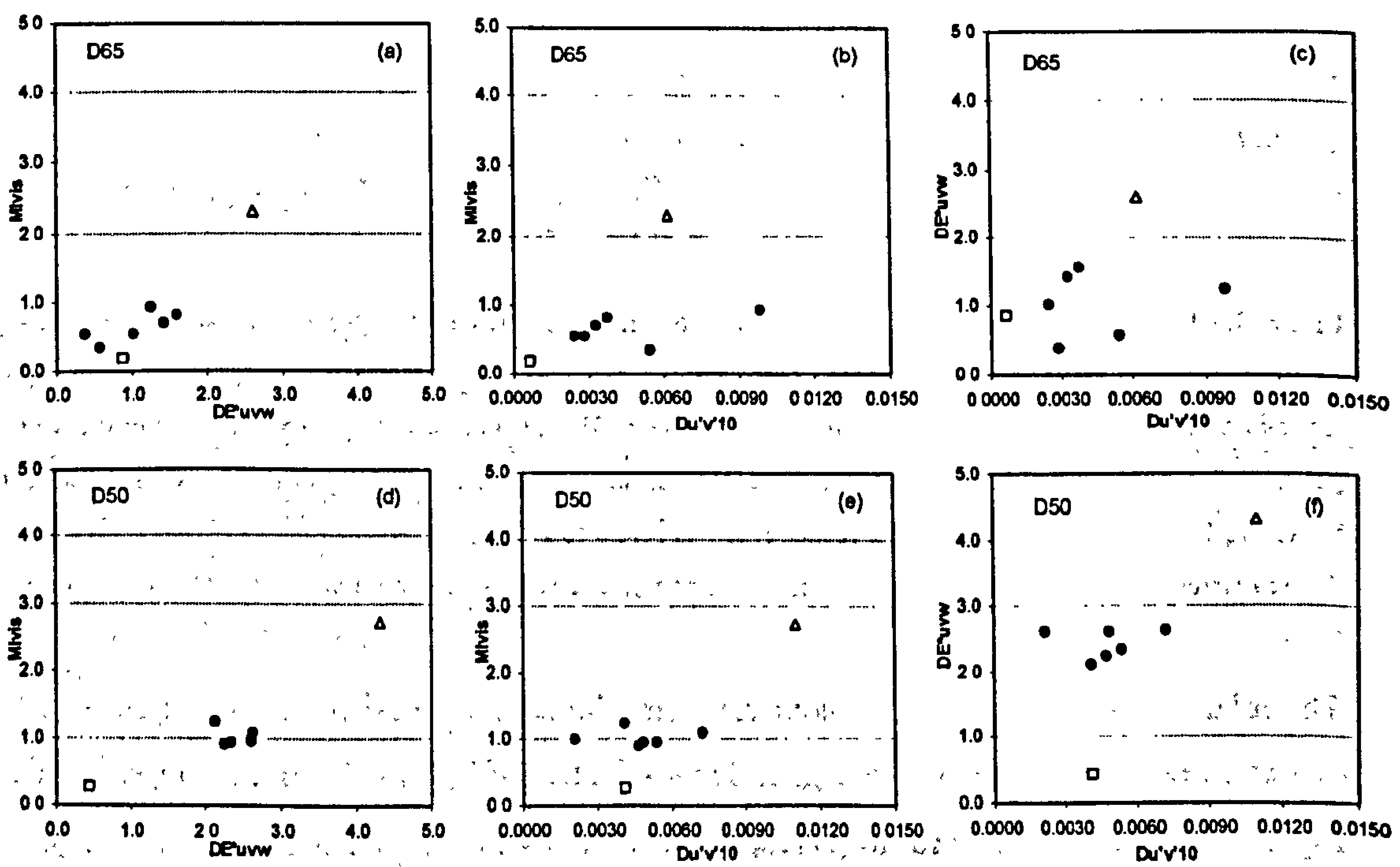


Figure 3.3.2 Comparing the CIE metamerism index, colour rendering index and chromaticity deviation results with each other for the selected D65 and D50 simulators in (a) to (c) and (d) to (f) respectively. The selected D65 and D50 simulators each include eight lamps, six representative broad band fluorescent (F7 or F8) lamps, one filtered tungsten lamp and one three- band fluorescent lamp, represented by signs '•', '□' and 'Δ' respectively in the diagrams.

3.3.2.2 Spectral Results

The spectral characteristics of daylight simulators are the key factors determining the quality of daylight simulators. Some methods for evaluating daylight simulators, such as the band value method specified in British standard BS 950 (see Section 2.5.1) and goodness-of-fit of SPD (Wyszecki 1970, see Section 2.7.1), examine the SPDs of daylight simulators. (Band value results and goodness-of-fit results for the D65 simulators are analysed in Chapters 4 and 5, respectively). Data analysis was thus carried out to investigate the spectral features associated with the quality of lamps such as the number of peaks in the SPDs, the location of the peaks, the power at each peak and the power distributions between peaks, etc. Only the F7 and F8 lamps were analysed.

The measured SPD for each F7 or F8 lamp was first normalised according to the CIE recommendation (CIE 1986) in which the normalized power at wavelength 560 nm is set equal to 100. The normalized (also referred to as relative) SPDs were then plotted for the F7 and F8 lamps respectively. The relative SPDs were inspected for each group of lamps (made by the same manufacturer) and representative lamps (made by different manufacturers). The representative lamps were chosen from each group, whose chromaticities are the closest to the group mean. The variations of relative SPDs for the group and representative lamps were investigated in terms of spread of relative power, which is expressed as the mean power with a range of 2 times the standard deviation at each reported wavelength, corresponding to 95% confidence interval. The relative power at each peak wavelength was tabulated for each group lamps. In addition, the power ratio between the main peak wavelength and other peak wavelengths are also reported.

The spectral results for the F7 and F8 lamps are given below. Note that the spectral results for the tungsten lamps and three-band lamps are not included because they both are very different to the F7 (or F8) lamps in terms of SPD. Also, only a few tungsten lamps and three-band lamps were accumulated in this study.

The relative SPDs for the F7 lamps, including the 7 VeriVide lamps and 6 representative lamps, are shown in Figures 3.3.3(a) and (b) respectively. The spread of relative power for the VeriVide and representative lamps is shown in Figures 3.3.4(a) and (b) respectively. The relative power at each peak wavelength and the power ratio between the main peak wavelength and other peak wavelengths are listed in Table 3.3.2.

Figure 3.3.3 shows that all the F7 lamps have similar power distributions, e.g. they have exactly the same peak wavelengths at 405 nm, 435 nm, 545 nm and 580 nm, which is expected as these are approximate the wavelengths of mercury lines. However, these mercury lines could not be shown as narrow 'chimneys' in both Figures 3.3.3 and 3.3.5 due to the measurement conditions used by the instruments (see Section 3.3.1), which all adopted 5nm as the bandwidth and wavelength interval. The power spread in Figure 3.3.4 shows that the VeriVide lamps have less variation than the representative lamps, which is expected as fluorescent lamps from the same manufacturer would normally exhibit similar performances provided they are of the same make. Figure 3.3.4 also shows that the maximum power spread occurs at the several peak wavelengths, implying that the power at the peak wavelengths may have a large impact in determining the variations between different F7 lamps.

Table 3.3.2 reports the relative power results for all the F7 lamps investigated at four major peak wavelengths. The main peak wavelength was taken to be 435 nm because all lamps except the BYK lamp have maximum power at this wavelength. The second highest peak wavelength was found at 545 nm, followed by 580 nm and 405 nm. The VeriVide and GretagMacbeth lamps also have an additional peak wavelength at 660 nm. The results in Table 3.3.2 also show that there is a considerable degree of variation for the relative power at each peak wavelength. A further inspection on the overall results shows that the lamps have much larger power variations at the main peak wavelength (435 nm) and second peak wavelength (545 nm) than those at the other peak wavelengths.

The relative SPDs for each brand of F8 lamps are shown in Figures 3.3.5(a) to (f) respectively. The relative SPDs for the 6 representative lamps, chosen from each brand, are shown in Figure 3.3.5(g). The spread of relative powers for each brand of lamp is shown in Figures 3.3.6(a) to (f) respectively. The spread of relative powers for the representative lamps is shown in Figures 3.3.6(g). The relative power at each peak wavelength and the power ratio between the main peak wavelength and other peak wavelengths are reported in Table 3.3.3.

Figures 3.3.5 shows that relative SPDs of the F8 lamps have similar characteristics as those of the F7 lamps (see Figure 3.3.3). For instance, all the F8 lamps have similar power distributions with peak wavelengths at 405 nm, 435 nm, 545 nm and 580 nm. It was noted that some of the F8 lamps have maximum power at peak wavelength of 545 nm. However, the main peak wavelength was again taken to be 435 nm because on average, all brand lamps have the maximum power at this wavelength. The GretagMacbeth lamps have two additional peak wavelengths of 630 nm and 655 nm. Figure 3.3.6 also shows that the lamps of the same brand exhibit less power spread than the representative lamps and that the maximum power spread occurs at the several peak wavelengths, as was observed for the F7 lamps (see Figure 3.3.4).

A further inspection of the results in Table 3.3.3 shows that the F8 lamps have large power variations at each peak wavelength. However, for group and overall results, the degree of variation at the main peak wavelength and second peak wavelengths is generally smaller than that of the F7 lamps. The largest variation occurs at 655 nm due to the existence and nonexistence of a peak at this wavelength.

3.3.2.3 Relationship between Colorimetric and Spectral Results

The above analysis described colorimetric and spectral results separately. The relationships between the two types of results were also investigated. The results should be useful for lamp manufacturers to improve the quality of daylight simulators. The SPD of a daylight simulator determines its colorimetric results in terms of luminance, chromaticity, CCT, colour rendering index and metamerism index. The luminance is not a critical measure in relation to the quality of daylight simulators because many factors could affect the luminance value such as the number of lamps used in a cabinet and, the distance from the lamp surface to the measuring surface. Regarding chromaticity and CCT, it is known that a given CCT could correspond to many possible chromaticities and one given chromaticity could correspond to many possible SPDs (McCamy 1999). This causes complexity in analysing the variation of chromaticity and the variation of SPD. For example, it is quite obvious that the variations of SPDs for the representative F7 lamps made by different manufacturers (see Figure 3.3.4(b)) are much larger than those for the F7 lamps made by the same manufacturer, VeriVide (see Figure 3.3.4(a)). However, the chromaticity variation in terms of standard deviation (see Table 3.3.1) is of a similar degree for both the representative and VeriVide lamps.

Tables 3.3.2 and 3.3.3 also list the largest chromaticity deviation with the corresponding CIELAB colour difference (ΔE^*_{ab}) for a reference white, the worst CIE colour rendering index and metamerism index results for D65 and D50 simulators respectively. In addition, the spectral results in terms of relative power and power ratio at each peak wavelength were included. For the F7 lamps (see Table 3.3.2), the BYK and GE lamps having at least one extreme (highest or lowest) power value at one or two major peak wavelengths (435 nm and 545 nm) have the worst metamerism index and relatively poor colour rendering index. It is also found that the lamp having the largest chromaticity deviation also has the worst metamerism index result. For the F8 lamps (see Table 3.3.3), a careful inspection of each group results leads to a similar finding. This again indicates that the relative power at peak wavelengths, especially at the main and second peak wavelength, plays an important role in determining the quality of daylight simulators.

It worth noting that the above results for the fluorescent lamps as D65 and D50 simulators are somewhat biased since the output of a fluorescent lamp is a function of the fixture, ballast and ambient temperature. These parameters affect the relative SPD of the mercury gas discharge spectra and hence the relative spectral distribution of the lamp (Rea 2000, p.6-29). Furthermore, the maintenance of lamps also affects the quality of daylight simulators, and a well-maintained lamp is more likely to meet the manufacturer specification. However, this study was not able to gather sufficient information of lamp maintenance. In Chapter 7, further analysis on the SPDs of daylight simulators will be conducted to develop effective methods for improving the quality of daylight simulators. An experiment including visual assessment to evaluate six D65 simulators will be introduced in Chapter 4.

Table 3.3.2 Relative power and power ratio at each peak wavelength for the F7 lamps

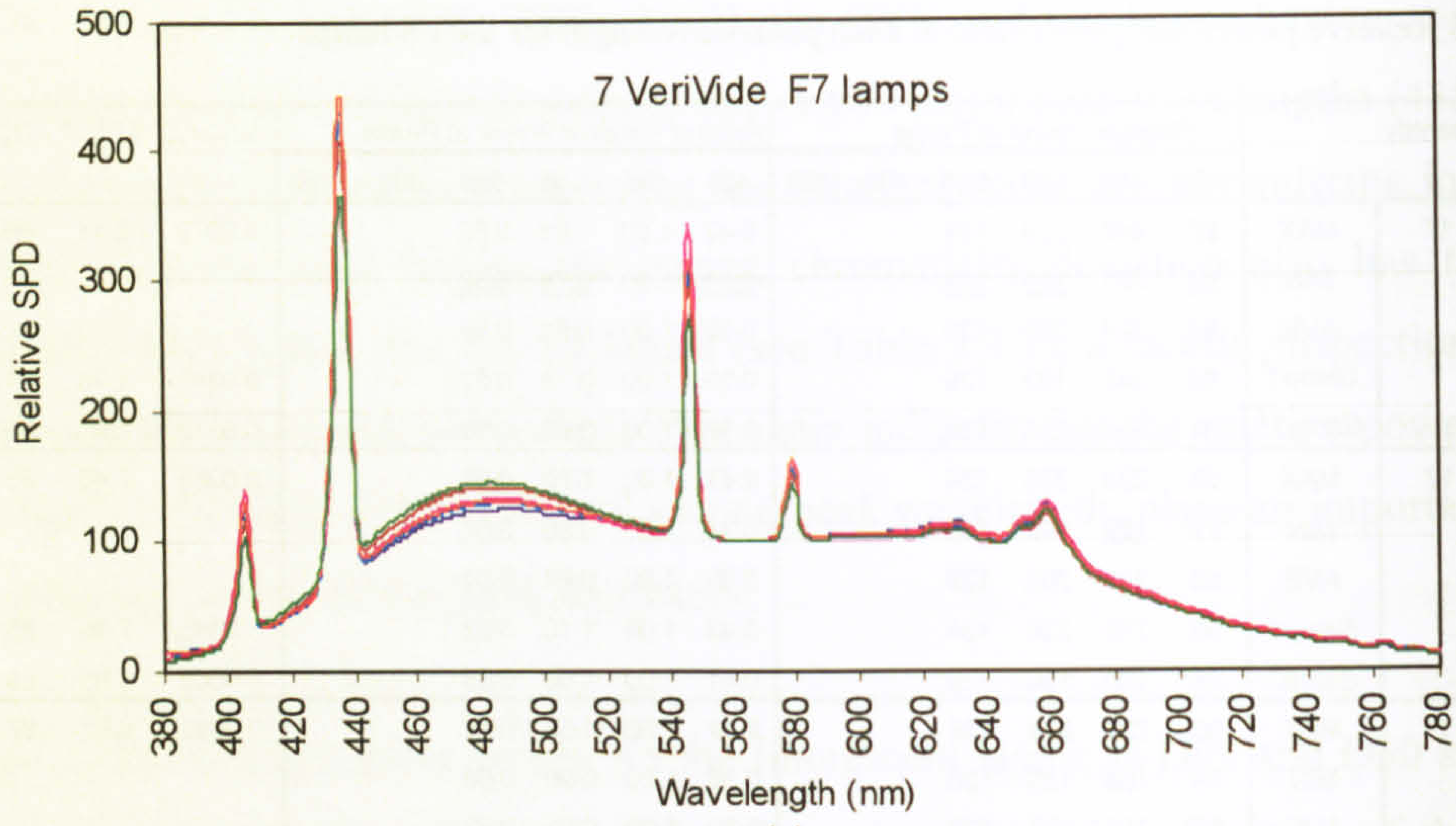
Lamp	Quantity		Relative Power at Peaks					Ratio of Relative Power at Peaks					$\Delta u'_{10}v'_{10}$	ΔE^*_{ab} [a]	R_a	MI_{vis} [b]
			405	435	545	580	660	405	435	545	580	660				
VeriVide	7	MAX	***139***	379	303	141	128	***0.45***	1.00	0.98	0.46	0.41	0.0062	4.20	95	0.62 (C)
		MIN	99	306	242	126	117	0.31	1.00	0.74	0.36	0.33				
		AVE	118	340	269	133	122	0.35	1.00	0.80	0.39	0.36				
GE	1		131	***381***	249	135		0.34	1.00	0.65	0.35		0.0037	1.92	93	0.82 (C)
GM [c]	1		102	296	237	122	***144***	0.35	1.00	0.80	0.41	***0.49***	0.0033	2.11	93	0.70 (C)
Philips	1		***139***	354	326	***148***		0.39	1.00	0.92	0.42		0.0028	1.30	98	0.55 (C)
BYK	1		114	289	***334***	143		0.39	1.00	***1.16***	***0.49***		0.0098	7.35	94	0.92 (C)
Toshiba	1		120	347	269	141		0.35	1.00	0.78	0.41		0.0054	3.50	97	0.34 (B)
Overall	12	MAX	139	381	334	148		0.45	1.00	1.16	0.49		0.0098	7.35	93	0.92 (C)
		MIN	99	289	237	122		0.31	1.00	0.65	0.35					
		AVE	119	337	275	135		0.35	1.00	0.82	0.40					
Standard Deviation																
VeriVide	7		15	30	21	6	4	0.05	0.00	0.08	0.03	0.03				
Rep. [d]	6		13	36	36	3		0.03	0.00	0.19	0.05					
Overall [e]	12		14	32	32	8		0.04	0.00	0.13	0.04					

a ΔE^*_{ab} is the CIELAB colour difference for a reference white (perfect diffuser) illuminated under a D65 simulator and CIE D65 illuminant.
b The letters in parentheses are the category of CIE metamerism index.
c GM is the abbreviation for GretagMacbeth.
d Rep. is an abbreviated term for the representative F7 lamps, each chosen from different lamp groups.
e Overall refers to the overall F7 lamps.

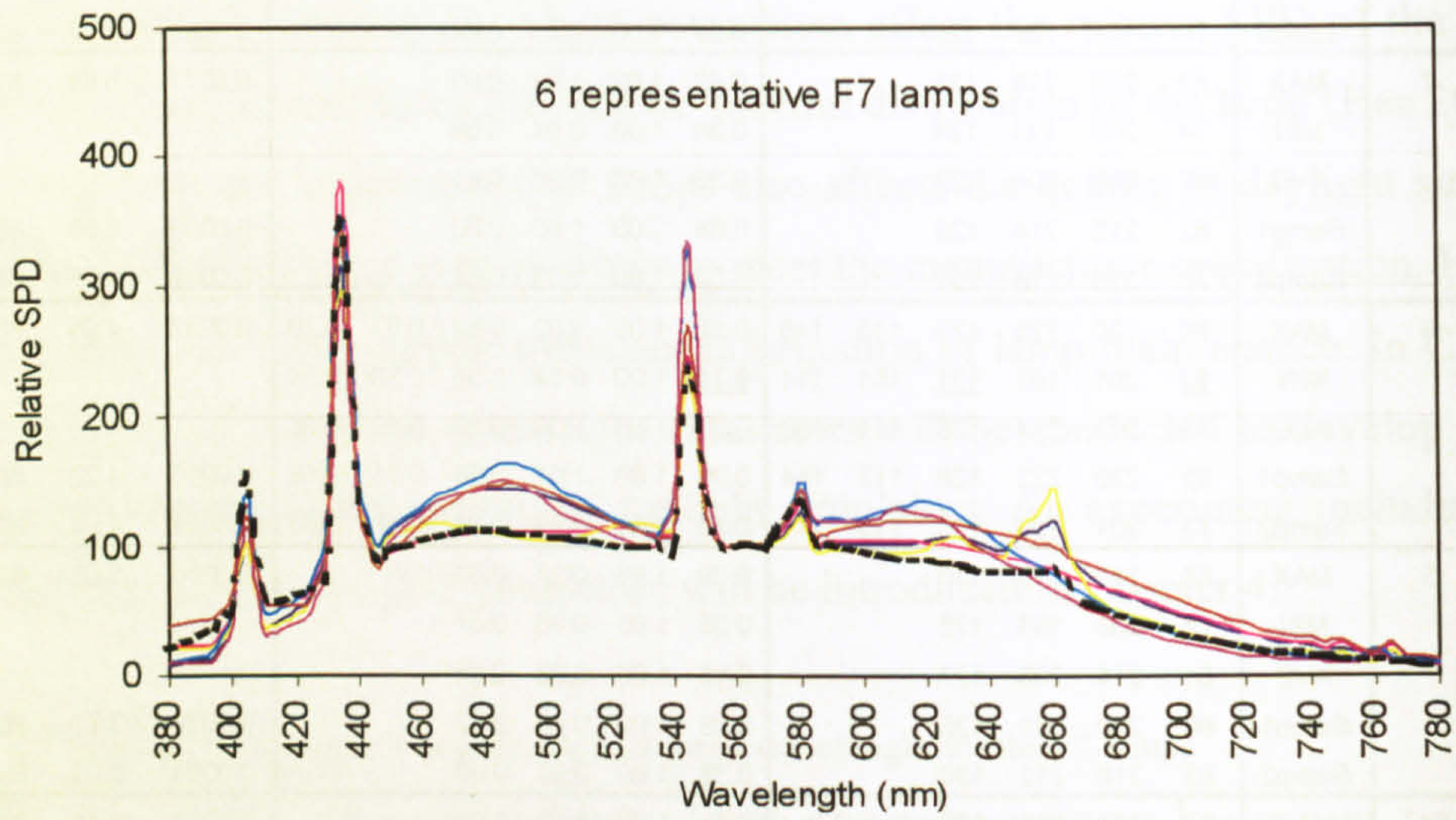
Table 3.3.3 Relative power and power ratio at each peak wavelength for the F8 lamps

Lamp	Quantity		Relative Power at Peaks						Ratio of Relative Power at Peaks						$\Delta u'_{10}v'_{10}$	ΔE^*_{ab} [a]	R_a	MI_{vis} [b]
			405	435	545	580	630	655	405	435	545	580	630	655				
GTI	17	MAX	97	247	223	134			0.42	1.00	1.01	0.62			0.0072	8.11	86	1.36 (D)
		MIN	63	201	184	121			0.31	1.00	0.78	0.52						
		AVE	84	224	202	129			0.38	1.00	0.91	0.58						
		Samp1 [f]	82	247	193	129			0.33	1.00	0.78	0.52			0.0043	1.78	91	1.36 (D)
		Samp2 [f]	84	230	223	134			0.37	1.00	0.97	0.59			0.0072	5.97	89	1.32 (D)
MEGA	12	MAX	93	223	236	134			0.43	1.00	1.10	0.68			0.0085	7.46	85	1.07 (D)
		MIN	77	190	190	126			0.34	1.00	0.86	0.57						
		AVE	83	211	205	129			0.39	1.00	0.97	0.61						
		Samp1	93	215	236	134			0.43	1.00	1.10	0.62			0.0085	7.46	85	1.07 (D)
		Samp2	78	190	190	129			0.41	1.00	1.00	0.68			0.0060	5.85	88	1.02 (D)
GE	7	MAX	90	221	238	136			0.43	1.00	1.08	0.64			0.0082	6.62	87	1.09 (D)
		MIN	74	198	189	126			0.36	1.00	0.90	0.60						
		AVE	82	210	202	129			0.39	1.00	0.96	0.62						
		Samp1	86	221	238	136			0.39	1.00	1.08	0.62			0.0072	5.95	88	1.09 (D)
		Samp2	74	198	189	128			0.37	1.00	0.95	0.64			0.0082	6.62	87	1.02 (D)
Sylvania	7	MAX	88	215	218	131			0.42	1.00	1.03	0.63			0.0077	6.68	87	1.06 (D)
		MIN	74	200	193	124			0.36	1.00	0.91	0.58						
		AVE	82	208	204	127			0.39	1.00	0.98	0.61						
		Samp1	82	215	214	129			0.38	1.00	1.00	0.60			0.0056	5.56	88	1.06 (D)
		Samp2	77	213	218	131			0.36	1.00	1.03	0.61			0.0077	6.68	88	1.05 (D)
GM [c]	6	MAX	86	220	225	129	115	145	0.39	1.00	1.02	0.62	0.57	0.70	0.0057	4.94	88	1.01 (D)
		MIN	63	201	192	121	101	111	0.31	1.00	0.94	0.58	0.50	0.54				
		AVE	79	213	214	126	111	138	0.37	1.00	1.00	0.59	0.52	0.65				
		Samp1	85	220	222	128	112	144	0.39	1.00	1.01	0.58	0.51	0.66	0.0016	4.29	88	1.01 (D)
		Samp2	73	201	198	125	115	141	0.36	1.00	0.99	0.62	0.57	0.70	0.0057	4.94	90	1.00 (D)
Philips	5	MAX	83	219	212	130			0.39	1.00	0.97	0.62			0.0056	5.03	89	0.98 (C)
		MIN	78	208	193	125			0.36	1.00	0.88	0.57						
		AVE	81	214	200	127			0.38	1.00	0.93	0.60						
		Samp1	80	219	193	125			0.36	1.00	0.88	0.57			0.0022	2.77	90	0.98 (C)
		Samp2	83	218	212	130			0.38	1.00	0.97	0.60			0.0054	5.02	89	0.97 (C)
Overall	54	MAX	97	247	238	136			0.43	1.00	1.10	0.68			0.0085	8.11	85	1.36 (D)
		MIN	63	190	184	121			0.31	1.00	0.78	0.52						
		AVE	82	215	204	129			0.38	1.00	0.95	0.60						
Standard Deviation																		
GTI	17		7	12	11	3			0.03	0.00	0.06	0.03						
MEGA	12		4	8	14	2			0.02	0.00	0.06	0.03						
GE	7		7	8	17	3			0.03	0.00	0.06	0.01						
Sylvania	7		5	6	9	2			0.02	0.00	0.04	0.02						
GM [c]	6		9	8	14	3	5	13	0.03	0.00	0.03	0.02	0.03	0.05				
Philips	5		2	5	8	2			0.01	0.00	0.04	0.02						
Rep. [d]	6		2	10	16	3			0.01	0.00	0.06	0.02						
Overall [e]	54		6	11	12	3			0.03	0.00	0.06	0.03						

a ΔE^*_{ab} is the CIELAB colour difference for a reference white (perfect diffuser) illuminated under a D50 simulator and CIE D50 illuminant.
b The letters in parentheses are the category of CIE metamerism index.
c GM is the abbreviation for GretagMacbeth.
d Rep. is an abbreviated term for the representative F8 lamps, each chosen from different lamp groups.
e Overall refers to the overall F8 lamps.
f Samp1 and Samp2 refer to the two F8 lamps having the worst metamerism index results in each group.

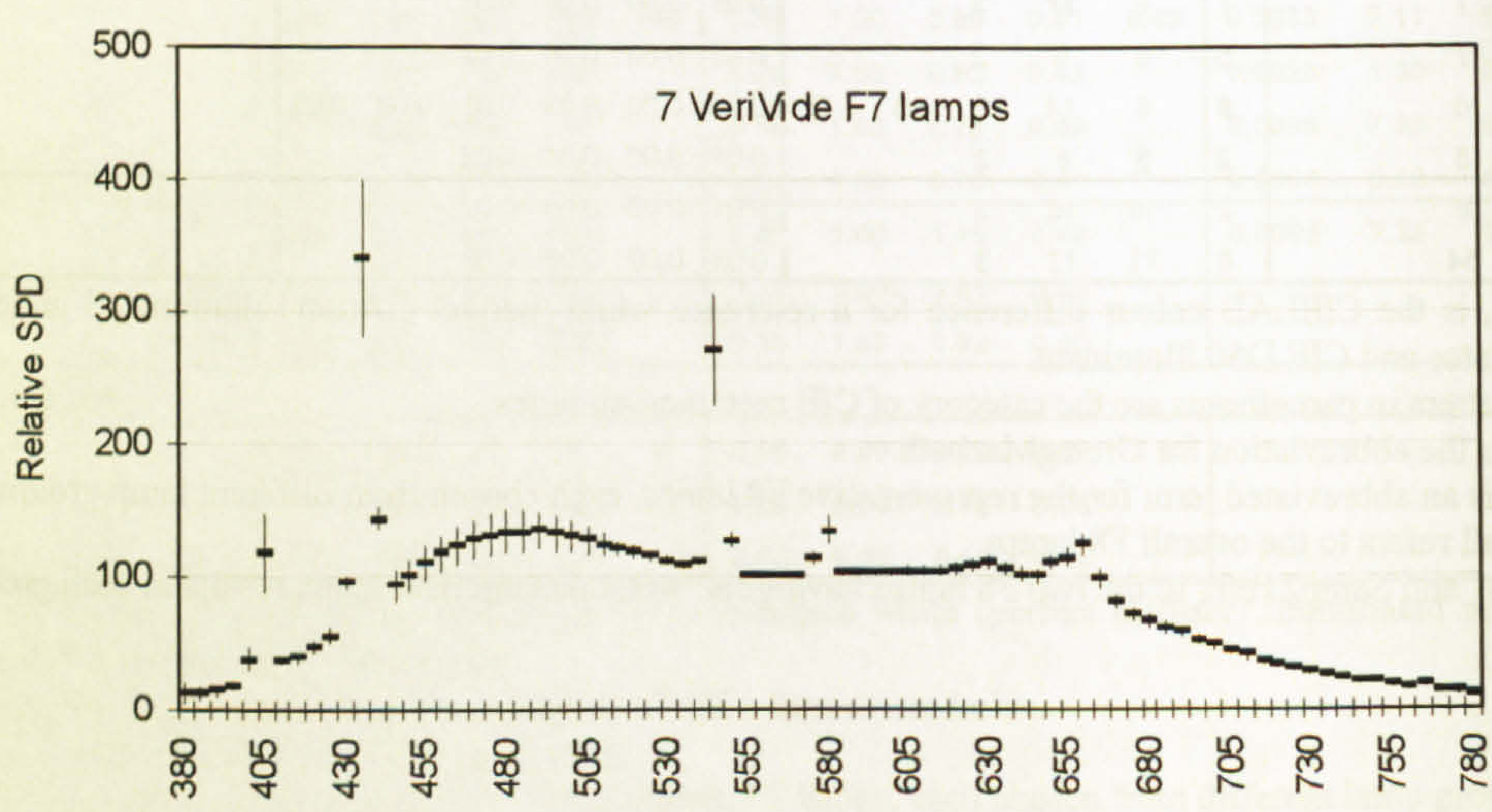


(a)



(b)

Figure 3.3.3 Relative SPDs of F7 lamps: (a) VeriVide, (b) representative lamps made by different manufacturers, plus CIE F7 illuminant (dotted line).



(a)

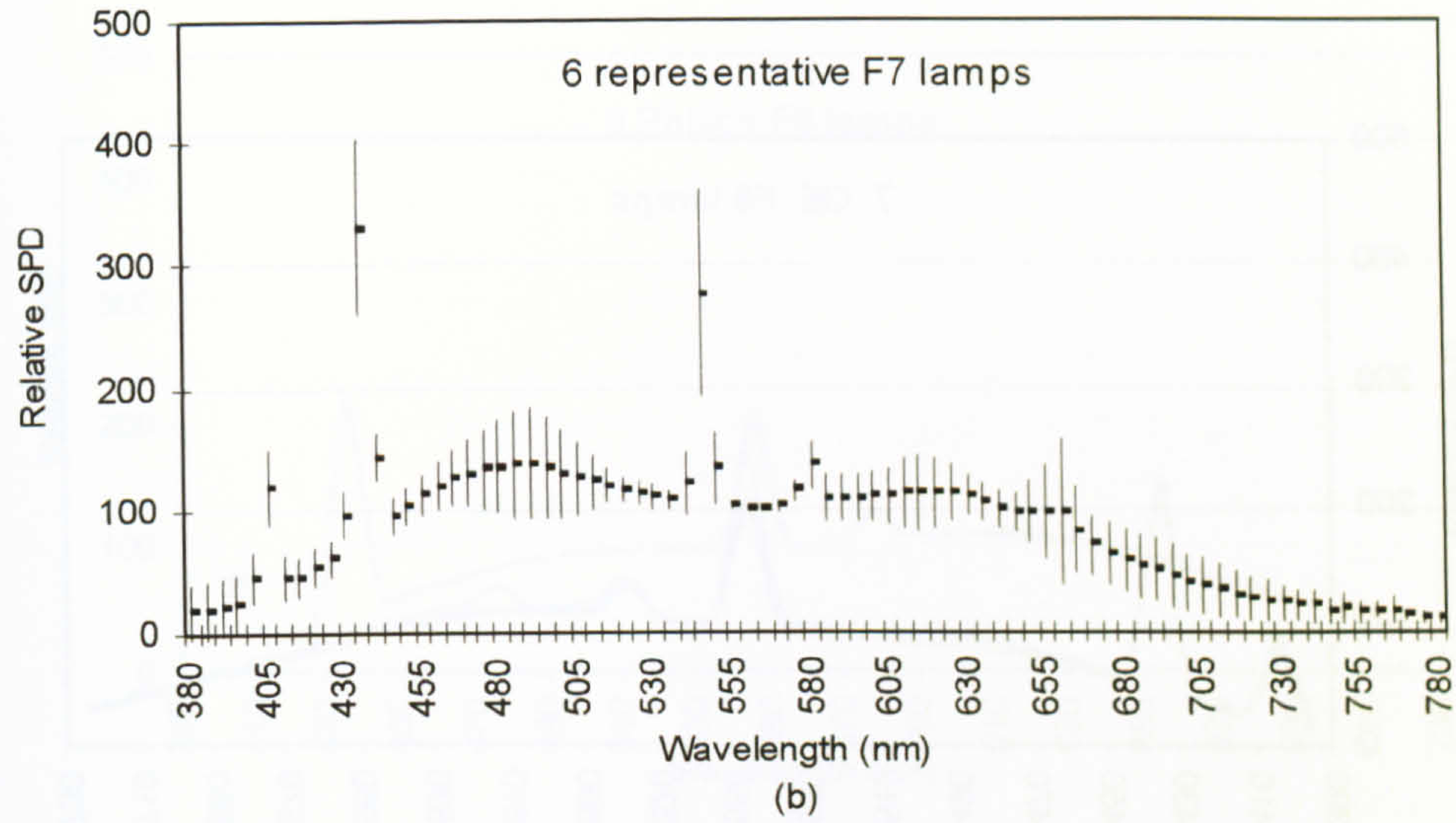
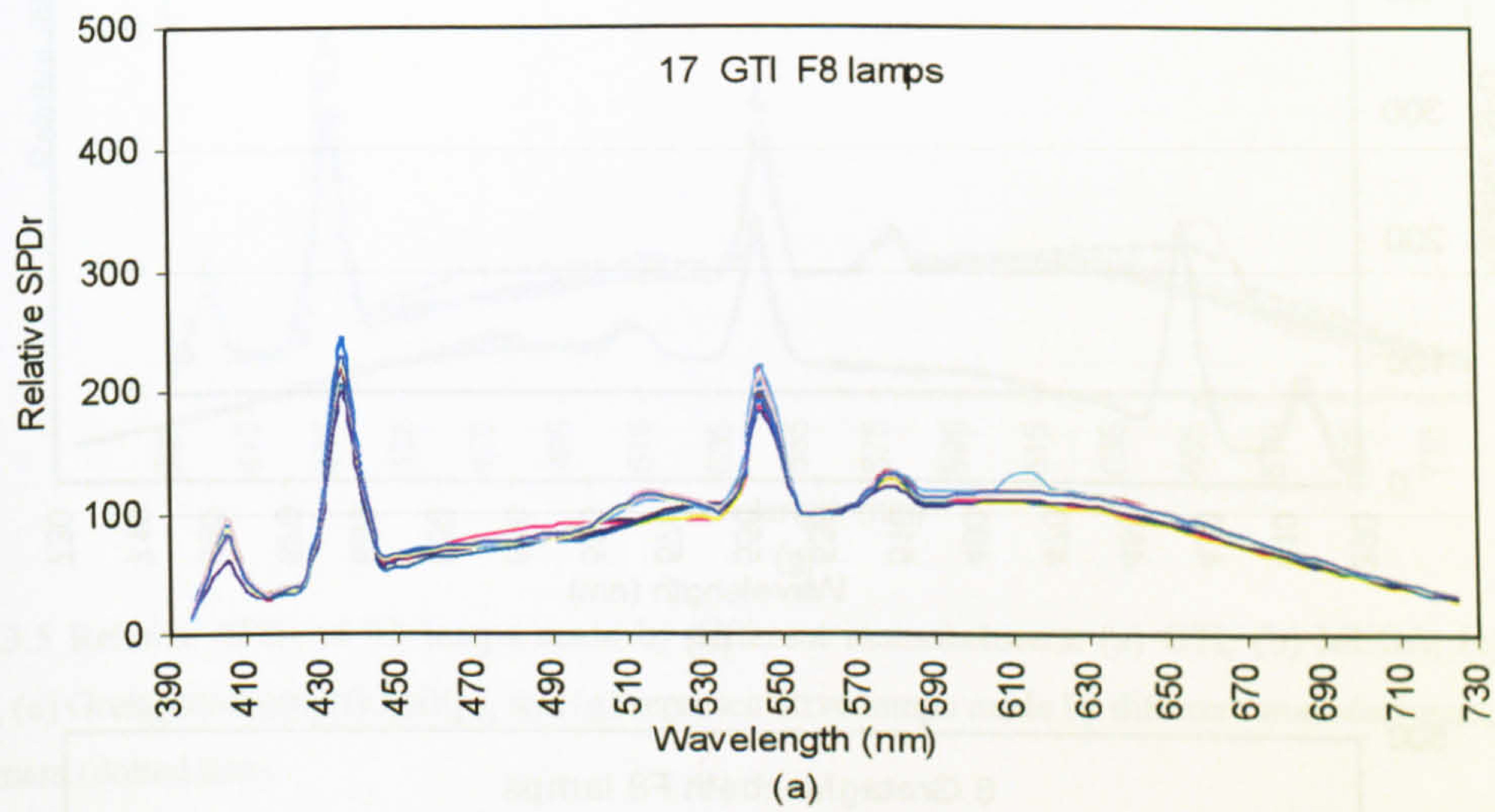
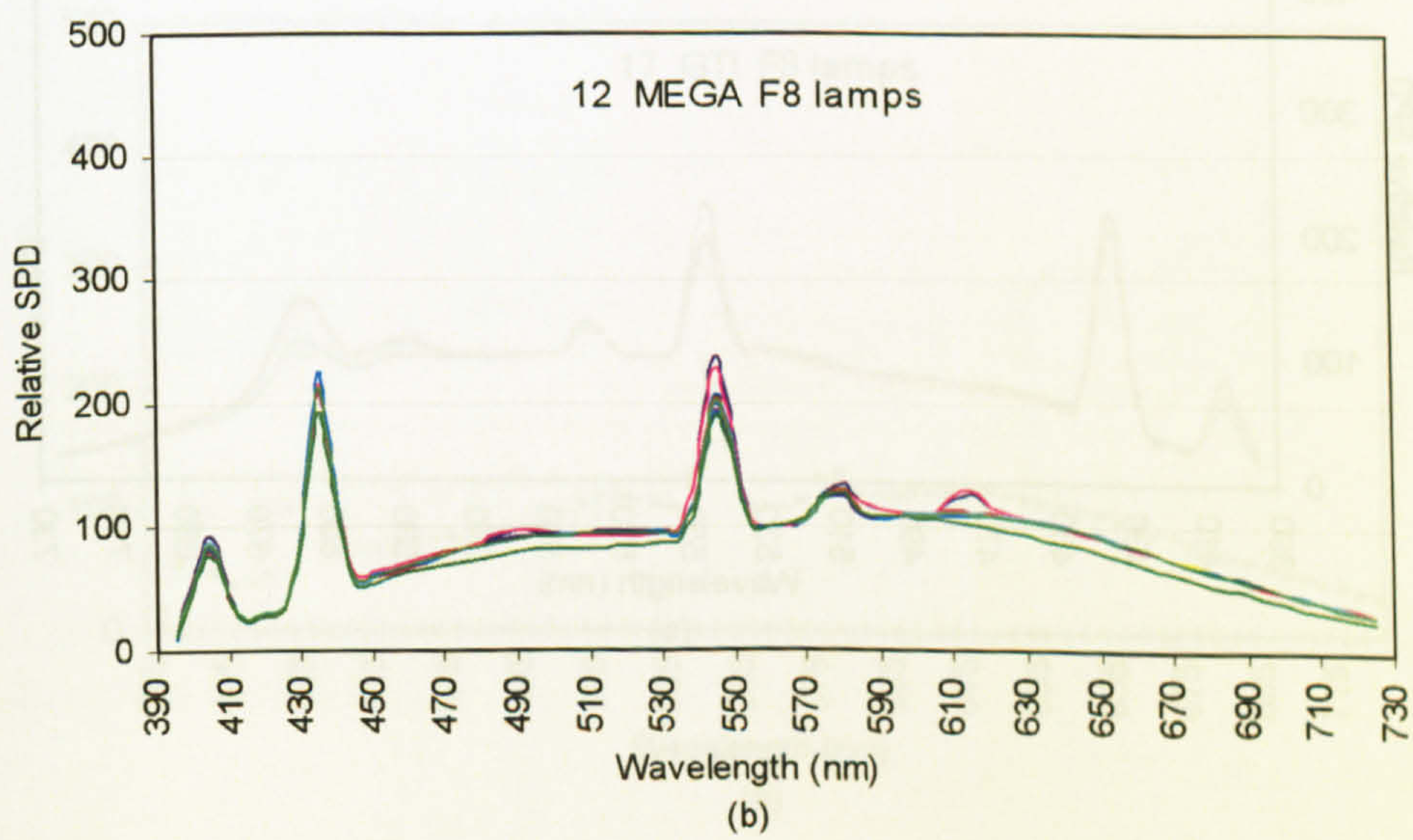
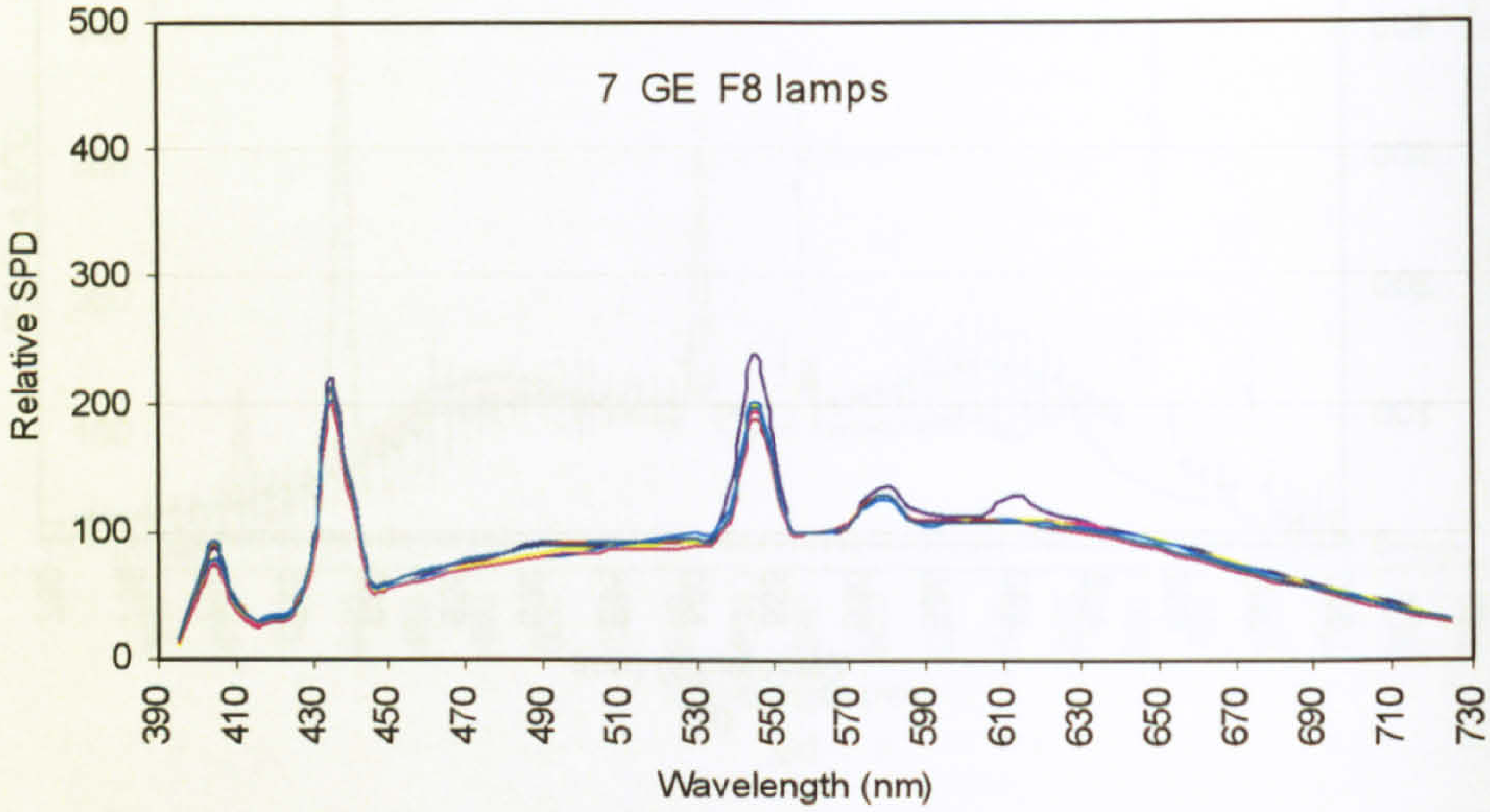
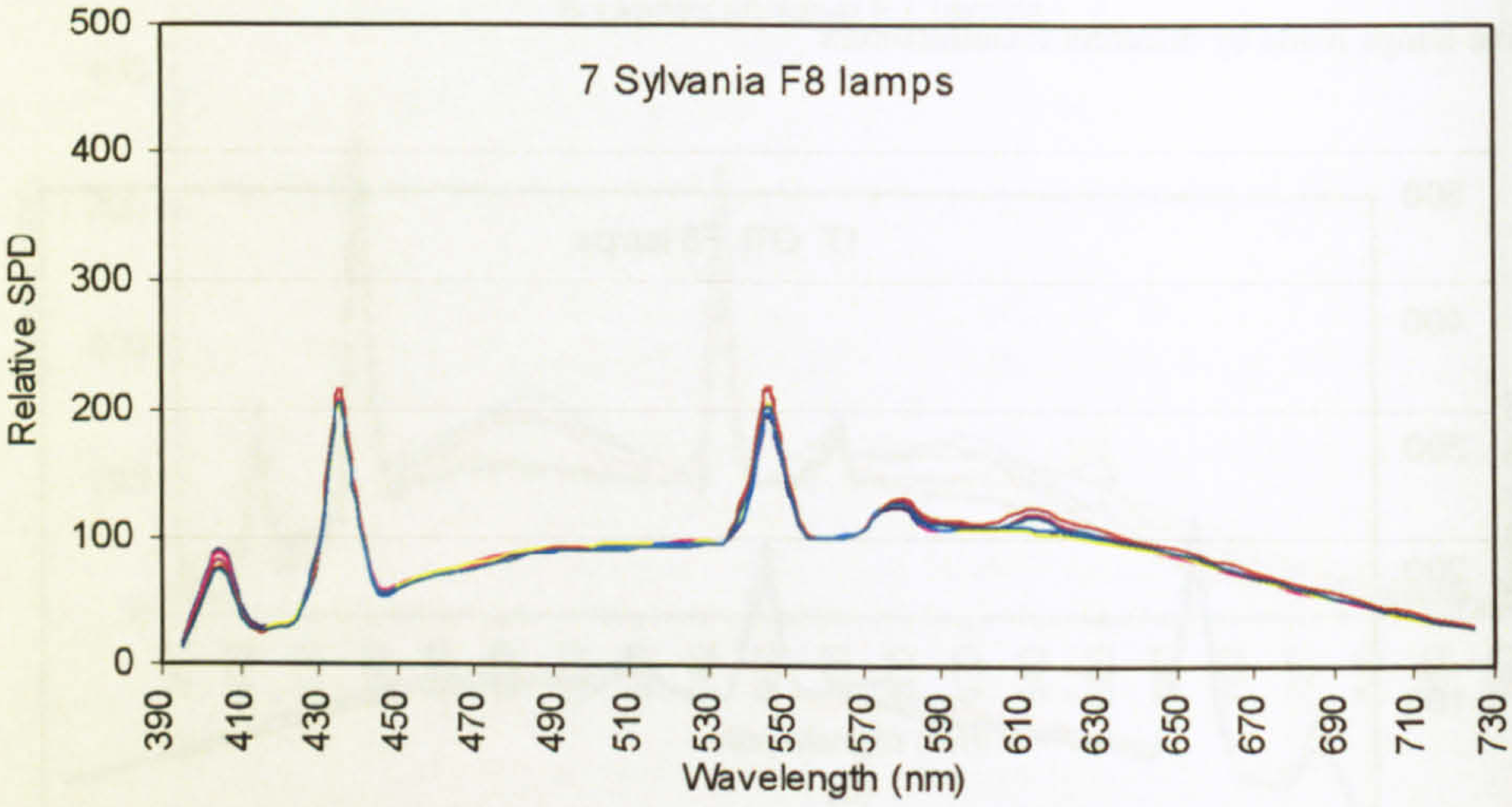


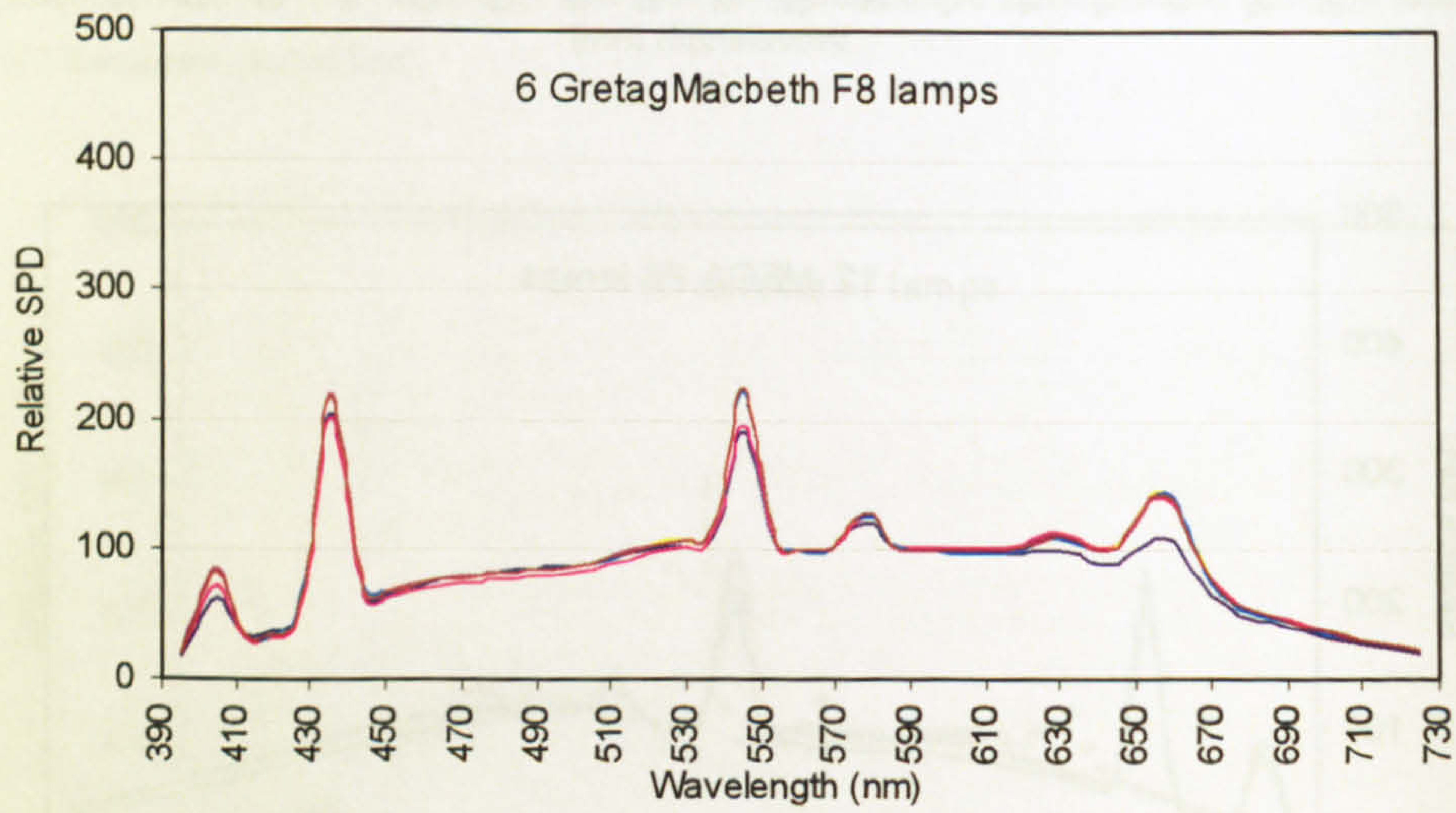
Figure 3.3.4 Averaged SPDs with a range of 2 times of standard deviation for the F7 lamps: (a) VeriVide, (b) representative lamps made by different manufacturers

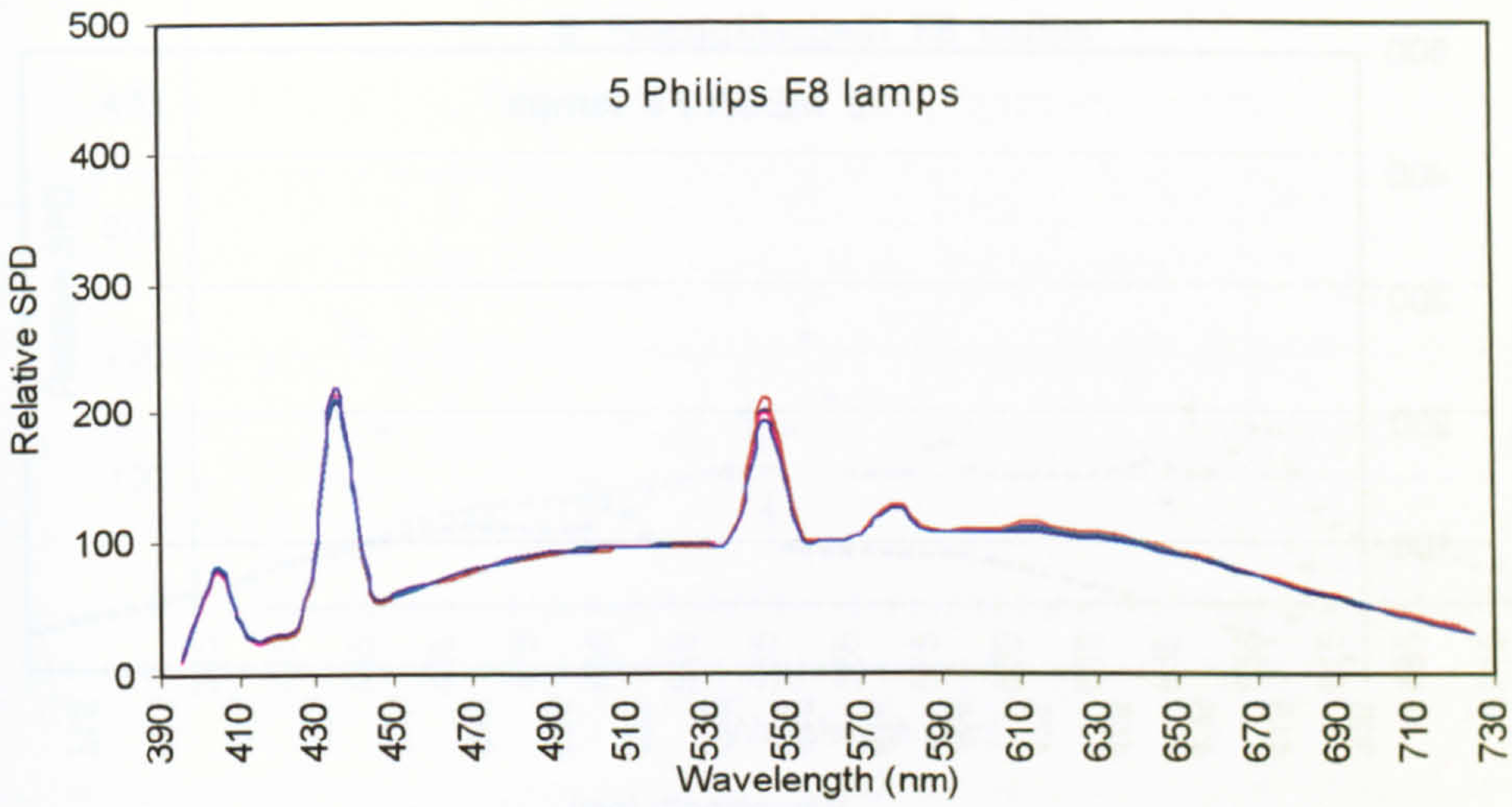




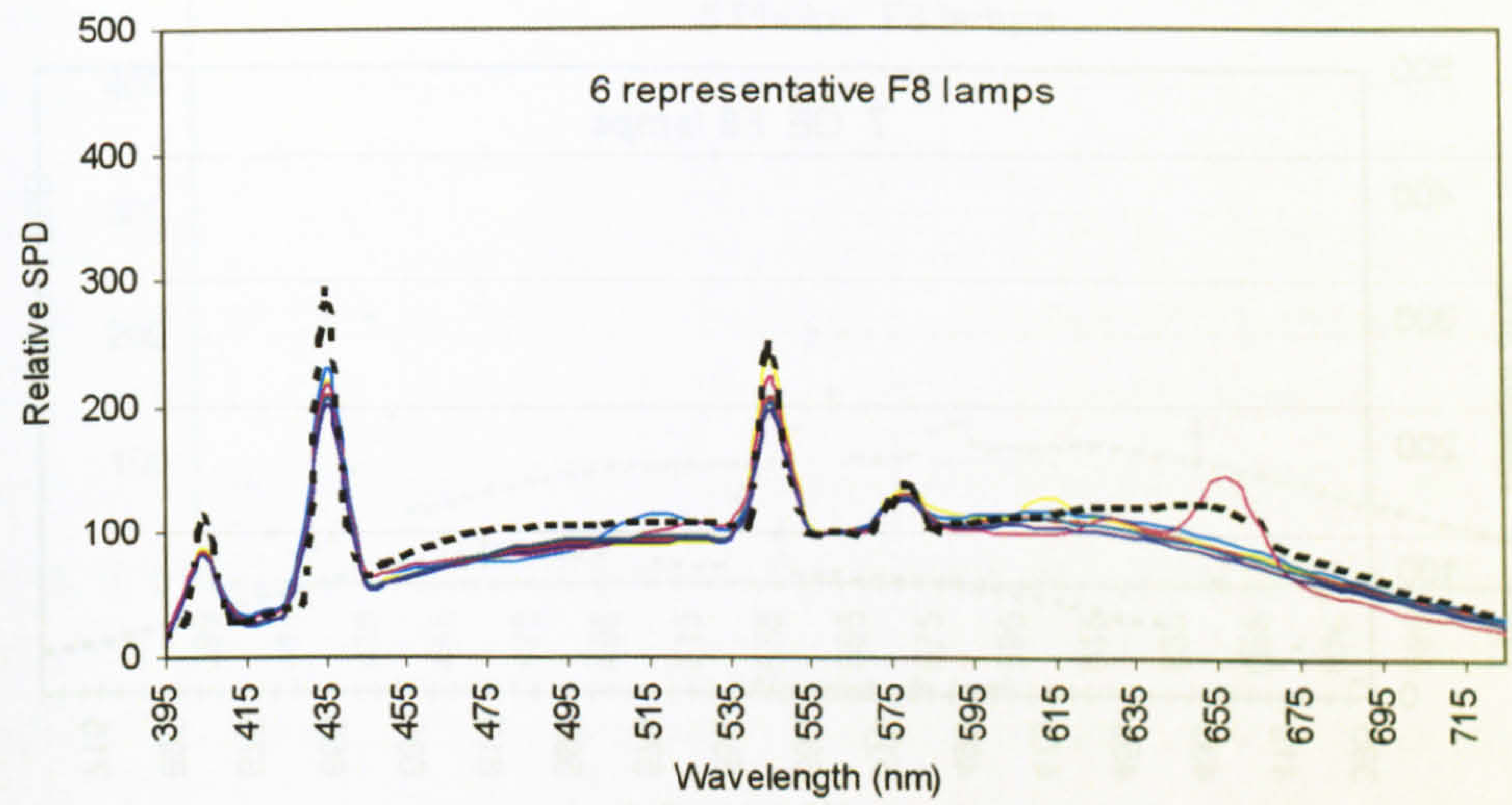

7 GE F8 lamps
Relative SPD
500
400
300
200
100
0
390 410 430 450 470 490 510 530 550 570 590 610 630 650 670 690 710 730
Wavelength (nm)
(c)


7 Sylvania F8 lamps
Relative SPD
500
400
300
200
100
0
390 410 430 450 470 490 510 530 550 570 590 610 630 650 670 690 710 730
Wavelength (nm)
(d)


6 GretagMacbeth F8 lamps
Relative SPD
500
400
300
200
100
0
390 410 430 450 470 490 510 530 550 570 590 610 630 650 670 690 710 730
Wavelength (nm)
(e)

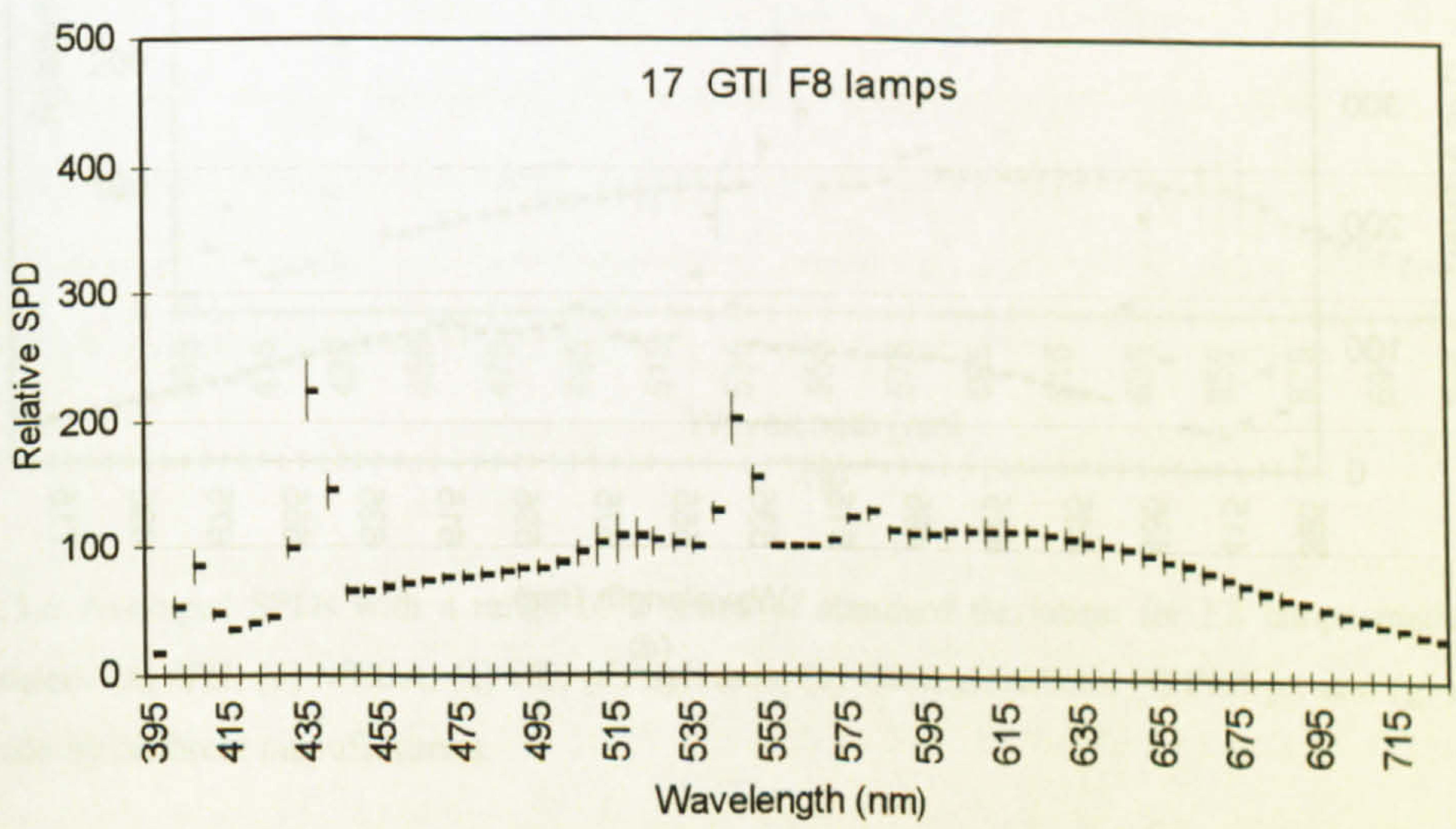


(f)

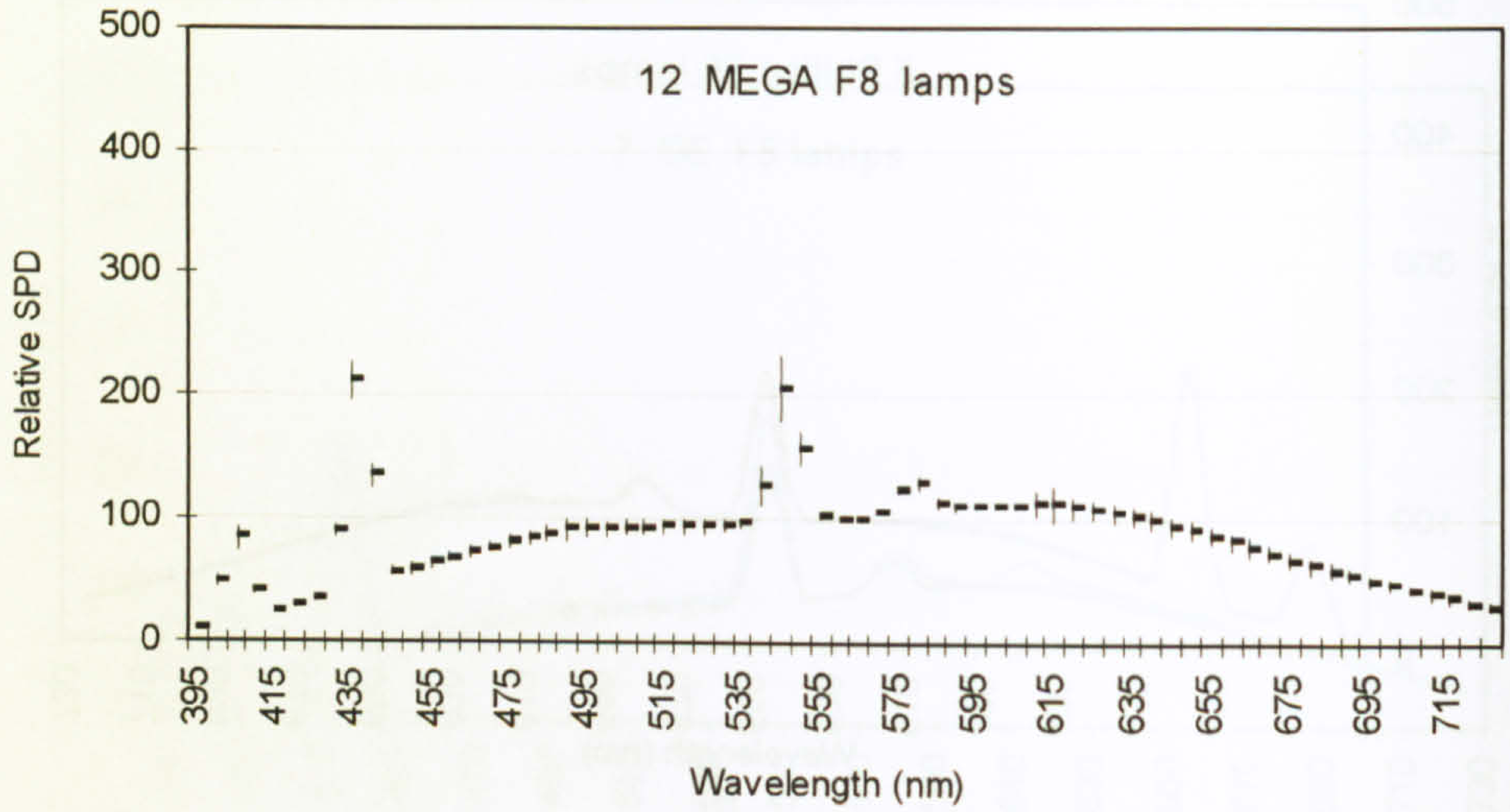


(g)

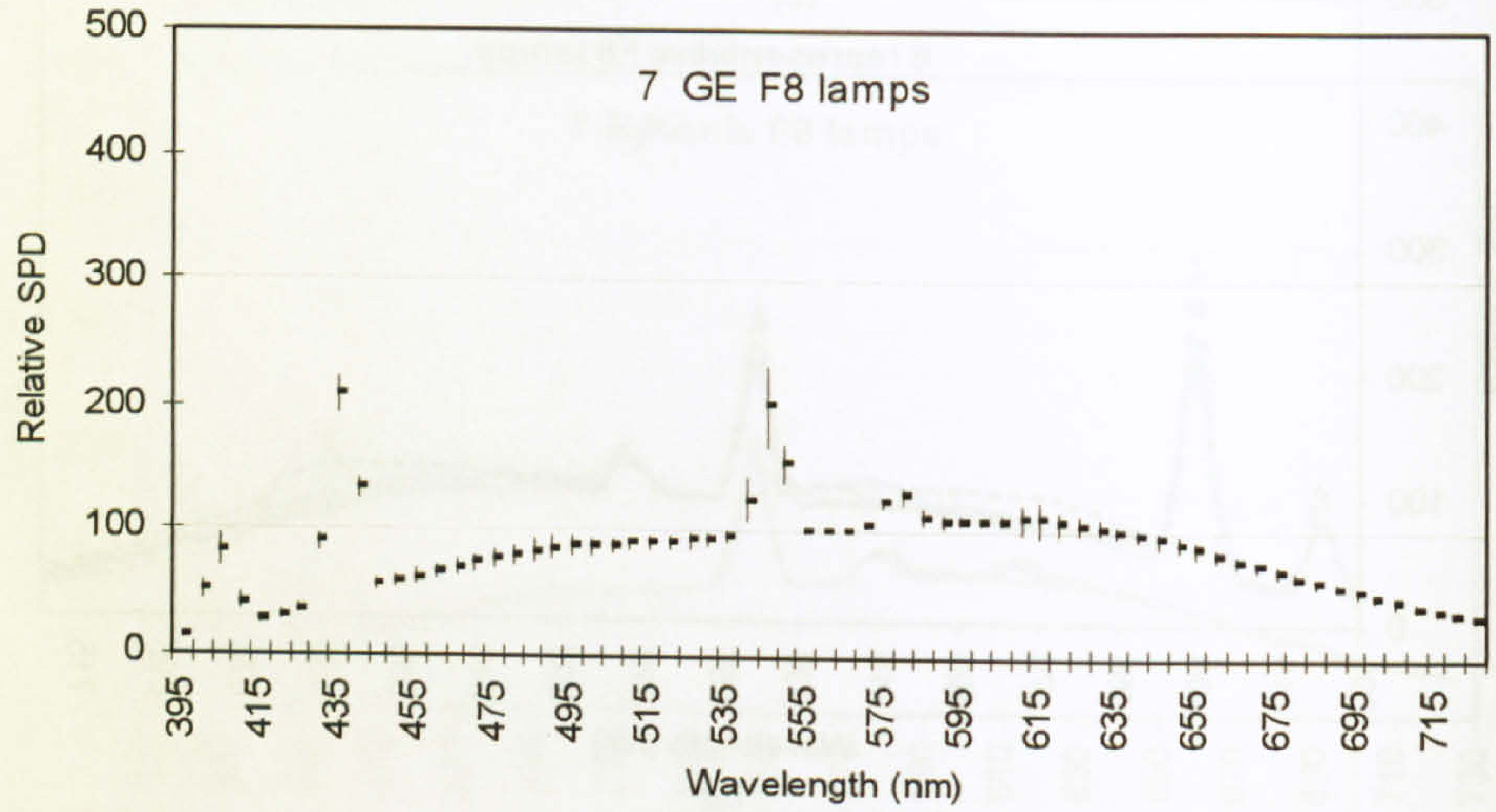
Figure 3.3.5 Relative SPDs of F8 lamps made by different manufacturers: (a) GTI, (b) MEGA, (c) GE, (d) Sylvania, (e) GretagMacbeth, (f) Philips, and (g) representative lamps made by different manufacturers, plus CIE F8 illuminant (dotted line)



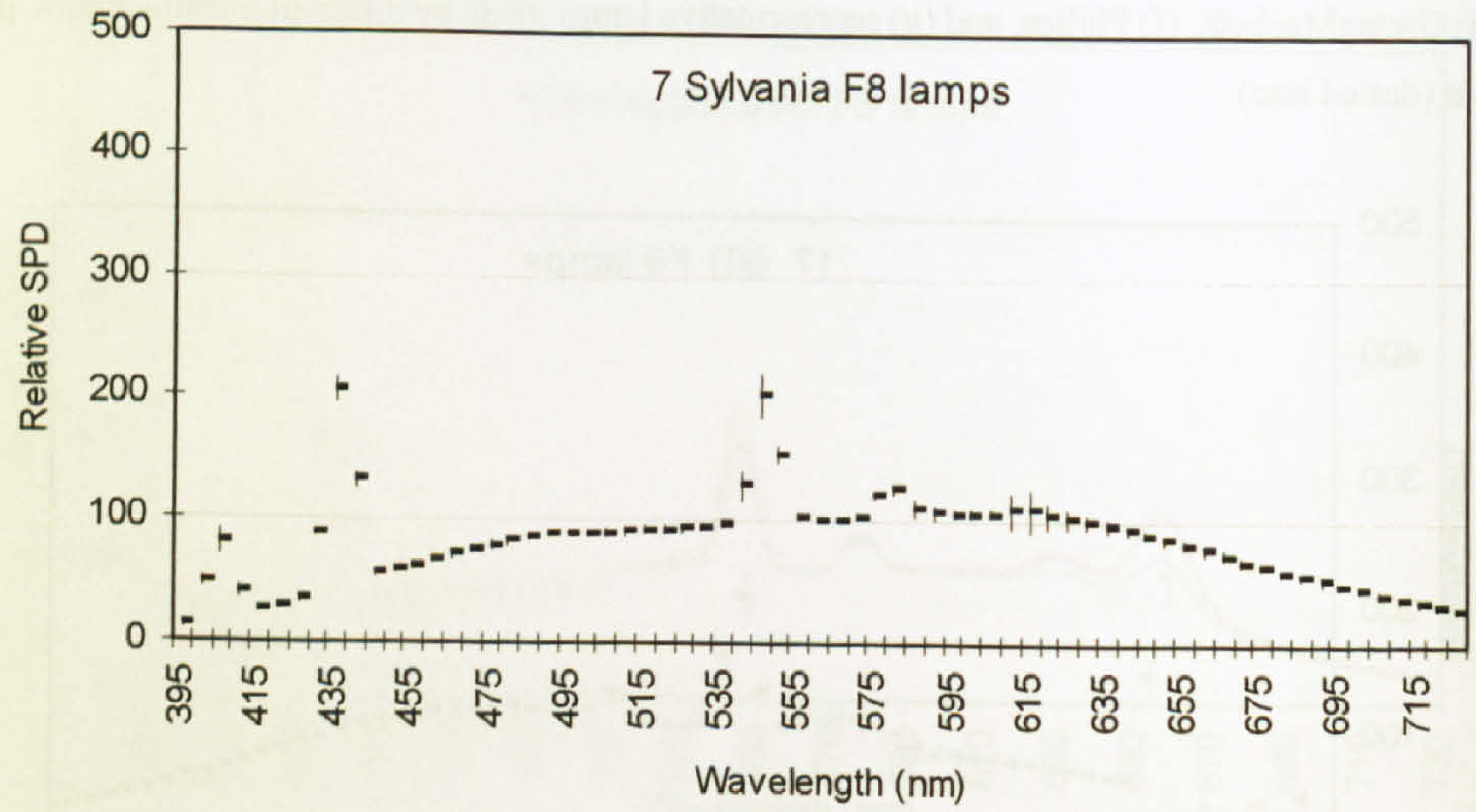
(a)


12 MEGA F8 lamps
Relative SPD
Wavelength (nm)

(b)


7 GE F8 lamps
Relative SPD
Wavelength (nm)

(c)


7 Sylvania F8 lamps
Relative SPD
Wavelength (nm)

(d)

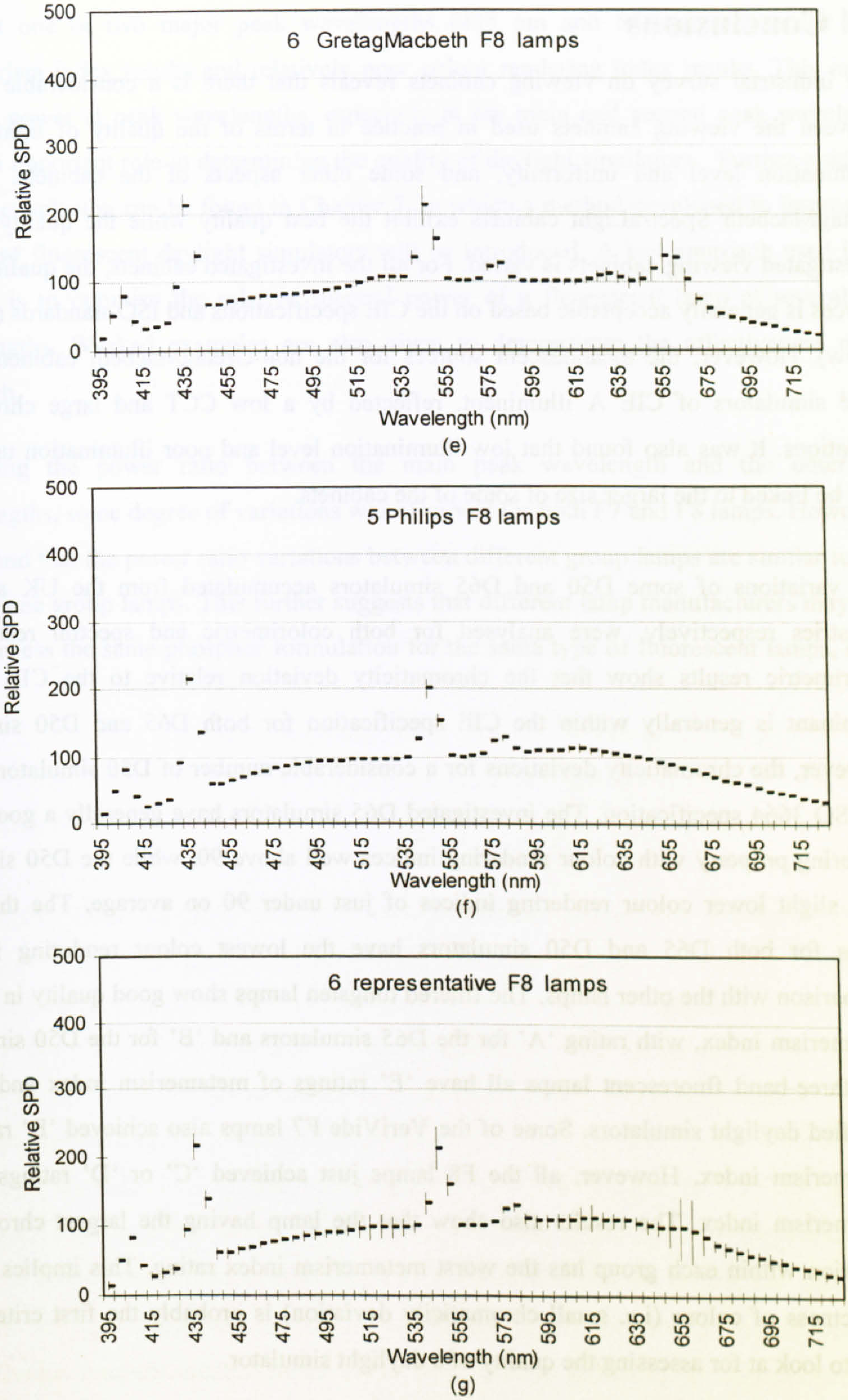


Figure 3.3.6 Averaged SPDs with a range of 2 times of standard deviation for F8 lamps made by different manufacturers: (a) GTI, (b) MEGA, (c) GE, (d) Sylvania, (e) GretagMacbeth, (f) Philips, and (g) representative lamps made by different manufacturers.

3.4 Conclusions

The industrial survey on viewing cabinets reveals that there is a considerable variation between the viewing cabinets used in practice in terms of the quality of light sources, illumination level and uniformity, and some other aspects of the cabinets. The two GretagMacbeth SpectraLight cabinets exhibit the best quality while the quality of other investigated viewing cabinets is varied. For all the investigated cabinets, the quality of D65 sources is generally acceptable based on the CIE specifications and ISO standards (see more below). However, the incandescent sources for the non-GretagMacbeth cabinets are not good simulators of CIE A illuminant, reflected by a low CCT and large chromaticity deviations. It was also found that low illumination level and poor illumination uniformity may be linked to the larger size of some of the cabinets.

The variations of some D50 and D65 simulators accumulated from the UK and USA industries respectively, were analysed for both colorimetric and spectral results. The colorimetric results show that the chromaticity deviation relative to the CIE daylight illuminant is generally within the CIE specification for both D65 and D50 simulators. However, the chromaticity deviations for a considerable number of D50 simulators exceed the ISO 3664 specification. The investigated D65 simulators have generally a good colour rendering property with colour rendering indices well above 90, while the D50 simulators have slight lower colour rendering indices of just under 90 on average. The three-band lamps for both D65 and D50 simulators have the lowest colour rendering index in comparison with the other lamps. The filtered tungsten lamps show good quality in terms of metamerism index, with rating 'A' for the D65 simulators and 'B' for the D50 simulators. The three-band fluorescent lamps all have 'E' ratings of metamerism index and are not qualified daylight simulators. Some of the VeriVide F7 lamps also achieved 'B' ratings of metamerism index. However, all the F8 lamps just achieved 'C' or 'D' ratings for the metamerism index. The results also show that the lamp having the largest chromaticity deviation within each group has the worst metamerism index rating. This implies that the correctness of colour (i.e. small chromaticity deviation) is probably the first criterion we need to look at for assessing the quality of a daylight simulator.

The spectral results show that all the F8 lamps and F7 lamps investigated have similar SPDs with exactly the same peak wavelengths. The lamps from the same manufacturer show less power spread in comparison with the lamps from different manufactures. For both F7 and F8 lamps, two lamps within each group with at least one extreme (highest or lowest) power value at one or two major peak wavelengths (435 nm and 545 nm), have the worst metamerism index results and relatively poor colour rendering index results. This implies that the power at peak wavelengths, especially at the main and second peak wavelength, plays an important role in determining the quality of daylight simulators. Further evidences for this conclusion can be found in Chapter 7, in which a method developed to improve the quality of fluorescent daylight simulators will be introduced. A key approach used in this method is to optimise the relative spectral power of a fluorescent lamp at several peak wavelengths. Worked examples are also given to demonstrate the effectiveness of this approach.

Regarding the power ratio between the main peak wavelength and the other peak wavelengths, some degree of variations was observed for both F7 and F8 lamps. However, it was found that the power ratio variations between different group lamps are similar to those of the same group lamps. This further suggests that different lamp manufacturers may adopt more or less the same phosphor formulation for the same type of fluorescent lamps, say F7 lamps.

CHAPTER 4
EXPERIMENTAL ASSESSMENT ON THE QUALITY OF D65 SIMULATORS

4.1 Introduction

In Chapter 3, a number of D65 and D50 simulators currently used in industry were evaluated. Their quality in terms of colorimetric and spectral variations was reported. It was found that a considerable variation existed among these simulators. Also, there were significant discrepancies between the national and international standards in specifying the quality of daylight simulators (see Section 2.5). These standards include the British standard BS 950 (1967), the American standards ANSI PH 2.31 (Johnson 1998, pp.37), ASTM D1729 (1996) and AATCC EP9 (1999), the Japanese standard JIS Z 8716 (JIS 1991), CIE Publication 13.3, 51, 51.2 (CIE 1995a, 1981 and 1999), and the ISO standard 3664 (2000).

The British, USA and ISO standards were established mainly for specifying standard viewing conditions for specific industrial applications. As daylight illumination is one of the most important viewing conditions in practice, CIE daylight illuminants (see Section 2.3.3.1) were chosen as standard in these standards. The specifications for daylight simulators are thus the key contents in these standards. Colorimetric features such as chromaticity coordinates, correlated colour temperature (see Section 2.3.2), colour rendering index (see Section 2.5.4.1) and metamerism index (see Section 2.5.4.2) are generally considered with respect to the quality of daylight simulators. The spectral power distribution (SPD) of a daylight simulator determines its colorimetric results. Hence, the quality of a daylight simulator depends primarily on its SPD and it is important to find an appropriate measure to reflect the characteristics of the SPD relative to that of the corresponding CIE daylight illuminant.

Several important measures have so far been developed for evaluating the quality of daylight simulators with focus on the SPDs of the simulators (see Section 2.7). These include the CIE metamerism index method (CIE 1981 and 1999, see Section 2.5.4.2), band value method (BS 950, see Section 2.5.1) and goodness-of-fit of SPD (Wyzescki 1970, see Section 2.7.1). The band value method and CIE metamerism index method are of particular importance as they have been widely used by various industries as the main measures for assessing the quality of daylight simulators. The performances and correlation of these two methods thus are of high interest to the daylight simulator manufacturers and users. For the band value method, no study has yet been reported with respect to its performance. Investigations into the CIE metamerism index method have been reported by other researchers (see Section 2.8.2), however, there are still doubts on the performances of this method, one of which concerns whether the CIE metamers are good representatives of real metamers in practice.

This chapter introduces a psychophysical experiment, designed to visually assess the quality of daylight simulators. The experimental results were used to investigate the performances of the band value method and the CIE metamerism index method for evaluating the quality of daylight simulators. Recommendations were also made for using the two methods in practice. The majority of the results in this chapter were published in *Coloration Technology* by the author (Xu 2003b).

4.2 Experimental

The psychophysical experiment employed seventy real metameric pairs and six test simulators. A panel of ten observers participated in this experiment and each of them assessed the visual colour differences of these metameric pairs, displayed in a viewing cabinet under the illumination of a test simulator. The following describes the characteristics of the test simulators and metameric pairs in use. The method to deal with the visual results is also described.

4.2.1 Characteristics of the D65 Simulators Tested

4.2.1.1 Simulator Details

The six D65 simulators chosen for this experiment were made by four manufacturers. They are among those used for the variation analysis in Chapter 3. These simulators are different with respect to type or manufacturer, and include one GretagMacbeth filtered tungsten lamp (see Section 2.4.1.1), four broad-band fluorescent lamps (see Section 2.4.1.3) made by VeriVide, GE, GretagMacbeth and Toshiba respectively, and one three-band fluorescent lamp made by Toshiba. The filtered tungsten lamp was fitted within a GretagMacbeth SpectraLight II viewing cabinet while all the fluorescent lamps were housed in a VeriVide purpose-built viewing cabinet to accommodate the slight differences of lamp length. The former has a larger size than the latter, which is of similar size to a VeriVide CAC 60 cabinet (see Table 3.2.4). The interior paint of the two cabinets was also different (in lightness), with the former having a Munsell Value of N7 and the latter of N5. Details of these simulators are listed in Table 4.2.1

Table 4.2.1 Details of the six D65 simulators studied

Characteristics of Lamp			Characteristics of Accommodating Cabinet		
Manufacturer	Lamp type	Band type	Make	Interior Paint[b]	Diffuser
GM[a]	Filtered tungsten		GM SpectraLight II	N7	With
VeriVide	Fluorescent	Broad band	VeriVide purpose-built	N5	Without
GM	Fluorescent	Broad band	VeriVide purpose-built	N5	Without
GE	Fluorescent	Broad band	VeriVide purpose-built	N5	Without
Toshiba	Fluorescent	Broad band	VeriVide purpose-built	N5	Without
Toshiba	Fluorescent	Three-band	VeriVide purpose-built	N5	Without

a GM is the abbreviation for GretagMacbeth.
b Interior paint refers to the lightness of cabinet wall, defined by Munsell Value.

4.2.1.2 SPD Measurements

The measurement conditions used for each simulator were the same as those described in Section 3.2.1.2, for which the SPD of each simulator was evaluated by measuring a PTFE white tile displayed in the centre of the viewing cabinet floor using a Minolta CS1000 tele-spectroradiometer (see Sections 2.3.12.2). The instrument performance in terms of accuracy and repeatability was also reported in Section 3.3.1.2. The measured SPD was corrected using the reflectance of the white tile. The normalised SPDs for the six investigated simulators are shown in Figures 4.2.1(a) to (f). Note that the three-band fluorescent lamp (see Figure 4.2.1(f)) has relatively low power at 560 nm so in this case the maximum power (not the power at 560 nm) was scaled to 400. The normalised SPD of the three-band lamp thus has a similar scale to those of the other simulators.

4.2.1.3 Simulator Stability Tests

The stability for the six simulators over the whole experiment period (about three months) was examined by measuring each simulator three times, before, during and after the experiment. The measurement conditions and measurement variations between different measurement time were described in Section 3.2.1.2. The results showed that the GE broad band fluorescent lamp had the worst measurement variations with Maximum Difference (the difference between the average and the most deviated results) are 5.7%, 0.0012 and 0.0021 for luminance (cd/m^2), chromaticities x and y respectively. Comparing to the instrument long-term repeatability (see Table 3.2.2), it is clear that that these measurement variations were mainly caused by the change of lamp output due to working hour, fluctuation of power supply, changes in measurement set-up, etc. In general, the measurement variations in terms of Maximum Difference are thought to be insignificant for the six simulators comparing to the measurement uncertainty quoted by NPL (see Table 3.2.2) for the CII standard lamp, which is a tungsten lamp. This suggests that the simulators were reasonably stable over the whole experimental period.

4.2.1.4 Colorimetric Results

The colorimetric results together with quality measures for the six simulators studied (taken from Table 3.3.1) are listed in Table 4.2.2. The results demonstrate a certain degree of variation amongst the six simulators investigated. For luminance results, the Toshiba three-band fluorescent lamp has the highest level while the GretagMacbeth filtered tungsten lamp has the lowest level. This suggests that the three-band fluorescent lamp has higher energy-efficiency than the broad band fluorescent lamps, given the fact that all the investigated fluorescent lamps were measured at the same wattage. The filtered tungsten lamp is much more energy consuming than the fluorescent lamps. For chromaticity results, the filtered tungsten lamp has the least chromaticity deviation ($\Delta u'_{10}v'_{10}$) of 0.0006 while the three-band fluorescent lamp has the largest chromaticity deviation of 0.0062, still well within the CIE specifications on chromaticity tolerance of 0.015 (CIE 1999).

Regarding CIE general colour rendering index (R_a) results, the VeriVide broad band fluorescent lamp has the best result of 98 and the three-band lamp has the worst result of 88. The filtered tungsten lamp has the best rating of 'A' for CIE metamerism index and the three-band fluorescent lamp has the worst rating of 'E'. The broad band fluorescent lamps have either 'B' or 'C' ratings. It should be noted that the colour rendering index considers the close match of colour appearance for some test samples between a reference illuminant (one phase of CIE D illuminants) and a test simulator. (A full investigation of the CIE colour rendering index method is given in Chapter 6.) It is different from the metamerism index which considers the change of colour difference of pairs of samples between a fixed reference illuminant (e.g. CIE D65) and a test simulator. The results show that simulators having high metamerism index ratings, such as the filtered tungsten lamp and VeriVide broad band fluorescent lamp, also have good colour rendering property, indicating that some degree of correlation may exist between the two kinds of results.

Table 4.2.2 Colorimetric results for the 6 D65 simulators studied

D65 Simulator [a]	L (cd/m^2)	x	y	u'_{10}	v'_{10}	$\Delta u'_{10}v'_{10}$	CCT (K)	ΔE^*_{ab} [b]	R_a	MI_{vis}
GM[c] (FT[d])	410.7	0.3127	0.3311	0.1978	0.4701	0.0006	6486	1.37	96	0.18 (A)
VV[c] (F7[d])	562.8	0.3087	0.3259	0.1956	0.4689	0.0024	6751	2.07	98	0.26 (B)
GM (F7)	550.8	0.3158	0.3317	0.2000	0.4720	0.0033	6296	2.11	93	0.70 (C)
GE (F7)	534.8	0.3156	0.3272	0.2016	0.4694	0.0037	6326	1.92	93	0.82 (C)
TO[c](F7)	491.9	0.3198	0.3314	0.2012	0.4738	0.0054	6090	3.50	97	0.34 (B)
TO (3B[d])	*985.2*	0.3135	0.3212	*0.2025*	0.4654	0.0062	6529	4.89	88	2.30 (E)

a The same lamps were analysed in an earlier paper by the author (Xu 2001). The colorimetric results shown here are slightly different from those in the earlier paper. The reason for this is that these lamps were measured three times. The previous paper used the first measurement results and this thesis used the average measurement results for the calculation.

b ΔE^*_{ab} is the CIELAB colour difference for a reference white (perfect diffuser) illuminated under a test simulator and CIE D65 illuminant.

c GM, VV and TO are the abbreviations for GretagMacbeth, VeriVide and Toshiba, respectively.

d FT and 3B are the abbreviations for filtered tungsten lamp and three-band fluorescent lamp respectively, F7 represents the broad band fluorescent lamps which have SPDs similar to CIE F7 illuminant.

4.2.1.5 Band Value Results

Table 4.2.3 lists the band value and band deviation results as specified in BS 950 for the six simulators investigated. Only the 6 visible bands were considered. The band deviation results exceeding the BS 950 tolerance (±15%) are noted in bold with italic. In addition, the summation of the absolute value of the band deviation for the six visible bands, an index suggested by the author to represent the total band deviation for a simulator, is also included in the table.

Table 4.2.3 Band value and band deviation results for the 6 D65 simulators studied

Simulator[a]	Band Value						Deviation of Band Value (%)						
	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	sum(abs)
	400-455nm	455-510nm	510-540nm	540-590nm	590-620nm	620-760nm	400-455nm	455-510nm	510-540nm	540-590nm	590-620nm	620-760nm	
GM (FT)	0.8	10.8	21.9	46.3	13.7	6.6	1.6	-3.8	-5.3	5.8	-4.6	-3.6	24.9
VV(F7)	0.8	11.6	21.3	45.4	13.8	7.0	4.3	3.4	-7.7	4.0	-4.1	2.9	26.4
GM (F7)	0.8	9.5	22.0	47.0	13.5	7.2	4.0	***-15.2***	-4.9	7.5	-6.1	5.6	43.3
GE (F7)	0.9	9.6	21.1	47.4	14.5	6.6	7.6	-14.7	-8.6	8.5	0.7	-3.5	43.6
TO (F7)	0.7	11.2	20.2	45.6	15.0	7.2	-6.2	0.0	-12.6	4.4	4.5	5.9	33.7
TO (3B)	1.0	8.7	10.9	57.1	18.7	3.7	***25.7***	***-22.3***	***-52.8***	***30.6***	***29.6***	***-45.9***	206.9

a See footnote of Table 4.2.2 for abbreviations for the simulators

The band value results in Tables 4.2.2 show that simulators (e.g. the GretagMacbeth filtered tungsten lamp and VeriVide broad band fluorescent lamp) with an appropriate power distributions for the six visible bands specified in BS 950 have band deviation results well below the BS 950 tolerance of ±15%. These simulators also show good quality with high metamerism index ratings and good colour rendering index. On the contrary, a simulator having band deviation close or exceeding the BS 950 tolerance at one or more of the six bands, e.g. the Toshiba three band fluorescent lamp, corresponds to a poor CIE metamerism index rating and colour rendering index.

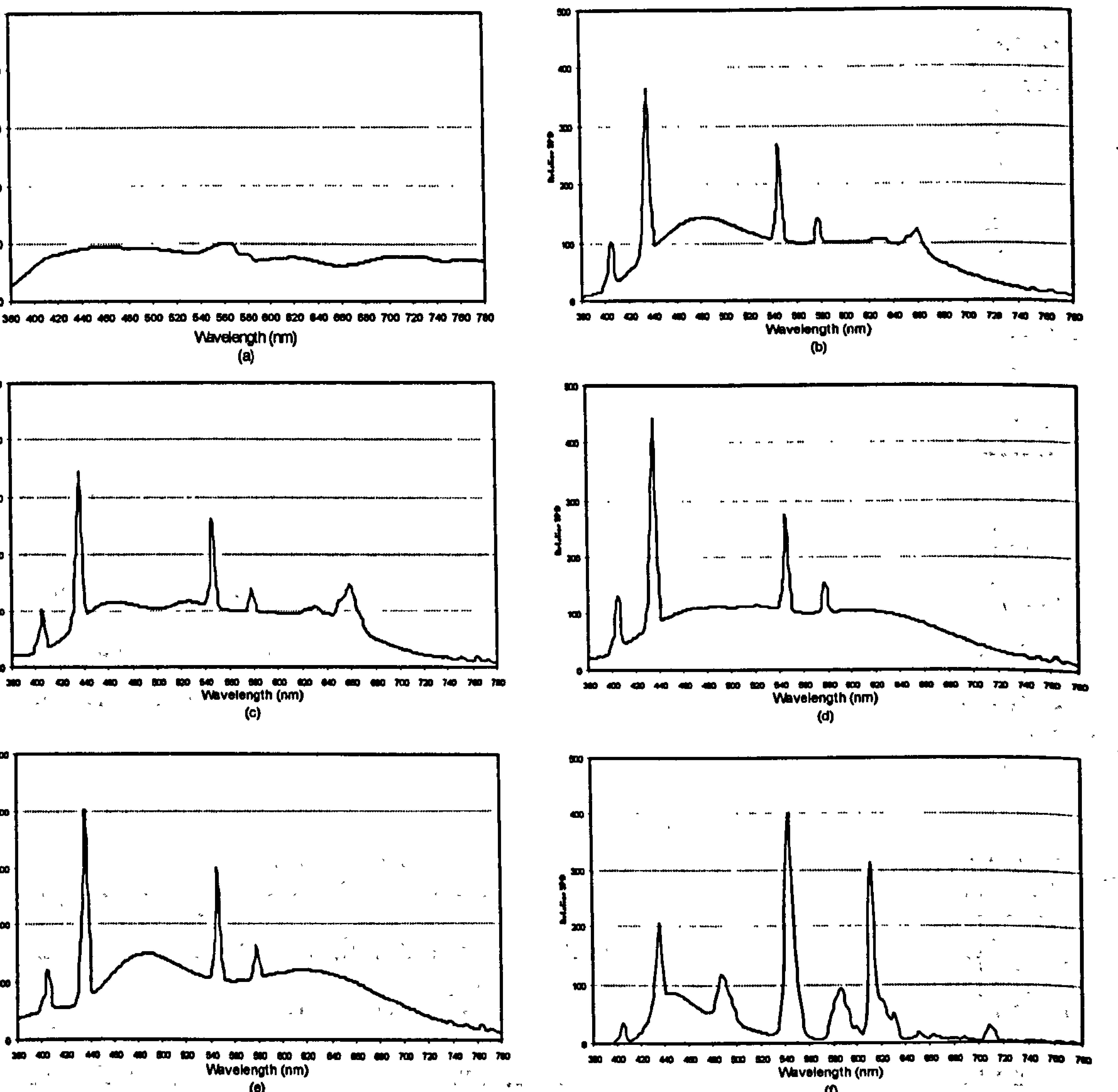


Figure 4.2.1 The relative SPDs for the six D65 simulators investigated: (a) refers to GretagMacbeth filtered tungsten lamp, (b) to (e) refer to broad band fluorescent lamps made by VeriVide, GretagMacbeth, GE, Toshiba, (f) refers to Toshiba three band fluorescent lamp. The lamps in (a) to (f) are abbreviated as GM (FT), VV (F7), GM (F7), GE (F7), TO (F7) and TO (3B) respectively. Note that the SPDs of all simulators were scaled to 100 at 560 nm except the three-band lamp, which was scaled to 400 at the maximum radiance.

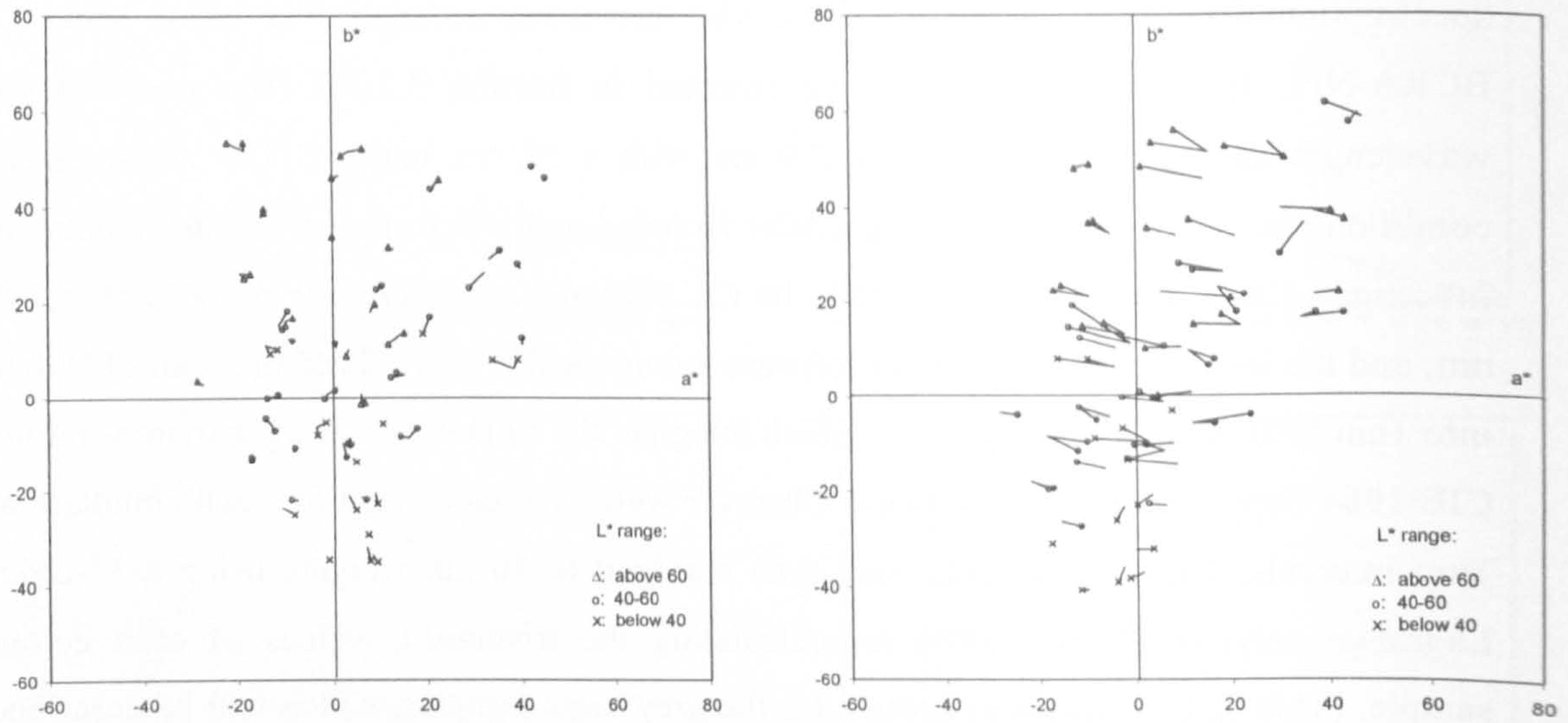
4.2.2 Sample Preparation

4.2.2.1 Seventy Metameric Pairs

Seventy metameric pairs prepared by Kuo and Luo (1996a) were used in this experiment. These samples were made by dyeing plain wool serge and were mounted in two layers on a stiff card (3" by 3"). All the samples were measured by a GretagMacbeth Color-Eye 7000A spectrophotometer (see Section 2.3.12.1). The instrument accuracy was tested using 12 BCRA-NPL tiles and the results were reported in Section 3.2.1.2. The measurement wavelength ranged from 400 nm to 700 nm with a 10 nm interval. The measurement condition was set to large aperture, specular included and UV included. All the simulators investigated were measured using a Minolta CS 1000 at 5 nm interval from 380 nm to 780 nm, and the instrument measurement software automatically interpolated the 5nm SPD data into 1nm SPD data. Weighting tables which integrate the SPD data of a light source and the CIE 1964 Supplementary Colorimetric Observer were then calculated for each simulator at 1nm intervals. The 1nm weights were then abridged to 10 nm weights using a 3rd-order Lagrange polynomials (Li 2004) for calculating the tristimulus values of each colour sample. (This method was also applied for the grey scale samples, which will be described in the next Section.) For the whole seventy pairs, the Mean/Maximum colour differences (CIELAB) are 1.9/4.9 under CIE D65 illuminant and 7.1/14.5 under CIE A illuminant.

The sample distributions for these metameric pairs under CIE D65 and A illuminants are shown in Figures 4.2.2, each vector in the figure representing a pair of samples. It can be seen that the sample pairs cover a large colour and lightness volume. Figure 4.2.2(a) shows that the majority of sample pairs have a close match with each other, i.e. the magnitudes of vectors are quite small. This is expected because these pairs were designed to have a close match under CIE illuminant D65. Note that it is not possible to produce exact matches under illuminant D65 although several corrections to the dye formulations were made. The majority of the metamers were visually assessed to give a reasonable match between the two samples. The others were chosen because although they had a somewhat large perceived colour difference under illuminant D65, they also had a much larger colour difference under other light sources, say illuminant A. The magnitudes of vectors in Figure 4.2.2(b) are much larger (illuminant A), indicating a high degree of metameric property of these pairs. Figure 4.2.2(b) also shows the majority of vectors shift mainly along the red-green direction.

Figure 4.2.3 shows the sample distributions in frequency for the colour differences of 70 metameric pairs under both CIE D65 and A illuminants. It shows about 90% of the 70 metameric pairs have colour differences less than 3.0 ΔE^*_{ab} under CIE D65 illuminant, and above 90% of the 70 pairs have colour differences larger than 3.0 ΔE^*_{ab} under CIE A illuminant.



(a) (b)

Figure 4.2.2 Sample distributions for the colour differences of 70 metameric pairs under CIE A and D65 illuminants in (a) and (b) respectively

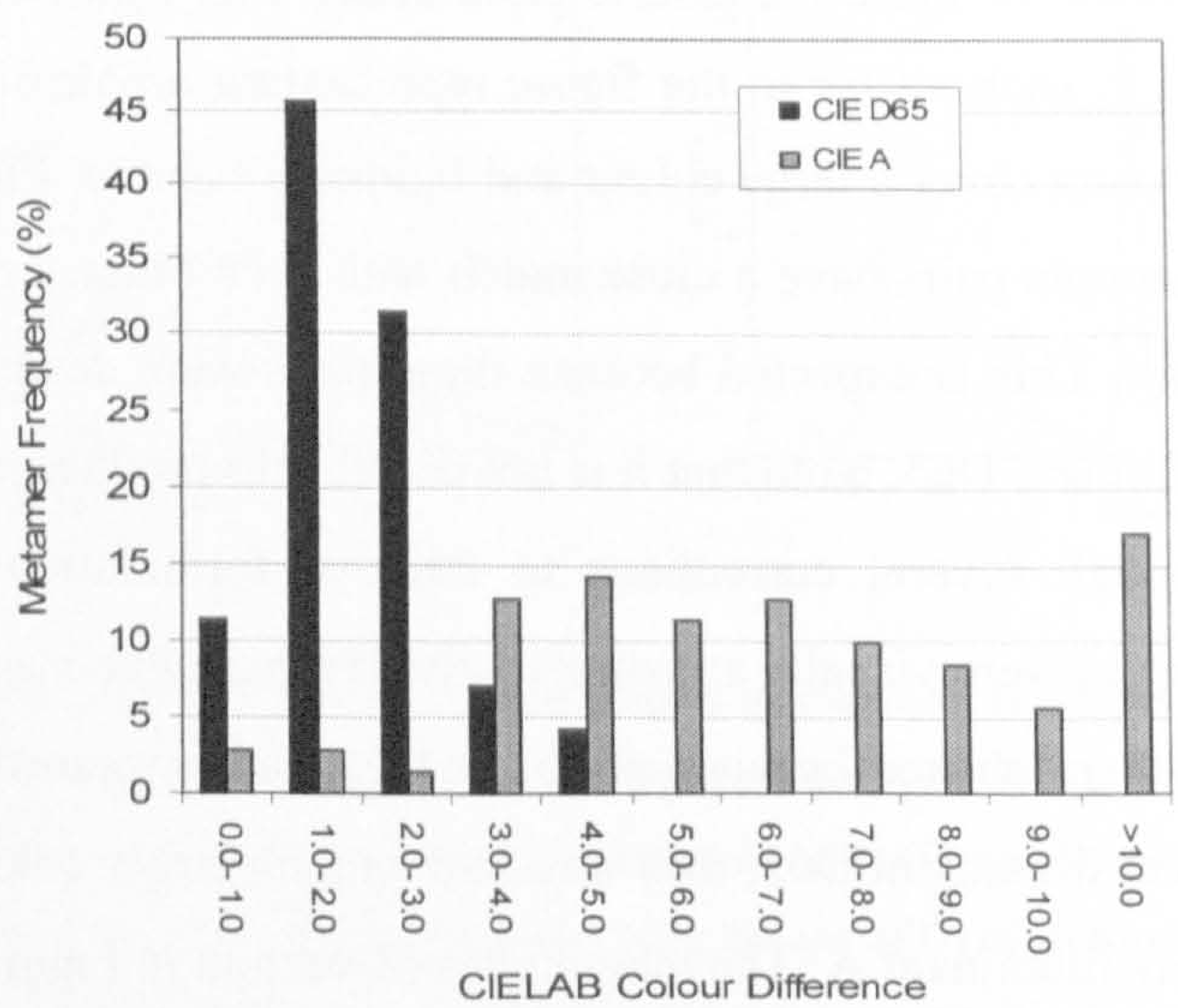


Figure 4.2.3 Sample distribution in frequency for the colour differences of 70 metameric pairs under CIE D65 and A illuminants. About 90% of the 70 metameric pairs have colour difference less than 3.0 ΔE^*_{ab} under CIE D65 illuminant, and above 90% of the 70 pairs have colour difference larger than 3.0 ΔE^*_{ab} under CIE A illuminant.

4.2.2.2 Grey Scale

A grey scale was used in the experiment. It consisted of a serial of matte paint colours coated on a paper substrate, including a standard and five grey samples, marked 'STD' and 1 to 5 on the back respectively. The grey scale samples had almost the same size as that of the metameric pairs. The samples are all neutral in colour, with Sample 1 being the lightest colour and Sample 5 the darkest colour. The Standard 'STD' is a duplication of Sample 5. All the grey scale samples were measured using the same spectrophotometer, GretagMacbeth Color-Eye 7000A (see Section 2.3.12.1). The same measurement condition used for the metameric pairs was adopted for the grey scale samples. The tristimulus values of the grey scale samples under different reference illuminants were calculated in the same way as that for the 70 metameric pairs, see Section above. The CIE L*, a* and b* values for each grade and the colour difference results between the standard and each grade are tabulated in Table 4.2.4. The results show all grades are close to neutral and have very good colour constancy (see Section 2.3.8) under the six simulators investigated, plus the CIE D65 and A illuminants.

Table 4.2.4 CIE L*a*b* and colour difference results for each grade under the six simulators investigated, plus CIE D65 and A illuminants

	L*	a*	b*	ΔE^*_{ab}	L*	a*	b*	ΔE^*_{ab}	L*	a*	b*	ΔE^*_{ab}	L*	a*	b*	ΔE^*_{ab}
Simul.[a]	GM (FT)				VV (F7)				GM (F7)				GE (F7)			
Grade 1	53.89	-0.23	-0.49	15.19	53.89	-0.24	-0.51	15.19	53.89	-0.23	-0.52	15.19	53.89	-0.19	-0.50	15.18
Grade 2	46.83	-0.11	-0.60	8.13	46.83	-0.10	-0.63	8.14	46.82	-0.11	-0.65	8.13	46.83	-0.07	-0.63	8.13
Grade 3	43.59	-0.79	-0.28	4.96	43.59	-0.79	-0.33	4.96	43.59	-0.81	-0.33	4.96	43.59	-0.77	-0.29	4.95
Grade 4	40.92	-0.38	-0.26	2.26	40.92	-0.38	-0.29	2.27	40.92	-0.39	-0.30	2.26	40.92	-0.36	-0.26	2.26
Grade 5	38.70	0.08	-0.22	0.03	38.70	0.09	-0.24	0.03	38.70	0.07	-0.25	0.03	38.71	0.09	-0.23	0.03
Simul.[a]	TO (F7)				TO (3B)				CIE D65				CIE A			
Grade 1	53.89	-0.26	-0.50	15.19	53.89	-0.12	-0.54	15.17	53.89	-0.25	-0.48	15.19	53.82	-0.49	-0.60	15.14
Grade 2	46.82	-0.13	-0.61	8.13	46.83	0.01	-0.67	8.13	46.83	-0.13	-0.60	8.13	46.77	-0.42	-0.68	8.09
Grade 3	43.58	-0.83	-0.31	4.95	43.61	-0.71	-0.33	4.97	43.58	-0.82	-0.29	4.96	43.47	-1.06	-0.52	4.87
Grade 4	40.92	-0.40	-0.27	2.26	40.96	-0.30	-0.29	2.28	40.92	-0.40	-0.27	2.26	40.85	-0.60	-0.40	2.21
Grade 5	38.70	0.07	-0.22	0.03	38.71	0.15	-0.27	0.03	38.70	0.07	-0.22	0.03	38.69	-0.14	-0.21	0.03

a See footnote of Table 4.2.2 for abbreviations for the simulators

4.2.2.3 Sample Stability Test

The colour change during the whole experimental period was investigated for each sample of the metameric pairs and grey scale. All the samples were measured three times (before, during and after the experiment) over the whole experimental period. For each sample, the colour difference (CIELAB) was calculated between an individual measurement and the mean of the three measurements. The Mean/Maximum colour difference (CIELAB) for all the samples are 0.1/0.3 under CIE D65 illuminant.

4.2.3 Visual Assessments

4.2.3.1 Observers

A panel of 10 observers, 4 males and 6 females, aged from 23 to 38, took part in assessing the colour differences of the 70 metameric pairs under each of the D65 simulators. They were either students or staff of the Institute and had experience in various visual assessments. Before performing the experiment, all the observers passed the Ishihara colour vision test and received 1-hour training for using the grey scale method, as described below.

4.2.3.2 Grey Scale Method

The grey scale method, which has been extensively used by many researchers (Luo 1987, Kuo 1996, Cui 2001 and Lam 2002), was employed in this study. When using the method in the experiment, the observer was first asked to choose a sample from the grey scale (see Section 4.2.2.2), say Sample 3, alongside the Standard giving a colour difference closest to that of the metameric pair. The observer was then asked to read a number (termed as Grade 'G') corresponding to the colour difference of the metameric pair. For instance, Grade '3' means the colour difference of the metameric pairs is exactly as same as that of the grey pair, including Sample 3 and the Standard. The observer was encouraged to gives intermediate grades, say 3.4.

4.2.3.3 Experimental Conditions

The whole experiment was conducted using a viewing cabinet located in a dark room. During the experiment, the observer sat in front of the viewing cabinet at about 50cm viewing distance with the Illuminating/Viewing geometry about 0/45. Each sample subtended about 10° at the observer's eyes. Before commencing the experiment, the observer was first asked to adapt to the interior grey wall of viewing cabinet illuminated by a test simulator for about 2 minutes. The experimenter then randomly chose a metameric pair from the 70 pairs and presented it in the viewing cabinet, see Figure 4.2.4 for the sample arrangement. The observer was asked to judge the colour difference of the metameric pair in terms of grade 'G'. Note that after each assessment, the positions of the metameric pair and the grey pair were swapped. The same pair was assessed twice in two separate sessions by each observer. In total, twenty observations (2 x 10 observers) were accumulated for each pair under each test simulator.

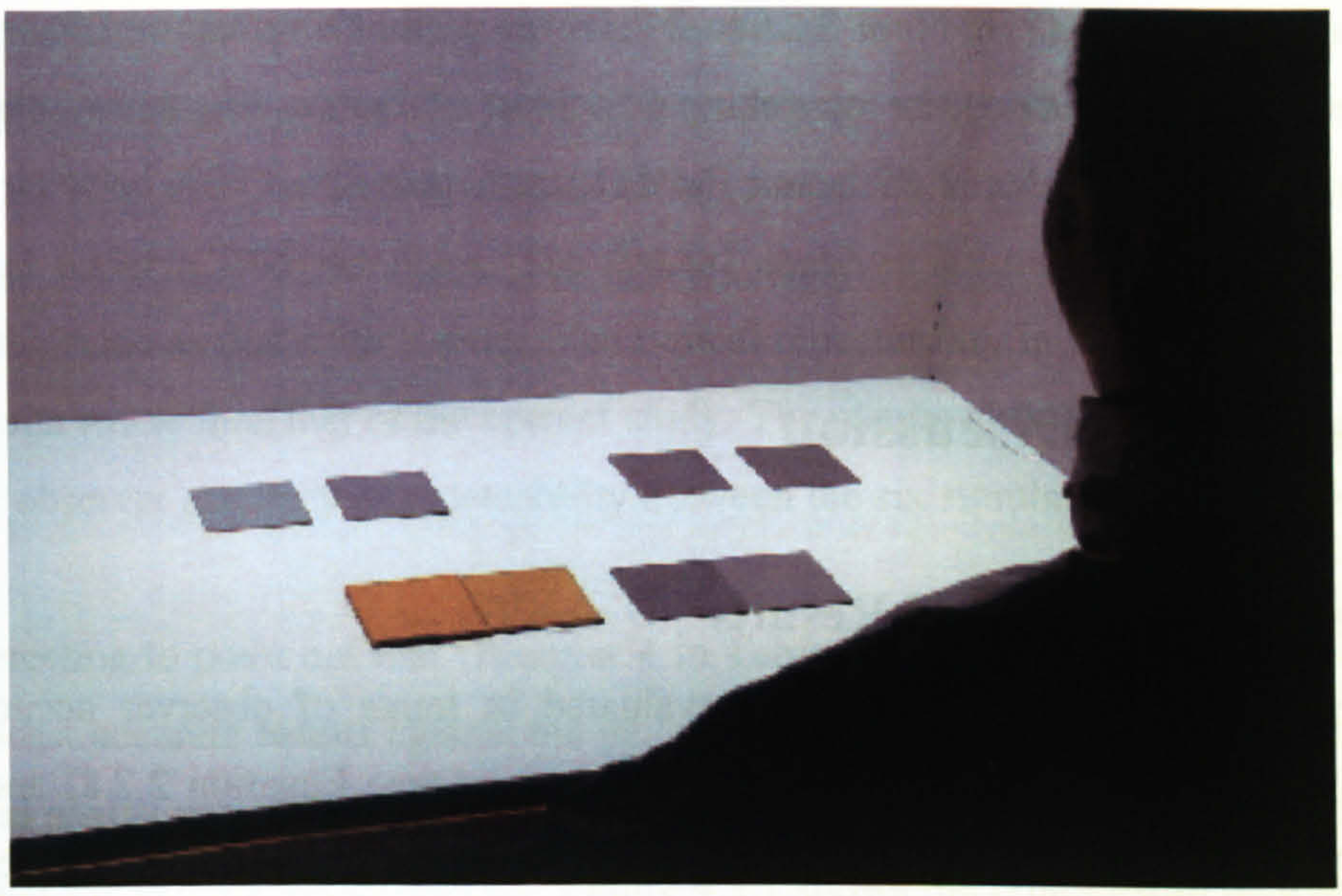


Figure 4.2.4 Sample arrangement for the experiment. Note that the two samples of the metameric pair and the grey pair are put along with each other closely together. The gap between the metameric pair and grey pair is about 1". The grey scale samples are arranged in sequence (Grade 1 to 5 from left to right) with a gap of about 1" between them. The gap between the grey scale and the two pairs is bout 3.5".

4.2.4 Data Analysis for the Visual Results

4.2.4.1 Visual Colour Difference ΔV

As the raw experimental data in terms of grade 'G' is not directly proportional to the visual colour difference ΔV, a fourth-order polynomial was constructed to correlate G to ΔV, as given in Equation 4.3.1. The coefficients of the equation were derived by fitting the CIELAB colour difference (ΔE^*_{ab}), given in Table 4.2.4, and the corresponding grade 'G'.

$$\Delta V = 0.14117G^4 - 1.97900G^3 + 10.28683G^2 - 26.18400G + 32.92700 \qquad 4.2.1$$

The results in Table 4.2.4 show the grey scale has good colour constancy. The CIELAB colour differences for each grade under the six test simulators are almost identical to those under CIE D65 illuminant. Therefore, the coefficients in Equation 4.2.1 were actually optimised using the colour differences (ΔE^*_{ab}) under CIE D65 and the equation is equally applicable for all the test simulators.

4.2.4.2 Performance Factor (PF/3)

The Performance Factor (PF/3) (see Section 2.7.7) was used as a measure of fit to indicate the agreement between two sets of data, i.e. colour difference ΔE_i and visual colour difference ΔV_i. A PF/3 value of 30 means the disagreement is about 30% between two sets of data.

4.3 Results and Discussion

4.3.1 Reliability of Visual Results

The reliability of the visual results was evaluated in terms of observer accuracy and repeatability in PF/3 units. Note that the scaling factor f (see Equation 2.7.8) and F (see Equation 2.7.10) were both set to 1 in calculating the PF/3 values. This is because there is no point in comparing the scaled data for each individual observer. For each simulator, the mean ΔV of the twenty observations was taken to be the true value for each pair. (Appendix D lists the mean ΔV values for each pair under each investigated simulator.) The accuracy for each observer was then calculated as the PF/3 measure between each observation and mean visual results for each of the metameric pairs. Each observer's two PF/3 values were then averaged to represent his or her accuracy. The repeatability is calculated similarly between the two results for each observer. Table 4.3.1 gives the accuracy and repeatability results for each observer.

Table 4.3.1 Observer accuracy and repeatability results (PF/3)

	PF/3 (Observer Accuracy)							PF/3 (Observer Repeatability)						
Obs./ Simul.[a]	GM (FT)	VV (F7)	GM (F7)	GE (F7)	TO (F7)	TO (3B)	Ave.	GM (FT)	VV (F7)	GM (F7)	GE (F7)	TO (F7)	TO (3B)	Ave.
1	27	38	33	26	27	24	29	30	30	31	25	26	24	27
2	52	32	36	34	29	41	37	31	35	32	31	33	27	31
3	35	40	32	40	34	29	35	26	24	24	20	26	27	25
4	38	40	45	48	40	41	42	22	22	21	24	16	17	20
5	42	41	30	32	40	25	35	30	33	27	37	34	30	32
6	32	32	43	39	24	27	33	21	34	34	33	22	25	28
7	29	23	29	35	25	20	27	26	21	21	31	22	17	23
8	36	43	31	24	22	37	32	29	24	28	25	29	29	27
9	35	41	32	25	21	33	31	26	31	23	17	15	13	21
10	37	36	32	27	29	26	31	23	32	27	21	26	26	26
Ave.	36	37	34	33	29	30	<u>33</u>	26	29	27	26	25	23	<u>26</u>
Max.	52	43	45	48	40	41	42	31	35	34	37	34	30	32
Min	27	23	29	24	21	20	27	21	21	21	17	15	13	20

a. See footnote to Table 4.2.2 for abbreviations for the simulators.

The observer accuracy results in terms of the Average across the six simulators in Table 4.3.1 range from 27 to 42 with an average of 33 in PF/3 values, while the observer repeatability results range from 20 to 32 with an average of 26. The results are quite close to those from Kuo and Luo's study (Kuo 1996a), for which similar visual assessments were conducted under a D65 simulator. The typical observer accuracy in their study was 33, exactly the same as that of this study. The typical repeatability in Kuo and Luo's study was 39, 13 units worse than that of the current study. The results also reveal not much difference of either observer accuracy or repeatability between the six simulators investigated.

It is interesting to point out that Observer 4 in Table 4.3.1 gave the most repeatable results but the least accurate results against the panel results. A further investigation into Observer 4's visual results reveals that a high PF/3 value for the accuracy results does not necessarily means that she is not a good observer. Figure 4.3.1 shows the relationship between the mean ΔV and the ΔV given by Observer 4 under one test simulator, GE broad band fluorescent lamp. It can be seen that the reason for Observer 4's poor accuracy results is that she gave systematically higher ΔV than the mean ΔV. If scaling factors *f* (see Equation 2.7.8) and *F* (see Equation 2.7.10) are applied to Observer 4's visual results in calculating the PF/3 values, her accuracy results can be largely improved, the original PF/3 value reduced from 48 to 19.

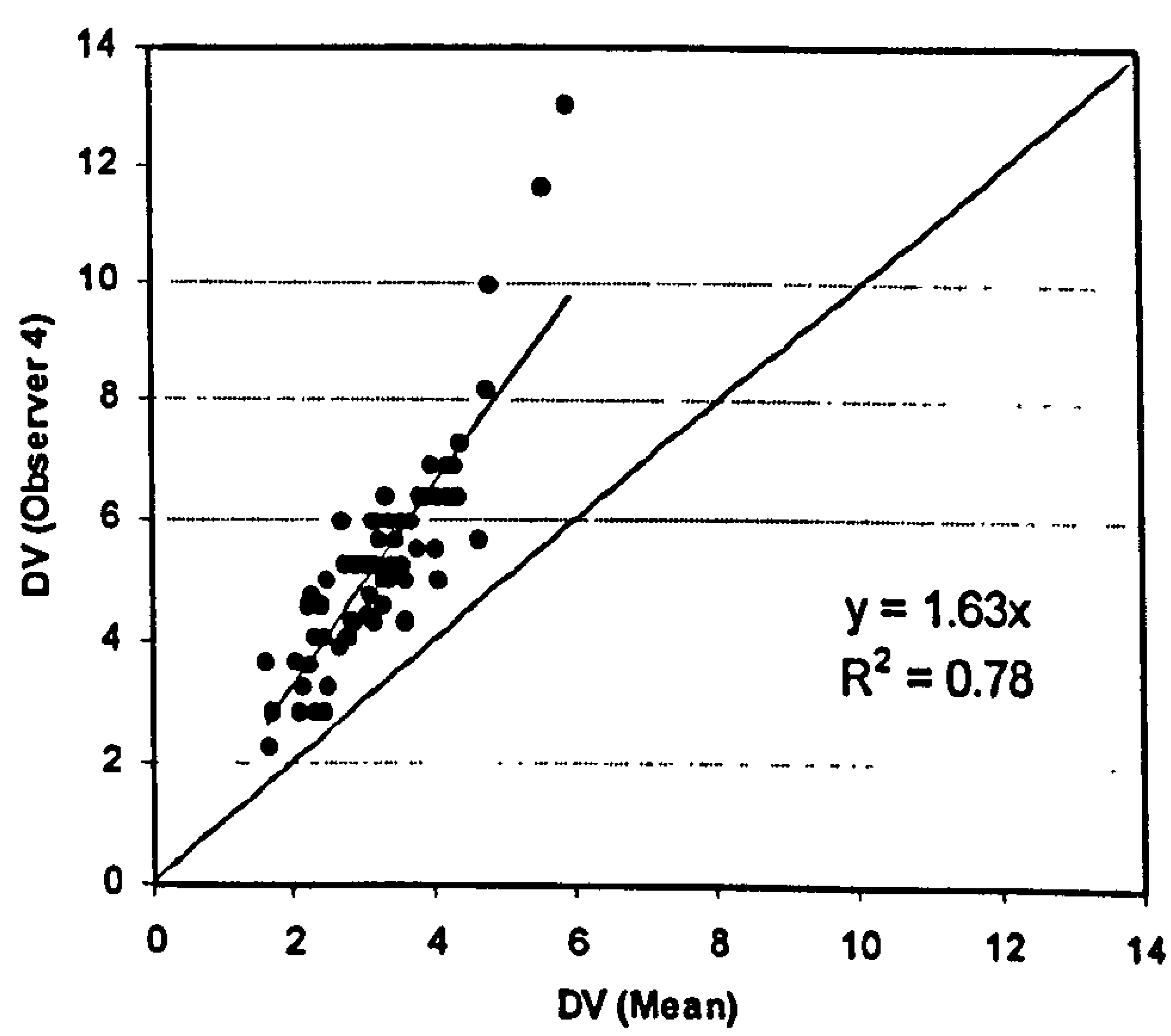


Figure 4.3.1 The relationship between the mean ΔV and the ΔV given by Observer 4 under one test simulator, GE broad band fluorescent lamp.

4.3.2 Performances of Colour Difference Formulae

The experimental results were used to test four colour difference formulae (see Section 2.3.5), including CIELAB (CIE 1986), CIE94 (CIE 1995b), CMC (Clarke 1984) and CIEDE2000 (CIE 2001). The CIE tristimulus values calculated using the appropriate energy distribution for each simulator were used to calculate the ΔE values. The PF/3 value was calculated between the ΔE values predicted by a formula under a specific simulator and the visual colour differences, ΔV. These are given in Table 4.3.2 together with the mean values for each formula and for each simulator. Note that the best scaling factors f (see Equation 2.7.8) and F (see Equation 2.7.10) were calculated to allow for different colour difference magnitudes predicted by each formula to be adjusted to the same scale as the visual data.

The colour differences were also calculated using each formula for two conditions: reference condition and optimised condition. For the reference condition, each of the parametric factors, k_L, k_C, k_H (correction terms for variation in perceived colour-difference component sensitivity with variation in experimental conditions) is assumed to be unity in using the colour difference formulae (CIE 2001). For the optimised condition, the minimum PF/3 value between the formulaic colour differences ΔE and the visual colour differences ΔV calculated by optimising the parametric factor k_L while leaving the other two parametric factors k_C and k_H at unity is reported.

The results in Table 4.3.2 show that the optimised PF/3 results are similar to the non-optimised results (improved PF/3 results are highlighted in bold; only slight improvement was found in most cases). This indicates that the experimental condition for this study is close to the reference condition for visual colour difference assessments. Both the optimised and non-optimised PF/3 results also show the same trend in that CIEDE2000 performed the best by giving the least PF/3 results for all the simulators studied. However, not much difference was found between CIE94, CMC and CIEDE2000. These three formulae all outperformed the CIELAB formula and their average PF/3 values are quite close to the typical observer accuracy of 33. It was also found that the performance of each formula is quite consistent under each test simulator, i.e. all the formulae gave smaller PF/3 values under the GE broad band and Toshiba three-band fluorescent lamps, which show worse quality than other lamps. The reason for this may lie in two aspects. Firstly, the ΔE and ΔV values are obviously larger for a bad simulator, which also means that the experimental errors (in percentage) inherent in the PF/3 results are smaller. Secondly, it was found that for a high quality D65 simulator, e.g. the GretagMacbeth filter tungsten lamp, the variations of ΔV values between observers are mainly caused by the observer metamerism, while for a low quality D65 simulator, e.g. the Toshiba three-band fluorescent lamp, the variations of ΔV values between observers are mainly caused by the illuminant metamerism. Similar finding was also reported by other researchers (Kuo and Luo 1996a & b, see Section 2.3.10).

Table 4.3.2 Performances of different colour difference formulae (PF/3)

C.D.F / Simul. [a]	GM (FT)	VV (F7)	GM (F7)	GE (F7)	TO (F7)	TO (3B)	Ave.
PF/3							
CIELAB	46	45	52	39	46	42	45
CIE94(1:1:1)	43	44	44	32	40	34	39
CMC(1:1)	40	41	45	30	40	34	38
CIEDE2000 (1:1:1)	39	40	43	27	38	35	37
Ave.	42	43	46	32	41	36	
PF/3 (Opt.)							
CIELAB (k_L:1:1)	45	45	50	39	44	41	44
CIE94 (k_L:1:1)	41	43	43	30	40	33	38
CMC (k_L:1)	40	41	44	30	40	32	38
CIEDE2000 (k_L:1:1)	39	40	43	27	38	35	37
Ave.	41	42	45	32	41	35	
k_L (Opt.)							
CIELAB (k_L:1:1)	0.84	0.75	0.68	0.79	0.65	0.67	0.73
CIE94 (k_L:1:1)	1.44	1.35	1.26	1.46	1.20	1.30	1.34
CMC (k_L:1)	1.24	1.12	0.93	1.10	0.96	0.84	1.03
CIEDE2000 (k_L:1:1)	1.14	1.09	0.95	1.16	0.96	0.91	1.04

a See footnote of Table 4.2.2 for abbreviations for the simulators.

4.3.3 Comparing Different Simulators

The PF/3 measure was also calculated for the visual difference ΔV between all possible combinations of two simulators. The results are given in Table 4.3.3. It was found that the Toshiba broad band fluorescent lamp is the most representative simulator as its visual results agreed best to all the other simulators. The Toshiba three-band fluorescent lamp agreed worst, which was expected. In general, the visual results obtained from all simulators except the three-band lamp are quite similar and have small disagreements of about 21 PF/3 values on average. This implies that the variation of visual results caused by using different daylight simulators in practice may not be so significant in comparison with the observer variation in terms of observer accuracy and repeatability results, shown in Table 4.3.1.

Table 4.3.3 Correlation of visual results between every two simulators (PF/3)

Simul. / Simul.[a]	GM (FT)	VV (F7)	GM (F7)	GE (F7)	TO (F7)	TO (3B)
VV (F7)	16					
GM (F7)	20	18				
GE (F7)	17	17	17			
TO (F7)	11	13	13	11		
TO (3B)	44	52	44	39	39	
Ave.	21	23	22	20	17	44

a See footnote of Table 4.2.2 for abbreviations for the simulators.

The mean visual difference ΔV for each pair were also compared between every two simulators using scatter diagrams, as shown in Figures 4.3.2(a) to (o). The degree of scatter in the diagrams reflects the degree of disagreement between two sets of ΔV data compared. For a perfect agreement, the data points in the scatter diagram should all be located on the 45° line. Figures 4.3.2(e), (i), (l), (n) and (o) show that visual colour differences ΔV under the three-band fluorescent lamp have the worst agreement with those under the other simulators. This again illustrates that the three-band lamp is very different from the others in terms of visual assessment results. Figures 4.3.2(d), (h), (k) and (m) also show that visual colour differences ΔV under the Toshiba broad band fluorescent lamp have best agreement with those under other simulators, further confirming that this particular fluorescent lamp is highly representative of the D65 simulators investigated, except for the three-band one. The fact that excellent agreement is obtained in some cases adds considerable confidence to the mean visual results.

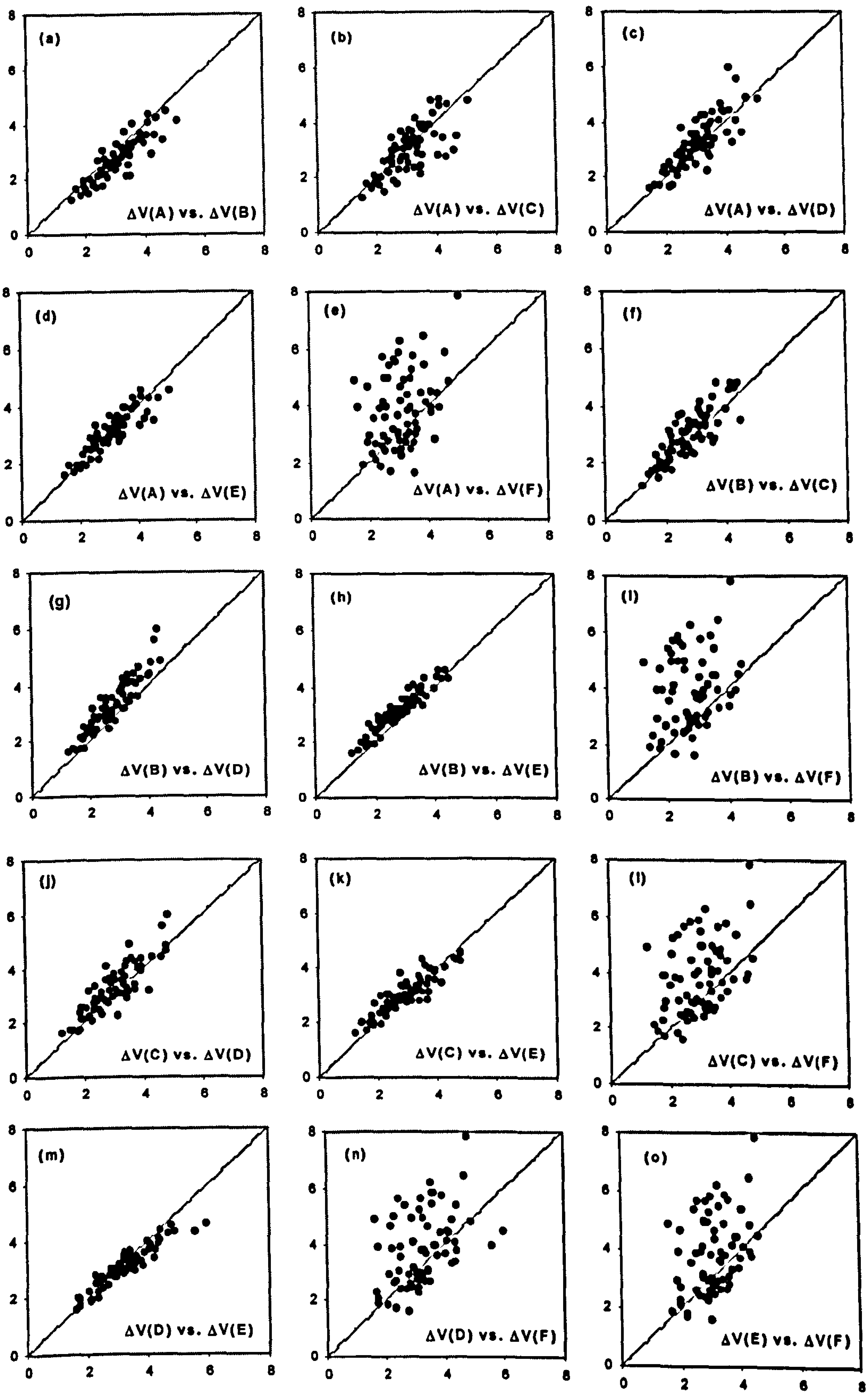


Figure 4.3.2 Comparing visual colour differences ΔV between all possible combinations of two simulators. The simulators are coded as: 'A' for GM (FT), 'B' for VV (F7), 'C' for GM (F7), 'D' for GE (F7), 'E' for TO (F7) and 'F' for TO (3B). Also see footnote to Table 4.2.2 for abbreviations for the simulators.

4.3.4 Testing Band-value and CIE Metamerism Index Methods

4.3.4.1 Four Kinds of Results Reported

The final analysis was carried out applying four methods for evaluating the quality of each investigated simulator. The results are shown in Table 4.3.4. Note that some of the results in Tables 4.3.2 and 4.3.4 were slightly different from those reported earlier by the author (Xu 2001). The reason for this is that the colour measurement results were updated due to an instrument shift previously undetected. However, these changes do not alter the conclusions.

The first method is to calculate the PF/3 measure between the visual results (ΔV) and the corresponding colour differences obtained from the SPD of CIE D65 illuminant. The results are expressed in Table 4.3.4 under the title of 'PF/3: ΔV (Simulator) vs. ΔE^*_{ab} (CIE D65 Illuminant)' and 'PF/3: ΔV (Simulator) vs. ΔE^*_{00} (CIE D65 Illuminant)'. This measure assumes that the visual results from a high quality simulator should agree well with the colour differences calculated using the SPD of CIE D65 illuminant. Only the CIELAB and CIEDE2000 colour differences were calculated because these are two typical colour difference formulae. The former is an established and widely used formula, while the latter is a newly developed and sophisticated formula.

The second method is also to calculate the PF/3 measure between pairs of colour differences calculated using the SPD of each simulator and CIE D65 illuminant. The results are expressed in Table 4.3.4 under the title of 'PF/3: ΔE^*_{ab} (Simulator) vs. ΔE^*_{ab} (CIE D65 Illuminant)' and 'PF/3: ΔE^*_{00} (Simulator) vs. ΔE^*_{00} (CIE D65 Illuminant)'. This measure removes the observation errors included in the visual results (ΔV). In other words, it is similar to the CIE metamerism index but uses many more pairs of real metamers.

The third method is the CIE metamerism index for the visible range (MI_{vis}), which is the mean colour difference of the CIE 5 virtual metamers. Note that the CIE method only calculates CIELAB colour differences while this study also adopted the CIEDE2000 formula in computing the metamterism index. The fourth method is to calculate the summation of absolute band value deviation in percentage terms, an index suggested by the author to represent the total band value deviation of a simulator. Finally, the rankings based on the above four kinds of results for each simulator, plus the CIE metamerism index category, are included in Table 4.3.4. The results in Table 4.3.4 are also illumistrated in Figure 4.3.3.

Table 4.3.4 Comparing the performances of each investigated simulator using four methods

Evaluating methods / Simulator [a]	GM (FT)	VV (F7)	GM (F7)	GE (F7)	TO (F7)	TO (3B)
PF/3: ΔV (simul.) vs.ΔE^*_{ab} (CIE D65 ill.)	43	46	53	51	47	66
PF/3: ΔV (simul.) vs.ΔE^*_{00} (CIE D65 ill.)	38	42	51	47	43	67
PF/3: ΔE^*_{ab} (simul.) vs.ΔE^*_{ab} (CIE D65 ill.)	10	23	52	43	25	101
PF/3: ΔE^*_{00} (simul.) vs.ΔE^*_{00} (CIE D65 ill.)	12	23	59	37	25	103
CIE MI_{vis} (CIELAB)	0.18	0.26	0.70	0.82	0.33	2.30
CIE MI_{vis} (CIEDE2000)	0.14	0.17	0.61	0.50	0.23	1.69
Sum of absolute band-value deviation (%)	25	26	43	44	34	207
Ranking:ΔV (simul.) vs.ΔE^*_{ab} (CIE D65 ill.)	1	2	5	4	3	6
Ranking:ΔV (simul.) vs.ΔE^*_{00} (CIE D65 ill.)	1	2	5	4	3	6
Ranking:ΔE^*_{ab} (simul.) vs.ΔE^*_{ab} (CIE D65 ill.)	1	2	5	4	3	6
Ranking:ΔE^*_{00} (simul.) vs.ΔE^*_{00} (CIE D65 ill.)	1	2	5	4	3	6
Ranking: CIE MI_v (CIELAB), Category	1 (A)	2 (B)	4 (C)	5 (C)	3 (B)	6 (E)
Ranking: CIE MI_v (CIEDE2000)	1	2	5	4	3	6
Ranking: Sum of absolute band-value deviation (%)	1	2	4	5	3	6

a See footnote to Table 4.2.2 for abbreviations for the simulators.

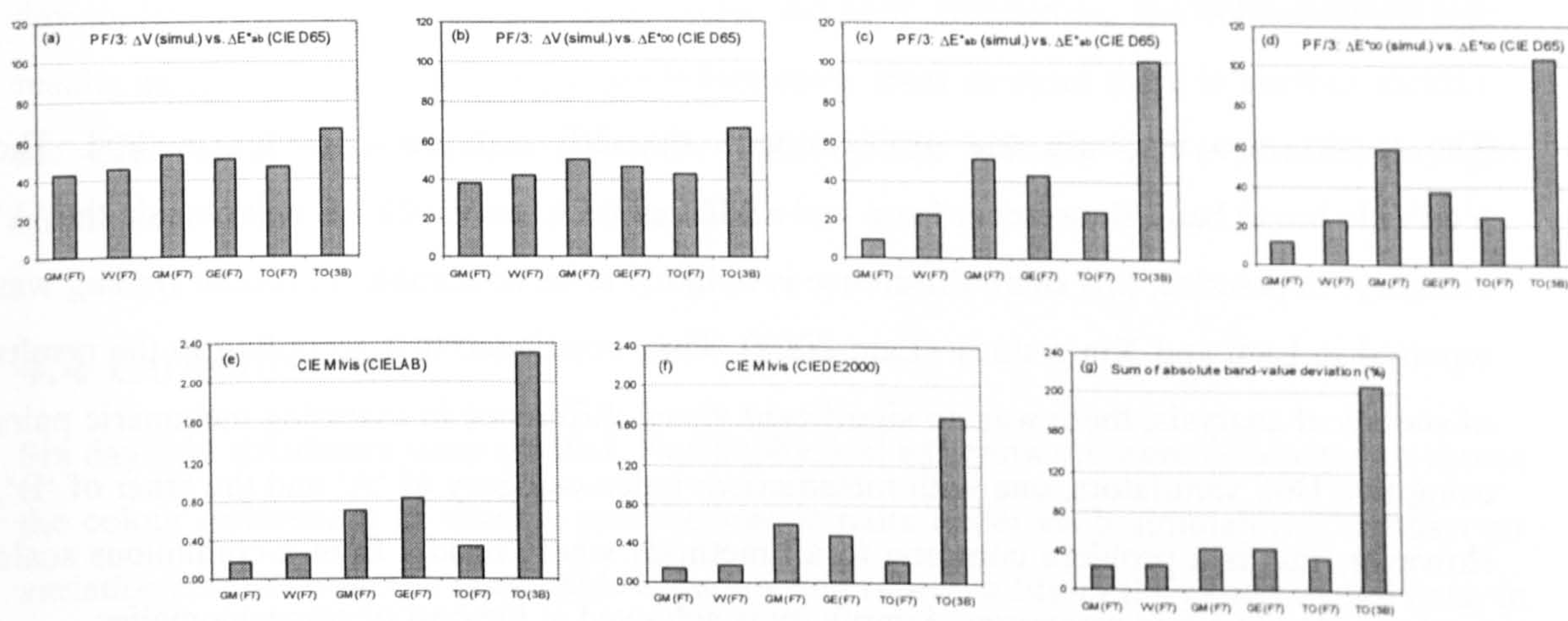


Figure 4.3.3 Comparing the performances of each investigated simulator using four different methods

4.3.4.2 Performances of the PF/3 Measures

In Table 4.3.4, the PF/3 values derived from the visual colour differences vary much less than the PF/3 values calculated from the colour differences, however, their PF/3 magnitudes are much larger than those of the other measures. The large PF/3 values are connected with errors in the visual results, errors in the colour difference equations as well as the fact that visual differences would obviously be expected to agree best with colour differences calculated using the appropriate SPD for the source used. A similar finding was also reported by Lam and Xin (2002, see Section 2.8.2.2), and Kuo and Luo (1996a & b).

However, the two kinds of PF/3 results correspond to the same ranking results for the six simulators investigated (see the bottom part of Table 4.3.4).

4.3.4.3 Performances of CIE Metamerism Index Method

The CIE metamerism index results generally agree with the two types of PF/3 results, i.e. they give almost the same rankings for the six simulators. The only disagreement between the PF/3 results and CIE metamerism index results are for the GM and GE broad band fluorescent lamps, i.e. the PF/3 results give slightly better results for the GE lamp while the CIE metamerism index results show the opposite. However, both the GM and GE lamps belong to the same category 'C' according to the CIE specifications (CIE 1999), and, this disagreement disappears if CIELAB colour difference formula is replaced by CIEDE2000 in calculating the metamerism index. This indicates that the CIE method is a suitable measure in evaluating the quality of daylight simulators and its performance may be improved by using more advanced colour difference formula, such as CIEDE2000, for the calculation of metamerism index.

The results also illustrate one problem with the CIE metamerism index method. The VeriVide broad band fluorescent lamp had a MI_{vis} of 0.26, only 0.01 ΔE unit outside the 'A' category. In practice, this small difference is unlikely to be noticeable. A similar finding was reported in Lam and Xin's study (Lam 2002). They concluded that according to the results of statistical analysis, there was no significant visual difference in assessing metameric pairs using two D65 simulators, one with metamerism index category of 'A' and the other of 'B'. However, this is a problem common to all methods where results from a continuous scale are converted to a few categories. Simplicity is achieved at the cost of some anomalies.

4.3.4.4 Performances of Band-value Method

The summation of band-value deviation gives exactly the same ranking results as the CIE metamerism index results for the six simulator investigated, indicating that the band value method is also an effective measure for evaluating the quality of daylight simulators. Tables 4.2.2 and 4.2.3 reveal that a good quality simulator with CIE metamerism index rating of 'A' or 'B', such as the GM filtered tungsten lamp and VeriVide broad band fluorescent lamp, corresponds to band value deviations well below the BS 950 tolerance of ±15%. The quality of a simulator, such as the GM and GE broad band fluorescent lamps, will be affected if its band value deviations exceed the tolerance at one or more bands. Although these conclusions are based on results obtained using only six simulators, they were chosen to represent all the types of simulators in common use.

4.3.4.5 Recommendations for Using the Band-value and CIE Methods

Although the band value method and the CIE metamerism index method use quite different strategies for assessing the quality of daylight simulators, both methods are reliable measures according to the current study. Therefore, they are both useful for industrial applications. An advantage in using the band value method is that unlike the CIE metamerism index method, the band value method reveals information on the spectral deviation of a daylight simulator relative to the corresponding CIE daylight illuminant without using any testing metamers. In addition, the band value method provides information for judging whether a band power is adequate or not, hence, it is valuable for lamp manufacturers in knowing the band value results. However, the CIE metamerism index has been widely used in the lighting industry. Furthermore, for a colourist who conducts day-to-day visual colour assessments under daylight simulators, the metamerism index results using the CIE method are more informative. Bear in mind there is another measure, the CIE colour rendering index, widely used by the industry for evaluating daylight simulators. Chapter 6 will discuss this method.

4.4 Conclusions

Six daylight simulators were studied. Psychophysical experiments were conducted to assess the colour differences of seventy real metameric pairs under each simulator. The observer variation results showed a reasonable accuracy and repeatability in the experimental data, in good agreement with those from an earlier study (Kuo 1996a). The visual results were used to test four colour difference formulae, CIELAB, CIE94, CMC, CIEDE2000. It was found that the last three formulae gave a similar degree of performance in predicting visual data and all outperform the CIELAB formula. In general, all the simulators studied agreed well with each other in terms of visual results, except for one simulator having a three-band SPD, unlike broad-band for the others. Finally, four kinds of methods were used to quantify the quality of each investigated simulator, including two kinds of PF/3 results, CIE metamerism index results and the summation of absolute band-value deviation specified in BS 950. The results showed that these two new methods using a combined statistical measure PF/3 agree well with the CIE method and band-value method, indicating that both CIE method and band value method are equally reliable for evaluating the quality of daylight simulators. The results also revealed that a simulator having band-value deviation well below the BS 950 tolerance corresponds to a high metamerism index rating and therefore is of good quality.

CHAPTER 5
GENERATING NEW SETS OF METAMERS FOR EVALUATING D65 SIMULATORS

5.1 Introduction

In Chapter 4, the visual results from a psychophysical experiment were used to test the performances of both the CIE metamerism index method (CIE 1981, 1999, see Section 2.5.4.2) and the band value method (BS 950, see Section 2.5.1) for evaluating the quality of daylight simulators. It was found that the experimental results using seventy real metameric pairs gave almost the same ranking results for the six daylight simulators investigated as those predicted using the CIE method and band value method. A conclusion drawn from this experiment is that both the CIE method and the band value method are reliable measures for evaluating daylight simulators (see Section 4.3.4). However, three aspects are required for further investigation with respect to the evaluation of daylight simulators. A brief account for each aspect is given below.

Firstly, the ranking results in Chapter 4 only reported the performance of the CIE method using a single number (the band value method is not investigated in this chapter as only the CIE method has been widely used as an international standard for evaluating daylight simulators). In practice, a dyer who conducts recipe predictions would normally check the colour samples using a viewing cabinet. S/he needs to know exactly how much difference in terms of colour differences might be introduced in the visual assessment due to the deviation of daylight simulators relative to the CIE D65 illuminant.

Secondly, the seventy metameric pairs used for visual assessment in Chapter 4 do not perfectly match under CIE D65 illuminant though they were originally designed to have a close match under CIE D65 illuminant (Kuo 1995, see Section 4.3.2.1). These metameric pairs are actually paramers (specimens having different spectrophotometric curves that produce approximately the same colour sensation under the same illuminating and viewing conditions, see Berns 2000, p.128) instead of metamers. The CIE metamerism index method for evaluating daylight simulators uses virtual metamers, which are perfect matches under the CIE daylight illuminant. Therefore, a direct comparison of the results from the real metameric pairs and those from the CIE metamers is an imperfect approach for evaluating the CIE method.

Thirdly, the performances of CIE metamerism index method rely primarily on the effectiveness of the CIE virtual metamers, and yet not many studies have been reported on this. Earlier research conducted by Schlüpfer *et al* (1999, see Section 2.8.2.2) tested the CIE metamers using ISO 12642 colour patches for D50 simulators. They concluded that the CIE metamerism index method could be regarded as a satisfactory measure for predicting the metamerism occurring with typical D50 simulators used in the graphic arts industry. McCamy (1999, see Section 2.8.2.1) evaluated the CIE metamers using different types of perturbations which are assumed to be associated with the generation of the SPDs of daylight simulators. Although McCamy concluded positively with respect to the effectiveness of CIE metamers, his assumption of the nature of the perturbations is rather theoretical.

This chapter aims to investigate the CIE method using more representative metamer sets, which were generated mathematically to represent a broad range of metamers in practice. The quality of fifteen D65 simulators accumulated (see Section 3.3.1.1) was evaluated using the generated metamer sets as well as the CIE metamer set. In addition, the metameric properties of different metamer sets were also analysed. A set of effective metamers was found to give a similar performance to the CIE metamer set for evaluating daylight simulators.

5.2 Generating New Sets of Metamers

The calculation of metamerism index, e.g. CIE special index of metamerism and other general Indices of metamerism (see Section 2.3.10.2), requires that the metameric pair is a perfect match under the reference illuminant. Unfortunately, for most of real samples, this condition is not satisfied. This section introduces methods to generate perfect metamers. (Note that the generated metamers are just theoretical metamers, each was represented by a pair of reflectance functions.) In total, four sets of metamer were prepared for the evaluation of daylight simulators.

The first set is based on the 70 metameric pairs described in Chapter 4 (see Section 4.2.2.1).

These pairs are real textile samples. Although the pairs exhibit large colour differences under CIE A illuminant, they also show some degree of colour differences under CIE D65 illuminant. To make these pairs real metamers, a correction method proposed by Fairman (1987, see Section 2.3.10.3) was applied. After the Fairman correction, each pair had a zero colour difference under CIE D65 illuminant while keeping almost the same size of colour difference under CIE A illuminant. Since the corrections are small, the reflectance values are close to those of real samples. The other three metamer sets were generated using colorant formulation method, each including 88 pairs, 36 pairs and 54 pairs respectively. Again the reflectance values calculated are very close to those obtained for real samples.

5.2.1 Generating 70 Metamers Using the Fairman Correction

The seventy metameric pairs used for visual assessments in Chapter 4 (see Section 4.2.2.1) do not exactly match under CIE D65 illuminant (taken as reference illuminant). The Fairman correction method (Fairman 1987, see Section 2.3.10.3, designated as Fairman correction below) was used to correct these pairs. The essence of the method is to apply spectral correction to one of the specimens of a pair using the Cohen-Kappauf decomposition technique (Cohen 1982, 1985, see Section 2.3.10.3).

In the process of Fairman correction, the weight set used for matrix A (see Equation 2.3.39) adopts ASTM E 308-95, Weighting Table 5.19 (CIE D65 illuminant, CIE 10° Observer and 10 nm interval). Note that CIE 10° Observer was used throughout this chapter for calculating the tristimulus values of a colour. MATLAB software was used for matrix manipulation in implementing the Fairman correction method. Figure 5.2.1 demonstrates the effect of Fairman correction using one metameric pair.

Figure 5.2.1 shows the reflectance change caused by the Fairman correction applied to either sample of a pair, Pair No.15 in this case. This pair has the maximum colour difference change after the Fairman correction under both CIE D65 and A illuminants. The original colour differences (ΔE^*_{ab}) under the CIE D65 and A illuminants are 4.87 and 8.71 respectively. After the Fairman correction, the colour difference under the CIE D65 illuminant reduced to zero and that under CIE A illuminant also reduced, by 4.02 for correction of Sample A and 4.26 for correction of Sample B. The pair demonstrates how the Fairman correction could correct the reflectance of one specimen of a pair to a considerable extent.

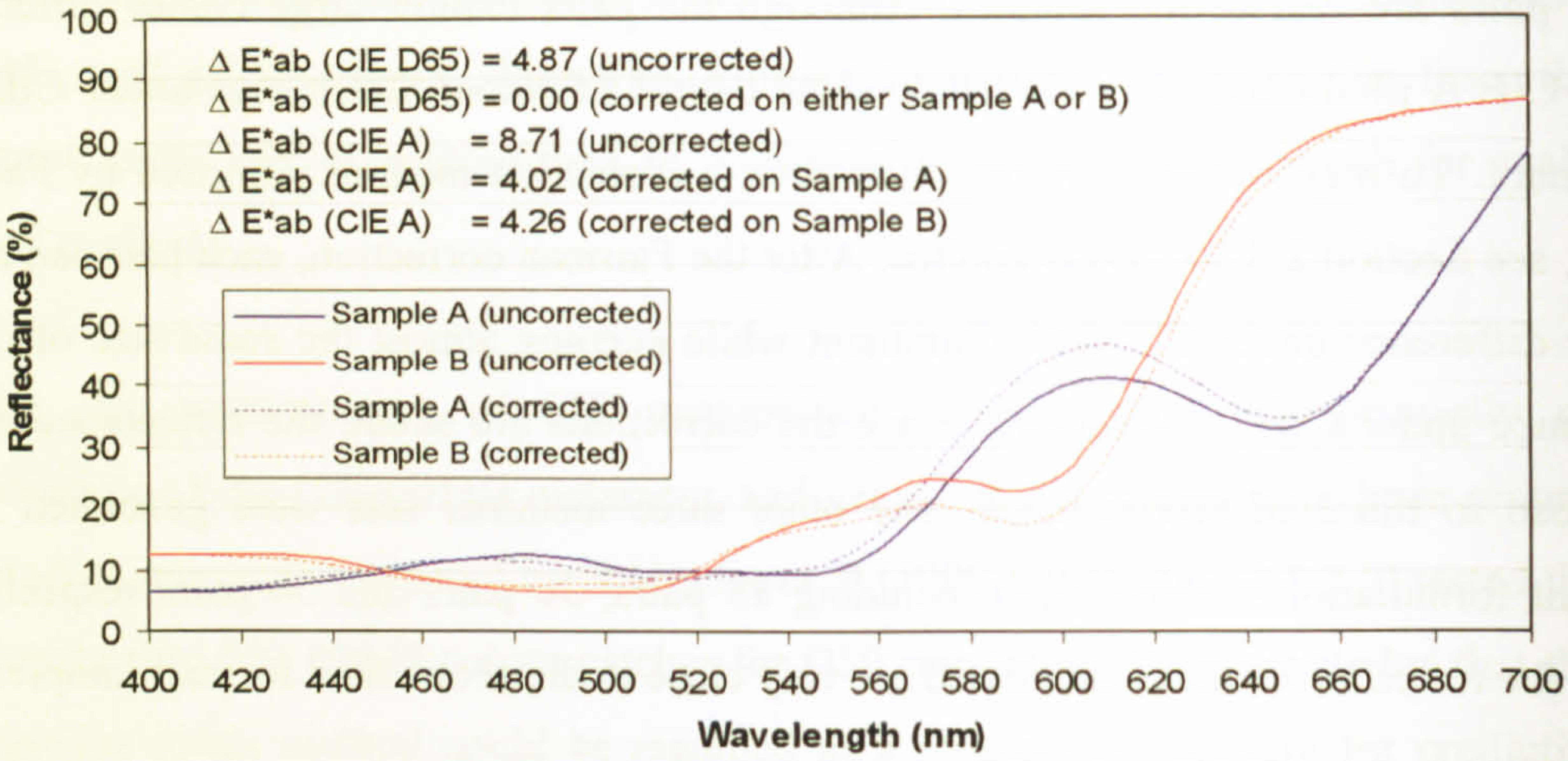


Figure 5.2.1 The reflectance spectra for the two samples of a pair before and after the Fairman correction (the original reflectance in solid line and corrected reflectance in dotted line). This pair has the maximum colour difference change after Fairman correction under CIE D65 and A illuminants. The original colour differences (ΔE^*_{ab}) under CIE D65 and A illuminants are 4.87 and 8.71 respectively. After Fairman correction, the colour differences under CIE A illuminant are 4.02 for correction to Sample A and 4.26 for correction to Sample B.

A careful inspection of Figure 5.2.1 also shows that the corrected reflectance spectra (dotted lines) follow the trends of the original reflectance spectra (solid lines) for both Samples A (in blue) and B (in red). It also shows that after applying the Fairman correction to one sample of the pair (e.g. Sample B), the crossovers (also termed as wavelength intersection, see Section 2.3.10.1) between the two reflectance of the pair, Sample A original (solid blue line) and Sample B corrected (dotted red line), has shifted. However, the shift is less than 10 nm for all the crossovers across the whole wavelength range. It was further observed that whichever Sample A or Sample B of the pair was corrected, the crossover shift had a similar pattern with respect to the wavelength change and direction (shift to a longer wavelength or shorter wavelength). A further investigation for the 70 metameric pairs revealed that the Fairman correction changed the original colour differences of each pair (i.e. $\Delta E_{corrected} - \Delta E_{original}$) by a similar amount for both the CIE D65 and CIE A illuminants. This means that in general the larger colour difference of a pair under CIE D65 illuminant which was minimised by the Fairman correction, the larger colour difference change which occurred for the pair under CIE A illuminant. Note that the Fairman correction was designed to minimize the colour difference of a pair under a reference illuminant (say CIE D65), however, it does not necessarily reduce the colour difference of the pair under a test illuminant (e.g. CIE A).

Table 5.2.1 summarise the maximum, minimum, average and median colour differences

(ΔE^*_{ab}) for the 70 pairs before and after the Fairman correction for both CIE D65 and A illuminants. In addition, the changes of colour difference ($\Delta E_{corrected}$ - $\Delta E_{original}$) for the 70 pairs after the Fairman correction were also expressed in terms of maximum decrease 'Max (-)', maximum increase 'Max (+)', average decrease in percentage 'Ave (-) (%)' and average increase in percentage 'Ave (+) (%)', respectively.

Table 5.2.1 Colour differences and changes of colour difference for the 70 metameric pairs before and after the Fairman correction

		Colour difference (ΔE^*_{ab})				Change of Colour difference (ΔE^*_{ab}) [a]			
		Max	Min	Ave	Median	Max(-)	Max(+)	Ave(-) (%)	Ave(+) (%)
Uncorrected	CIED65	4.95	0.59	1.99	1.83	-	-	-	-
	CIE A	14.52	0.23	6.79	6.22	-	-	-	-
Corrected	CIE D65	0.00	0.00	0.00	0.00	4.95	-	-	-
(sample A)[b]	CIE A	14.82	0.63	6.97	6.66	4.69	2.87	13.0	49.1
(sample B)[b]	CIE A	14.33	0.65	6.96	6.71	4.45	2.91	13.2	49.0

a The changes of colour difference ($\Delta E_{corrected}$ -$\Delta E_{original}$) for the 70 metameric pairs after the Fairman correction were expressed in terms of maximum decrease 'Max (-)', maximum increase 'Max (+)', average decrease in percentage 'Ave (-) (%)' and average increase in percentage 'Ave (+) (%)', respectively.

b The Fairman correction can be applied on either sample of a pair. The names 'Sample A' and 'Sample B' are used to represent the two individual samples of a pair. They are used hereafter.

Table 5.2.1 shows that the original Maximum/Average colour differences (ΔE^*_{ab}) for the 70 pairs are 4.95/1.99 and 14.52/6.79 for CIE illuminants D65 and A respectively. After applying the Fairman correction, all pairs had zero colour differences under the CIE D65 illuminant. The effect of Fairman correction on the metameric properties of metamers was examined in terms of the change of colour difference for CIE A illuminant. It was found that after the Fairman correction, a considerable degree of changes of colour difference occurred for some of the pairs under the CIE A illuminant. The maximum decrease (or increase) of colour difference (reducing or strengthening the metameric property of the pair) is 4.69 and 2.91 respectively. However, in general, the changes of colour difference for the 70 pairs were insignificant under the CIE A illuminant, with the maximum and average colour difference results almost unchanged before and after applying Fairman correction. It was also found that the colour difference and change of colour difference results in Table 5.2.1 are very close for the two conditions with Fairman correction applied to either Samples A or B of a pair. This suggests that the metameric property of a pair remains unchanged no matter which sample in the pair was corrected.

The colour distributions for the 70 pairs under CIE A illuminant before and after the Fairman correction are shown in Figure 5.2.2, with each vector representing a pair of samples (see Figure 4.2.2 for the colour distributions under CIE D65 illuminant). It can be seen that, in general, all the pairs have similar distributions in CIE a* b* space with or without Fairman correction. However, Fairman correction made the majority of the vectors along the red-green direction more nearly parallel to each other.

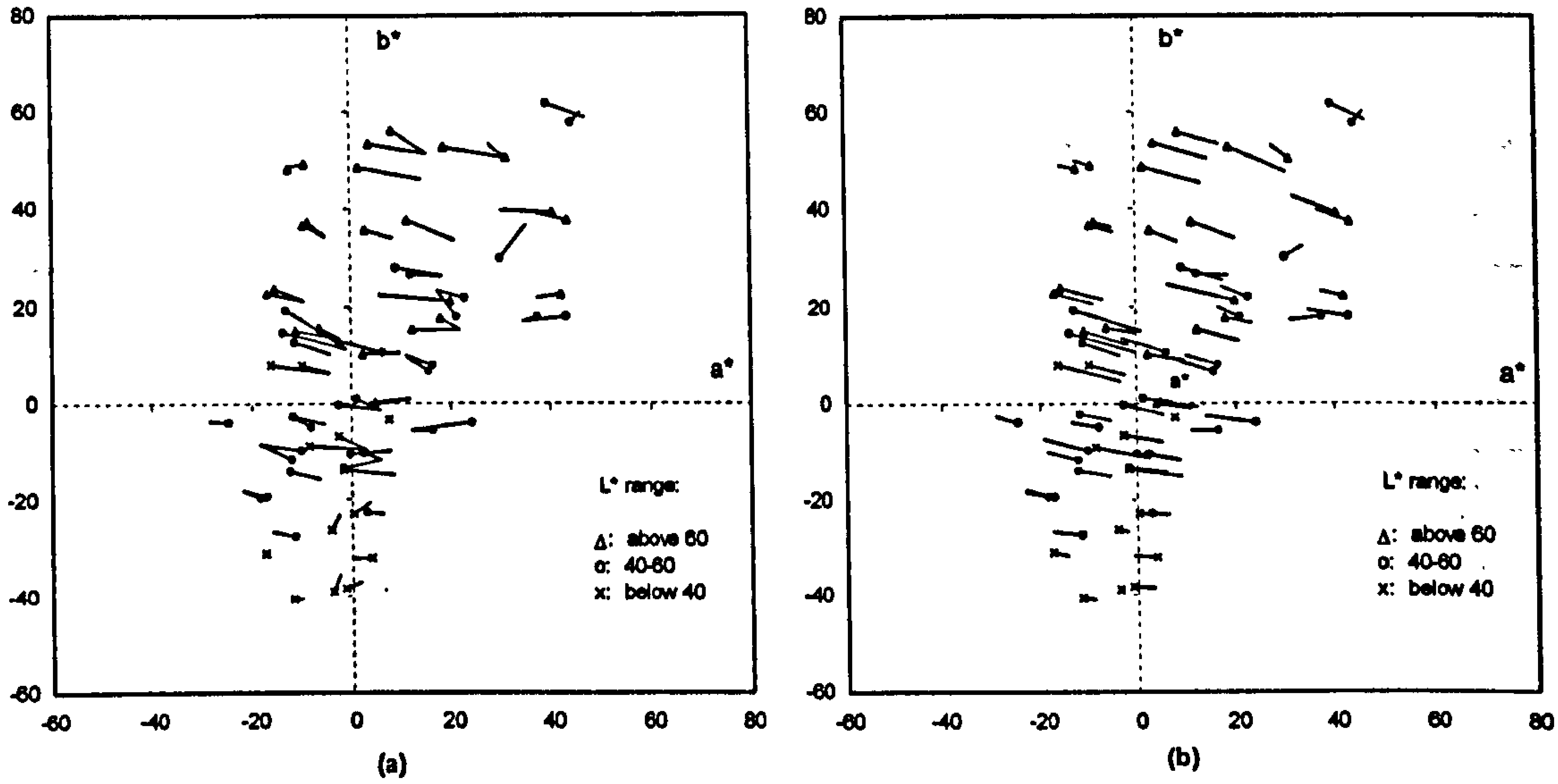


Figure 5.2.2 Colour distributions for the 70 pairs under CIE A illuminant, before and after Fairman correction in (a) and (b) respectively.

5.2.2 Deriving 88 Metamers Using Match Prediction Software

Although the seventy metamers described in Section 5.2.1 occupy a large colour gamut (see Figure 5.2.2), it was found that there are still insufficient samples in some colour regions, e.g. the magenta region. In addition, these pairs were originally prepared using colorant formulation (see Section 2.3.11) software for a wool substrate (Kuo 1995). In order to make metamers having a larger colour gamut, more colours were selected for match prediction using dyestuff for various substrates.

In total, 302 colours were selected from the PCC-GENIE colour atlas, which is a colour specification system used by the UK textile industry. All the colours in the atlas were fabric samples made by Nautilus Press & Paper Mill, London. The atlas was intended to reproduce colours from a colour space approximating CMC(1:1) colour difference formula (Luo 1986a). There are 40 pages included in the atlas, each page representing one hue angle. For each hue angle, the colours are arranged from light to dark (lightness scale, top to bottom) and from the least saturated to the most saturated (chroma scale, left to right). The 302 colours were selected by showing a large colour gamut with a reasonable gap between each other. Colours of different luminance levels were equally included. The selected colours were measured using a GretagMacbeth Color-Eye 7000A spectrophotometer (see Section 2.3.12.1).

The measured colours were then taken as standard samples for match predication. Software named SCOPE, developed by the Colour & Imaging Institute for the textile industry, was used for this purpose. Several functions, such as Colour Measurement, Colour Quality Control, are included in the system. Match Prediction is one of the functions developed based on the colorant formulation principles (McDonald 1997, p.209, see Section 2.3.11). Two sets of dyestuff database, one for a cotton substrate and one for a polyester substrate, were used. The dyestuffs for the cotton substrate include ten dyes, at ten concentrations prepared for each dye, while the dyestuffs for the polyester substrate include sixteen dyes, and eight to twelve concentration levels for each dye, see Table 5.2.2 for details.

Table 5.2.2 Dyestuff used for match prediction in generating the 88 metamers

Substrate	Cotton	Polyester (PET)
Dyestuff	Blue H-ERD, brown H-3R Green H-E4BD, navy H-ER Red H-E3B, red H-E7B Scarlet H-E3G, turquoise H-A Yellow H-E4R, yellow H-E6G	BBLRDSF, DBCRN, DNBXF, DruXF, KTBGLS, NY8GF, PV3RL, SBERPD, SBSE, SRERPD, SRSE, SSDSF, SYERPD, SYSE, TSDFGL, TY4GA
Concentration	0.25, 0.50, 0.75, 1.00, 1.50, 2.00, 2.50, 3.00, 3.50, 4.00	Varied from 8 to 12 for different dyes. (e.g. 0.01, 0.05, 0.10, 0.40, 0.75, 1.05, 1.40, 1.70, 2.05, 2.35, 2.70, 3.00)
Number of pairs	46	42

Using the SCOPE system, many recipes, each represented by a reflectance curve, were generated corresponding to a standard colour. Each of them is a metameric match to the standard colour under CIE D65 illuminant (taken as reference illuminant). To make metamers of large metamerism degree, the CIE special index of metamerism (see Section 2.3.10.2), which was calculated as the average colour difference of a pair under CIE A and CIE F11 illuminants (both were taken as test illuminants), was used as a criterion for choosing the 'qualified' recipes. Of the 302 PCC-GENIE colours used for match prediction, only some samples gave recipes which were strongly metameric matches, with CIE special index of metamerism larger than 4.0 ΔE^*_{ab} units. In total, 88 metamers were produced, amongst which 46 pairs were generated using the dyestuffs for the cotton substrate and 42 pairs were generated using the dyestuffs for the polyester substrate.

Figure 5.2.3 shows the colour distributions for the 88 metamers in comparison with those previously obtained for the 70 metamers (see Section 5.2.1) under CIE D65 illuminant. It can be seen that the 88 metamers significantly expand the colour gamut of the 70 metamers, with more saturated colours for almost all the hue regions.

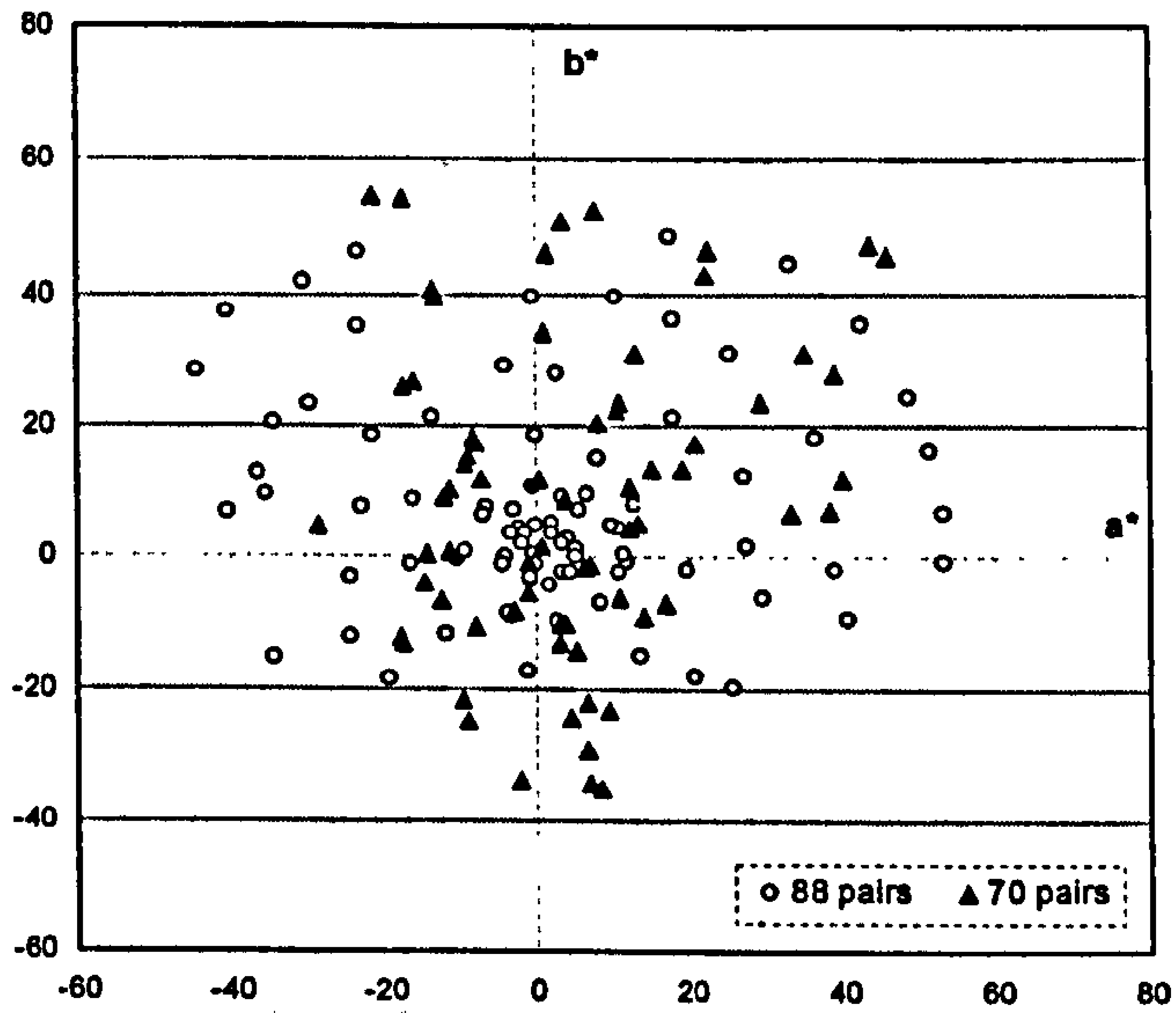


Figure 5.2.3 Colour gamut (CIE D65/10°) for the 88 metamers and the 70 metamers

The colour distribution of the 88 metamers is also shown in Figure 5.2.4. Each vector represents the colour difference of a pair under the CIE A illuminant. It shows that the majority of the vectors shift along the red-green direction. A close examination of the vectors also revealed that the colours with high chroma value usually do not exhibit a strong metameric effect. A considerable number of the metamers are located in the centre area, which corresponds to neutral colours. The majority of the metamers have medium lightness with CIE L* between 40 and 60. The Maximum/Minimum/Average/Median colour differences (ΔE^*_{ab}) are 8.72/1.29/4.81/4.82 for the 88 metamers under CIE A illuminant.

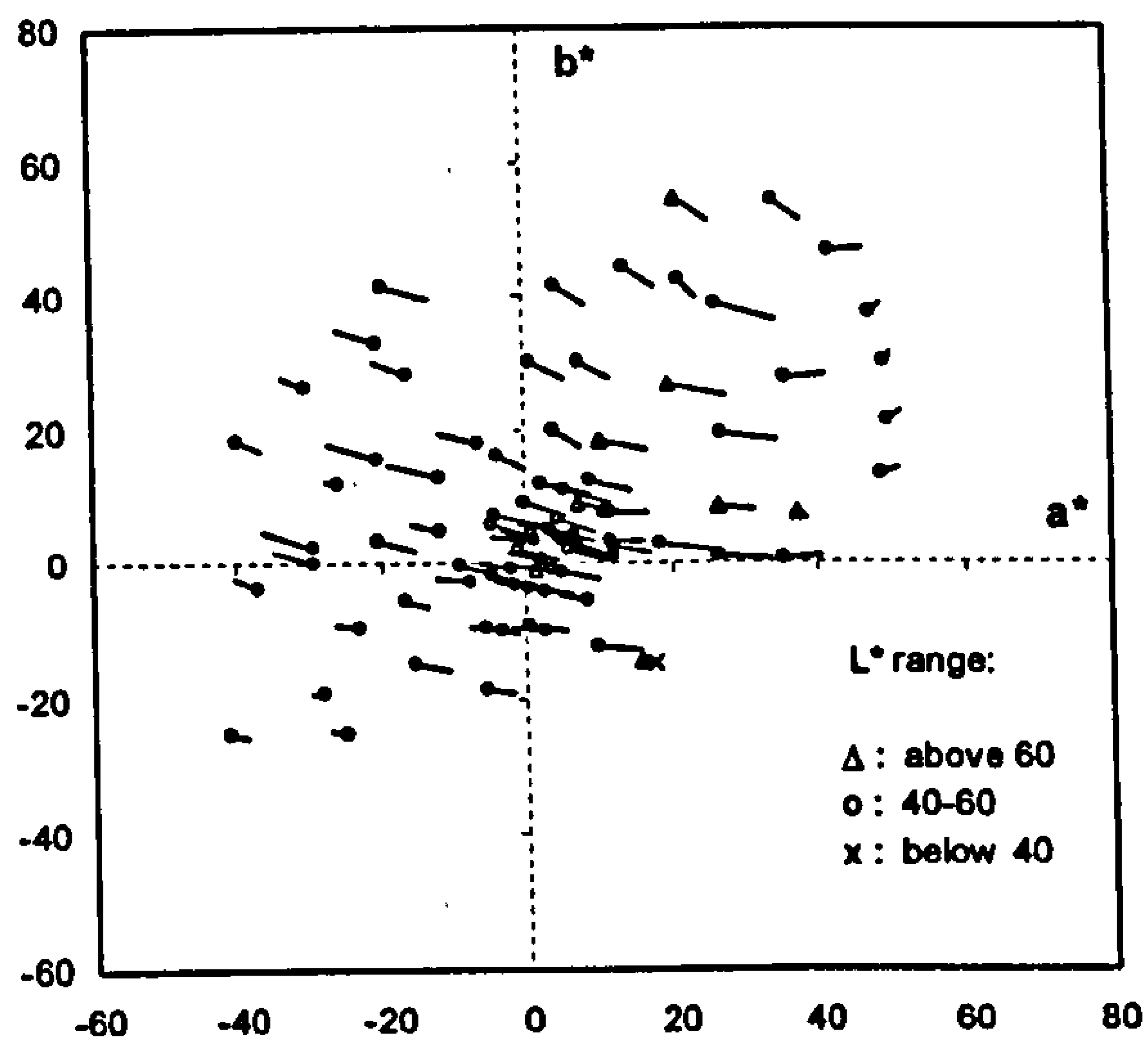


Figure 5.2.4 Colour distributions for the 88 metamers under CIE A illuminant

5.2.3 Generating Metamers with Built-in Spectral Characteristics

The purpose of generating metamers is to use them for the evaluation of daylight simulators (see Section 5.4). The 70-pair and 88-pair metamer sets described above were both made to show considerable metameric effect. These metamers can be regarded as normal metamers because they can be produced using real dyestuffs with substrates such as wool, cotton and polyester.

According to Thornton (1974), the metamer crossovers tend to occur at three wavelengths, which are the sensitivity peaks of the human visual system (see Section 2.3.10.1). He termed these wavelengths (458, 541 and 611 nm) as the prime wavelengths and demonstrated their importance in light source design (Thornton 1986). Ohta (1987) and Finlayson (2000) claimed that the wavelength intersections of metamers are most likely around 450 nm, 540 nm and 610 nm, which are close to Thornton's three prime wavelengths (these latter three wavelengths are quoted as prime wavelengths below). A further analysis on the metameric properties of the 70-pair and 88-pair will also reveal that the crossovers of these metamers converge around these three prime wavelengths (see Section 5.3.3).

For a daylight simulator having SPD similar to that of CIE F7 illuminant (F7 lamp), the SPD has four major peaks at wavelength of 405 nm, 435 nm, 545 nm and 580 nm (see Section 3.3.2.2), resulting from the mercury lines at 404.7 nm 435.8 nm, 546.1 nm and 578.0 nm. It was found earlier that the spectral power at the peak wavelengths of a F7 lamp plays an important role in determining its quality (see Section 3.3.2.3). Therefore, matemers generated by taking the spectral characteristics of F7 lamps into account are more effective in revealing the lamp quality. For instance, if the peak wavelengths of the a lamp coincide with the crossover wavelengths of a metameric pair, the degree of metamerism is likely to be small even if the reflectances are very different at other wavelengths. On the contrary, a metameric pair could possibly show large metamerism degree if the crossover wavelengths are much away from the peak wavelength of the fluorescent lamp.

Figure 5.2.5(a) shows the relative spectral power (S1 and S2) of the two specimens of a metamer under CIE D65 illuminant together with CIE 1964 10° colour matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$. Figure 5.2.5(b) shows the relative spectral power of CIE F7 illuminant. The three prime wavelengths (450, 540 and 610 nm) and the peak wavelengths of CIE F7 illuminant (435, 545 and 580 nm) are also indicated in the figures. It can be seen from Figure 5.2.5(a) that the prime wavelength at 450 nm is very close to the peak-sensitivity wavelength of the $\bar{z}_{10}(\lambda)$ function, and the prime wavelength at 540nm is very close to the peak wavelength of F7 illuminant. This implies that for the two spectra of a metamer crossing at these two prime wavelengths, the degree of metamerism will be very small even for a simulator which has spectral power very different from that of the standard illuminant. Hence, one way to increase the effectiveness of a metamer for evaluating daylight simulators, particularly F7 lamps, is to shift the crossovers from the prime wavelengths, e.g. shift crossover at 450 nm to a longer wavelength and that at 540 nm to a shorter wavelength. An alternative approach is to make metamers with large reflectance differences at the peak-power wavelengths of the F7 lamps. Two sets of metamers were generated based on these two approaches.

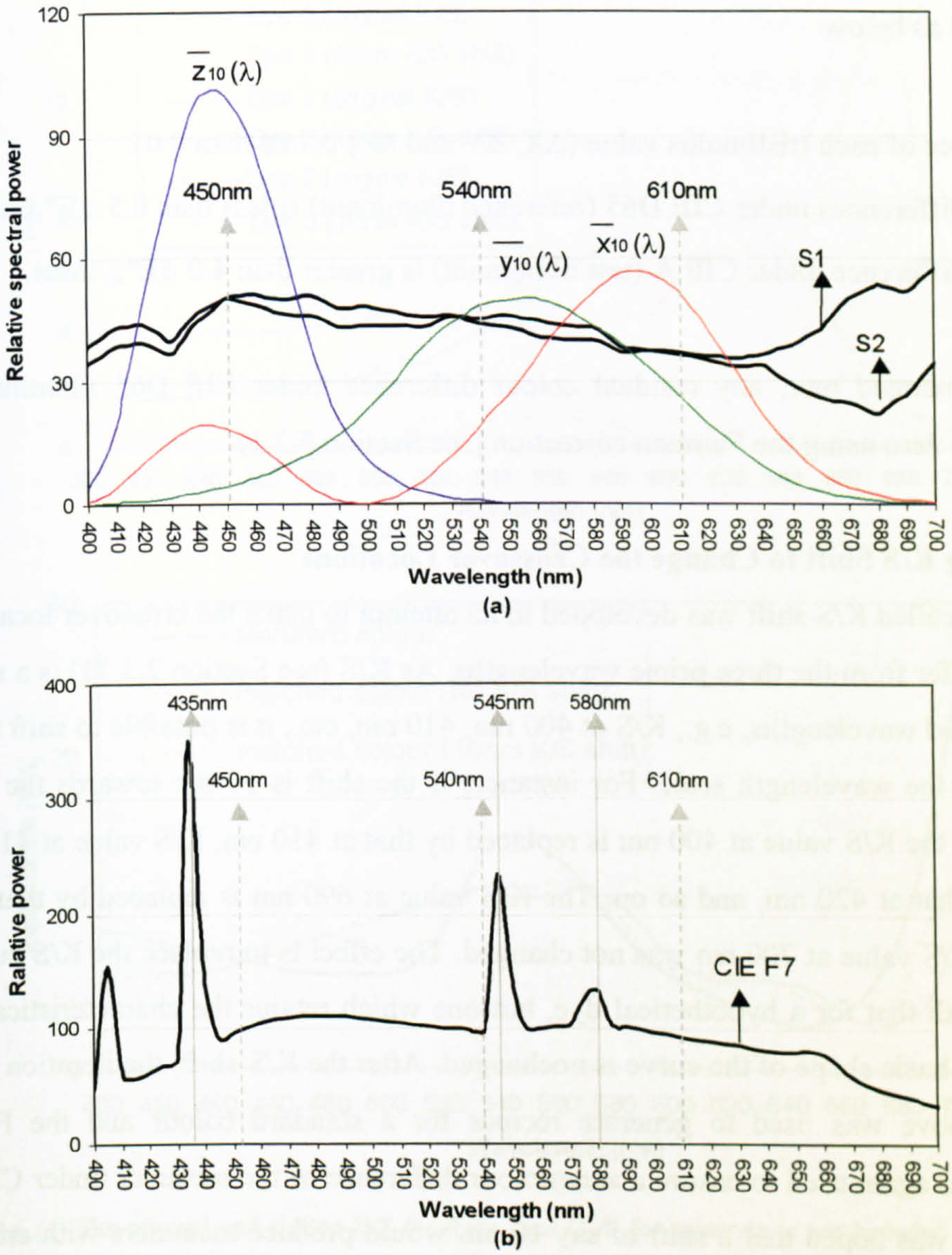


Figure 5.2.5 The relative spectral power (S1 and S2) of the two specimens of a metamer under CIE D65 illuminant together with CIE 1964 10° colour matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ multiplied by 50 in (a), the relative spectral power of CIE F7 illuminant in (b). Note that the three prime wavelengths (450, 540 and 610 nm) and the peak wavelengths of CIE F7 illuminant (435, 545 and 580 nm) are indicated in dotted-line and solid-line arrows respectively.

5.2.3.1 Developing Iteration Routine to Generate Metamers

The SCOPE system was used to produce the 88-pair set (see Section 5.2.2), however, the system is a commercial product so that it is not designed to make metamers with purpose-built characteristics. To overcome this difficulty, an iteration routine based on Kubelka-Munk optical theory (see Section 2.3.11) was developed in C code. The workflow of the routine is similar to that described by McDonald (1997, p.218, see Figure 2.3.11) except that the current routine uses 10 nm wavelength interval instead of 20 nm in McDonald's workflow for the reflectance values. To make the iterative loop converge, three conditions are specified as below:

- Difference of each tristimulus value (ΔX, ΔY and ΔZ) is less than 0.01.
- Colour differences under CIE D65 (reference illuminant) is less than 0.5 ΔE^*_{ab} units.
- Colour difference under CIE A (test illuminant) is greater than 4.0 ΔE^*_{ab} units.

For each generated pair, any residual colour difference under CIE D65 illuminant was minimised to zero using the Fairman correction (see Section 5.2.1).

5.2.3.2 Using K/S Shift to Change the Crossover Locations

A technique called K/S shift was developed in an attempt to make the crossover locations of metamers differ from the three prime wavelengths. As K/S (see Section 2.3.11) is a ratio for all the reported wavelengths, e.g., K/S at 400 nm, 410 nm, etc., it is possible to shift the K/S values along the wavelength scale. For instance, if the shift is 10 nm towards the shorter wavelengths, the K/S value at 400 nm is replaced by that at 410 nm, K/S value at 410 nm is replaced by that at 420 nm, and so on. The K/S value at 690 nm is replaced by that at 700 nm and the K/S value at 700 nm was not changed. The effect is to replace the K/S curve for a real dye with that for a hypothetical dye, but one which retains the characteristics of the real dye. The basic shape of the curve is unchanged. After the K/S shift, the iteration routine developed above was used to generate recipes for a standard colour and the Fairman correction was again used to ensure a zero colour difference of the metamer under CIE D65 illuminant. It was hoped that a shift of say 10 nm would produce metamers with crossover wavelengths shifted by about 10 nm.

Figure 5.2.6 demonstrates an example of using the K/S shift. It can be seen from the figure that by using the K/S shift, the matched spectrum shifted in the same direction while almost remaining its original shape. This means that the K/S shift can change the crossover locations of a metamer. However, the crossover shift is not the same as the K/S shift, and for some crossovers, e.g. the one near 450 nm in Figure 5.2.7(b), that shift is not even noticeable.

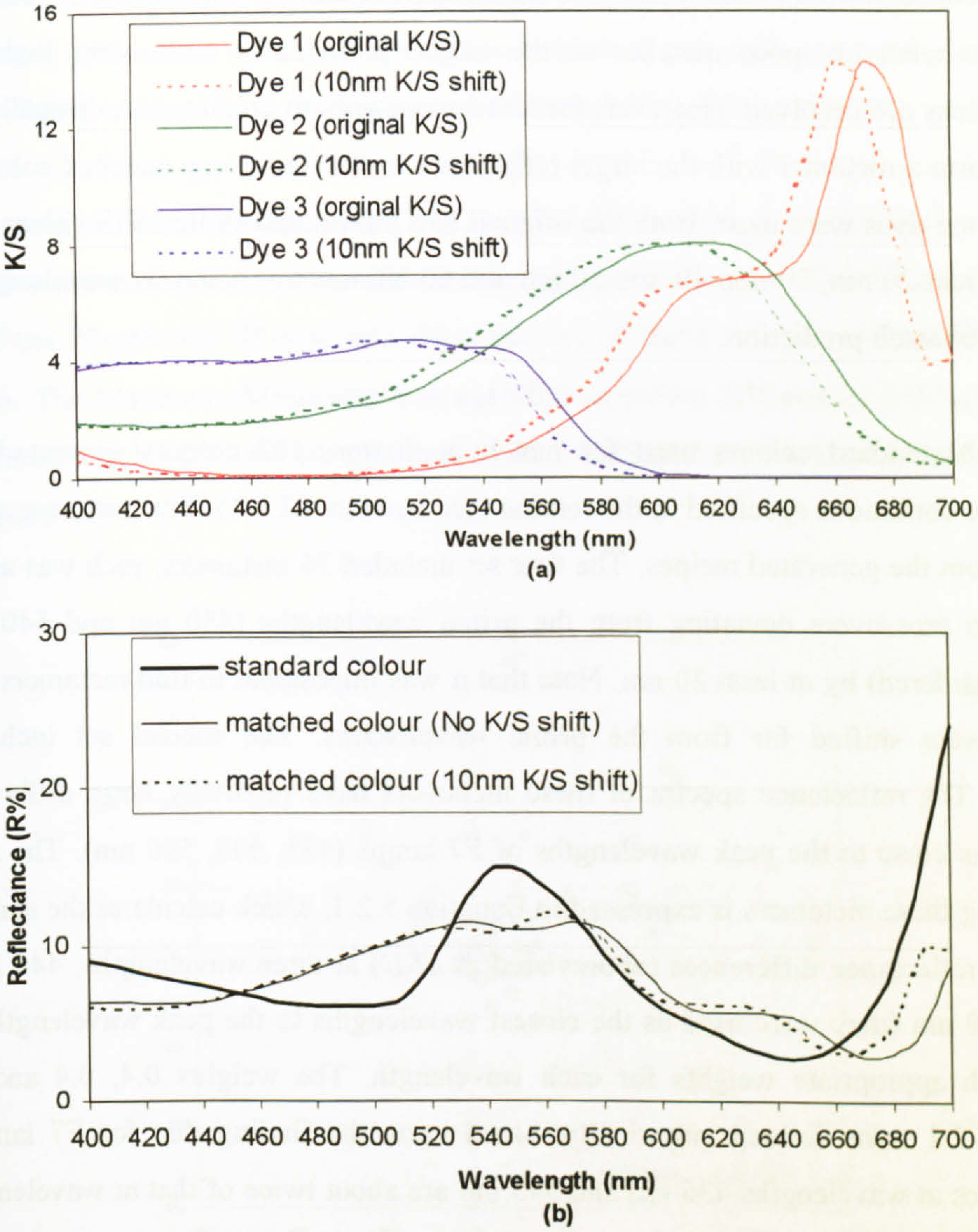


Figure 5.2.6 (a) The original and shifted K/S for three dyes (K/S for substrate is not included as it is not in a similar scale to that for the dyes) used for matching a colour, (b) The reflectance curves of a metamer, including those for the standard colour and the matched colour without K/S shift and with K/S shift.

5.2.3.3 Generating Two Sets of Metamers with Built-in Spectral Characteristics

In total, 158 colours were selected based on the 70-pair and 88-pair sets. Only one sample was selected from each pair. For the 70-pair set, the colour without Fairman correction in each pair was selected, and for the 88-pair set, the measured PCC-GENIE colour in each pair was selected. These selected colours were used as standard colours for generating new metamers. The iteration routine developed above (see Section 5.2.3.1) was used for the match prediction. The dyestuff database for cotton substrate (see Section 5.2.2) was again used. For each of the ten dyes, only a concentration of 1.0 was used to build a database, as a linear relationship between dye concentration and K/S values was assumed. The benefit of using one concentration is that it can save substantial computing time. In reality, this method could give relatively poor matches to the target, particularly when very high or low concentrations are involved. However, the aim here is only to produce a realistically shaped curve to form a metamer with the target reflectance curve. For every matched colour, three out of the ten dyes were used. Both the original K/S values and shifted K/S values with six scales (10 nm, 20 nm, 30 nm, 40 nm, 50 nm and 60 nm towards a shorter wavelength) were used for the match prediction.

Of the 158 standard colours used for match prediction, 102 colours generated recipes meeting the conditions specified in the routine (see Section 5.2.3.1). Two metamer sets were selected from the generated recipes. The first set included 36 metamers, each was as having one or two crossovers deviating from the prime wavelengths (450 nm and 540 nm are mostly considered) by at least 20 nm. Note that it was impossible to find metamers with all the crossovers shifted far from the prime wavelengths. The second set included 54 metamers. The reflectance spectra of these metamers have relatively large differences at wavelengths close to the peak wavelengths of F7 lamps (435, 545, 580 nm). The measure for selecting these metamers is expressed in Equation 5.2.1, which calculates the summation of relative reflectance differences (abbreviated as *SRD*) at three wavelengths, 440 nm, 540 nm and 580 nm (they were used as the closest wavelengths to the peak wavelengths of F7 lamps) with appropriate weights for each wavelength. The weights 0.4, 0.4 and 0.2 in Equation 5.2.1 were defined empirically, based upon the finding that for F7 lamps, the power values at wavelengths 435 nm and 545 nm are about twice of that at wavelength 580 nm (see Section 3.3.2.2).

$$SRD = 0.4\times\left|\left(\frac{R_m - R_s}{R_m}\right)_{440}\right| + 0.4\times\left|\left(\frac{R_m - R_s}{R_m}\right)_{540}\right| + 0.2\times\left|\left(\frac{R_m - R_s}{R_m}\right)_{580}\right| \qquad 5.2.1$$

where R_s and R_m are the spectral reflectances for the standard and matched colours. An overall analysis on the *SRD* values of the 560 metamers resulted in 54 pairs being selected, which had relatively large SRD values.

The colour distributions of the 36-pair and 54-pair sets in CIE a* b* space (CIE D65/10°) are shown in Figure 5.2.7. As the standard colours for making these metamers are from the 70-pair and 88-pair sets, the colour gamut of these two sets is a part of that for the 70-pair and 88-pair sets (see Figure 5.2.3). It also shows that there are overlaps of colours for the

36-pair and 54-pair sets. It can be seen that most colours of the two sets are distributed in neutral, red, yellow and green regions and very limited colour in cyan, blue and magenta regions. This could be due to the criterion used for selecting these metamers.

The colour distributions for these two sets are also shown in Figure 5.2.8, each vector in the diagrams representing the colour difference of a metamer under CIE illuminant A. Like those of the 70-pair and 88-pair sets, most vectors of these two sets shift in the red-green direction. The Maximum/Minimum/Average/Median colour differences (ΔE^*_{ab}) under CIE A illuminant are 8.18/2.14/4.49/4.34 and 11.43/3.82/5.85/5.29 for the 36-pair and 54-pair sets respectively.

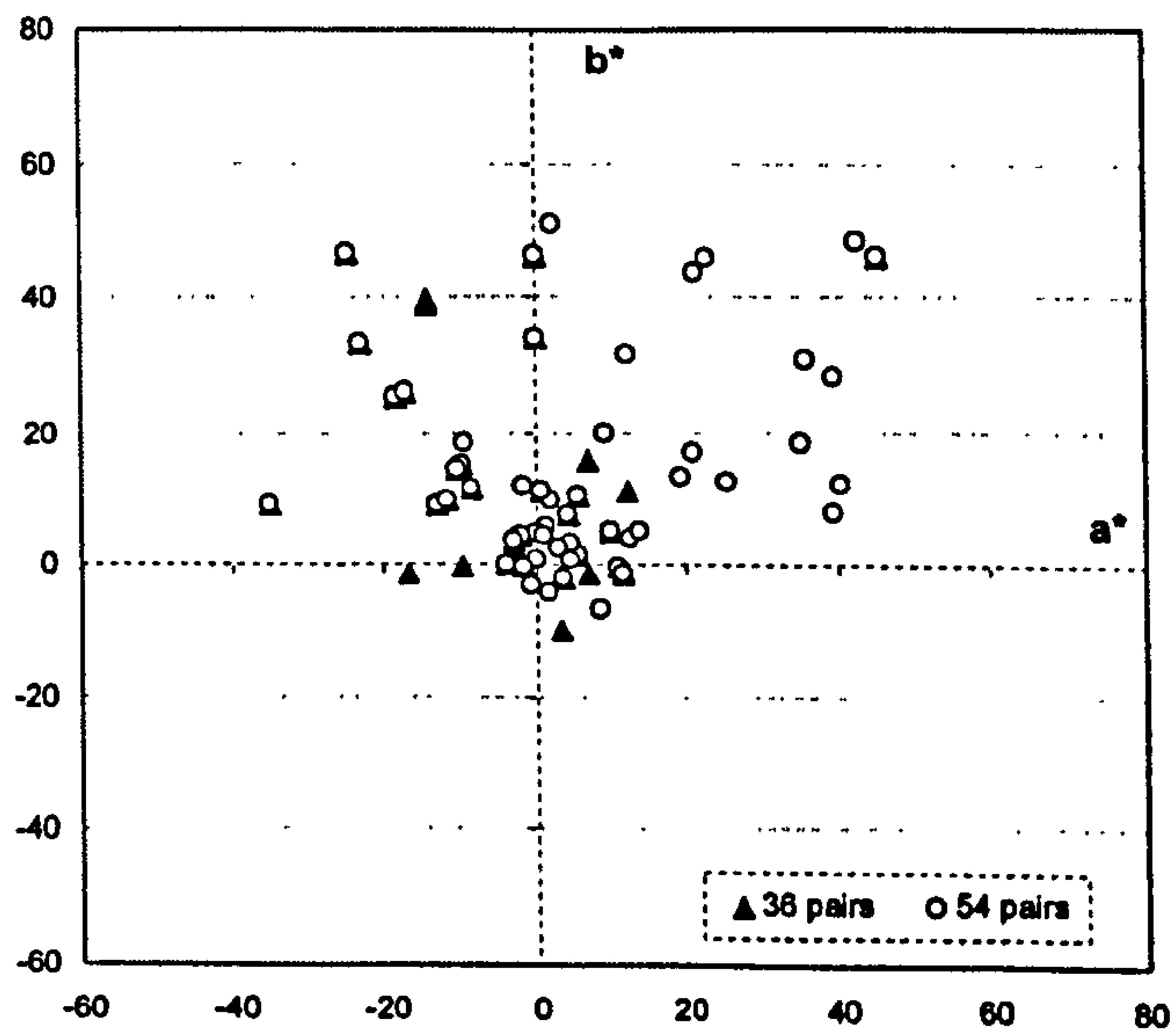


Figure 5.2.7 Colour distributions for the metamers of 36-pair and 54-pair sets (CIE D65/10°)

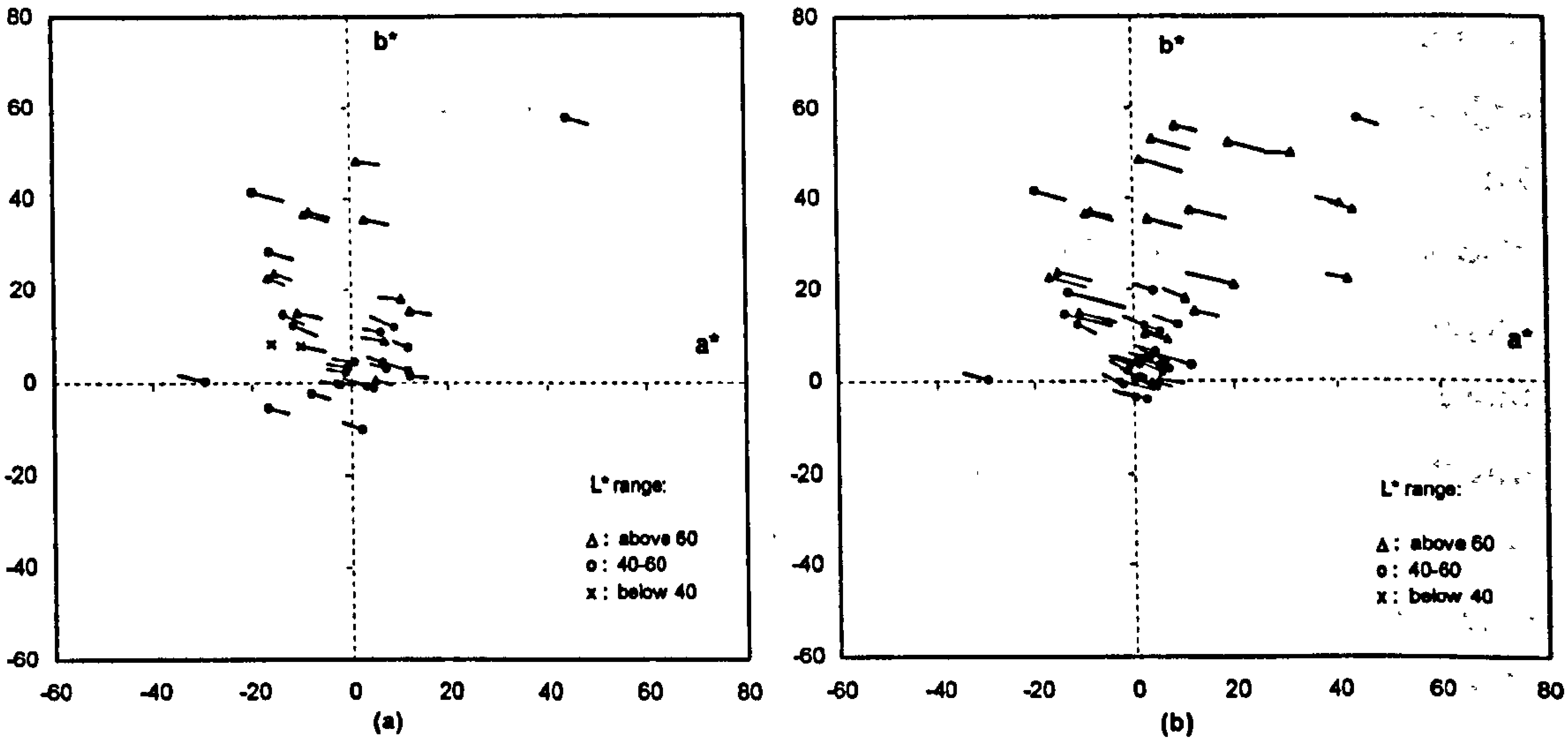


Figure 5.2.8 Colour distributions for the metamers under CIE illuminant A, with the 36-pair set in (a) and 54-pair set in (b)

5.3 Investigating the Metameric Properties of Metamers

Section 5.2 described the process used to generate four metamer sets and the characteristics of these metamers. In this section, a further investigation was conducted to reveal the matameric properties of these generated metamers using various metamerism indices, including the CIE special index of metamerism and other general indices of metamerism (see Section 2.3.10.2). The correlation between different metamerism indices was investigated by using the Performance Factor (PF/3) (see Section 2.7.7). Finally, the metamer crossovers were investigated with focus on the crossover numbers and locations on the spectra.

5.3.1 Metamerism Index Results

For a metamer the two samples of the pair show different reflectance spectra but have identical tristimulus values under a reference illuminant, say CIE D65. The distributions of the two spectra such as the reflectance values at different wavelength and the wavelength intersections are the key factors determining the metameric properties of the metamer. Metamerism index is a measure for quantifying the degree of metamerism. Ideally it should represent the extent of mismatch under various illuminants. However, in practice only a limited number of illuminants are used as test illuminants. According to Hunt (1998, p.119), suitable test illuminants include CIE A illuminant to represent tungsten light, and one of the CIE F illuminants to represent fluorescent lamps, particularly F2, F7 and F11. In industry, the CIE illuminants A and F11 are most widely used as test illuminants. Various metamerism indices have so far been developed for quantifying the metamerism degree.

5.3.1.1 Testing Different Metamerism Indices

An early matamerism index was proposed by Nimeroff and Yurow (1965), which calculates the reflectance differences weighted by colour matching functions (see Section 2.3.10.2). One colour matching function set, CIE 1931 $\bar{x}$, $\bar{y}$, $\bar{z}$ (see Equation 2.3.32) and one transformed colour matching function set, CIE 1960 $\bar{u}$, $\bar{v}$, $\bar{w}$ (see Equation 2.3.33), were used for calculating the index. At a late stage, Moradian (1977) adopted the lightness index of Wyszecki ($L_\lambda=25(R_\lambda)^{1/3}-17$) instead of the reflectance, and rewrote the Nimeroff-Yurow index as in Equation 2.3.34.

The CIE recommended a special index of metamerism (CIE 1986), which calculates the colour difference (CIELAB or other colour difference formula appropriate) between the two samples of a metamer under the test illuminant. Hence, the CIE special index of metamerism is an illuminant dependant measure, and the index results are largely decided by the choice of test illuminant. This measure could give problem for quantifying metamerism degree of metamers if new light sources developed in the future are very different from the present ones.

Viggiano (2001) proposed a perception-referenced metamerism index (also termed as spectral comparison index) as a metric for comparing the two spectra of a metamer. The metric is based on colorimetric principles and calculates the sum of a series of ΔE^*_{ab} values wherein the two spectra differ only within a single narrow wavelength band (see Equation 2.3.35).

The three general indices of metamerism (Nimeroff-Yurow, Moradian and Viggiano indices) are illuminant independent as the formulae for these indices only involve the use of reflectance values and colour matching functions. However, the Viggiano index calculates a weighting function which needs a reference illuminant (Viggiano recommended CIE D65 illuminant as the reference illuminant). For the CIE special index of metamerism, this study calculates CIEDE2000 (CIE 2001) colour difference for a metamer under CIE A illuminant (test illuminant). The reason for using the CIEDE2000 colour difference formula instead of the conventional CIELAB formula is that there is strong evidence proving that the former outperforms the latter for most cases (Luo 2001).

The four metamerism index results were calculated for the four metamer sets developed. The maximum, minimum, average and median results for each set are listed in Table 5.3.1. The maximum and minimum values in each column are noted in bold with italic and underlined respectively. It shows that three general indices gave results of similar size, of about 5 times that of the CIE index. The 70-pair set has the largest variation results, with the maximum and minimum values all included in this set. In addition, the set has the largest average results for all the metamerism indices considered, indicating a high degree of metamerism for the metamers of this set. It was also found that all the indices gave consistent results for the four metamer sets, in that the 88-pair set showed the least degree of metamerism, followed by the 36-pair set, the 54-pair set and the 70-pair set.

Table 5.3.1 The maximum, minimum, average and median metamerism index results for the four metamer sets generated

	C Index[a]	N Index1[b]	N Index2[c]	M Index[d]	V Index[e]
(70 pairs)					
Max.	***13.4***	***67.8***	***74.6***	***69.0***	***52.6***
Min.	<u>0.4</u>	<u>2.5</u>	<u>1.5</u>	<u>3.8</u>	<u>3.1</u>
Ave.	5.8	29.7	29.9	31.3	25.4
Median	5.5	26.8	28.7	30.1	24.1
(88 pairs)					
Max.	8.3	41.0	36.2	40.8	36.2
Min.	0.6	3.9	5.1	6.1	5.0
Ave.	4.1	20.1	19.0	20.6	17.8
Median	4.1	19.4	19.1	20.6	18.7
(36 pairs)					
Max.	7.5	30.8	35.3	34.8	27.3
Min.	2.1	8.8	9.1	11.5	11.7
Ave.	4.2	19.3	21.2	22.5	18.0
Median	3.9	19.8	20.6	21.9	17.7
(54 pairs)					
Max.	10.0	49.3	54.1	47.3	38.8
Min.	2.0	10.8	12.0	18.9	14.7
Ave.	5.3	25.3	26.1	28.9	23.5
Median	5.6	22.7	23.5	27.8	22.9

a C Index refers to CIE special index of metamerism (CIE illuminant A used as the test illuminant)
b N Index1 refers to Nimeroff-Yurow metamerism index weighted by CIE 1931 $\bar{x}$, $\bar{y}$, $\bar{z}$ colour matching functions.
c N Index2 refers to Nimeroff-Yurow metamerism index weighted by CIE 1960 $\bar{u}$, $\bar{v}$, $\bar{w}$ functions.
d M Index refers to Moradian metamerism index.
e V Index refers to Viggiano metamerism index.
f These abbreviations apply to the tables and figures reported below.

5.3.1.2 Agreement between Different Metamerism Indices

The four metamerism indices described above were developed based on different principles. The CIE special index of metamerism is most frequently used as a criterion for quantifying the metamerism degree of metamers. In this section, the correlation between different indices was investigated using a statistical measure, Performance Factor (PF/3) (see Section 2.7.7). Table 5.3.2 reports the PF/3 values between a pair of metamerism indices for each metamer set. The comparisons were also illustrated using scatter diagrams, as shown in Figures 5.3.1 and 5.3.2.

Figure 5.3.1 compares the CIE special index of metamerism (C Index) with the three general metamerism indices. The diagrams in Rows 1 to 4 are for C Index versus Nimeroff-Yurow index weighted by CIE 1931 $\bar{x}$, $\bar{y}$, $\bar{z}$ colour matching functions (N Index1), Nimeroff-Yurow index weighted by CIE 1960 $\bar{u}$, $\bar{v}$, $\bar{w}$ functions (N Index2), Moradian index (M Index) and Viggiano index (V Index) respectively. The diagrams from left to right are arranged for the 70-pair, 88-pair, 36-pair and 54-pair sets respectively.

Figure 5.3.2 compares the three general metamerism indices. The diagrams in Rows 1 to 3 are for N Index1 versus N Index2, M Index and V Index respectively. The diagrams in Rows 4 to 5 are for N Index2 versus M Index and V Index respectively. The diagrams in Row 6 are for M Index versus V Index. The diagrams from left to right are arranged for the 70-pair, 88-pair, 36-pair and 54-pair sets respectively.

The results in Table 5.3.2 reveal that the PF/3 values between the CIE index and the three general metamerism indices are quite large, particularly for the 70-pair and 88-pair sets, with PF/3 values all above 50%. A large degree of scatter was also observed in the scatter diagrams of Figure 5.3.1, which further confirms that no strong signs of correlation exist between the CIE index and the general metamerism indices. This suggests that the CIE special index of metamerism is a measure quite different from the general metamerism indices for assessing the metamerism degree of metamers. The reason for this might lie in the fact that the CIE special index of metamerism is illuminant dependent while the three general metamerism inidices are illuminant independent. This also implies that a metamer with a good agreement in spectral reflectance does not guarantee a small CIE special index of metamerism, which is highly depending upon the reference and test illuminants.

The PF/3 values between the two Nimeroff-Yurow indices, which are weighted by different colour matching functions, are around 15% for the four metamer sets investigated, indicating a good correlation between the two indices. The diagrams in Row 1 of Figure 5.3.2 also show little scatter between the two indices, suggesting that there is no significant difference using either CIE 1931 $\bar{x}$, $\bar{y}$, $\bar{z}$ colour matching functions or CIE 1960 $\bar{u}$, $\bar{v}$, $\bar{w}$ functions for the calculation of Nimeroff-Yurow metamerism index.

The PF/3 values between Nimeroff-Yurow and Moradian indices, Nimeroff-Yurow and Viggiano indices are about 32% on average, the 70-pair set having the largest PF/3 values amongst the four sets. The scatter diagrams in Rows 2 to 5 of Figure 5.3.2 also show some degree of correlation between Nimeroff-Yurow and Moradian indices, Nimeroff-Yurow and Viggiano indices.

The PF/3 values between Moradian and Viggiano indices are surprisingly small, with the values for each set less than 10%. The scatter diagrams in Row 6 of Figure 5.3.2 also show a very good agreement between the two indices. Although the equations involved (see Equations 2.3.34 and 2.3.35) look quite different, there is presumably a very similar underlined principle in both cases.

Table 5.3.2 PF/3 values between different metamerism indices

Pair \ PF3	C Index vs. N Index1	C Index vs. N Index2	C Index vs. M Index	C Index vs. V Index	N Index1 vs. N Index2	N Index1 vs. M Index	N Index1 vs. V Index	N Index2 vs. M Index	N Index2 vs. V Index	M Index vs. V Index
70	75	79	57	51	17	36	37	42	43	8
88	79	75	72	67	14	28	26	22	20	7
36	46	51	37	32	15	30	30	29	30	9
54	57	56	40	33	12	27	30	27	29	9
Ave.	64	66	51	46	15	30	31	30	31	8

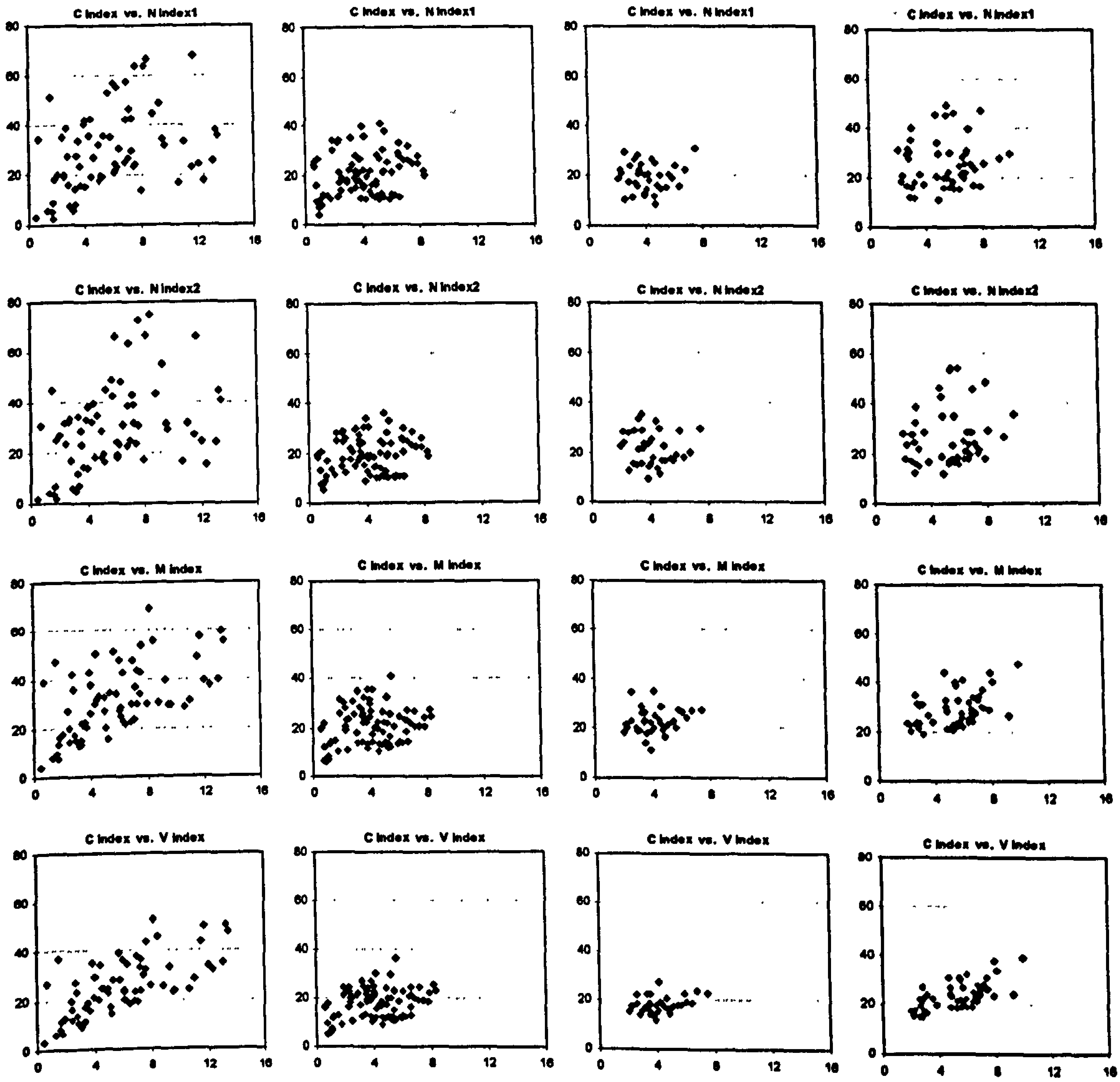


Figure 5.3.1 Comparing the CIE special index of metamerism with the three general metamerism indices: C Index vs. N Index1 (Row 1), N Index2 (Row 2), M Index (Row 3) and V Index (Row 4). The diagrams from left to right are arranged for the 70-pair, 88-pair, 36-pair and 54-pair sets respectively.

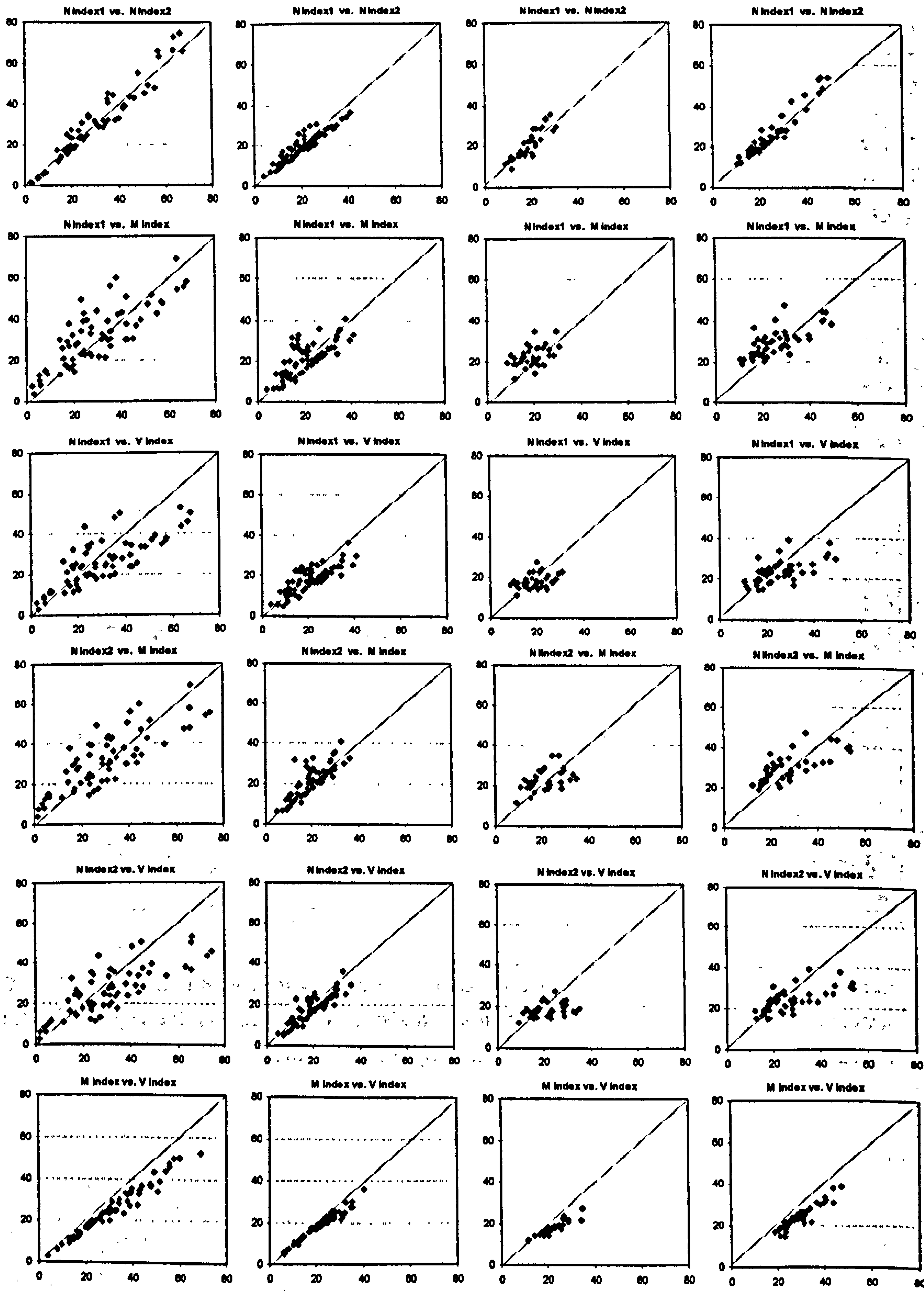


Figure 5.3.2 Comparing different general metamerism indices: N Index1 vs. N Index2 (Row 1), M Index (Row 2) and V Index (Row 3), N Index2 vs. M Index (Row 4) and V Index (Row 5), M Index vs. V Index (Row 6). The diagrams from left to right are arranged for the 70-pair, 88-pair, 36-pair and 54-pair sets respectively.

5.3.2 Crossover Characteristics

For an object pair to be metameric, the reflectance curves of its members must be non-identical and must cross at multiple wavelengths across the visible range. It is generally regarded that the location and number of crossovers (also termed as wavelength intersection) of the spectra are important features of metamers. Stiles and Wyszecki (1977) verified on a theoretical basis that two stimuli must cross at least three times to be metameric. Kuehni (1978) further showed that for metameric textile samples more four or six-point crossovers can be observed than three-point crossings. There are also debates on whether the locations of crossover show any characteristics related to the metameric property of metamers (see Section 2.3.10.1). In this section, the characteristics of the four generated metamer sets were investigated in terms of crossover number and location on the spectra.

5.3.2.1 Crossover Number

Table 5.3.3 lists the percentage of metamers for different crossover numbers (3, 4, 5, 6 and above) for the four metamer sets. The results show that the 70-pair and 88-pair sets have a large proportion of metamers with crossover number of 3 and 4 respectively, with the former 70% and the latter 49%. The 36-pair and 54-pair sets have a larger proportion of metamers than the 70-pair and 88-pair set with crossover number above 4, implying the purpose-made metamers of these two sets are somewhat special with more than average number of crossovers.

To investigate whether the crossover numbers have an impact on the metamerism degree of metamers, the percentage of metamers for different crossover number is also reported for the 70-pair and 88-pair sets after sorting the metamers of the two sets and excluding metamers with a low metamerism degree. The 36-pair and 54-pair sets were not included for the analysis because the sample size of the two sets is much smaller. The metamerism degree was calculated using the CIE special index of metamerism, the Nimeroff-Yurow metamerism index and the Moradian metamerism index (C Index, N Index2 and M Index respectively in Table 5.3.1). For the Nimeroff-Yurow index, only the CIE 1960 $\bar{u}$, $\bar{v}$, $\bar{w}$ functions were used in the calculation. The Viggiano metamerism index was not included because it was found that the Viggiano index is highly correlated to the Moradian index (see Section 5.3.1.2).

Three metamerism indices, the CIE special index of metamerism (ΔE^*_{00} under CIE A illuminant), Nimeroff-Yurow index (weighted by CIE 1960 $\bar{u}$, $\bar{v}$, $\bar{w}$ functions) and Moradian index were used as different measures for excluding metamers of low metamerism degree. For using the CIE index, metamers having indices less than 4 were excluded. The original metamer numbers in the 70-pair and 88-pair sets were reduced to 45 and 47 respectively. For using the Nimeroff-Yurow index, metamers having indices less than 20 were excluded. The original metamer numbers in the 70-pair and 88-pair sets were reduced to 49 and 38 respectively. For using the Moradian index, metamers having indices less than 20 were excluded. The original metamer numbers in the 70-pair and 88-pair sets were reduced to 55 and 50 respectively. Note that it was revealed earlier that the CIE index does not correlate well with the Nimeroff-Yurow and Moradian indices (see Section 5.3.1.2). However, dividing lines for excluding metamers could be allocated for the three indices, 4, 20 and 20 in this case, which correspond to approximately the same degree of metamerism.

An examination of the results in Table 5.3.3 revealed that for the 70-pair set, the percentage of metamers for different crossover numbers does not change much after excluding metamers with low metamerism degree, regardless which type of metamerism index the results were based on. However, for the 88-pair set, more changes were observed for the percentage of metamers after excluding metamers, especially when the Nimeroff-Yurow and Moridian indices were used. Strangely, the percentage of three-point crossovers increased for the 70-pair set and decreased for the 88-pair set. The results suggest that there is no clear relationship between crossover number and metamerism degree of metamers.

Table 5.3.3 Percentage of metamers for different crossover numbers (3, 4, 5, 6 and above)

Pairs / Metamer Number(%)	Crossover Number				
	3	4	5	6	>=7
70	70	16	10	3	1
88	44	49	7	0	0
36	25	25	31	14	6
54	31	26	30	13	0
70-[a]					
45 (C Index >=4.0)	89	11	0	0	0
49 (N Index2 >=20)	84	14	0	2	0
55 (M index >=20)	80	16	2	2	0
88-[a]					
47 (C Index >=4.0)	45	45	11	0	0
38 (N Index2 >=20)	21	74	5	0	0
50 (M Index >=20)	24	64	12	0	0

a '70-' and '88-' represent the 70-pair and 88-pair sets after excluding metamers of low metamerism degree.

5.3.2.2 Crossover Locations

The crossover wavelength distributions in frequency terms are shown in Figure 5.3.3 for the 70-pair, 88-pair, 36-pair and 54-pair sets respectively (from top to bottom). The frequency in each chart is normalised so that the maximum value for each set equals to 100. Thornton's three prime wavelengths (450, 540 and 610 nm, see Section 2.3.10.1) and the main peak wavelengths of F7 lamps (435, 545 and 580 nm, see Section 3.3.2.2) are also indicated in each chart. It can be seen from Figure 5.3.3 that each set has 3 to 5 peaks of high frequency, representing a high concentration of crossovers. For the 70-pair, 88-pair and 54-pair sets, the locations of these frequency peaks are fairly close to the three prime wavelengths, with maximum deviation of 10 nm. However, the frequency peaks of the 36-pair set are further away from the three prime wavelengths, with maximum deviation of 20 nm. This is expected because the 36-pair set was deliberately designed with this spectral characteristic (see Section 5.2.3.3). Both the 36 and 54-pair sets also include a considerable number of crossovers located above 640 nm.

The crossover wavelength distributions before and after the exclusion of metamers of low metamerism degree are shown in Figures 5.3.4 and 5.3.5 for the 70-pair and 88-pair sets respectively. The top chart is for the original set and the bottom three charts are for the reduced number sets. The frequency in each chart is again normalised so that the maximum value for each set equals to 100. The figures show that the locations of frequency peaks are not changed after metamers with low metamerism degree were excluded from the original 70-pair and 88-pair sets. However, a comparison of the top chart with the bottom three charts reveals that for metamers with high metamerism degree, their crossovers tend to be located close to the three prime wavelengths. The 88-pair set particularly demonstrates this feature. A similar finding was reported by Ohta (1987) in which he claimed that strong metameric colours show intersection convergence to Thornton's three prime wavelengths.

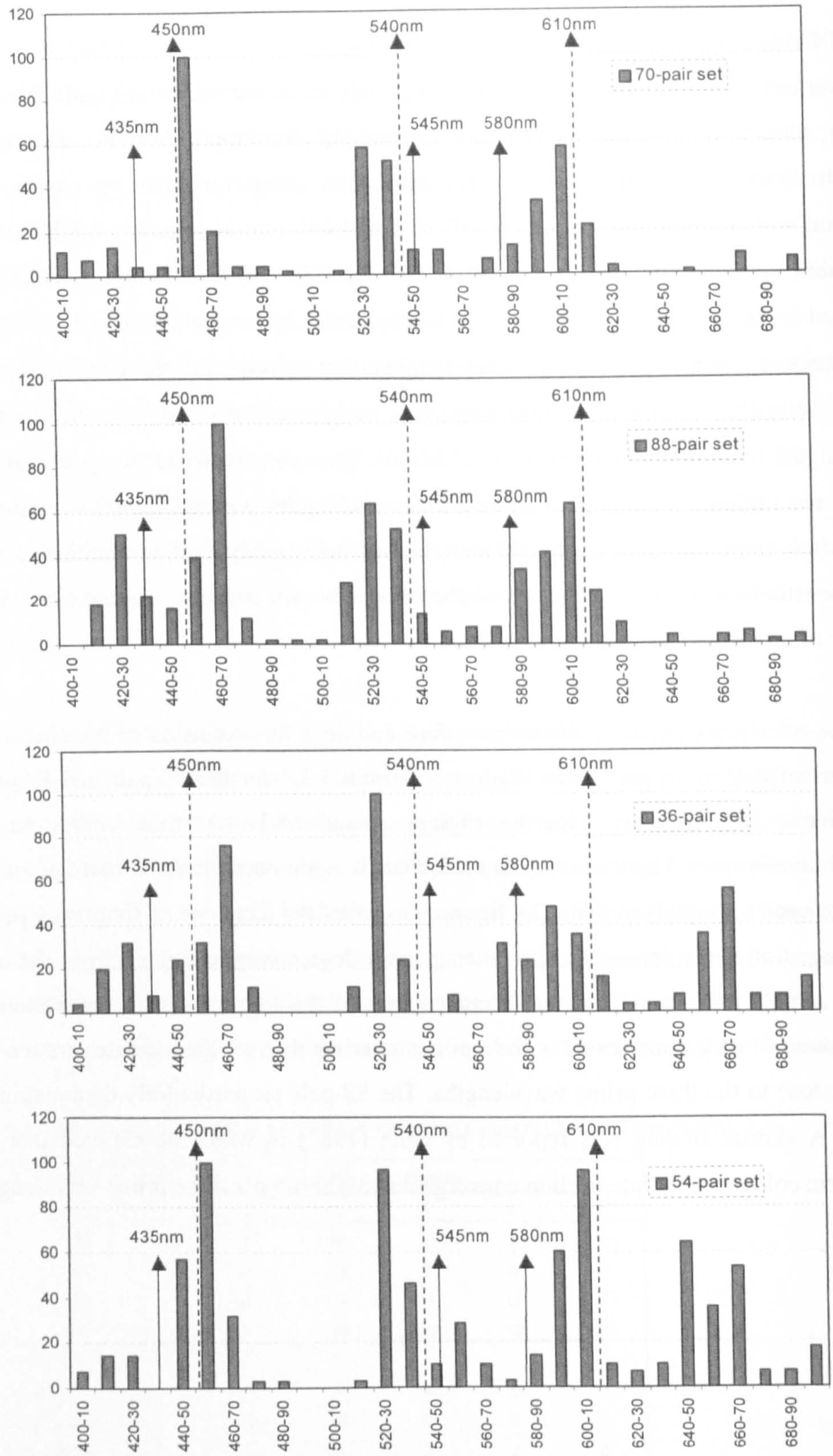


Figure 5.3.3 Charts from top to bottom are for the crossover distributions in frequency for the 70-pair, 88-pair, 36-pair and 54-pair sets, respectively. The frequency is normalised so that the maximum value in each set is equal to 100. Thornton's three prime wavelengths and the peak wavelengths of F7 lamps are indicated in dotted-line and solid-line arrows respectively, also see Figures 5.3.4 and 5.3.5.

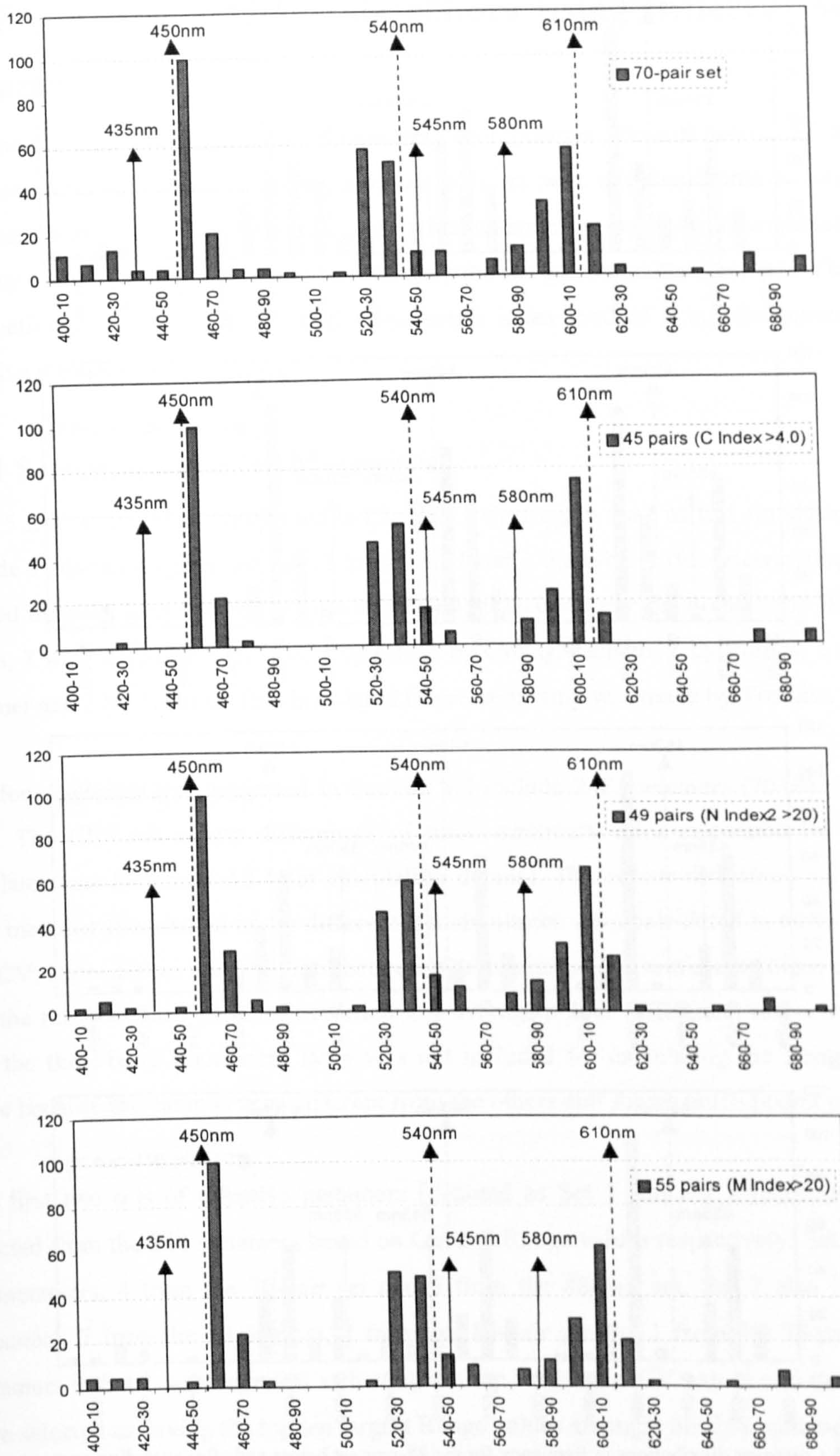


Figure 5.3.4 Crossover distributions in frequency for the 70-pair set before and after excluding metamers of low metamerism degree: original set (Top 1), reduced number sets based on C Index (Top 2), N Index2 (Top 3) and M Index (bottom). The frequency is normalised so that the maximum value for each set equals to 100.

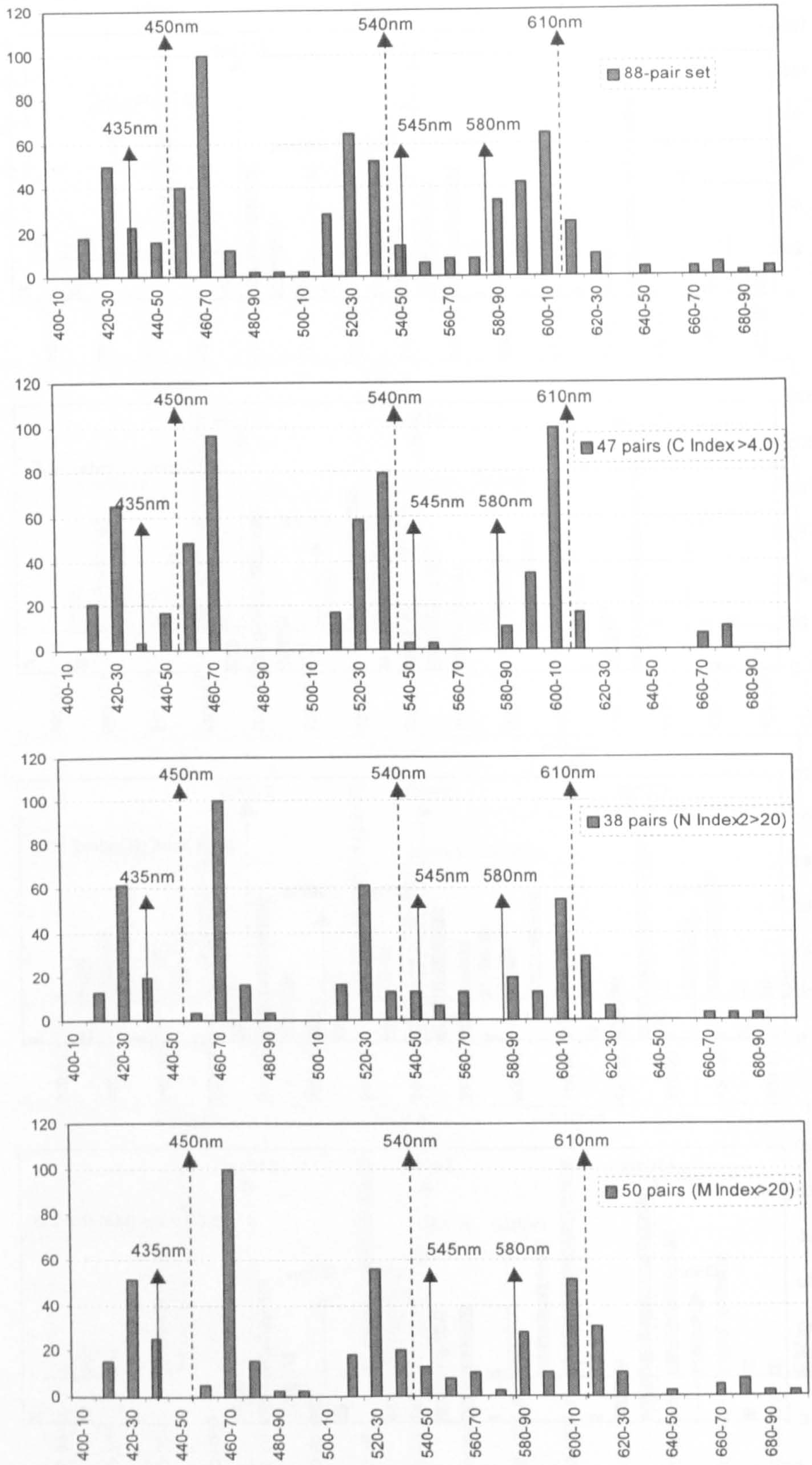


Figure 5.3.5 Crossover distributions in frequency for the 88-pair set before and after excluding metamers of low metamerism degree: original set (Top 1), reduced number sets based on C Index (Top 2), N Index2 (Top 3) and M Index (bottom). The frequency is normalised so that the maximum value for each set equals to 100.

5.4 Evaluating Daylight Simulators Using Different Sets of Metamers

Sections 5.2 described the process of generating four metamer sets and Section 5.3 analysed the metameric properties of these metamer sets. It was envisaged that a number of metamers, particularly suitable for evaluating the metamerism quality of daylight simulators (namely effective metamers), could be selected from the generated metamer sets. The aim of this section is to investigate the CIE metamerism index method using the generated and effective metamer sets.

5.4.1 Selecting Effective Metamers

The 15 D65 simulators investigated in Chapter 3 were again used as test simulators. These include 2 filtered tungsten lamps, 12 broad band and 1 three-band fluorescent lamps. The 2 filtered tungsten lamps were both made by GretagMacbeth. For the broad band fluorescent lamps, 7 were made by VeriVide, 1 by GE, 1 by GretagMacbeth, 1 by Philips, 1 by BYK-Gardner and 1 by Toshiba. The three-band fluorescent lamp was made by Toshiba.

The four metamer sets generated in Section 5.2 include 248 metamers (70+88+36+54) in total. The CIELAB colour differences of these metamers were calculated for each test simulator (see Section 4.2.2.1 for calculation details). The colour difference variations of each metamer illuminated under different test simulators were calculated in terms of Range and CV, expressed as the difference between the maximum and minimum colour difference, and the ratio between standard deviation and average colour difference, respectively. Note that the three-band fluorescent lamp was not included for calculating the Range and CV value because this lamp is very different from the others and shows much poorer quality.

The first two sets of effective metamers (denoted as Set 1 and Set 2 respectively) were selected from the 248 metamers based on CV and Range values respectively. Set 1 includes 10 metamers, 4 from the 70-pair set and 6 from the 88-pair set. Set 2 also includes 10 metamers, 7 from the 70-pair set, 2 from the 88-pair set and 1 from the 36-pair set. The metamers in Set 1 were selected as having the top ten largest CV values and those in Set 2 were selected as having the top ten largest Range values amongst the 248 metamers.

The third set of effective metamers (denoted as Set 3) was selected only from the 54-pair set. The criterion for selecting these metamers is purely based on reflectance characteristics, which means they are independent of the test simulators. Set 3 includes 6 metamers, each was selected as having a relatively large *SRD* value (see Equation 5.2.1) as well as having a different reflectance curve in comparison with the CIE metamers (see Figure 2.5.1 for the reflectance curves of the CIE metamers). It was also ensured that the selected metamers do not show tailbacks on the spectra of matched colours, which means that the K/S shift (see Section 5.2.3.2) was not used for generating these metamers.

The reflectance curves for the three effective metamer sets (Set 1, Set 2 and Set 3) are shown in Figures 5.4.1 to 5.4.3. The colour distributions for the effective metamer sets and the CIE metamer set are shown in Figure 5.4.4. It can be seen that the effective metamers fill the CIE a* b* space much better than the CIE metamers. However, it was found that neither the CIE metamers nor the effective metamers are in the cyan region. This may be due to the difficulty in producing cyan colour pairs which are highly metameric. Note that two metamers in Set 1 and Set 2 are identical, as is shown by an overlap of two colours in Figure 5.4.4.

Table 5.4.1 lists the colour difference (ΔE^*_{ab}) and metamerism index results for the three effective metamer sets and the CIE set. The colour difference results includes the maximum, minimum, Range and CV values for each metamer under the 15 test simulators. The metamerism index results were reported for each metamer in terms of CIE index, Nimeroff-Yurow index, Moridian index and Viggiano index. For each set, the maximum and minimum values of each column are noted in bold with italic and underlined, respectively. The results show that on average Set 1 has the largest CV value and Set 2 has the largest Range value. This is expected as the metamers of these two sets were selected as having large CV and Range values respectively. The average Range and CV values for Set 3 and the CIE set are much smaller than those for Set 1 and Set 2, with Set 3 having the smallest CV value and the CIE set having the smallest Range value. For the metamerism index results, in general Set 2 has the largest values for all the metamerism indices investigated, and the CIE set has the smallest values, about half of those of Set 2. This implies that a high degree of metamerism results in large colour difference variations in terms of Range.

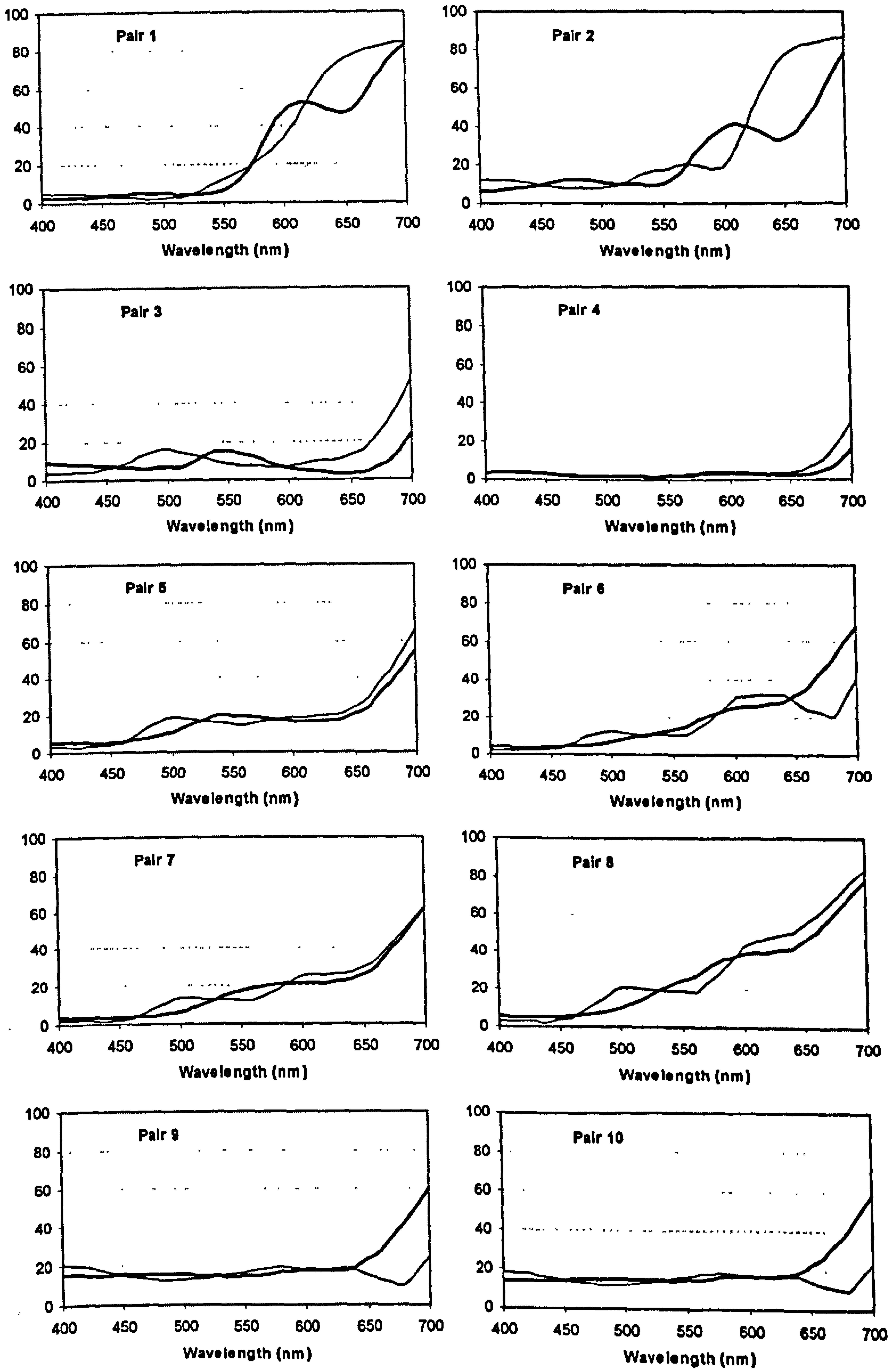


Figure 5.4.1 Reflectance curves for the 10 metamers in Set 1 (standard spectrum in bold line and matched spectrum in fine line)

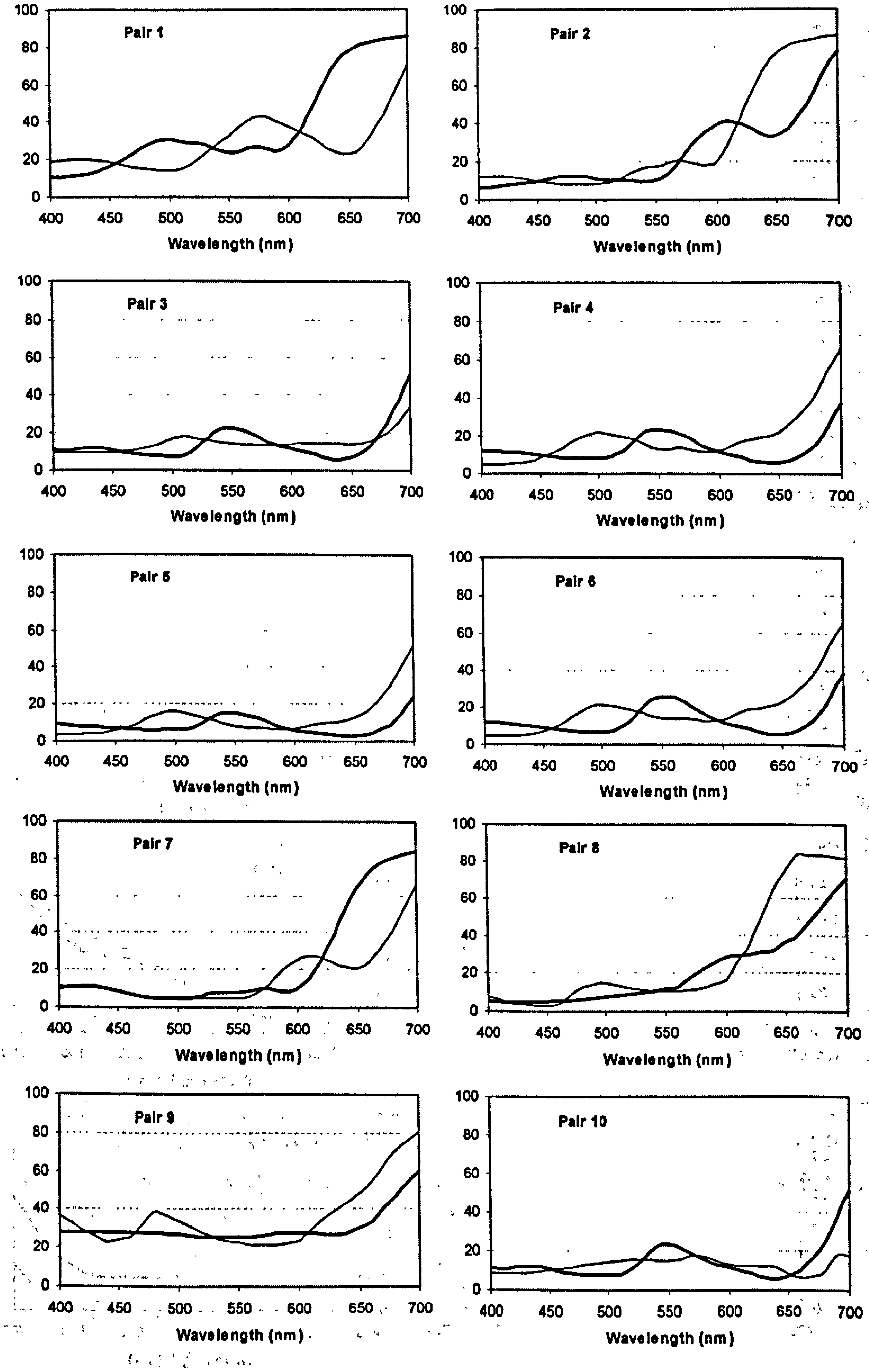


Figure 5.4.2 Reflectance curves for the 10 metamers in Set 2 (standard spectrum in bold line and matched spectrum in fine line)

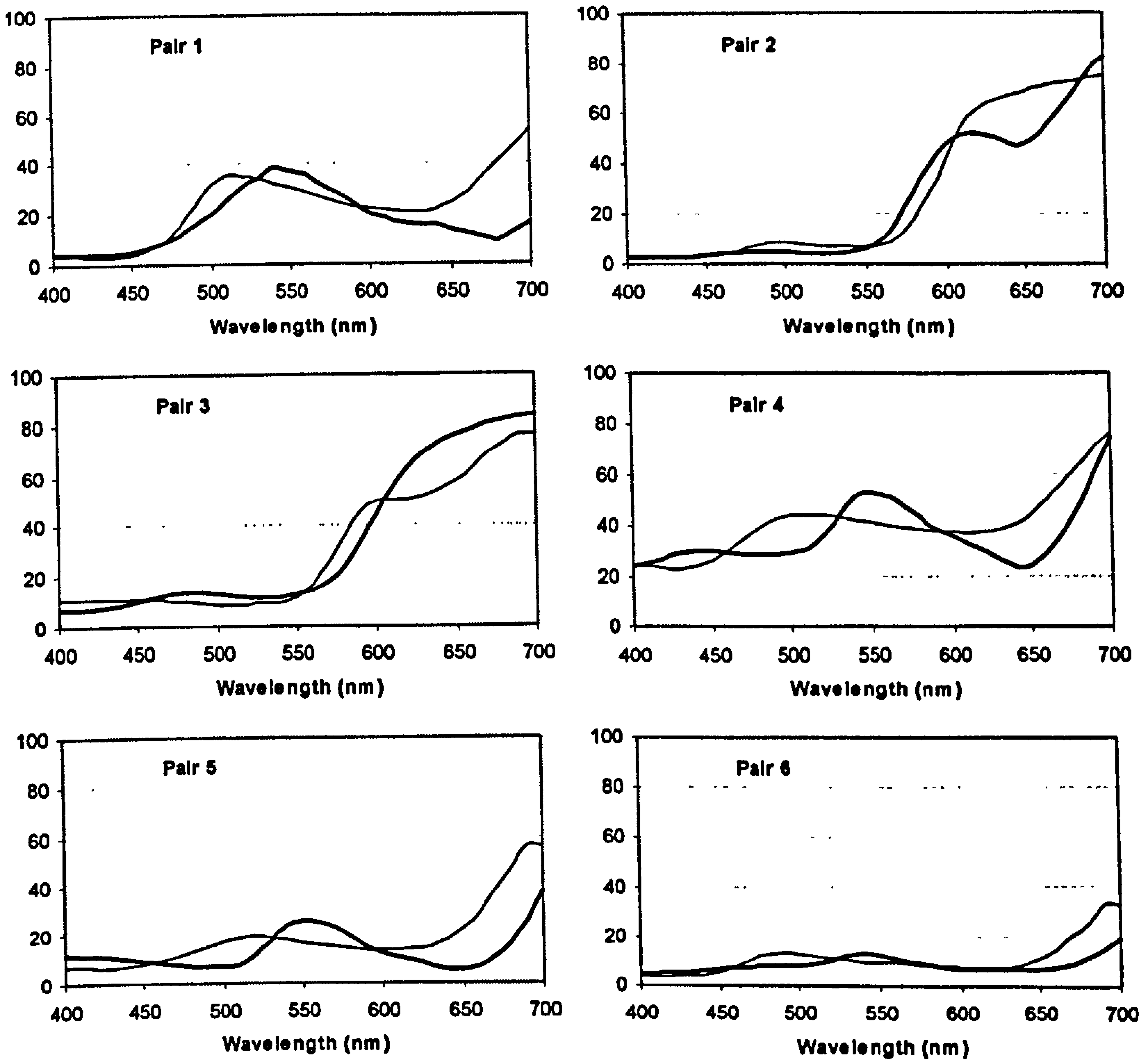


Figure 5.4.3 Reflectance curves for the 6 metamers in Set 3 (standard spectrum in bold line and matched spectrum in fine line)

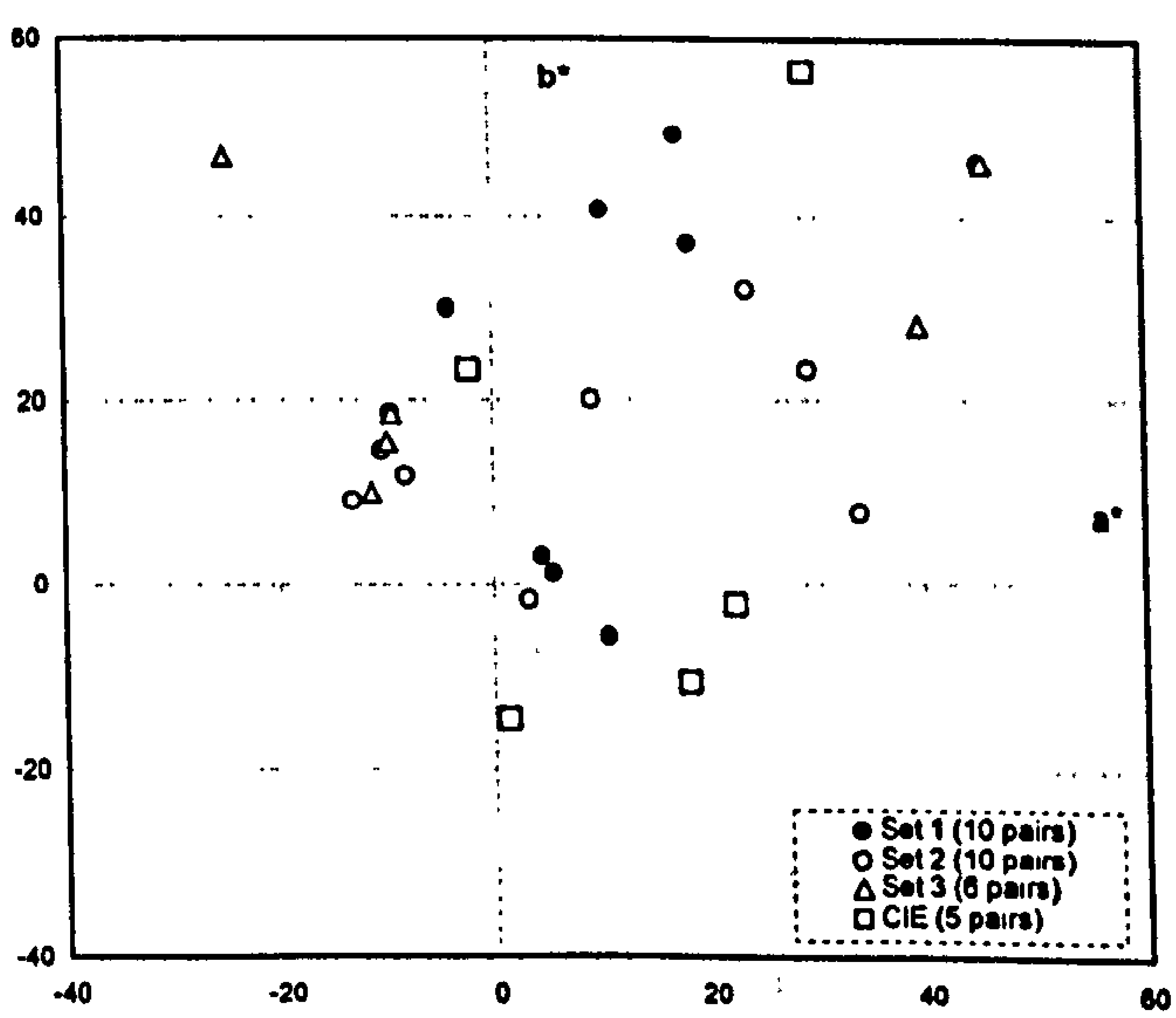


Figure 5.4.4 Colour distributions in CIE a* b* space (CIE D65/10°) for the three sets of effective metamers and the CIE metamer set

Table 5.4.1 Colour difference variations and metamerism index results for the three effective metamer sets and the CIE set

		ΔE*ab				Metamerism index				
		Max	Min	Range	CV	C Index	N Index1	N Index2	M Index	V Index
Set 1										
From 70-pair set	No. 1	1.9	0.3	1.6	75.7	0.7	34.4	30.9	38.9	27.1
	No. 2	***2.8***	***0.4***	2.4	76.7	1.5	***51.4***	***45.2***	47.1	37.0
	No. 3	2.8	0.1	***2.6***	70.2	***11.5***	23.1	26.8	***49.3***	***43.3***
	No. 4	0.8	0.1	0.7	70.1	1.7	2.5	2.0	7.5	6.4
From 88-pair set	No. 5	1.3	0.1	1.2	***77.4***	4.1	15.8	18.7	26.7	21.9
	No. 6	1.7	0.1	1.6	69.6	2.3	17.1	17.7	27.9	22.8
	No. 7	1.5	0.1	1.4	70.0	3.6	17.4	20.5	32.6	24.5
	No. 8	1.6	0.1	1.5	69.7	3.8	26.5	30.3	35.7	27.1
	No. 9	1.4	0.2	1.2	72.1	4.6	11.7	10.3	13.5	12.3
	No. 10	1.2	0.2	1.0	72.2	4.8	10.8	9.9	13.2	12.0
	Ave.	1.7	0.2	1.5	72.4	3.9	21.1	21.2	29 2	23.4
Set 2										
From 70-pair set	No. 1	2.9	0.3	2.6	55.1	11.7	***67.8***	***66.0***	57.4	50.0
	No. 2	2.8	0.4	2.4	***76.7***	1.5	51.4	45.2	47.1	37.0
	No. 3	2.8	***0.4***	2.4	57.0	7.5	24.4	30.7	42.8	32.8
	No. 4	3.1	0.3	2.8	66.0	***13.4***	35.5	40.8	55.7	47.8
	No. 5	2.8	0.1	2.6	70.2	11.5	23.1	26.8	49.3	43.3
	No. 6	***3.4***	0.3	***3.1***	63.6	13.2	38.0	44.5	***59.8***	***50.3***
	No. 7	2.9	0.2	2.8	63 2	2.7	38.7	32.3	42.1	27.6
From 88-pair set	No. 8	2.4	0.2	2.3	52.9	5.6	37.7	33.1	40.8	36.2
	No. 9	2.5	0.2	2.3	56.6	6.4	28.8	25.8	23.3	21.0
From 36-pair set	No. 10	2.9	0.2	2.6	60.3	4.1	20.5	25.0	34.8	27.3
	Ave.	2.8	0.2	2.6	62.2	7.8	36.6	37 0	45 3	37.3
Set 3										
From 54-pair set	No. 1	1.4	0.2	1.2	54.7	3.5	21.3	28.4	26.2	22.4
	No. 2	1.0	0.2	0.8	39.5	2.6	29.5	27.7	34.6	21.7
	No. 3	1.0	0.2	0.8	41.1	2.9	35.2	32.3	30.4	22.8
	No. 4	1.6	0.3	1.3	53.8	7.0	***39.5***	***45.6***	32.6	26.9
	No. 5	***2.4***	***0.4***	***2.1***	***58.9***	***10.0***	29.3	35.5	***47.3***	***38.8***
	No. 6	1.0	0.2	0.7	47.4	4.8	10.8	12.0	21.1	18.7
	Ave.	1.4	0.3	1.1	49.2	5.1	27.6	30.3	32.0	25.2
CIE Set										
	No. 1	0.9	0.1	0.8	60.2	2.5	19.5	***19.9***	***23.0***	***17.1***
	No. 2	***1.2***	0.1	***1.2***	53.7	2.4	6.6	5.4	13.8	11.8
	No. 3	1.2	0.1	1.1	***67.5***	2.4	6.9	8.7	18.2	13.9
	No. 4	1.0	0.2	0.8	49.3	***6.4***	***24.3***	18.8	16.9	16.5
	No. 5	1.1	***0.2***	0.9	50.1	1.1	15.4	10.5	13.9	13.1
	Ave.	1.1	0.2	0.9	56.1	3.0	14.5	12.6	17.1	14.5

5.4.2 Performances of Different Sets of Metamers for Evaluating D65 Simulators

The performance of a metamer set for evaluating daylight simulators is mainly reflected by its capability in revealing the quality differences between various daylight simulators. So far, seven metamer sets, which include two normal sets (70-pair and 88-pair), two special sets (36-pair and 54-pair) and three effective metamer sets (Sets 1, 2 and 3), have been developed using different strategies. The spectral reflectance values for each metamer of the seven sets, plus those for the 70 metameric pairs without Fairman correction (see Section 4.2.2.1), are provided in Appendices E1 to E8. The 70-pair and 88-pair sets are described as 'normal' as the metamers of these two sets are generated through normal match prediction procedure. The 36-pair and 54-pair sets are described as 'special' as the metamers of these two sets are made with built-in spectral characteristics.

In this section, the performances of different metamer sets for evaluating D65 simulators were investigated in terms of average and maximum colour differences. In addition, the goodness-of-fit index (Nimeroff 1965, Wyszecki 1970, see Section 2.7.1) was also used as a measure for evaluating D65 simulators.

5.4.2.1 Colour Difference Results

The metamers of the seven sets were designed to have a zero colour difference under a reference illuminant (CIE D65) but to exhibit some degrees of colour difference under a test illuminant (CIE A). These metamers therefore exhibit certain degrees of colour difference under a D65 simulator. The size of this colour difference depends on two factors, which are metamer-related and illuminant-related. The metamer-related factor refers to the metameric property of a metamer, which can be quantified by a general metamerism index, such as Nimeroff-Yurow index, Moradian index or Viggiano index (see Section 2.3.10.2). The illuminant-related factor refers to the simulation of spectral power of a simulator relative to the CIE D65 illuminant. The closer the simulation, the smaller the colour differences will be.

For the 15 D65 test simulators, the average and maximum colour differences for each metamer set are listed in Tables 5.4.2 and 5.4.3 for CIELAB and CIEDE2000 colour differences respectively. The reason for using only the CIELAB and CIEDE2000 colour difference formulae (see Section 2.3.5) is that the former is a basic but important formula which has been widely used in industry for many years, while the latter is a newly developed formula with more accurate predictions to the visual results. The maximum and minimum values in each row of these two tables are noted in bold with italic and underlined respectively.

Tables 5.4.2 and 5.4.3 show that different metamer sets give different average and maximum colour differences for the same test simulator. A comparison of the two tables revealed that CIELAB and CIEDE2000 colour difference results demonstrate the same pattern in revealing the quality of the test simulators. For instance, in general, Set 2 and the 70-pair set have the largest values for the average and maximum colour differences respectively while the 88-pair and CIE sets have the smallest values for the average and maximum colour differences respectively.

It was also revealed that the Toshiba three-band fluorescent lamp has much larger colour differences while one of the GretagMacbeth filter tungsten lamps has the smallest colour differences in comparison with the other simulators, indicating that these two lamps have the worst and best quality amongst the simulators investigated. The maximum colour difference of metamers under the three-band lamp reached 11.5 ΔE^*_{ab} units.

Table 5.4.2 shows that the average colour difference (ΔE^*_{ab}) for the CIE set is 0.53 and 0.90 for the Philips and BYK F7 lamps respectively. According to the CIE specifications on metamerism index category (see Table 2.5.3), these two simulators belong to the same category of 'C'. However, the maximum colour differences shown by the 70-pair set are 1.86 and 3.41 for these two lamps respectively, which indicates the two lamps could give quite different performances for certain metamers. It is expected that the CIE set gives smaller colour differences because it exhibits a low metamerism degree in comparison with the other sets (see Tables 5.3.1 and 5.4.1). The results also revealed that Set 2 consistently gives large colour differences than the other sets, which suggests Set 2 is more effective than the other sets for discerning the quality different of D65 simulators.

Table 5.4.2 Average and maximum colour differences (CIELAB) for the seven sets and the CIE set under the 15 D65 simulators

ΔE^*_{ab} / Simul [a]	VV1	VV2	VV3	VV4	VV5	VV6	VV7	GE	GM	PH	BYK	TO	TO(3B)	GM(FT)1	GM (FT)2
(AVE)															
70-pair Set	1.26	1.10	0.49	0.97	0.61	1.03	0.52	1.10	1.37	0.64	1.25	0.64	***3.69***	0.46	0.29
88-pair Set	0.72	0.59	0.46	0.60	0.51	0.63	0.51	0.73	0.91	0.57	0.79	0.32	***2.13***	0.33	0.18
36-pair Set	0.91	0.88	0.40	0.68	0.44	0.72	0.40	0.80	1.05	0.58	1.20	0.43	***4.03***	0.30	0.25
54-pair Set	1.10	1.03	0.53	0.85	0.56	0.89	0.52	1.00	1.24	0.73	1.52	0.55	***5.05***	0.37	0.29
Set 1 (10)	0.83	0.76	0.23	0.61	0.26	0.67	0.23	1.29	1.02	0.68	1.66	0.35	***5.56***	0.41	0.31
Set 2 (10)	1.80	1.74	0.60	1.31	0.66	1.40	0.56	1.59	2.14	1.15	2.66	0.75	***8.40***	0.64	0.39
Set 3 (6)	1.15	1.00	0.37	0.83	0.47	0.90	0.39	0.98	1.32	0.52	1.16	0.49	***4.12***	0.46	0.31
CIE (5)	0.62	0.51	0.28	0.51	0.32	0.54	0.27	0.78	0.71	0.53	0.90	0.35	***2.21***	0.26	0.20
Mean	1.05	0.95	0.42	0.79	0.48	0.85	0.42	1.03	1.22	0.68	1.39	0.48	***4.40***	0.40	0.28
(MAX)															
70-pair Set	2.73	2.72	0.99	2.06	1.26	2.23	1.12	2.67	2.94	1.86	3.41	1.49	***11.48***	0.96	0.76
88-pair Set	1.78	1.45	1.08	1.43	1.09	1.53	1.12	1.60	2.43	1.68	2.13	0.59	***6.24***	0.63	0.40
36-pair Set	1.64	1.63	0.83	1.27	0.93	1.35	0.85	1.80	1.80	1.63	2.85	0.98	***9.48***	0.79	0.84
54-pair Set	2.04	2.03	0.99	1.60	1.05	1.70	1.02	1.65	2.30	1.56	2.81	1.05	***8.85***	0.79	0.60
Set 1 (10)	2.07	2.03	0.64	1.30	0.42	1.40	0.68	1.95	2.49	1.53	2.77	0.69	***11.28***	0.79	0.45
Set 2 (10)	2.60	2.54	0.83	1.87	0.98	2.00	0.88	2.11	2.94	1.86	3.41	1.09	***11.48***	0.91	0.55
Set 3 (6)	2.02	2.03	0.43	1.37	0.57	1.47	0.47	1.38	2.25	0.69	2.44	0.85	***7.52***	0.79	0.55
CIE (5)	0.79	0.67	0.51	0.60	0.53	0.64	0.53	1.14	0.96	1.02	1.24	0.49	***3.75***	0.31	0.36

a VV, GM, PH and TO are the abbreviations for VeriVide, GretagMacbeth, Philips and Toshiba respectively. TO(3B) and GM(FT) are the abbreviations for Toshiba three-band fluorescent lamp and GretagMacbeth filtered tungsten lamp respectively. All the other simulators are broad band fluorescent lamps with SPDs similar to that of the CIE F7 illuminant (short for F7 lamps). The same applies to the following four tables.

Table 5.4.3 Average and maximum colour differences (CIEDE2000) for the seven sets and the CIE set under the 15 D65 simulators

ΔE^*_{00} / Simul	VV1	VV2	VV3	VV4	VV5	VV6	VV7	GE	GM	PH	BYK	TO	TO(3B)	GM(FT)1	GM (FT)2
(AVE)															
70-pair Set	0.93	0.84	0.33	0.68	0.41	0.73	0.35	0.71	1.06	0.42	0.82	0.44	***2.51***	0.35	0.21
88-pair Set	0.55	0.45	0.33	0.41	0.37	0.43	0.37	0.51	0.70	0.47	0.56	0.22	***1.38***	0.27	0.16
36-pair Set	0.82	0.79	0.33	0.60	0.37	0.63	0.33	0.70	0.93	0.52	1.02	0.38	***3.65***	0.24	0.20
54-pair Set	0.93	0.88	0.44	0.70	0.46	0.73	0.42	0.82	1.05	0.62	1.28	0.46	***8.07***	0.28	0.23
Set 1 (10)	0.64	0.62	0.16	0.44	0.18	0.47	0.16	0.69	0.79	0.42	1.17	0.25	***4.06***	0.29	0.25
Set 2 (10)	1.48	1.41	0.44	1.05	0.52	1.12	0.39	1.19	1.72	0.85	1.83	0.65	***5.92***	0.46	0.32
Set 3 (6)	0.77	0.67	0.25	0.57	0.32	0.61	0.26	0.69	0.89	0.37	0.66	0.32	***2.66***	0.35	0.23
CIE (5)	0.51	0.44	0.18	0.38	0.20	0.40	0.17	0.50	0.61	0.41	0.62	0.23	***1.69***	0.20	0.14
Mean	0.83	0.76	0.31	0.60	0.35	0.64	0.31	0.73	0.97	0.51	0.99	0.37	***3.74***	0.30	0.22
(MAX)															
70-pair Set	2.21	2.02	0.69	1.51	0.85	1.62	0.79	1.73	2.45	1.33	2.27	1.04	***7.57***	0.74	0.57
88-pair Set	1.24	0.99	0.75	0.87	0.85	0.91	0.84	0.97	1.52	0.95	1.35	0.52	***3.78***	0.43	0.32
36-pair Set	1.76	1.85	0.86	1.32	0.83	1.36	0.72	1.65	2.01	1.53	2.89	0.95	***9.64***	0.58	0.72
54-pair Set	1.70	1.72	1.03	1.19	1.12	1.26	1.14	1.50	2.14	1.39	3.13	0.83	***11.18***	0.68	0.47
Set 1 (10)	1.64	1.49	0.38	1.04	0.35	1.12	0.38	1.23	1.93	0.63	1.78	0.54	***6.42***	0.66	0.38
Set 2 (10)	2.21	2.02	0.86	1.51	0.83	1.62	0.72	1.73	2.45	1.53	2.89	1.00	***8.79***	0.74	0.60
Set 3 (6)	1.70	1.61	0.35	1.17	0.50	1.26	0.31	1.15	1.85	0.53	1.50	0.73	***4.78***	0.68	0.47
CIE (5)	0.90	0.84	0.29	0.59	0.29	0.62	0.29	0.73	1.20	0.66	1.02	0.29	***3.22***	0.31	0.22

5.4.2.2 Goodness-of-fit Indices

Goodness-of-fit of SPDs (Nimeroff 1965, Wyszecki 1970, see Section 2.7.1) is another measure for quantifying the quality of daylight simulators. The measure is different from the CIE method in a way that it only calculates the spectral power disagreement between a target illuminant and a test simulator either with or without the weighting of colour matching functions, while the CIE method uses metamers. The measure has three different forms, two are non-weighted, denoted as WY Index1 (see Equation 2.7.1) and WY Index2 (see Equation 2.7.3) respectively, one is weighted, denoted as WY Index3 (see Equation 2.7.4).

Table 5.4.4 reports the three goodness-of-fit indices for the 15 test simulators, which were calculated using the measured SPDs (ranging from 380 nm to 780 nm at 5 nm interval, see Section 3.3.1.1 for the measurement conditions). The CIE 1964 10° colour matching functions were used as the weights for calculating WY Index3. The results show that the three goodness-of-fit indices are on a similar scale with WY Index1 giving slightly larger results. Figure 5.4.5 shows the scatter diagrams comparing every two goodness-of-fit indices for all the test simulators. The three-band fluorescent lamp was not included in the diagrams as this lamp is very different from the others with much larger goodness-fit indices. It can be seen that in general, the three indices correlate well with each other in an almost linear relationship. However, for simulators of same type, e.g. filtered tungsten lamps, the goodness-of-fit results do not exhibit much difference between the different lamps.

Table 5.4.4 Testing three goodness-of-fit indices using the 15 D65 simulators

Index / Simul	W1	W2	W3	W4	W5	W6	W7	GE	GM	PH	BYK	TO	TO(3B)	GM(FT)1	GM (FT)2
WY Index1	38.90	37.34	35.80	39.89	38.13	40.26	35.99	39.42	37.88	41.28	42.83	34.97	69.62	10.02	11.48
WY Index2	27.66	27.35	26.57	27.84	27.64	28.32	27.01	26.69	27.61	36.10	37.18	25.94	183.42	8.00	9.14
WY Index3	30 13	30 70	24 75	30.12	28 02	31.00	24 55	29 80	25 18	30 69	32 18	28 20	65 08	6 42	6 76

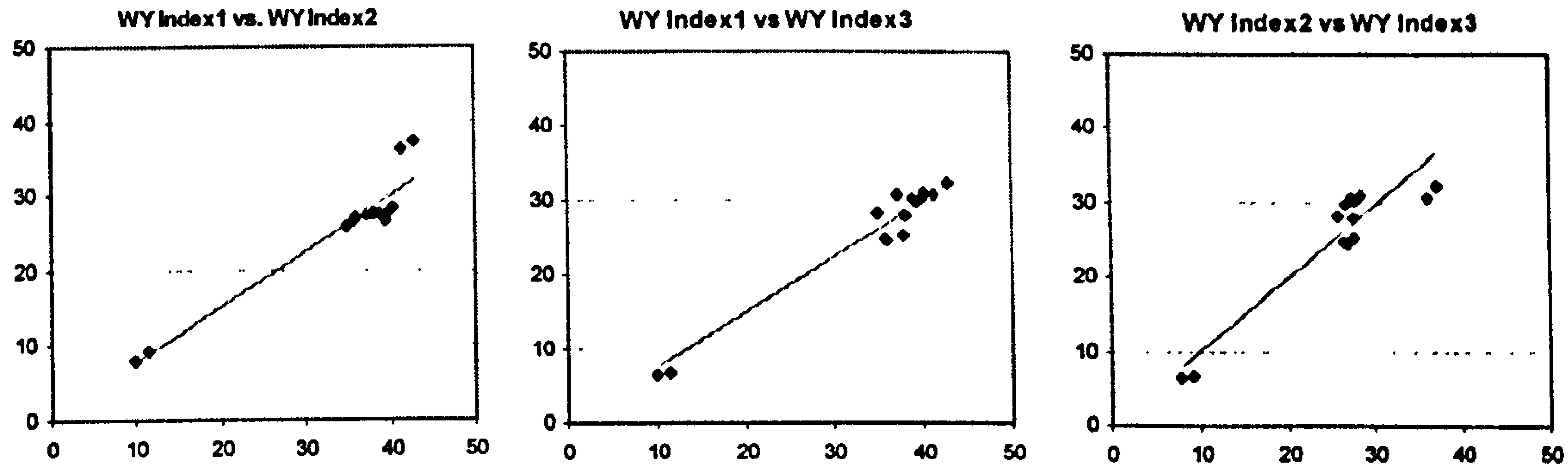


Figure 5.4.5 Comparison between every two goodness-of-fit indices for the 14 D65 simulators (the three-band fluorescent lamp was not included as its indices are much larger than those of the other simulators)

5.4.2.3 Ranking Results

Table 5.4.5 lists the ranking results for the 15 test simulators based on average colour differences and goodness-of-fit indices, with ranking '1' for the best quality and '15' for the worst quality. It shows that different metamer sets and goodness-of-fit indices give different ranking results for the test simulators. Furthermore, the colour difference results disagree with the goodness-of-fit indices quite markedly for the rankings of some test simulators, e.g. the GretagMacbeth (GM) and Philips (PH) broad band fluorescent lamps, one of the GretagMacbeth filtered tungsten lamps, etc. This is expected as the goodness-of-fit indices only count the spectral differences between the target and test illuminants, while the colour differences given by the metamer sets reflect both the SPD of the test illuminant and the metameric properties of the metamers used. It can be concluded that the ranking results for the quality of daylight simulators very much depend on the assessment measures used.

For the ranking results based on the average colour differences of the metamer sets, it was found that in general, different sets agree with each other for most of the test simulators. However, odd ranking results are given by the three effective metamer sets for the two filtered tungsten lamps. For instance, according to the CIE set and the three general sets (70-pair, 36-pair and 54-pair), the two filtered tungsten lamps are ranked 1 and 2 respectively. However, according to Set 1, these two lamps are ranked 4 and 6 respectively. The reason for this may lie in the fact that the effective metamers were selected based on colour difference variations (Sets 1 and 2) and reflectance differences (Set 3), and these effective metamers mainly reflect the spectral characteristics of broad band fluorescent lamps. Therefore, these effective sets are more applicable for evaluating fluorescent lamps than for evaluating filtered tungsten lamps, particularly in the case of Set 1.

Table 5.4.5 Ranking results for the 15 test simulators based on average colour differences and goodness-of-fit indices

Ranking/Simul	VV1	VV2	VV3	VV4	VV5	VV6	VV7	GE	GM	PH	BYK	TO	TO(3B)	GM(FT)1	GM (FT)2
(Ave ΔE^*_{ab})															
70-pair Set	13	11	3	8	5	9	4	10	14	7	12	6	15	2	1
88-pair Set	11	8	4	9	6	10	5	12	14	7	13	2	15	3	1
36-pair Set	12	11	4	8	6	9	3	10	13	7	14	5	15	2	1
54-pair Set	12	11	4	8	6	9	3	10	13	7	14	5	15	2	1
Set 1 (10)	11	10	2	7	3	8	1	13	12	9	14	5	15	6	4
Set 2 (10)	12	11	3	8	5	9	2	10	13	7	14	6	15	4	1
Set 3 (6)	12	11	2	8	5	9	3	10	14	7	13	6	15	4	1
CIE (5)	11	8	4	7	5	10	3	13	12	9	14	6	15	2	1
(Ave ΔE^*_{00})															
70-pair Set	13	12	2	8	5	10	4	9	14	6	11	7	15	3	1
88-pair Set	12	9	4	7	5	8	6	11	14	10	13	2	15	3	1
36-pair Set	12	11	4	8	5	9	3	10	13	7	14	6	15	2	1
54-pair Set	12	11	4	8	6	9	3	10	13	7	14	5	15	2	1
Set 1 (10)	11	10	2	8	3	9	1	12	13	7	14	5	15	6	4
Set 2 (10)	12	11	3	8	5	9	2	10	13	7	14	6	15	4	1
Set 3 (6)	13	11	2	8	4	9	3	12	14	7	10	5	15	6	1
CIE (5)	12	10	3	7	4	8	2	11	13	9	14	6	15	5	1
(WY Index)															
WY Index1	9	6	4	11	8	12	5	10	7	13	14	3	15	1	2
WY Index2	10	7	4	11	9	12	6	5	8	13	14	3	15	1	2
WY Index3	10	12	4	9	6	13	3	8	5	11	14	7	15	1	2

5.4.2.4 Agreement between Different Metamer Sets

The agreement between two different metamer sets in evaluating daylight simulators can be reflected by the ranking results in Table 5.4.5. However, the ranking results provide only a rough indicator. To compare the performances of different metamer sets in a more quantitative way, the Performance Factor (PF/3) (see Section 2.7.7) was again used as a measure to define the relationship between two sets of metamers. The smaller the PF/3 value, the better agreement between two sets of metamers in comparison. For a perfect linear relationship between two metamer sets, the PF/3 value equals to zero.

The comparison was first conducted for the four general metamer sets, including the two normal sets (70-pair and 88-pair sets) and the two special sets (36-pair and 54-pair sets). Table 5.4.6 reports the PF/3 results between every two general sets for the average colour difference results (CIELAB and CIEDE2000). These sets were also compared with each other using scatter diagrams, shown in Figures 5.4.6 and 5.4.7 for the CIELAB and CIEDE2000 colour difference results respectively. Table 5.4.6 shows that the four general metamer sets agree with each other well, all PF/3 values are less than 20 with average of 15. The two special sets (36-pair and 54-pair sets) exhibit an almost perfectly linear relationship between each other, while the agreement between the two normal sets (70-pair and 88-pair sets) is slightly worse. The reason for this may lie in the fact that the two normal sets were generated using different dyestuff database and the two special sets using the same dyestuff databases. This finding implies that metamer sets selected from a large database based upon same material may have a similar performance for evaluating daylight simulators.

The three effective metamer sets (Sets 1, 2 and 3) and the CIE set were also compared to the four general sets. Table 5.4.7 reports the PF/3 values between the effective sets (or the CIE set) and the general sets for the average colour difference results (CIELAB and CIEDE2000). The corelation between the effective sets (or the CIE set) and the general sets was also illustrated using scatter diagrams, see Figures 5.4.8 and 5.4.9 for CIELAB and CIEDE2000 colour difference results respectively. It shows that the CIE set agreed best with the four general sets, the average PF/3 values are less than 20. This further proved that the CIE metamers are representatives of real metamers. Set 2 and Set 3 show better agreement with the general sets than Set 1. On average, these two sets have PF/3 values quite close to the CIE set, suggesting that their performances for evaluating daylight simulators are similar to the CIE set. However, it worth noting that the performances of these two sets are more or less related to the test simulators used. For instance, the metamers in Set 2 were selected by showing large colour difference variations under different test simulators, while those in Set 3 were selected by showing large reflectance differences near the three peak wavelengths of broad band fluorescent lamps.

Table 5.4.6 PF/3 values between each pair of general metamer sets

	70-pair Set	88-pair Set	36-pair Set	54-pair Set
ΔE^*_{ab}				
88-pair Set	20			
36-pair Set	12	21		
54-pair Set	12	19	4	
Ave.	15	20	12	12
ΔE^*_{00}				
88-pair Set	25			
36-pair Set	15	24		
54-pair Set	18	22	6	
Ave.	19	24	15	15

Table 5.4.7 PF/3 values between the general metamer sets and the effective sets (plus the CIE set)

	70-pair Set	88-pair Set	36-pair Set	54-pair Set	Ave.
ΔE^*_{ab}					
Set 1	39	49	34	35	39
Set 2	19	32	14	15	20
Set 3	10	27	14	17	17
CIE Set	18	23	14	14	17
ΔE^*_{00}					
Set 1	37	48	30	32	37
Set 2	18	34	12	16	20
Set 3	10	27	20	23	20
CIE Set	19	26	13	16	19

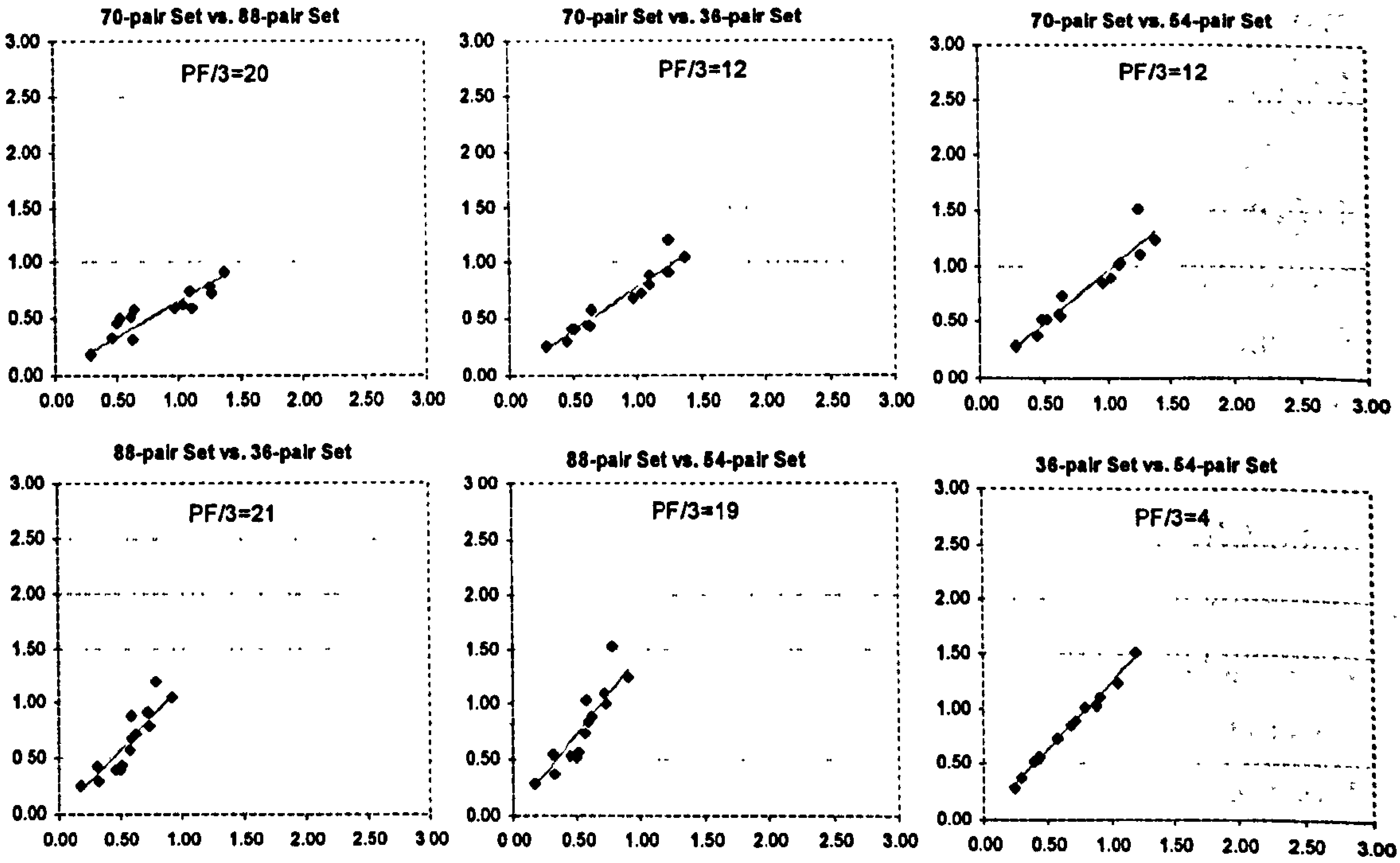


Figure 5.4.6 Comparing each pair of general metamer sets for the average colour differences (CIELAB)

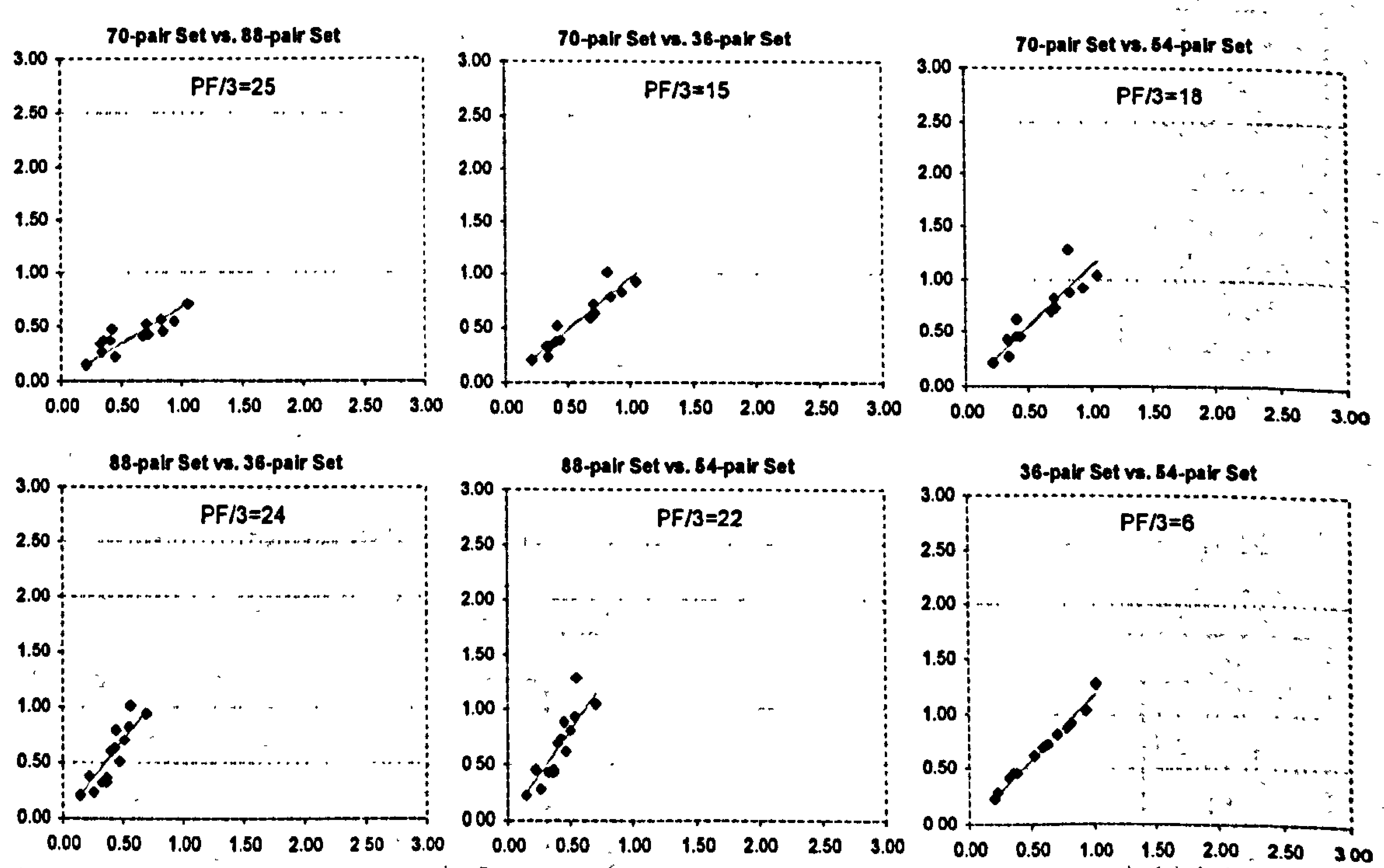


Figure 5.4.7 Comparing each pair of general metamer sets for the average colour differences (CIEDE2000)

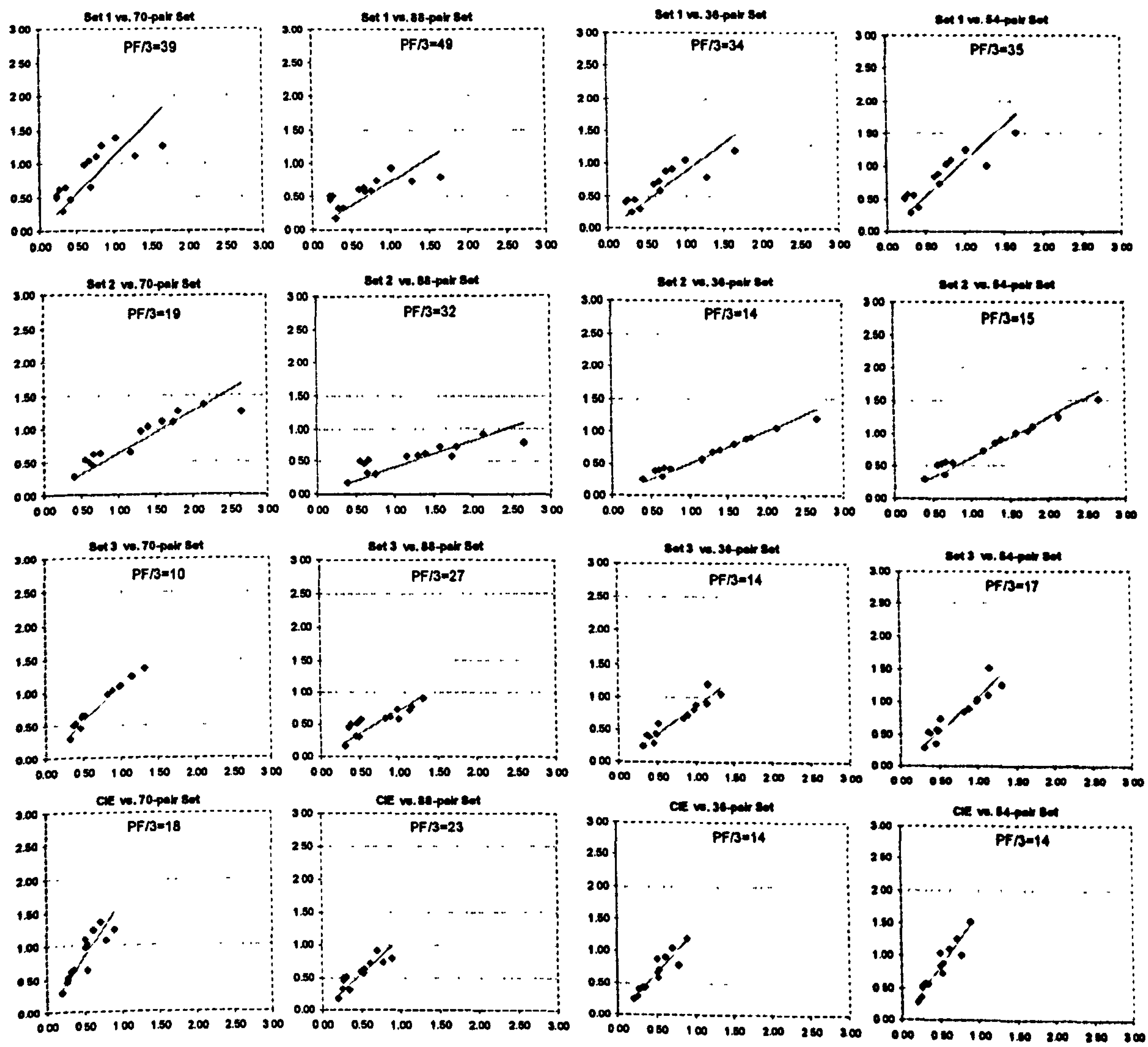


Figure 5.4.8 Comparing the effective sets with the general sets for the average colour differences (CIELAB)

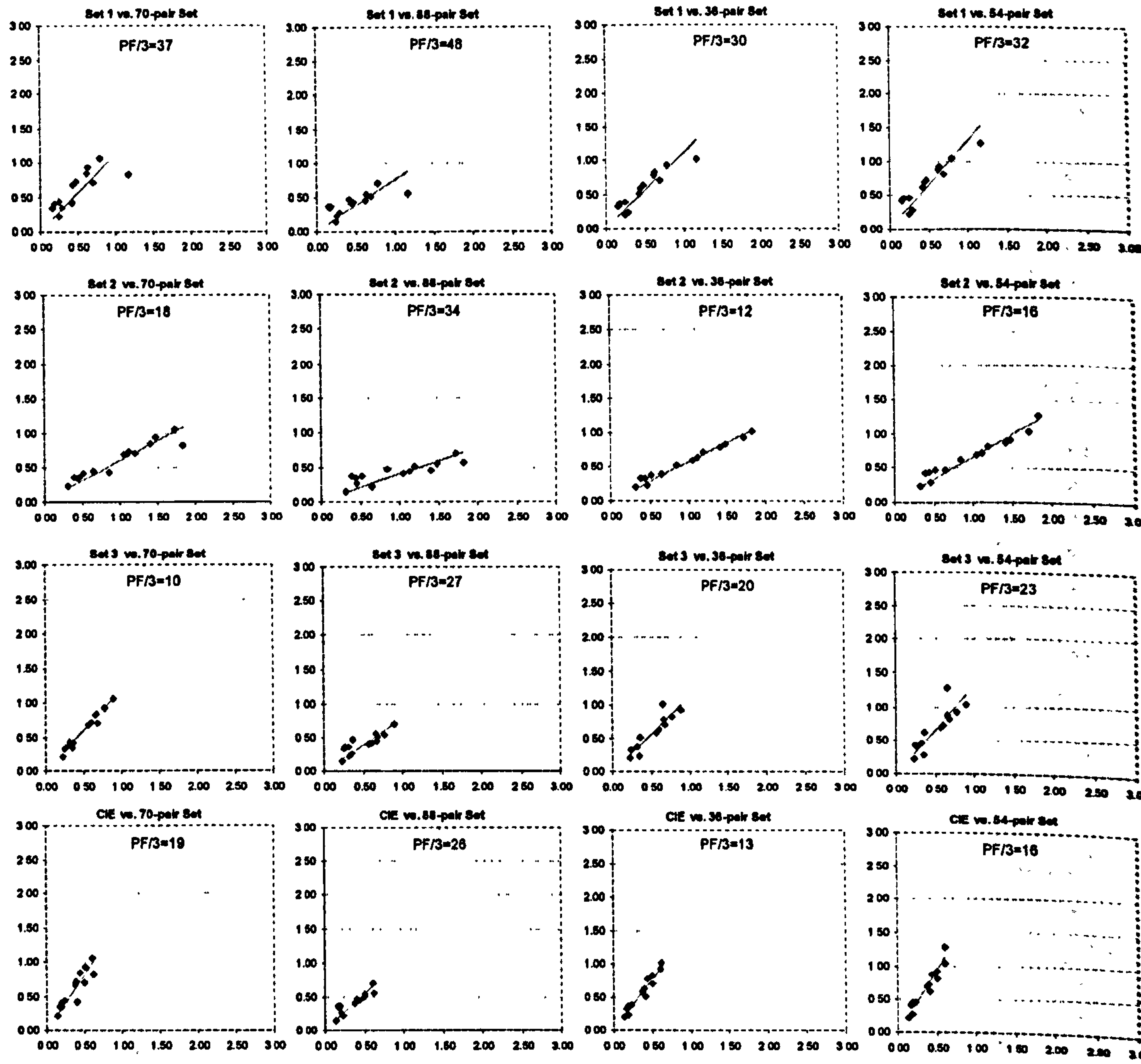


Figure 5.4.9 Comparing the effective sets with the general sets for the average colour differences (CIEDE2000)

5.5 Conclusions

Seven metamer sets, including two normal sets, two special sets, and three effective sets, were generated for evaluating the quality of 15 D65 simulators. Fairman correction method was implemented for generating the former four sets. An investigation into the metameric properties of metamers revealed that the CIE special index of metamerism gives very different results from the general metamerism indices such as those developed by Nimeroff-Yurow, Moradian and Viggiano. A close agreement was found between the Moradian and Viggiano indices. A further investigation into the crossovers of metamers shows that the number of crossovers has no obvious connections with the metamerism degree of metamers, and a large proportion of crossovers occur at or near Thornton's three prime wavelengths at 450 nm, 540 nm and 610 nm.

The 15 test simulators accumulated earlier were evaluated in terms of the average and maximum colour differences for each metamer set. It was found the one of the GretagMacbeth filter tungsten lamps shows the best quality while the Toshiba three-band fluorescent lamp shows the worst quality. The maximum colour difference of metamers could reach as large as 11.5 ΔE^*_{ab} units under the Toshiba three-band lamp. It was also found that simulators with the same CIE metamerism index category may give very different colour differences for metamers. The CIE metamer set exhibits lower metamerism degree in comparison with the generated metamer sets, hence it gives smaller colour differences for the test simulators. The test simulators were also evaluated using the three indices based on the goodness-of-fit of SPDs. It was found that different indices of goodness-of-fit generally agree with each other, however, they are not sensitive measures for evaluating the same type of daylight simulators, e.g. broad band fluorescent lamps. The rankings of test simulators based on the goodness-of-fit indices are not in good agreement with those based on the average colour difference results of metamer sets.

It was also found that the four general metamer sets agree well with each other for the average colour difference results, in particular, the two special metamer sets, generated using the same dyestuff and substrate, exhibit an almost perfect linear relationship. This implies that metamer sets selected from a large database based upon the same material may have a similar performance for evaluating daylight simulators. On average, the CIE set agrees best with the four general sets for evaluating the test simulators, which proves the CIE metamers are representatives of real metamers. It was also found that a limited number of metamers could be selected from a range of real metamers to perform as effective as the CIE set for evaluating daylight simulators.

CHAPTER 6
INVESTIGATING THE CIE COLOUR RENDERING INDEX METHOD FOR EVALUATING D65 SIMULATORS

6.1 Introduction

In Chapter 5, the quality of 15 D65 simulators was evaluated using different metamer sets, for which metamerism is a major concern. In practice, the colour rendering properties (see Section 2.3.9) of daylight simulators are also a major interest of lamp manufacturers and users with respect to the lamp quality. A good daylight simulator should render colours correctly, which means the colour appearance of a specimen is preserved when the light source is changed from a reference illuminant (e.g. one phase of CIE D illuminants, see Section 2.3.3.1) to a test simulator.

The CIE colour rendering index (see Section 2.5.4.1), including the CIE general colour rendering index (CRI) and CIE special colour rendering index, was first recommended by the CIE in 1965. The CRI is most widely quoted by the lighting industry as a criterion for evaluating the colour rendering properties of light sources so that this chapter only deals with the CRI results. Numerous researchers investigated the CIE colour rendering index method (see Section 2.8.1) and their results indicated that CIE colour rendering index is generally a reliable measure for quantifying the colour rendering properties of light sources. However, no specific research was reported for evaluating daylight simulators using the CIE colour rendering index method. Hence, this chapter is dedicated to the investigation of CRI for evaluating daylight simulators.

In this chapter, the CRI results for the 15 D65 simulators accumulated earlier were first examined, and questions were raised with respect to the validity of the CIE method. Ten test colour sets, including six normal colour sets, three selected colour sets and one combined set, were generated. The characteristics of these test colour sets together with the CIE test colour set were analysed in terms of colour distributions and colour inconstancy index results. The generated test colour sets and the CIE test colour set were used to investigate the CIE colour rendering index method. The performance of the CIE method was also tested using two chromatic adaptation transforms (CATs), incorporated with five colour difference formulae, for evaluating daylight simulators.

6.2 Investigating the CRI Results for D65 Simulators

To investigate the CIE colour rendering index method for evaluating daylight simulators, the 15 D65 simulators accumulated in Chapter 3 (see Section 3.3.1.1) were again used as test simulators in this chapter. These lamps include 12 broad-band fluorescent lamps having SPDs similar to that of CIE F7 illuminant (called F7 lamps below), 1 three-band fluorescent lamp and 2 filtered tungsten lamps. Their CRI results were analysed below.

6.2.1 CRI Results for D65 Simulators

Table 6.2.1 reports the colorimetric results for the 15 D65 test simulators (part of the results were taken from Table 3.3.1). The results in Table 6.2.1 include CIE chromaticity co-ordinates (x, y) and (u, v), correlated colour temperature (CCT), CRI (the reference illuminant for each test simulator was taken either according to the CIE recommendation or using CIE D65 illuminant) and CIE metamerisin index for visible range (MI_{vis}). The maximum and minimum values in each column are noted in bold with italic and underlined respectively. Figure 6.2.1 shows the colour distributions of these simulators in CIE 1960 (u, v) chromaticity diagram.

It should be noted that to calculate CRI for a light source, a reference illuminant should be chosen. According to the CIE (1995a, see Section 2.5.4.1), the reference illuminant for a daylight simulator should be one phase of CIE daylight illuminants (see Section 2.3.3.1) having the same CCT as that of the test simulator. This means the reference illuminant chosen for a test simulator is located on the locus of CIE daylight illuminants (see Figure 6.2.1) and has the closest distance to the test simulator in the CIE 1960 (u, v) chromaticity diagram (Hunt 1998, pp.96). For instance, the reference illuminant for the BYK F7 lamp should be a phase of CIE daylight illuminants close to a CCT at 6000K. However, this study aims to test the CIE colour rendering index method especially for evaluating daylight simulators, it is reasonable to take the CIE D65 illuminant as the reference illuminant for all the D65 test simulators.

Table 6.2.1 Colorimetric results for the 15 D65 simulators investigated

Simulator [a]	x	y	u	v	Δ uv1 [b]	Δ uv2 [b]	CCT (K)	Ra [c]	Ra [d]	MIvis
CIE D65	0.3127	0.3290	0.1978	0.3122	0.0000	0.0000	6504	100	100	0.00
VV1	0.3203	0.3344	0.2011	0.3149	0.0041	0.0004	6058	95	94	0.62
VV2	0.3188	0.3361	0.1994	0.3153	0.0034	0.0011	6141	96	95	0.49
VV3	0.3096	0.3280	0.1960	0.3116	0.0020	0.0016	6688	98	99	0.25
VV4	0.3150	0.3307	0.1988	0.3130	0.0012	0.0003	6366	96	95	0.51
VV5	0.3090	0.3250	0.1968	0.3104	0.0021	0.0004	6741	98	98	0.32
VV6	0.3147	0.3296	0.1990	0.3126	0.0012	0.0001	6387	95	95	0.54
VV7	0.3085	0.3247	0.1965	0.3103	0.0024	0.0005	6751	98	99	0.26
GE	0.3156	0.3272	0.2005	0.3119	0.0027	0.0018	6326	93	93	0.82
GM	0.3158	0.3317	0.1990	0.3135	0.0016	0.0003	6296	93	93	0.70
PH	0.3153	0.3298	0.1993	0.3128	0.0015	0.0004	6341	98	98	0.55
BYK	0.3219	0.3419	0.1993	0.3176	0.0056	0.0025	5963	94	95	0.92
TO	0.3198	0.3314	0.2019	0.3138	0.0042	0.0018	6090	97	95	0.34
TO (3B)	0.3135	0.3212	0.2014	0.3095	0.0044	0.0041	6529	88	88	2.31
GM(FT)1	0.3131	0.3341	0.1962	0.3141	0.0025	0.0024	6440	94	95	0.23
GM(FT)2	0.3127	0.3311	0.1970	0.3130	0.0011	0.0011	6486	96	96	0.18

a VV, GM, PH and TO are the abbreviations for VeriVide, GretagMacbeth, Philips and Toshiba respectively. TO(3B) and GM(FT) are the abbreviations for Toshiba three-band fluorescent lamps and GretagMacbeth filtered tungsten lamps respectively. All the other simulators are broad band fluorescent lamps with SPDs similar to that of CIE F7 illuminant (short for F7 lamps).

b Δuv1 and Δuv2 are the chromaticity deviations relative to the CIE D65 illuminant and test simulator's own reference illuminant respectively.

c CIE general colour rendering index when the reference illuminants for each test simulator were chosen based on the CIE recommendations using the closest CIE daylight illuminant as the reference illuminant.

d CIE general colour rendering index when CIE D65 illuminant was taken as the reference illuminant for all the 15 test simulators.

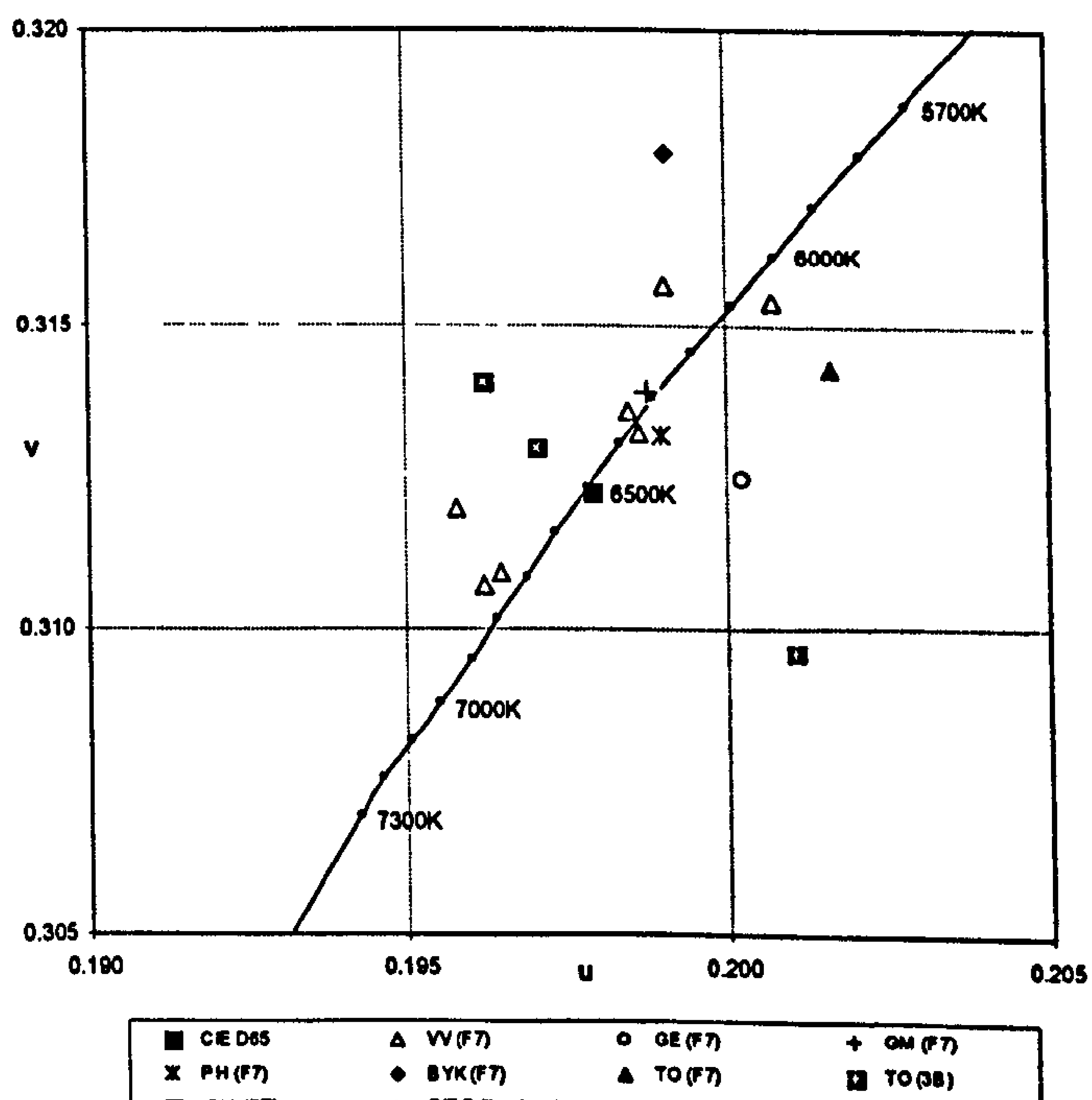


Figure 6.2.1 Chromaticity co-ordinates (u, v) for the 15 D65 simulators investigated together with the chromaticity locus for CIE daylight illuminants.

The CRI results (R_a) in Table 6.2.1 were calculated for each test simulator under two conditions. Firstly, the reference illuminant for each simulator was chosen according to the CIE recommendation (see above). Secondly, CIE D65 illuminant was taken as the reference illuminant for all the test simulators. This was done because the lamps investigated are all supposed to simulate CIE D65 rather than daylight of any other CCT. The results from this method should correlate visual results under one of the lamps with calculations based on CIE D65. It can be seen that the two CRI results are very close, indicating that the SPDs of test simulators' own reference illuminants are very similar to that of the CIE D65 illuminant. The reason for this is that all the test simulators have close CCT to the CIE D65 illuminant, with a range between around 6000K and 6750K.

CIE (1995a, see Section 2.5.4.1) also specified that the distance between a test simulator and its reference illuminant should be less than 0.0054 in CIE 1960 (u, v) chromaticity diagram. The chromaticity deviation results in Table 6.2.1 were calculated for each test simulator relative to CIE D65 illuminant and to its own reference illuminant. The BYK F7 lamp has chromaticities furthest from CIE D65 illuminant while the Toshiba three-band fluorescent lamp has chromaticities furthest from its own reference illuminant. All the test simulators have chromaticity deviations within the CIE tolerance of 0.0054.

6.2.2 Comparing Filtered Tungsten lamps with Broad Band Fluorescent lamps

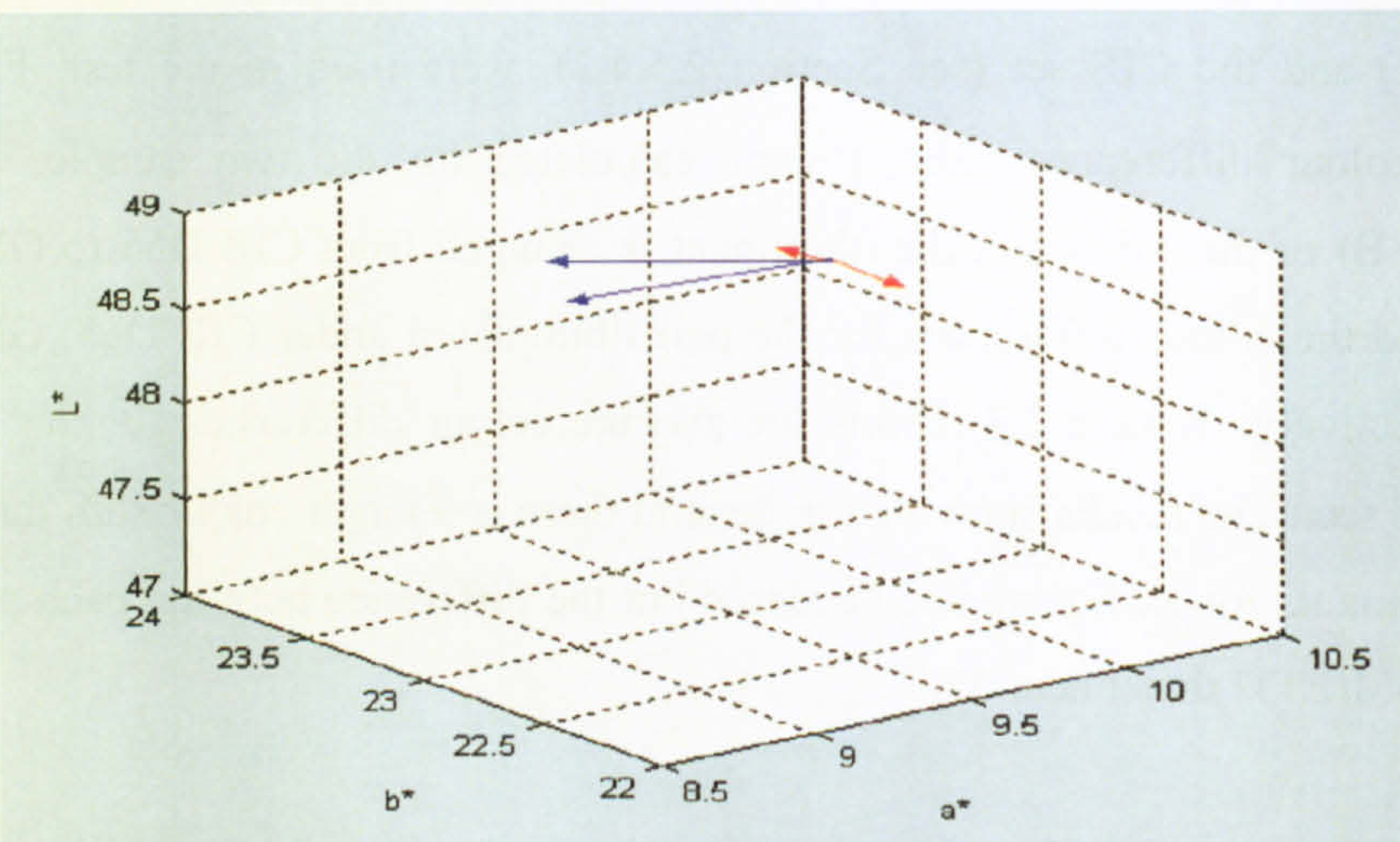
An inspection in Table 6.2.1 shows that the CRT results (using test simulators' own reference illuminants) of the F7 lamps and filtered tungsten lamps range from 93 to 98, with that of the three-band fluorescent lamp being the lowest of 88. A further inspection in Figure 6.2.1 reveals that a daylight simulator having a correct CCT, e.g. Toshiba three-band fluorescent lamp (TO(3B)), or having chromaticities close to the CIE daylight illuminant locus, e.g. GretagMacbeth F7 lamp (GM(F7)), does not necessarily have better CRI results. This suggests that the SPDs of daylight simulators play a crucial role in determining the CRI results. It was also found that four F7 lamps, including three VeriVide lamps (VV3, VV5 and VV7) and one Philips lamp (PH), have the best index results of 98, outperforming the two GretagMacbeth filtered tungsten lamps (GM(FT)1 and GM(FT)2), which were designed to have a better simulation of CIE D65 illuminant. This is somewhat surprised, given the fact that the filtered tungsten lamps show close chromaticities, CCT and better metamerism index results in comparison with the fluorescent lamps. An earlier investigation of D65 simulators also revealed that there are no clear relations between CRI and metamerism index, and between CRI and chromaticities (see Figure 3.3.2). In particular, the BYK F7 lamp, despite its chromaticities, CCT and the worst metamerism index results amongst all the test simulators investigated, achieved a CRI of 94, the same value as the filtered tungsten lamp GM(FT)1.

To further investigate this, a test was carried out to compare a filtered tungsten lamp GM(FT)2 to a broad band fluorescent lamp VV3 for rendering metameric pairs. Three metamer sets, including the 70-pair and 88-pair sets generated in Chapter 5 (see Sections 5.2.1 and 5.2.2) and the CIE set (see Section 2.5.4.2), were used in the test. For each metamer, the colour differences (ΔE^*_{ab}) were calculated for the two samples (named Samples A and B) of the pair when the illuminant is changed from CIE D65 to GM(FT)2 and to VV3, and the colour differences for the pair illuminated under CIE D65, GM(FT)2 and VV3, respectively. Table 6.2.2 reports the average colour differences for the 70-pair, 88-pair and CIE sets. The results show that in general there is a larger colour shift due to the change of illuminants for each sample considered but the difference between each pair was smaller under GM(FT)2 than under VV3.

An example is demonstrated in Figure 6.2.2, in which the colour distributions (CIE L* a* b* space) of the two samples of a metamer illuminated under CIE D65, GM(FT)2 and VV3 (CIE 10° Observer was used) are shown. It can be seen that the two metameric samples are perfectly matched under CIE D65 (reference illuminant). However, they do not match with each other when illuminated under either GM(FT)2 or VV3. Larger colour shifts were observed for the two samples when the illuminant is changed from CIE D65 to GM(FT)2 (shown by the two blue vectors) than to VV3 (shown by the two red vectors). However, the colour shifts under GM(FT)2 are more or less in the same direction, though they are larger in magnitudes than those under VV3. This indicates that GM(FT)2 changes the colour appearance of the two metameric samples more than VV3 does. For metamerism, the colour difference between the two samples is smaller under GM(FT)2 (shown by the distance between the two ends of blue vectors) than under VV3 (shown by the distance between the two ends of red vectors). For this particular pair, it is clear that VV3 is better in colour rendering corresponding to a larger CRI, but GM(FT)2 gives better metamerism index.

Table 6.2.2 The colour differences (ΔE^*_{ab}) were calculated for the two samples of a metamer pair when the illuminant is changed from CIE D65 to GM(FT)2 and to VV3, and for a metamer pair illuminated under CIE D65, GM(FT)2 and VV3, respectively. Only the average colour differences for the 70-pair, 88-pair and CIE sets were reported in this table.

Ave. ΔE^*_{ab}	CIE D65 --> VV3		CIE D65 --> GM(FT)2		CIE D65	VV3	GMT(FT)2
	Sample A	Sample B	Sample A	Sample B	Sample A & B	Sample A & B	Sample A & B
70-pair	0.57	0.49	0.61	0.57	0.00	0.49	0.29
88-pair	0.36	0.51	0.51	0.55	0.00	0.46	0.18
5-pair (CIE)	0.32	0.50	0.60	0.56	0.00	0.28	0.20



	(Sample A) L*	a*	b*	(Sample B) L*	a*	b*	ΔE^*_{ab}
CIED65	48.11	9.60	22.82	48.11	9.60	22.82	0.0
GM(FT)2	48.36	8.75	22.99	48.05	8.98	22.95	0.39
VV3	48.12	9.31	22.62	48.05	9.94	22.69	0.64

Figure 6.2.2 Colour distributions in CIE L* a* b* space for the two samples (A and B) of a metamer under CIE D65 (starting point of the four vectors), filtered tungsten lamp GM(FT)2 (ending points of two blue vectors) and F7 lamp VV3 (ending points of two red vectors).

6.2.3 Doubts with Respect to the Validity of CIE Colour Rendering Index Method

As the CIE colour rendering index method was originally developed for assessing the colour rendering properties of a wide range of light sources, it is in question whether the CIE method is sufficiently accurate in discerning the relatively small differences in colour rendering properties of daylight simulators. Some doubts with respect to the validity of the CIE method are raised here:

- Are the limited number of test samples, originally chosen from the Munsell color order system based on their colour features (i.e. Hue, Chroma, Value), sufficient for calculating colour rendering index for a wide range of colours illuminated under test simulators?
- Do the colour inconstancy (see Section 2.3.8) characteristics of the CIE test colours affect their effectiveness for evaluating colour rendering properties of light sources. (The CIE test colours were originally chosen by the CIE based on their colour attributes without any consideration of their colour inconstancy characteristics.)
- Is the von Kries chromatic adaptation transform (see Section 2.3.7.1), adopted by the CIE method to account the chromatic adaptation effect resulting from a change of light source from the reference illuminant to a test illuminant, elaborate enough to be used for daylight simulators?
- Is the CIE U*V*W* colour difference formula (2.3.5.1) accurate enough for calculating colour differences in the method?

The following sections further investigate the CIE method in order to clarify these doubts.

6.3 Generating Different Test Colour Sets

The CIE method uses 14 test colours (CIE 1995a, see Section 2.5.4.1), chosen from the Munsell colour order system, for calculating the colour rendering index. The first eight test colours (Samples 1 to 8) cover the hue circle with moderate saturation and approximately the same lightness and the other six colours (Samples 9 to 14) represent four highly saturated primary colours (R, Y, G, B) as well as complexion and foliage colours. Although the CIE test colours were carefully chosen with a considerable colour gamut (see Figure 6.3.3), it was found that there are limitations in using these samples. First, the reflectance values of the CIE test colours, provided by the CIE as part of the method, were obtained based on Munsell colour patches. Hence, the CIE test colours are only representatives of one type of surface colours (paint). Second, as the method was recommended by the CIE almost five decades ago, there was no consideration with regard to the colour inconstancy (see Section 2.3.8) of the test colours. It has been known for a long time that the appearance of a colour tends to remain approximately constant over a wide range of illumination conditions, a phenomenon termed as colour constancy (Hunt 1998, pp.123). However, in most situations, it is impossible for a colour to fully preserve its original colour appearance when the illumination condition changed. A colour incontancy index was proposed by Luo et al

(2000a, see Section 2.3.8) to quantify the degree of a colour in departing from colour constancy. For the test colours used to revealing the colour rendering properties of daylight simulators, it is important to know the degree of their colour inconstancy. If the test samples are almost colour constant, calculations will not reveal differences between light sources. It may be better to use colour inconstant samples.

In this section, ten sets of test colours, including six sets of normal colours, three sets of selected colours and one set of combined colours, were generated. (The normal colours were obtained from the physical samples, e.g. Munsell colour patches. The selected colours were chosen from the normal colours to include samples exhibiting a large degree of colour inconstancy. Finally, a combined colour set, including a limited number of colours chosen from the CIE test colour set and selected colour sets, was formed.) These generated test colour sets together with the CIE test colour set were used to investigate the CIE method for evaluating the colour rendering properties of 15 D65 simulators.

Note that although the CIE recommended the use of 2° Observer for calculating CRI (see Section 2.5.4.1), the evaluation of daylight simulators also involves the assessment of CIE metamerism index results, which are calculated using the 10° Observer according to the CIE recommendation (see Section 2.5.4.2). Hence, for consistency, the 10° Observer was used throughout this chapter (except the CRI results in Table 6.2.1) for calculating the colour rendering index. It was found that there is no big difference between the colour rendering index results calculated using 2° Observer and 10° Observer. For a colour illuminated under a CIE illuminant, e.g. CIE D65, its tristimulus values were calculated using its reflectance and ASTM weights (see Weighting Tables 5.3, 5.19, 5.35 in ASTM E 308-95 for CIE illuminants A, D65 and F11 respectively). For a colour illuminated under a daylight simulator, its tristimulus values were calculated using the same method as described in Section 4.2.2.1.

6.3.1 Six Sets of Normal Colours

The 6 sets of normal colours include 3 sets of paint samples, 2 sets of textile samples and 1 set of thread samples. The 3 paint sample sets used the majority of colour patches in the Munsell Color Book, Glossy Edition (see Section 2.3.6.1), NCS Colour Atlas (see Section 2.2.6.2) and DIN Colour Charts (see Section 2.3.6.3), each including 1322, 1697 and 999 samples, abbreviated as P1, P2 and P3 respectively. All the samples of the 3 paint sets were measured using a spectrophotometer GretagMacbeth Color-Eye 7000A (see Section 2.3.12.1) with wavelength ranging from 400 nm to 700 nm and at a 10 nm interval. The measurement condition was set to be specular included and UV included. Each sample was represented by its measured reflectance.

The 2 textile sample sets are the same as the 70-pair and 88-pair metamer sets described in Chapter 5 (see Sections 5.2.1 and 5.2.2), each including 140 (2 times 70) and 176 (2 times 88) samples, abbreviated as T1 and T2 respectively. The 70-pair set was generated using dyestuff databases for wool substrate and the 88-pair set for cotton and polyester substrates. The reflectance of these metamer samples were used to represent the test colours here. The thread sample set, abbreviated as T3, includes 705 thread samples supplied by Coats Viyella Group. These thread samples were measured using a DataColor SF600 spectrophotometer under specular included and UV included measurement condition. The measured reflectance was recorded in 20 nm interval, ranging from 400 nm to 700 nm, which was later interpolated into 10 nm interval reflectance using a 3rd-order Lagrange polynomials (Li 2004).

6.3.1.1 Colour Distributions

Table 6.3.1 summarises the colour distributions in lightness for the six normal colour sets. Their colour distributions in CIE a* b* diagram are shown in Figures 6.3.1 and 6.3.2 for the paint sample sets (P1, P2 and P3) and for the textile and thread sample sets (T1, T2 and T3) respectively. The CIE L*, a* and b* results for all these samples were calculated under CIE D65/10°. The results in Table 6.3.1 show that P1 (Munsell colours) and P2 (NCS colours) have the largest proportion of colours showing high lightness (L* greater than 60), and P3 (DIN colours) has the largest proportion of colours exhibiting medium lightness (L* between 60 and 40). The two textile sample sets T1 and T2, both have the largest proportion of colours showing medium lightness, and that proportion is extremely high (94%) for T2. The thread sample set T3 has a similar proportion of colours showing high, medium and low lightness (L* less than 40) respectively.

Table 6.3.1 Details for the six sets of normal colours

Six Sets of Normal Colours	Abbreviated	Sample Number	Colour distributions in Lightness (%)		
			L*>60	40<L*<60	L*<40
Munsell Color Book (Glossy Edition)	P1	1322	47	32	21
NCS Altas	P2	1697	53	34	13
DIN Colour Charts	P3	999	23	40	37
Textile (wool substrate)	T1	140	30	47	23
Textile (cotton and polyester substrates)	T2	176	4	94	2
Thread	T3	705	34	33	33

Figure 6.3.1 shows that P1 and P2 each demonstrate a large colour gamut in the CIE a* b* diagram, while that for P3 is slightly smaller. Figure 6.3.2 shows that T1, T2 and T3 each occupy a considerably large colour gamut in the CIE a* b* diagram, particularly for T3 which contains many more samples than the two textile sample sets. Overall, the six sets covered a very large colour and lightness gamut.

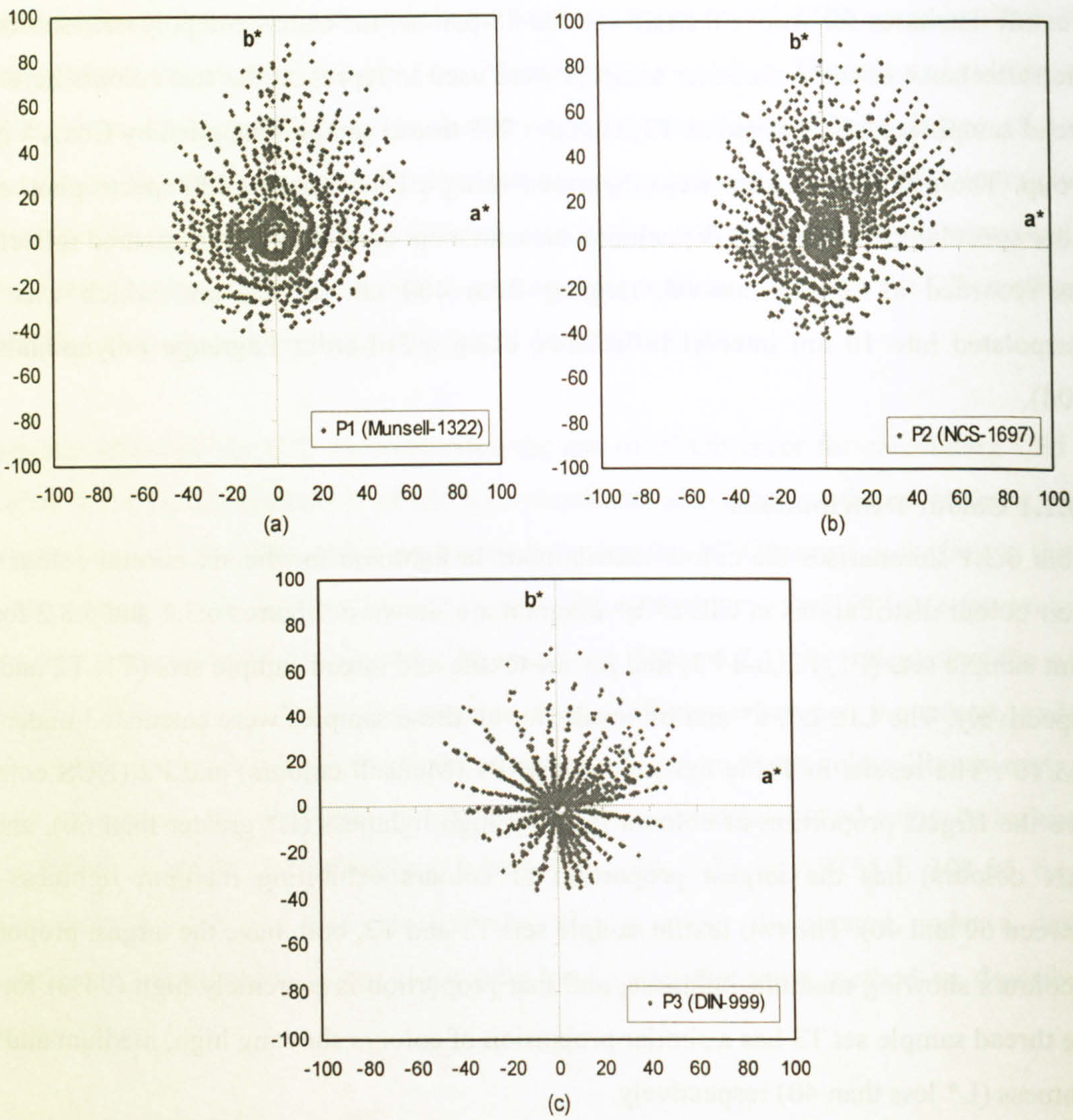


Figure 6.3.1 Colour distributions for the 3 paint sample sets: (a) P1 (1322 colours chosen from Munsell Color Book, Glossy Edition), (b) P2 (1697 colours chosen from NCS Colour Atlas), (c) P3 (999 colours chosen from DIN Colour Charts).

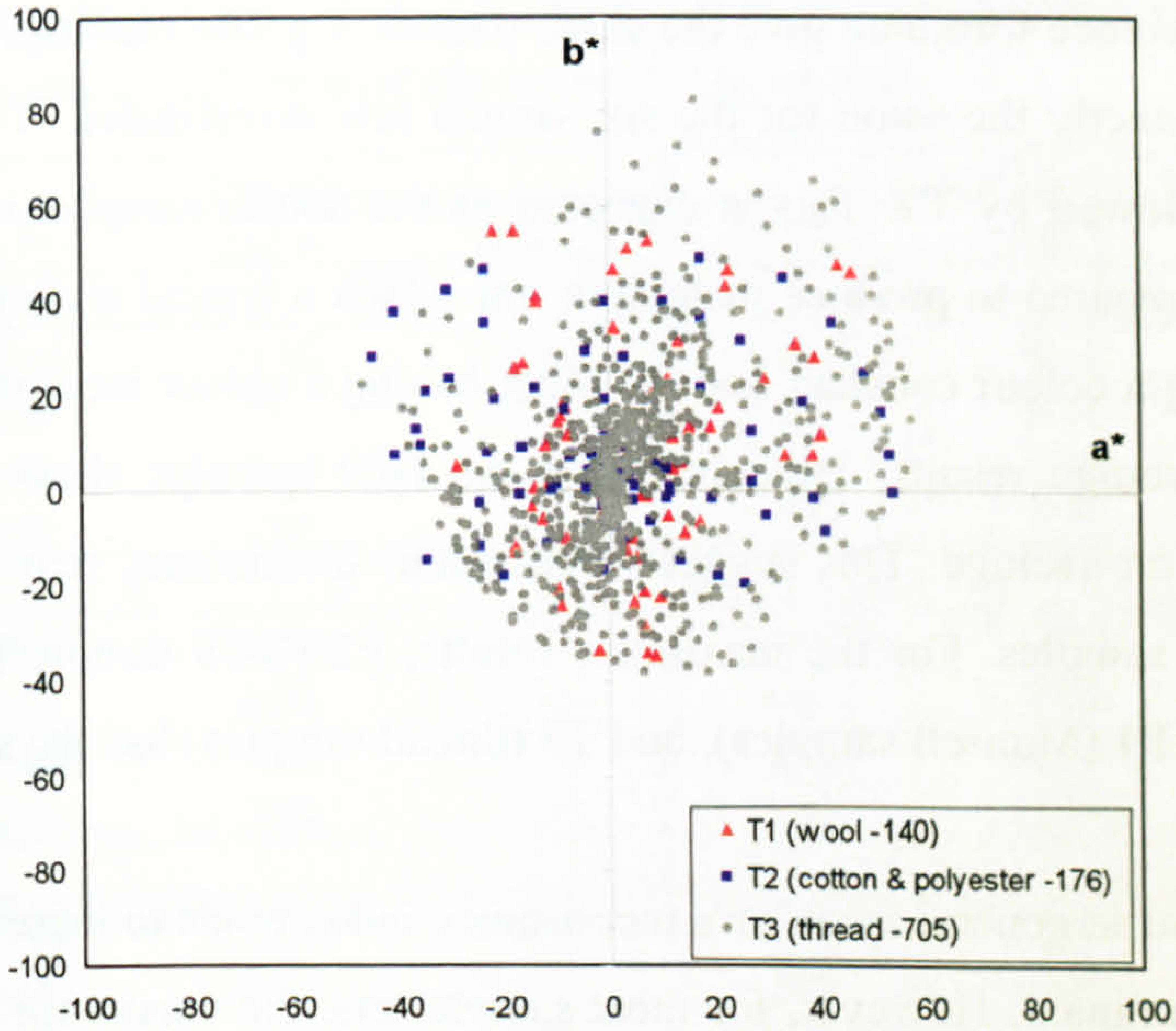


Figure 6.3.2 Colour distributions for the two textile sample sets T1, T2 (140 and 176 samples respectively) and the thread sample set T3 (705 samples).

6.3.1.2 Colour Inconstancy Index Results

The colour inconstancy index was calculated for each sample of the six normal colour sets. Note that CMCCON02 is the latest version of colour inconstancy index (Luo 2003). However, during the work of this study, CMCCON02 was not published so an earlier version called CMCCON00 was implemented. The difference between these two versions is that CMCCON00 uses CMCCAT2000 while CMCCON02 uses CAT02 chromatic adaptation transform (see Section 2.3.7). The results obtained from these two versions should not be very different.

Table 6.3.2 lists the maximum, minimum, average and median colour inconstancy index results for each of the six normal colour sets. Two colour difference formulae, CIELAB and CIEDE2000, were used for calculating the colour difference between the corresponding colour of a sample (when transformed, by means of chromatic adaptation transform, form a test to a reference illuminant) and the actual colour of that sample under the reference illuminant. CIE D65 illuminant was used as the reference illuminant and CIE illuminants F11 and A were used as the test illuminants respectively. The 'Average' results in Tables 6.3.2 are the average colour differences calculated under test illuminants CIE F11 and CIE A (also see Table 6.3.3), representing the final colour inconstancy index.

A detailed inspection in Table 6.3.2 revealed that the colour inconstancy index results using the two colour difference formulae give the same pattern, e.g. the rankings results from the two formulae are exactly the same for the six sample sets investigated. T1 has the largest average results, followed by T2. This is expected as the textile samples in these two sets were deliberately prepared to produce metamers, for which a typical metamer includes two samples, one having a colour constant and the other having a colour inconstant property. P3 has the smallest average results, indicating that the DIN samples show relatively small colour inconstancy on average. This suggests that colour inconstancy may be one criterion for producing DIN samples. For the maximum results, P2 (NCS samples) has the largest values, followed by P1 (Munsell samples), and T3 (thread samples) has the smallest values.

It was also found that in general a colour's inconstancy index tends to increase when CIE A was used as test illuminant. However, for most sample sets, the maximum results occurred under test illuminant CIE F11. This proves that the colour inconstancy index is an illuminant dependent measure, the choice of test illuminant (the reference illuminant is usually specified) may well determine the size of colour inconstancy index results for different colours.

Table 6.3.2 Colour inconstancy index results (using both CIELAB and CIEDE2000 colour difference formulae under test illuminants CIE F11 and CIE A respectively) for the six normal colour sets generated. Only the maximum, minimum, average and median results are reported for each set.

	CIELAB			CIEDE2000 (1:1:1)		
	CIE F11	CIE A	Average	CIE F11	CIE A	Average
P1 (Munsell)						
max	22.78	14.06	17.23	11.94	8.15	9.77
min	0.08	0.11	0.10	0.07	0.13	0.11
ave.	3.85	4.13	3.99	2.54	2.89	2.71
median	2.88	3.56	3.30	1.98	2.73	2.47
P2 (NCS)						
max	26.79	15.45	19.99	12.70	7.92	9.97
min	0.02	0.01	0.01	0.03	0.00	0.02
ave.	4.45	4.05	4.25	2.95	2.77	2.86
median	3.16	3.49	3.56	2.29	2.58	2.61
P3 (DIN)						
max	17.66	11.54	13.61	10.41	6.50	8.27
min	0.08	0.07	0.11	0.06	0.07	0.14
ave.	2.86	3.23	3.05	2.01	2.30	2.16
median	2.33	2.58	2.57	1.78	2.06	2.04
T1 (textile)						
max	16.95	10.31	13.16	13.03	11.65	9.92
min	0.77	0.56	0.66	0.55	0.56	0.81
ave.	5.35	5.81	5.58	3.61	4.45	4.03
median	4.07	6.37	5.42	2.56	4.44	3.57
T2 (textile)						
max	13.05	12.10	10.87	6.45	12.62	8.06
min	0.40	0.86	0.81	0.32	1.12	0.86
ave.	2.99	5.55	4.27	2.24	4.32	3.28
median	2.67	5.24	4.37	1.94	3.95	3.17
T3 (thread)						
max	10.94	12.47	8.72	7.79	7.25	5.47
min	0.20	0.31	0.45	0.20	0.24	0.38
ave.	3.29	3.68	3.48	2.50	2.80	2.65
median	2.77	2.98	3.02	2.26	2.63	2.53

6.3.2 Selected Colour Sets, CIE Test Colour Set and Combined Set

Three sample sets, denoted as S1, S2 and S3 respectively, were selected from the 6 normal colour sets described above. Each selected set includes 10 samples, chosen as having the top ten colour inconstancy indices amongst the normal colour sets. The colours in S1 were chosen from the three paint sample sets, P1, P2 and P3. The colours in S2 were chosen from the two textile sample sets, T1 and T2, and those in S3 from the thread sample set T3. The reason to make S2 and S3 individually is that the samples in T1 and T2 are all metamers on wool and cotton/polyester substrates and they are very different from the thread sample in T3. As the colour inconstancy index results calculated using both CIELAB and CIEDE2000 formulae demonstrated the same pattern for different sample sets, see Table 6.3.2, only the results based on CIEDE2000 colour difference formula were used for choosing the colours.

It was found that for the 10 selected samples in S1, 3 are from P1 and 7 from P2. P3 did not have any samples being selected due to its relatively small colour inconstancy index results. For the 10 selected samples in S2, 7 are from T1 and 3 from T2. Figure 6.3.3(a) shows the colour distributions in CIE a* b* diagram for the three selected colour sets and the CIE set. It was found that the colours in each selected set are highly concentrated in a small region, in particular, most colours in S2 are near neutral colours. Hence, a combined colour set (denoted as C1) is generated, which includes ten selected colours, six from the CIE set, one from S1 and three from S2. These colours were selected based on three criteria. First, they have high colour inconstancy indices. Second, they occupy a colour gamut as large as possible, see Figure 6.3.3(b). Third, for colours within a certain region in CIE a* b* diagram, (see Figure 6.3.3(a)), the priority was given to the CIE test colours to be included in C1. (The reflectance values for the samples in S1, S2, S3 and C1 are listed in Appendix F.)

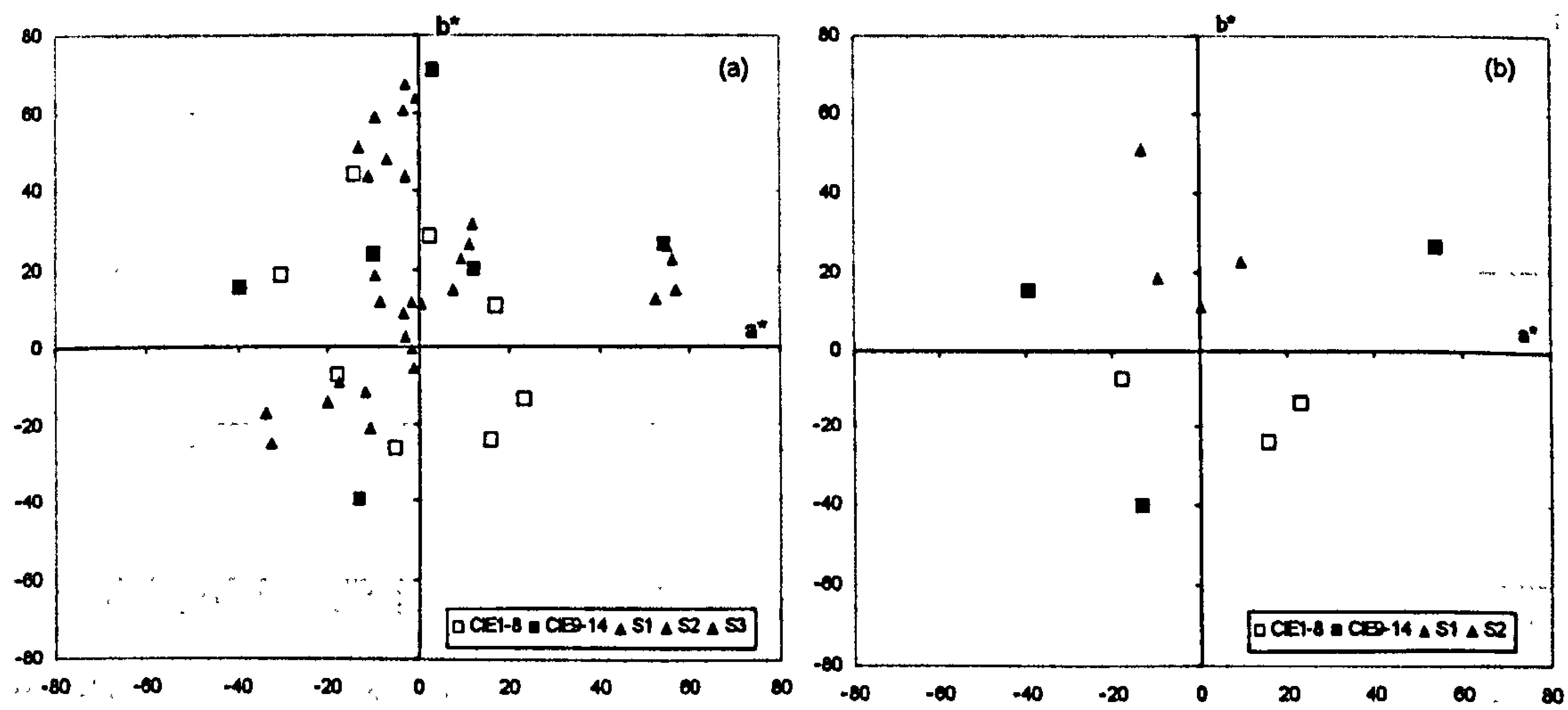


Figure 6.3.3 (a) Colour distributions for the three selected colour sets and the CIE test colour set, (b) Colour distributions for the combined set

Table 6.3.3 lists the colour inconstancy index and colorimetric results (CIE L*, a*, b*, C* and h under CIE D65 illuminant) for each sample in the three selected colour sets, the CIE test colour set and the combined set. For each set, the maximum and minimum colour inconstancy index results are noted in bold with italic and underlined respectively. A careful examination in Table 6.3.3 shows that all the CIE test colours and selected colours have medium to high lightness values, with S1 (selected paint samples) having the largest average results, followed by the CIE set, and S3 (selected thread samples) having the smallest average results. It was also found that the CIE test colours and selected colours generally exhibit medium to high chroma values except some samples in S2. For colour inconstancy results, S1 has the largest average results, followed by C1, and the CIE set has the smallest results. This is expected as the samples in S1 were selected from the three paint colour sets, which contain a considerable number of colours having large colour inconstancy indices. It worth noting that the majority of the CIE test colours do not exhibit large colour inconstancy indices (except Sample 12, which is a primary blue colour), however, the average results of the CIE set are slightly larger than those of the normal colour sets in Table 6.3.2.

Table 6.3.3 Colour inconstancy index results (using CIELAB and CIEDE2000 colour difference formulae under test illuminants CIE F11 and CIE A respectively) together with CIE L*, a*, b* and C* results for the three selected colour sets, CIE test colour set and combined set.

							CIELAB			CIEDE2000 (1:1:1)		
		L*	a*	b*	C*	h	CIE F11	CIE A	Average	CIE F11	CIE A	Average
S1												
From P1 (Munsell)	S1-1	49.16	-32.62	-25.36	41.32	217.87	20.10	***14.06***	17 08	11.40	***8.15***	9.77
	S1-2	72.56	-2.89	67.28	67.34	92.46	22.78	11.67	17.23	11.94	6.78	9.36
	S1-3	72.73	-3.27	60.51	60.60	93.10	21.16	10.34	15.75	11.36	6.33	8.84
From P2 (NCS)	S1-4	61.56	-13.14	51.23	52.88	104.39	***26.79***	13.19	***19.99***	12.33	7.61	***9.97***
	S1-5	52.81	-3.11	43.54	43.65	94.08	21.66	10.54	16.10	***12.70***	7.20	9.95
	S1-6	66.23	-0.83	63.78	63.78	90.75	20.05	12.16	16.11	11.34	7.36	9.35
	S1-7	53.67	-11.09	43.52	44.91	104.30	22.87	11.30	17.09	11.46	6.97	9.21
	S1-8	47.90	-33.77	-17.07	37.84	206.82	16.94	12.81	14.87	9.98	7.92	8.95
	S1-9	64 56	-9 61	58.73	59.51	99.29	20.38	12.10	16 24	10.35	7.08	8.71
	S1-10	56.39	-6.84	48.07	48.56	98.10	18 60	10.78	14.69	10.38	6.92	8.65
	Ave	59 76			52 04		21.13	11.90	16 51	11.32	7.23	9 28
S2												
From T1 (textile)	S2-1	38.82	-1.24	-5.39	5.53	257.06	6.48	9.18	7.83	8.24	11.59	***9.92***
	S2-2	42.30	0.67	11.31	11.33	86.64	8.13	7.07	7.60	9.60	8 31	8.96
	S2-3	48.11	9 60	22.82	24.76	67.19	14.11	5.08	9 60	***13.03***	4.59	8.81
	S2-4	56.64	-1.45	-0.38	1.50	194.59	4.56	8.30	6.43	6.11	10.65	8.38
	S2-5	47.16	-9.37	18.31	20.57	117.10	***16.95***	9.37	***13.16***	9.95	6.59	8.27
	S2-6	45.25	-8.26	11.79	14.39	125.02	15.48	7.37	11.42	10.28	5.93	8.10
	S2-7	71.56	12.15	31.54	33.80	68.94	13.16	6.69	9.93	10.28	5.23	7.76
From T2 (textile)	S2-8	47.55	-1.51	11.87	11.97	97.25	2.81	***9.98***	6.39	3.49	***12.62***	8.06
	S2-9	58 76	-2.89	2.71	3.96	136.86	3.35	7.93	5.64	4.48	11.00	7.74
	S2-10	59.10	-3.46	9.16	9.80	110 69	3.09	8.46	5.78	3.88	11.21	7.55
	Ave	51 52			13 76		8 81	7 94	8 38	7.93	8 77	8 35
S3												
From T3 (thread)	S3-1	28.86	-11.83	-11.79	16.70	224.90	5.92	6 54	6.23	5.15	5.80	***5.47***
	S3-2	55 05	11.51	26.55	28.94	66.57	***8.83***	3.98	6.40	7.54	3.32	5.43
	S3-3	44.24	57.15	14.90	59.06	14.61	4.75	***11.67***	***8.21***	3.54	***7.25***	5.39
	S3-4	32.53	-10.57	-21.24	23.72	243.55	8.52	6.00	7.26	6.35	4.30	5.32
	S3-5	48.39	7.57	15.00	16.80	63.23	6.68	2.94	4.81	***7.79***	2.86	5.32
	S3-6	44 66	56.10	23.08	60.66	22.36	5.38	10.59	7.98	3.85	6.77	5.31
	S3-7	29 94	-17.70	-8.90	19.82	206.70	7.43	5.91	6.67	5.96	4.62	5.29
	S3-8	46.04	55.14	25.90	60.92	25.16	5.53	10.08	7.81	3.92	6.56	5.24
	S3-9	48.14	52.67	12.45	54.12	13.30	3.83	11.10	7.46	3.02	7.15	5.08
	S3-10	38.01	-19.96	-14.50	24.67	215.99	8.24	5.88	7.06	5.93	4.15	5.04
	Ave	41 59			36 54		6 51	7.47	6 99	5.30	5.28	5 29
CIE Test Colour												
	CIE-1	61.03	17.27	10.94	20.45	32.37	1.58	3.35	2.46	1.16	2.42	1.79
	CIE-2	59.89	2.68	28.43	28 56	84.62	2.48	1.82	2.15	1.93	1.36	1 64
	CIE-3	60 86	-14.34	43.85	46.13	108.10	11.75	6.76	9 26	5 89	3.93	4.91
	CIE-4	61.07	-30.23	18.41	35.40	148.65	1.44	6.80	4.12	0.74	4.03	2.39
	CIE-5	62.90	-17.93	-7.19	19.31	201.84	2.32	3.90	3.11	1.84	2 83	2.34
	CIE-6	62.75	-5.06	-26.34	26.82	259.14	7.29	3.97	5.63	4.74	2.73	3.74
	CIE-7	61.89	15.91	-24.06	28.84	303.48	3.92	3.46	3.69	1.94	2.77	2.36
	CIE-8	63.15	23.38	-13.68	27.09	329.68	2.43	6.11	4.27	1.10	3.79	2.44
	CIE-9	39.28	54.43	26.56	60.56	26.01	4.75	10.96	7.86	3.03	5.99	4.51
	CIE-10	79.56	3.32	71.00	71.07	87.32	11.08	7.33	9.20	6.20	2.91	4.55
	CIE-11	52.36	-39.46	15.19	42.29	158.95	4.33	7.96	6.14	2.15	4.87	3.51
	CIE-12	33.65	-13.17	-39.70	41.82	251.65	***18.87***	***14.50***	***16.68***	***10.79***	***7.33***	***9.06***
	CIE-13	79.59	12.33	20.43	23.86	58.88	1.03	2.19	1.61	0.69	1.44	1.06
	CIE-14	40.00	-9.75	23.73	25.65	112.34	8.52	4.13	6.33	5.19	3.17	4.18
	Ave	57 51			35 56		5 84	5 94	5 89	3.39	3 54	3 46
C1												
From CIE test	CIE-5	62.90	-17.93	-7.19	19.31	201.84	2.32	3.90	3.11	1.84	2.83	2.34
	CIE-7	61.89	15.91	-24.06	28.84	303.48	3.92	3.46	3.69	1.94	2.77	2.36
	CIE-8	63.15	23.38	-13.68	27.09	329.68	2.43	6.11	4.27	1.10	3.79	2.44
	CIE-9	39.28	54.43	26.56	60.56	26.01	4.75	10.96	7.86	3.03	5.99	4.51
	CIE-11	52.36	-39.46	15.19	42.29	158.95	4.33	7.96	6.14	2.15	4.87	3.51
	CIE-12	33 65	-13.17	-39.70	41.82	251.65	18.87	***14.50***	16 68	10.79	7.33	9.06
From S1	S1-4	61.56	-13.14	51.23	52.88	104.39	***26.79***	13.19	***19.99***	12.33	7.61	***9.97***
From S2	S2-2	42.30	0.67	11.31	11.33	86.64	8.13	7.07	7.60	9 60	***8.31***	8.96
	S2-3	48 11	9.60	22.82	24.76	67.19	14.11	5.08	9.60	***13.03***	4.59	8.81
	S2-5	47.16	-9.37	18.31	20.57	117.10	16.95	9.37	13.16	9.95	6.59	8.27
	Ave	51 23			32 95		10 26	8 16	9 21	6.58	5 47	6.02

6.4 Investigating the Colour Rendering Properties of D65 Simulators Using Different Test Colour Sets

In this section, the colour rendering properties of 15 D65 simulators accumulated (see Section 6.2) were investigated using 12 test sets, including 6 normal sets (see Section 6.3.1), 3 selected sets, the CIE test colour set and combined set (see Section 6.3.2). The CIE test colours are grouped into two sets, denoted as CIE(1-8) and CIE(1-14) respectively. CIE(1-8) includes CIE test colours 1 to 8, which are recommended by the CIE for calculating CRI. CIE(1-14) includes the total 14 CIE test colours. Two chromatic adaptation transforms (CATs), the von Kries (see Section 2.3.7.1) and CMCCAT2000 (see Section 2.3.7.2), were used to account for the chromatic adaptation effects resulting from a change of light source from the reference illuminant to test illuminant. The von Kries transform was adopted in the CIE method (see Section 2.5.4.1) while the CMCCAT2000 was a more elaborate transform recently developed by Luo et al (2000b). For colour difference calculation, in addition to the formula (CIEU*V*W) used in the CIE method, four later developed formulae, CIELAB (see Section 2.3.5.2), CMC (see Section 2.3.5.3), CIE94 (see Section 2.3.5.4) and CIEDE2000 (see Section 2.3.5.5), were used.

6.4.1 Colour Rendering Properties of Different D65 Simulators

For each sample in the 12 test sets, the colour difference between its corresponding colour (transformed form a test illuminant to a reference illuminant by a CAT) and its actual colour under the reference illuminant was calculated. Here, the original CIE recommendation was applied, i.e. the test illuminant used one of the D65 simulators investigated and the reference illuminant used one phase of CIE daylight illuminants which has the same CCT as the test simulator (see Section 6.2). The colour rendering property of each test simulator was investigated using the average and maximum colour differences of each test set, and the ranking results based on the average colour differences of each test set.

6.4.1.1 Colour Difference Results

Tables 6.4.1 and 6.4.2 list the average and maximum colour differences respectively for each test set after applying von Kries CAT or CMCCAT2000 to all the test colours. It was found that the results using different colour difference formulae correlate with each other very well and they demonstrate the same pattern for revealing the colour rendering properties of the test simulators (see more in Section 6.4.2). Hence, only the CIEU*V*W* and CIEDE2000 colour differences were reported for simplicity. The maximum and minimum values in each row of the tables are noted in bold with italic and underlined respectively. The CRI results for these test simulators are also included in the tables (see the values in bracket).

Note that the CRI results were calculated using 5 nm interval data, including the reflectance of CIE test colours, the SPD of each simulator and CIE 2° Observer. The colour differences in Tables 6.4.1 and 6.4.2 were calculated using 10 nm interval data, including the reflectance of test colours and the weights of each simulator under CIE 10° Observer (see Section 4.2.2.1 for the calculation of weights). The reflectance of CIE test colours was provided at 5 nm interval in CIE Publication 13.3 and these values were abridged to 10 nm interval data using a 3rd-order Lagrange polynomial. This causes a small discrepancy between the average colour differences 'Ave ΔE (CIEU*V*W*+von Kries)' and the CRI results (in bracket) in Table 6.4.1.

A careful inspection of Table 6.4.1 show that the VeriVide F7 lamps (VV3, VV7) and Philips F7 lamp (PH), which have the highest CRI of 98, generally give the smallest average colour differences. The Toshiba three-band fluorescent lamp TO(3B) has the lowest CRI of 88 and it gives the largest average colour differences. Table 6.4.1 also shows that the average colour differences are quite varied with different test sets. In general, the selected sets (S1, S2) and combined set (C1) give larger results than the other sets. P2 (NCS samples) give the largest results amongst the 3 paint sample sets (P1, P2 and P3), and T1 (70-pair metamers) give the largest results amongst the textile and thread sample sets (T1, T2 and T3). The results given by CIE(1-8) are slightly larger than those given by P1, a set including the majority of Munsell colour patches. It was also found that the filtered tungsten lamp GM(FT)2 exhibits the smallest colour differences under S2, while the three-band fluorescent lamp exhibits the largest colour differences under S1. This suggests that selected sample sets such as S1, which were generated by choosing samples having large colour inconstancy indices, perform markedly different from the other sets for evaluating the colour rendering properties of daylight simulators.

Table 6.4.2 shows that simulators having the same CRI may exhibit very different colour differences, depending on the test colours used. For instance, the three VeriVide (VV3, VV5 and VV7) and Philips (PH) F7 lamps all have CRI of 98, however, the maximum colour differences under the Philips lamp are much larger than those under the VeriVide lamps, particularly when the textile set T1 was used. This suggests that the CIE test colours, originally selected from the Munsell colour patches, might not be representative of colours of different media (e.g. textile) for evaluating the colour rendering properties of daylight simulators. For the three-band fluorescent lamp, which has the lowest CRI of 88, the maximum colour differences given by S1 could reach as much as 15 in ΔE^*_{uvw} units, two times that given by the CIE test colours. This suggests that in practice, a daylight simulator with CRI lower than 90 may render colours, particularly colours of high colour inconstancy very poorly, much worse than the CIE test colours could reveal. In addition, the maximum colour differences under the three-band fluorescent lamp are about 10 times those under VV3, which is a good simulator with CRI of 98. This implies that a difference of 10 units in CRI could make a real difference for two daylight simulators in rendering colours, particularly colours showing high colour inconstancy.

6.4.1.2 Ranking Results

Tables 6.4.3 list the ranking results for the test simulators based on the average colour differences, with 1 and 15 for the best and worst colour rendering property. It shows the ranking results for the test simulators vary with the different test colour sets used. For some simulators, e.g. the three-band fluorescent lamp and GE and GM F7 lamps, the ranking results based on different sets are more or less similar, with a maximum difference of 3 grades. However, the variation of ranking results for the Philips F7 lamp and filtered tungsten lamps are much larger, with a maximum difference of 10 grades.

In general, the three paint sample sets (P1, P2 and P3) give similar ranking results for the test simulators, which are also in good agreement with those given by the CIE test colours, CIE(1-8) and CIE(1-14). This is expected given the fact that the CIE test colours were selected from the Munsell colour order system. The ranking results given by the textile sets (T1, T2) and the thread set (T3) generally agree with each other. A considerable variation was found for the ranking results given by the three selected sets (S1, S2 and S3) for VV1, VV5 and Philips F7 lamps, and the two filtered tungsten lamps. It was found S2 performs differently from the other sets by markedly increasing the ranking results of the filtered tungsten lamps. It was also found that the ranking results are slightly affected by using different colour difference formulae and CATs.

6.4.2 Performances of Different Colour Difference Formulae and CATs

The performances of the CIE colour rendering index method partly depend on the performances of the CAT and colour difference formula used. To investigate this, for each test set, a pair of average colour differences (see Table 6.4.1) using different formulae (e.g. CIEU*V*W* vs CIELAB) was compared for the 15 test simulators. The Performance Factor (PF/3) (see Section 2.7.7) was again adopted as a measure to define the relationship between two sets of data in comparison and the results are reported in Table 6.4.4. It shows that for the 12 test colour sets used, the colour difference results from the four modern formulae, CIELAB, CMC (1:1), CIE94 (1:1:1) and CIEDE2000 (1:1:1), agree with each other very well, with PF/3 values less than 10 for most of the cases. The CIEU*V*W* colour difference results generally agree with those using the four advanced formulae. However, it was found that the degree of agreement reduces if the test colours show high colour inconstancy (e.g. the colours in S3). This suggests that the four advanced formulae have a similar performance for quantifying the colour rendering properties of daylight simulators, and they all outperform CIEU*V*W* to some extent.

A further inspection in Table 6.4.4 also shows that the PF/3 results obtained using either von Kries or CMCCAT2000 are fairly close. No significant difference was found between the performances of these two CATs. As the test simulators used only need a small correction for chromatic adaptation (all the simulators except the three-band fluorescent lamp have CRIs well above 90, see Table 6.2.1), the results obtained from these simulators are insufficient for comparing the two CATs.

6.4.3 Correlation between a Pair of Test Sets

Table 6.4.5 lists the PF/3 values between a pair of test sets. The average colour differences of each set (see Table 6.4.1) are compared for the 15 test simulators. Only the results using CIEU*V*W* and CIEDE2000 (1:1:1) under von Kries and CMCCAT2000 are reported.

6.4.3.1 Performances of Normal Colour Sets and Selected Colour Sets

The results in Table 6.4.5 show that the three paint sets (P1, P2 and P3) have a perfect agreement between each other, with PF/3 values less than 10 for most of the cases. The textile sets (T1, T2) and thread set (T2) also exhibit good agreement between each other, with PF/3 values less than 20. However, it can be seen that the agreement between two sets of different material (e.g. a paint set vs. a textile set) is much worse, implying that test colours of different material may perform differently for evaluating the colour rendering properties of daylight simulators.

6.4.3.2 Performances of the CIE Sets, Selected Sets and Combined Set

The results in Tables 6.4.5 show that the two CIE sets, CIE(1-8) and CIE(1-14), agree better with the paint sets than with the textile (or thread) sets. This is not surprising as the CIE test colours were originally selected from Munsell Color Book. It was found that CIE(1-14) exhibits better agreement with the normal sets than CIE(1-8), which suggests that it may be more appropriate to adopt the total 14 CIE test colours rather than the first 8 colours for calculating CRI. It was also revealed that in general the three selected sets (S1, S2 and S3) do not show good agreement with the normal sets and CIE sets. This is expected as the colours in these three sets were selected from the normal sets exhibiting high colour inconstancy. These extreme test colours should not be used as representative of normal colours for evaluating the colour rendering properties of daylight simulators.

Figure 6.4.1 are the scatter diagrams comparing CIE(1-8), CIE(1-14) and combined set C1 with each of the six normal sets (P1, P2, P3, T1, T2, T3). Only the average colour differences (CIEDE2000) of each set under CMCCAT2000 were compared for the 15 test simulators. It can be seen that the correlation between the CIE sets and the paint sets is almost linear, but not for that between the CIE sets and the textile (or thread) sets. The combined set C1, however, shows a better agreement with the textile sets than the CIE sets, though it agrees slightly worse with the paint sets than the CIE sets. In addition, the selected colours in C1, which show larger colour inconstancy than the CIE test colours on average, are more effective for evaluating the colour rendering properties of daylight simulators. It is therefore reasonable to conclude that the performances of the current CIE colour rendering index method could be improved by replacing the CIE test colours with the selected colours in set C1.

Table 6.4.1 Average colour differences of each test colour set. Only the results using CIEU*V*W* and CIEDE2000 (1:1:1) under von Kries and CMCCAT2000 are reported.

Simulator[a]\ Test Set	W1 (95)[b]	W2 (96)	W3 (98)	W4 (96)	W5 (98)	W6 (95)	W7 (98)	GE (93)	GM (93)	PH (98)	BYK (94)	TO (97)	TO(3B) (88)	GM(FT)1 (94)	GM(FT)2 (96)
Ave ΔE (CIEU*V*W* + von Kries)															
P1	0.61	0.56	0 29	0.58	0.36	0.61	0.31	0.98	0.90	0.26	0.88	0 37	*1.86*	1.04	0.77
P2	0.67	0 64	0.30	0 64	0.39	0 67	0.31	1.10	0.97	0.31	1.01	0 35	*2.10*	1.06	0.80
P3	0.44	0.39	0 21	0.42	0.26	0.44	0.26	0.76	0.62	0.20	0.69	0.31	*1.26*	0.83	0 59
T1	0.81	0.71	0.43	0.76	0.52	0.80	0.47	1.27	1.07	0.74	1.35	0 47	*2.85*	1.02	0.75
T2	0.58	0.46	0.31	0.54	0.37	0.57	0.37	1.03	0.77	0.73	1.49	0.41	*2.14*	1.00	0.63
T3	0.56	0.54	0.30	0.55	0 36	0.56	0.30	1.11	0.77	0.70	1.41	0.38	*2.02*	1.01	0.72
S1	2.42	2.29	1.12	2 20	1.54	2.34	1.05	2.80	3.11	1.46	2.14	0.94	*10.89*	1.10	1.27
S2	1.10	0.96	0.52	0.99	0.70	1.06	0.52	1.34	1.44	1.18	1.70	0.57	*4.23*	0 60	0.45
S3	0.60	0.58	0.41	0.54	0.41	0.58	0.61	1.54	0.86	0.55	2.17	0.66	*2.36*	2.01	1.29
CIE(1-8)	0.87	0.74	0.40	0.83	0.52	0.87	0.42	1.26	1.17	0.32	0.96	0 43	*1.94*	0.94	0.72
CIE(1-14)	0.92	0 80	0.45	0.86	0.56	0.91	0.48	1.49	1.26	0.47	1.41	0.49	*2.91*	1.26	0.92
C1	1 25	1 11	0.68	1 13	0 84	1 21	0 76	1 70	1 56	0 93	1.92	0 75	*5.35*	1 20	0 87
Ave ΔE (CIEU*V*W* + CMCCAT2000)															
P1	0.55	0.41	0.22	0.48	0 27	0.53	0.28	1.02	0.79	0.23	0.69	0.32	*1.92*	0 83	0.63
P2	0 60	0 47	0.21	0 53	0 29	0.58	0.27	1.14	0.85	0.26	0.77	0.30	*2.22*	0 83	0.64
P3	0.40	0.29	0.18	0.35	0 21	0.38	0.24	0.79	0.54	0.18	0.56	0.27	*1.27*	0 68	0.48
T1	0.76	0.58	0.39	0.68	0.46	0.74	0.46	1.30	0.98	0.71	1.15	0 44	*2.94*	0.81	0.59
T2	0.55	0.40	0.29	0.50	0.33	0.54	0.37	1.07	0.72	0.71	1.38	0 37	*2.27*	0.87	0.55
T3	0.52	0.40	0.27	0.47	0.30	0.50	0.31	1.15	0.68	0.68	1.24	0 36	*2.17*	0.78	0.58
S1	2 22	1.89	0.68	1.90	1.24	2.10	0.78	2.78	2.81	1.26	1.58	0.89	*11.10*	0.75	0.92
S2	1.06	0.86	0 41	0.93	0.63	1.01	0.45	1.34	1.38	1.14	1.56	0.57	*4.30*	0.52	0.37
S3	0 57	0.46	0 54	0.50	0.42	0.55	0.70	1.65	0.78	0.54	1.85	0.58	*2.70*	1.64	1.07
CIE(1-8)	0 78	0.55	0.24	0 68	0.37	0.75	0.32	1.28	1.02	0.27	0.78	0.37	*2.05*	0 80	0.58
CIE(1-14)	0.83	0.61	0.32	0.73	0.43	0.80	0.41	1.53	1.12	0.42	1.12	0.43	*3.09*	1.02	0.74
C1	1 18	0 97	0.57	1.03	0 74	1 12	0 69	1 73	1 45	0 89	1.70	0 69	*5.54*	1 07	0 73
Ave ΔE (CIEDE2000 + von Kries)															
P1	0 42	0.38	0.20	0.40	0.25	0.42	0.20	0.64	0.61	0.18	0.49	0.21	*1.26*	0.59	0.46
P2	0 44	0.41	0.20	0 42	0.26	0.44	0.19	0.70	0.63	0.19	0.55	0.19	*1.34*	0.59	0.46
P3	0.37	0.32	0.17	0.35	0.22	0.37	0.17	0.59	0.51	0.16	0.41	0 19	*0.98*	0.52	0.39
T1	0 60	0.50	0.29	0.56	0.37	0.59	0.30	0.91	0.76	0.50	0.76	0.34	*1.89*	0.59	0.47
T2	0.45	0.34	0.20	0.42	0.26	0.44	0.21	0.77	0.56	0.52	0.83	0.30	*1.40*	0.51	0.35
T3	0.48	0.43	0.25	0.46	0.31	0.48	0.23	0.83	0.64	0.57	0.92	0 30	*1.55*	0.61	0.49
S1	1.13	1.11	0.53	1.03	0.73	1.10	0.49	1.33	1.51	0.69	1.19	0.50	*5.31*	0.69	0.71
S2	0.89	0.77	0.44	0.81	0.58	0.86	0.43	1.22	1.14	1.11	1.50	0.55	*3.47*	0.50	0.38
S3	0.46	0.50	0.22	0.45	0 26	0.47	0.24	0.81	0.79	0.38	0.91	0.36	*1.97*	0.92	0.72
CIE(1-8)	0.55	0.47	0.24	0.52	0.32	0.55	0.24	0.82	0.74	0.19	0.56	0 24	*1.19*	0.59	0.47
CIE(1-14)	0.56	0.50	0.24	0.53	0.31	0.55	0.23	0.87	0.83	0.22	0.67	0.28	*1.65*	0.68	0.53
C1	0 77	0 74	0 39	0 71	0 50	0 75	0.38	0 97	1.08	0 50	1 03	0 44	*3.21*	0 65	0 52
Ave ΔE (CIEDE2000 + CMCCAT2000)															
P1	0.39	0.29	0.15	0.35	0.19	0.37	0.17	0 66	0.55	0.16	0.38	0.19	*1.32*	0.46	0.37
P2	0.40	0.31	0.14	0.35	0.19	0.39	0.16	0.72	0.56	0.16	0.41	0.17	*1.42*	0.45	0.37
P3	0.34	0.25	0.13	0.30	0.17	0.33	0.15	0.60	0.45	0.13	0.31	0.16	*1.02*	0.40	0.31
T1	0.56	0.41	0.26	0.50	0.31	0.54	0.28	0.92	0.69	0.50	0.66	0.33	*1.96*	0.45	0.36
T2	0.44	0.29	0.19	0.39	0.24	0.42	0.21	0.79	0.53	0.51	0.77	0 29	*1.47*	0.43	0.30
T3	0.45	0.33	0.23	0.40	0.26	0.43	0.24	0 85	0.57	0.57	0.84	0.30	*1.65*	0.45	0.38
S1	1.04	0.92	0.34	0.89	0.59	0.99	0.39	1.33	1.37	0.61	0.93	0 47	*5.43*	0.52	0.55
S2	0.85	0.68	0.35	0.75	0.53	0.81	0.37	1.23	1.08	1.08	1.39	0.55	*3.53*	0.44	0.31
S3	0.43	0.39	0.27	0.39	0.24	0.42	0.30	0.85	0.71	0.39	0.75	0 34	*2.11*	0.70	0.59
CIE(1-8)	0.50	0.35	0.15	0.44	0.23	0.48	0.18	0.83	0.66	0.15	0.43	0.21	*1.28*	0.47	0.37
CIE(1-14)	0.50	0.36	0.17	0.43	0.23	0.48	0.20	0 89	0.73	0.20	0.48	0 25	*1.75*	0.51	0.40
C1	0 72	0 61	0.31	0 63	0 42	0 68	0 35	0 99	0 99	0 49	0 87	0 41	*3.32*	0 53	0 41

a See the footnote of Table 6.2.1 for the abbreviations of the test simulators, which are also applied in Tables 6.4.2 to 6.4.3.

b The values in bracket are the CRI results, also see Tables 6.4.2 to 6.4.3.

Table 6.4.2 Maximum colour differences of each test colour set. Only the results using CIEU*V*W* and CIEDE2000 (1:1:1) under von Kries and CMCCAT2000 are reported.

Simulator\ Test Set	W1 (95)	W2 (96)	W3 (98)	W4 (96)	W5 (98)	W6 (95)	W7 (98)	GE (93)	GM (93)	PH (98)	BYK (94)	TO (97)	TO(3B) (88)	GM(FT)1 (94)	GM(FT)2 (96)
Max ΔE (CIEU*V*W* + von Kries)															
P1	3.17	3.21	1.49	2.93	2.05	3.08	1.46	4.71	4.38	2.35	5.06	1.47	13.49	4.22	3.22
P2	3.13	3.31	1.49	2.96	2.03	3.12	1.75	4.65	4.21	2.25	6.35	1.41	14.75	4.35	3.65
P3	2.33	2.17	0.99	2.12	1.42	2.26	1.30	3.04	3.18	2.11	5.42	1.20	9.56	3.58	2.53
T1	2.58	2.56	1.29	2.38	1.72	2.52	1.30	3.33	3.28	2.97	6.07	1.09	13.56	4.07	2.62
T2	1.63	1.42	0.95	1.46	0.94	1.56	1.53	2.73	1.99	2.50	5.76	1.09	9.34	3.89	2.26
T3	1.85	1.89	0.88	1.82	0.99	1.88	1.40	3.44	2.98	2.89	5.69	1.19	9.59	4.15	3.05
S1	3.17	3.03	1.49	2.89	2.05	3.08	1.53	3.63	4.02	2.25	2.65	1.41	14.75	1.77	1.71
S2	1.93	2.00	0.93	1.79	1.23	1.89	0.99	2.55	2.64	1.80	2.94	0.95	8.79	1.59	1.49
S3	1.22	1.25	0.68	1.16	0.75	1.19	1.27	2.39	1.70	1.19	3.90	1.19	5.64	3.72	2.04
CIE(1-8)	1.72	1.46	0.79	1.56	1.06	1.65	0.85	2.04	2.15	1.01	1.75	0.69	6.18	1.32	1.04
CIE(1-14)	2.02	1.89	0.93	1.92	1.10	2.01	1.60	3.19	2.95	1.58	5.59	1.11	7.22	3.93	2.01
C1	3.03	2.82	1.49	2.71	2.03	2.91	1.60	3.18	3.53	2.25	5.59	1.41	14.75	3.93	2.01
Max ΔE (CIEU*V*W* + CMCCAT2000)															
P1	2.89	2.49	1.23	2.49	1.64	2.76	1.65	4.79	3.87	2.38	4.88	1.28	14.15	3.34	2.58
P2	2.84	2.58	1.44	2.47	1.73	2.74	1.91	4.73	3.71	2.20	5.91	1.33	14.82	3.42	3.00
P3	2.11	1.73	1.05	1.80	1.08	2.00	1.48	3.03	2.82	2.09	5.04	1.05	9.83	3.08	1.96
T1	2.37	2.07	1.02	2.06	1.39	2.27	1.38	3.45	2.95	2.98	5.81	0.99	13.83	3.35	2.18
T2	1.44	0.97	1.29	1.22	0.91	1.35	1.68	2.94	1.77	2.45	5.18	0.92	9.76	3.39	1.99
T3	1.58	1.21	1.18	1.36	0.81	1.52	1.59	3.53	2.52	2.89	5.41	0.99	9.90	3.35	2.45
S1	2.89	2.49	1.07	2.49	1.73	2.76	1.22	3.61	3.62	2.03	2.01	1.33	14.82	1.15	1.25
S2	1.79	1.65	0.79	1.56	1.08	1.71	0.89	2.60	2.40	1.71	2.58	0.90	8.99	1.09	1.16
S3	1.11	0.96	1.08	0.97	0.73	1.05	1.47	2.61	1.51	1.08	3.40	0.99	5.92	3.19	1.81
CIE(1-8)	1.53	1.13	0.52	1.31	0.80	1.44	0.71	1.98	1.90	0.82	1.83	0.59	6.31	1.25	0.78
CIE(1-14)	1.75	1.28	1.33	1.50	0.96	1.67	1.80	3.22	2.52	1.53	5.07	1.10	7.80	3.41	1.71
C1	2.81	2.44	1.33	2.41	1.73	2.66	1.80	3.11	3.24	2.03	5.07	1.33	14.82	3.41	1.71
Max ΔE (CIEDE2000 + von Kries)															
P1	1.40	1.35	0.65	1.28	0.91	1.37	0.60	1.96	1.92	0.86	1.72	0.73	5.78	1.49	1.26
P2	1.40	1.43	0.67	1.31	0.93	1.39	0.68	2.07	2.01	1.03	1.90	0.80	6.42	1.65	1.46
P3	1.17	1.10	0.53	1.09	0.71	1.14	0.46	1.72	1.75	0.92	1.77	0.57	4.70	1.33	1.13
T1	1.37	1.37	0.66	1.26	0.89	1.34	0.69	1.85	1.73	1.42	2.50	0.85	7.80	1.39	1.14
T2	0.97	0.83	0.42	0.92	0.57	0.94	0.45	1.72	1.19	1.73	2.26	0.79	4.40	1.19	0.92
T3	1.16	1.11	0.82	1.15	0.88	1.19	0.83	1.87	1.71	1.83	2.33	0.88	4.60	1.45	1.19
S1	1.40	1.35	0.67	1.28	0.93	1.37	0.68	1.65	1.78	1.01	1.67	0.73	6.19	1.20	0.96
S2	1.25	1.37	0.66	1.16	0.86	1.22	0.69	1.76	1.71	1.73	2.50	0.75	7.80	1.07	1.00
S3	0.80	0.87	0.50	0.79	0.60	0.81	0.40	1.34	1.24	0.97	1.84	0.79	4.60	1.26	1.12
CIE(1-8)	0.94	0.93	0.44	0.94	0.61	0.98	0.37	1.43	1.46	0.48	0.84	0.35	2.90	1.07	0.96
CIE(1-14)	0.96	1.00	0.44	0.94	0.61	0.98	0.37	1.53	2.04	0.48	1.39	0.95	4.67	1.35	1.10
C1	1.35	1.37	0.67	1.21	0.91	1.30	0.68	1.76	2.04	1.42	2.50	0.95	7.80	1.35	1.10
Max ΔE (CIEDE2000 + CMCCAT2000)															
P1	1.29	1.13	0.71	1.12	0.74	1.24	0.66	2.00	1.62	0.76	1.49	0.69	5.91	1.08	1.00
P2	1.29	1.16	0.58	1.12	0.79	1.25	0.55	2.11	1.68	1.03	1.62	0.78	6.66	1.30	1.21
P3	1.07	0.89	0.63	0.91	0.55	1.01	0.59	1.73	1.47	0.92	1.68	0.52	4.82	0.94	0.79
T1	1.27	1.18	0.59	1.10	0.77	1.21	0.65	1.87	1.59	1.34	2.20	0.82	7.96	1.08	0.94
T2	0.92	0.64	0.46	0.83	0.49	0.88	0.50	1.74	1.06	1.69	2.10	0.79	4.60	0.89	0.70
T3	1.00	0.86	0.73	0.91	0.80	0.95	0.75	1.87	1.42	1.85	2.16	0.88	4.78	1.03	0.83
S1	1.29	1.16	0.49	1.12	0.79	1.24	0.55	1.64	1.62	0.92	1.25	0.69	6.22	0.77	0.70
S2	1.17	1.18	0.59	1.03	0.77	1.12	0.65	1.79	1.59	1.69	2.20	0.77	7.96	0.77	0.81
S3	0.73	0.67	0.52	0.66	0.50	0.72	0.56	1.38	1.11	0.96	1.59	0.76	4.78	0.79	0.79
CIE(1-8)	0.80	0.61	0.24	0.70	0.39	0.78	0.31	1.42	1.22	0.40	0.76	0.32	2.96	0.61	0.62
CIE(1-14)	0.85	0.61	0.33	0.71	0.39	0.80	0.33	1.54	1.68	0.40	0.94	0.94	5.02	0.71	0.62
C1	1.26	1.18	0.54	1.09	0.79	1.20	0.61	1.79	1.68	1.34	2.20	0.94	7.96	0.71	0.68

Table 6.4.3 Ranking results for the test simulators based on the average colour differences reported in Table 6.4.1

Simulator\ Test Set	W1 (95)	W2 (96)	W3 (98)	W4 (96)	W5 (98)	W6 (95)	W7 (98)	GE (93)	GM (93)	PH (98)	BYK (94)	TO (97)	TO(3B) (88)	GM(FT)1 (94)	GM(FT)2 (96)
CIEU*V*W* + von Kries															
P1	9	6	2	7	4	8	3	13	12	1	11	5	15	14	10
P2	9	7	1	6	5	8	2	14	11	3	12	4	15	13	10
P3	9	6	2	7	4	8	3	13	11	1	12	5	15	14	10
T1	10	5	1	8	4	9	3	13	12	6	14	2	15	11	7
T2	8	5	1	6	3	7	2	13	11	10	14	4	15	12	9
T3	8	5	1	6	3	7	2	13	11	9	14	4	15	12	10
S1	12	10	4	9	7	11	2	13	14	6	8	1	15	3	5
S2	10	7	3	8	6	9	2	12	13	11	14	4	15	5	1
S3	7	5	2	3	1	6	8	12	10	4	14	9	15	13	11
CIE(1-8)	10	7	2	8	5	9	3	14	13	1	12	4	15	11	6
CIE(1-14)	9	6	1	7	5	8	3	14	11	2	13	4	15	12	10
C1	11	7	1	8	4	10	3	13	12	6	14	2	15	9	5
CIEU*V*W* + CMCCAT2000															
P1	9	6	1	7	3	8	4	14	12	2	11	5	15	13	10
P2	9	6	1	7	4	8	3	14	13	2	11	5	15	12	10
P3	9	6	1	7	3	8	4	14	11	2	12	5	15	13	10
T1	10	5	1	7	4	9	3	14	12	8	13	2	15	11	6
T2	9	5	1	6	2	7	3	13	11	10	14	4	15	12	8
T3	8	5	1	6	2	7	3	13	10	11	14	4	15	12	9
S1	12	9	1	10	6	11	3	13	14	7	8	4	15	2	5
S2	10	7	2	8	6	9	3	12	13	11	14	5	15	4	1
S3	7	2	5	3	1	6	9	13	10	4	14	8	15	12	11
CIE(1-8)	10	6	1	8	4	9	3	14	13	2	11	5	15	12	7
CIE(1-14)	10	6	1	7	4	9	2	14	13	3	12	5	15	11	8
C1	11	7	1	8	5	10	3	14	12	6	13	2	15	9	4
CIEDE2000 + von Kries															
P1	9	6	3	7	5	8	2	14	13	1	11	4	15	12	10
P2	9	6	4	7	5	8	1	14	13	3	11	2	15	12	10
P3	9	6	2	7	5	8	3	14	12	1	11	4	15	13	10
T1	11	6	1	8	4	9	2	14	12	7	13	3	15	10	5
T2	9	5	1	7	3	8	2	13	12	11	14	4	15	10	6
T3	8	5	2	6	4	7	1	13	12	10	14	3	15	11	9
S1	11	10	3	8	7	9	1	13	14	5	12	2	15	4	6
S2	10	7	3	8	6	9	2	13	12	11	14	5	15	4	1
S3	7	9	1	6	3	8	2	12	11	5	13	4	15	14	10
CIE(1-8)	10	7	4	8	5	9	2	14	13	1	11	3	15	12	6
CIE(1-14)	10	6	3	7	5	9	2	14	13	1	11	4	15	12	8
C1	11	9	2	8	4	10	1	12	14	5	13	3	15	7	6
CIEDE2000 + CMCCAT2000															
P1	11	6	1	7	5	9	3	14	13	2	10	4	15	12	8
P2	10	6	1	7	5	9	2	14	13	3	11	4	15	12	8
P3	11	6	1	7	5	10	3	14	13	2	9	4	15	12	8
T1	11	6	1	8	3	10	2	14	13	9	12	4	15	7	5
T2	10	5	1	7	3	8	2	14	12	11	13	4	15	9	6
T3	9	5	1	7	3	8	2	14	12	11	13	4	15	10	6
S1	12	9	1	8	6	11	2	13	14	7	10	3	15	4	5
S2	10	7	2	8	5	9	3	13	12	11	14	6	15	4	1
S3	9	5	2	7	1	8	3	14	12	6	13	4	15	11	10
CIE(1-8)	12	6	1	9	5	11	3	14	13	2	8	4	15	10	7
CIE(1-14)	11	6	1	8	4	9	2	14	13	3	10	5	15	12	7
C1	11	8	1	9	5	10	2	13	14	6	12	3	15	7	4

Table 6.4.4 PF/3 values between a pair of colour difference results using different formulae. The average colour differences of each test colour set for the 15 D65 simulators are compared.

	von Kries					CMCCAT2000				
	CIEU*V*W*	CIELAB	CMC	CIE94	CIEDE2000	CIEU*V*W*	CIELAB	CMC	CIE94	CIEDE2000
P1										
CIELAB	9					10				
CMC (1.1)	8	3				10	4			
CIE94 (1:1:1)	9	2	2			10	2	3		
CIEDE2000 (1:1:1)	8	2	2	1		10	2	3	1	
Ave.	9	4	4	4	3	10	5	5	4	4
P2										
CIELAB	7					8				
CMC (1.1)	6	3				8	4			
CIE94 (1:1:1)	7	2	2			8	2	3		
CIEDE2000 (1:1:1)	7	3	2	1		8	2	3	1	
Ave.	7	4	3	3	3	8	4	4	4	4
P3										
CIELAB	13					14				
CMC (1:1)	14	3				16	4			
CIE94 (1:1:1)	14	3	1			16	3	2		
CIEDE2000 (1:1:1)	14	3	1	1		16	2	2	1	
Ave	13	5	5	5	5	16	6	6	6	5
T1										
CIELAB	12					13				
CMC (1:1)	9	3				10	4			
CIE94 (1:1:1)	10	2	2			11	3	2		
CIEDE2000 (1:1:1)	9	5	2	3		9	5	2	3	
Ave	10	6	4	4	4	11	6	4	5	5
T2										
CIELAB	16					16				
CMC (1:1)	16	4				17	5			
CIE94 (1:1:1)	16	3	2			17	3	2		
CIEDE2000 (1:1:1)	14	7	3	4		15	7	3	5	
Ave	15	7	6	6	7	16	8	7	7	8
T3										
CIELAB	11					12				
CMC (1:1)	11	5				12	5			
CIE94 (1:1:1)	11	4	2			12	4	2		
CIEDE2000 (1:1:1)	11	6	2	3		12	8	3	4	
Ave	11	6	5	5	6	12	7	5	6	7
S1										
CIELAB	8					10				
CMC (1:1)	10	2				12	3			
CIE94 (1:1:1)	10	3	1			12	4	1		
CIEDE2000 (1:1:1)	8	3	2	2		10	3	2	3	
Ave	9	4	4	4	4	11	5	5	5	5
S2										
CIELAB	5					5				
CMC (1:1)	6	7				6	7			
CIE94 (1:1:1)	4	4	3			4	4	3		
CIEDE2000 (1:1:1)	6	7	4	5		6	8	4	6	
Ave	5	6	5	4	5	5	6	5	4	6
S3										
CIELAB	19					18				
CMC (1:1)	29	12				28	12			
CIE94 (1:1:1)	29	11	4			27	10	3		
CIEDE2000 (1:1:1)	31	13	2	4		30	13	3	4	
Ave	27	14	12	12	13	26	13	12	11	13
CIE(1-8)										
CIELAB	9					10				
CMC (1:1)	5	6				6	5			
CIE94 (1:1:1)	5	5	1			6	5	1		
CIEDE2000 (1:1:1)	5	7	2	3		5	6	2	2	
Ave	6	7	3	4	4	7	6	4	4	4
CIE(1-14)										
CIELAB	9					10				
CMC (1:1)	9	5				9	5			
CIE94 (1:1:1)	9	3	2			10	3	2		
CIEDE2000 (1:1:1)	10	7	4	5		11	7	4	4	
Ave	9	6	5	5	7	10	6	5	5	6
C1										
CIELAB	6					7				
CMC (1:1)	7	3				7	3			
CIE94 (1:1:1)	8	2	1			7	2	1		
CIEDE2000 (1:1:1)	8	5	3	4		8	4	3	3	
Ave	7	4	4	4	5	7	4	3	4	5

Table 6.4.5 PF/3 values between a pair of test colour sets. The average colour differences of each set for the 15 D65 simulators are compared. Only the results using CIEU*V*W* and CIEDE2000 (1:1:1) under von Kries and CMCCAT2000 are reported.

	P1	P2	P3	T1	T2	T3	S1	S2	S3	CIE(1-8)	CIE(9-14)	C1
CIEU*V*W*+ von Kries												
P2	6											
P3	7	11										
T1	24	21	26									
T2	31	29	30	16								
T3	28	25	27	17	8							
S1	51	48	57	37	54	55						
S2	51	47	55	29	39	42	24					
S3	35	36	29	39	29	28	75	68				
CIE(1-8)	16	16	19	25	37	35	41	44	46			
CIE(1-14)	10	8	14	15	25	23	40	40	36	15		
C1	33	30	36	15	28	31	24	21	51	32	23	
Ave.	27	25	28	24	30	29	46	42	43	30	23	29
CIEU*V*W*+ CMCCAT2000												
P2	7											
P3	8	14										
T1	27	25	28									
T2	33	32	31	18								
T3	31	30	30	18	6							
S1	57	52	64	43	61	60						
S2	52	48	56	27	39	40	28					
S3	36	39	29	38	28	29	79	66				
CIE(1-8)	14	13	18	27	37	36	46	46	46			
CIE(1-14)	11	8	16	18	27	26	43	40	38	14		
C1	33	30	37	14	28	29	30	22	48	33	23	
Ave	28	27	30	26	31	30	51	42	43	30	24	30
CIEDE2000 + von Kries												
P2	5											
P3	5	8										
T1	22	21	23									
T2	32	30	32	15								
T3	28	26	29	14	7							
S1	37	36	41	27	39	39						
S2	49	47	50	26	27	30	28					
S3	21	21	23	25	26	22	40	46				
CIE(1-8)	12	13	9	26	35	33	38	49	31			
CIE(1-14)	6	6	8	21	31	28	33	45	22	11		
C1	28	27	31	16	27	27	12	24	31	33	26	
Ave.	22	22	24	21	27	26	34	38	28	26	22	26
CIEDE2000 + CMCCAT2000												
P2	6											
P3	5	9										
T1	25	26	27									
T2	33	33	34	15								
T3	33	33	34	15	6							
S1	38	36	42	30	42	42						
S2	49	48	51	24	25	26	31					
S3	22	24	25	23	25	22	39	42				
CIE(1-8)	12	12	9	30	37	38	39	51	32			
CIE(1-14)	7	7	9	24	33	33	32	45	24	12		
C1	29	28	32	16	28	27	15	24	27	35	26	
Ave	24	24	25	23	28	28	35	38	28	28	23	26

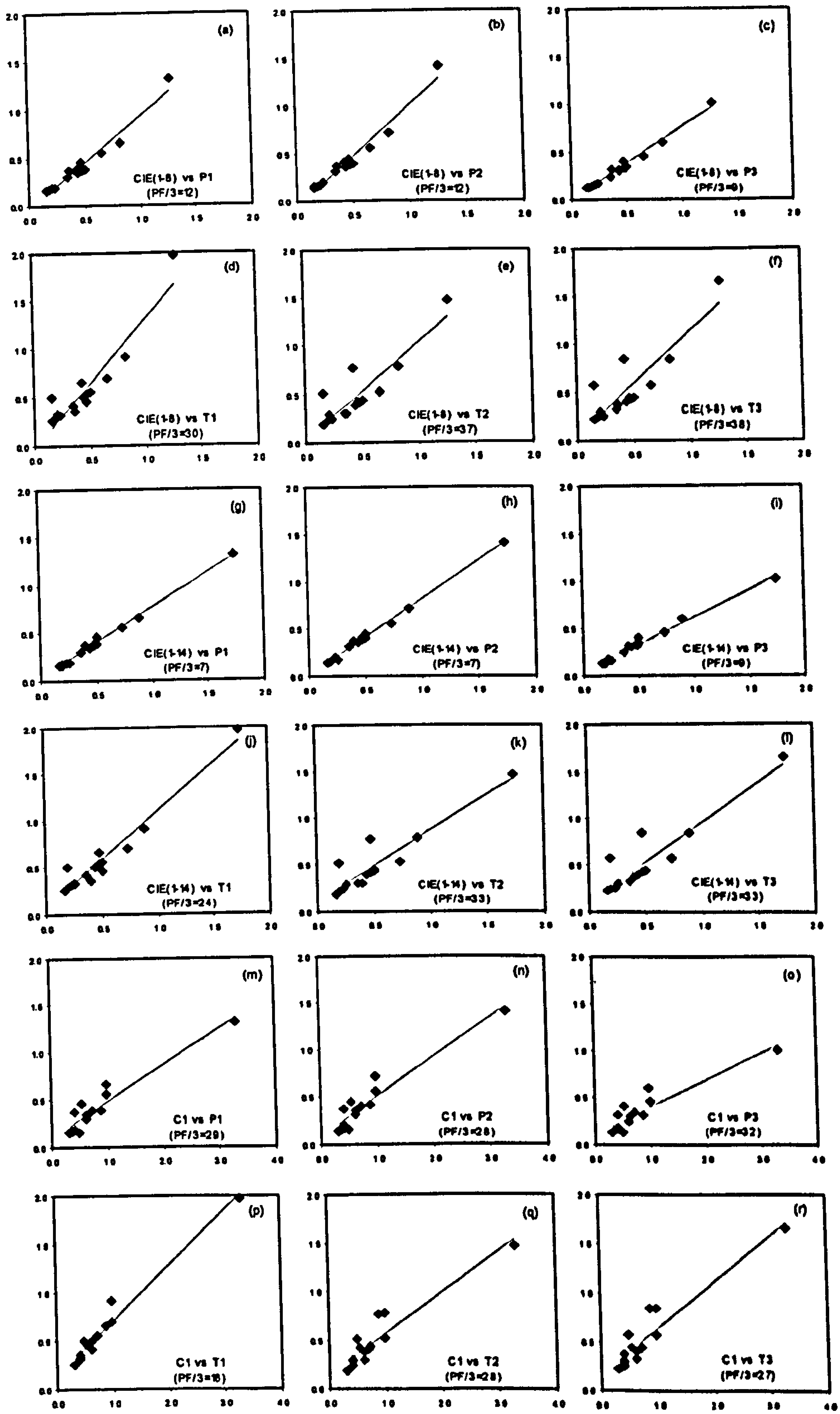


Figure 6.4.1 Comparing CIE(1-8), CIE(1-14) and combined set C1 with the normal sets (P1, P2, P3, T1, T2, T3) in (a) to (f), (g) to (l) and (m) to (r) respectively. Only the average colour differences of each set using CIEDE2000 (1:1:1) under CMCCAT2000 were plotted.

6.5 Conclusions

The results show that the choice of reference illuminant (either using one phase of CIE daylight illuminant which has the closest distance to the test simulator in the CIE 1960 (u, v) chromaticity diagram or using the CIE D65 illuminant) makes no difference in calculating the CRI for the D65 simulators investigated. It was also found that although the filtered tungsten lamps appear to have a closer power simulation to the CIE D65 illuminant, their colour rendering properties could be worse than some of the fluorescent lamps. The colour inconstancy index results of different test colour sets show that colour inconstancy index is an illuminant-related measure, the choice of test illuminant, e.g. CIE illuminants A or F11 (the reference illuminant is usually specified) may well determine the size of colour inconstancy index results. It was found that yellowish or bluish colours are more likely to show high colour inconstancy than other colours.

Different test colour sets rate the test simulators differently in terms of colour rendering properties. Daylight simulators with a CRI lower than 90 (e.g. three-band fluorescent lamp) gave poor colour rendering property, particularly for colours showing high colour inconstancy. A 10-unit difference in CRI for two simulators may result in a very significant difference for colour rendering. The four colour difference formulae, CIELAB, CMC, CIE94 and CIEDE2000, have similar a performance for calculating CRI and they all outperform CIEU*V*W*. No significant difference was found between the performances of two CATs, von Kries and CMCCAT2000.

Test colour sets of the same material agree with each other better than those of different material (e.g. a paint sample set vs. a textile sample set) for evaluating the colour rendering properties of daylight simulators. Note that this is unlikely to be concerned to the different surface structures of paints and textiles, but probably due to the attention paid to finding colour constant samples when producing the various sets. The CIE test colour sets agree better with the paint sample sets than with the textile or thread sample sets. This implies that the CIE test colours, originally chosen from the Munsell colour order system, might not be representatives of colours of a different material such as textile. It was also found that the average colour differences of the total 14 CIE test colours instead of the first 8 test colours show better agreement with those of the normal test sets. This suggests that it might be more appropriate to adopt the total CIE test colours instead of the first 8 colours for calculating CRI. A new test colour set, including 6 colours selected from the CIE sets, 1 from NCS paint colour set and 3 from textile colour sets, shows a better agreement with the textile sets than the CIE sets. The test colours in this new set were selected for showing relatively high colour inconstancy as well as covering a large colour gamut. The results show that the performances of the current CIE method could be improved by replacing the CIE test colours with these selected colours.

A new CIE CRI may be proposed to include a new advanced CAT such as CMCCAT2000 (or CAT02), a much reliable colour difference formula than CIEU*V*W* such as CIEDE2000, and finally, a new test colour set having a higher colour inconstancy than the present CIE set. However, this study only considered D65 simulators, more investigations using light sources with a much broad range of colour temperature are needed for validating the new CIE CRI proposal.

CHAPTER 7
IMPROVING THE QUALITY OF D65 AND D50 SIMULATORS

7.1 Introduction

In Chapter 3, the variations of practical daylight simulators were analysed. It was revealed that the spectral power distribution (SPD) of a daylight simulator determines its quality in terms of chromaticity, CCT, CIE metamerism index, CIE general colour rendering index (CRI), etc. (see Section 3.3.2.3). Chapters 4 to 6 investigated the performances of the standard methods such as the band value method specified in British standard BS 950 (see Section 2.5.1), the CIE metamerism index method (see Section 2.5.4.2) and CIE colour rendering index method (see Section 2.5.4.1) for evaluating the quality of daylight simulators. All the studies carried out so far provided sufficient clues for designing effective measures to achieve daylight simulators of good quality (see Section 2.9), which is also a major concern of this study.

In this chapter, an optimisation method was developed. The method was designed to optimise the SPD of a test simulator by modifying the power at the peak wavelengths as well as the power for the six bands specified in British standard BS 950 (termed as BS 950 band, see Table 2.5.2). The performance of the method was tested using some of the F7 and F8 lamps accumulated (see Section 3.3.1). The quality of these lamps before and after optimisation was compared.

7.2 Optimising the SPDs of Daylight Simulators

Software aiming to optimise the SPD of a test simulator was developed based on the 'Solver' optimisation tool embedded in Microsoft EXCEL. A nonlinear optimisation technique based on Generalized Reduced Gradient (GRG) method (Pardalos 2002, p.271) was employed by Solver.

7.2.1 Standard Data for Constructing the Initial Spreadsheet

To run the software, some standard data should be entered, including:

(1) CIE 1931 $\bar{y}(\lambda)$ colour matching function (5nm interval) for calculating BS950 band values for CIE illuminants D65 and D50, and the test simulator.

(2) CIE 1964 Supplementary Standard Colorimetric Observer $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ (5nm interval) for calculating the tristimulus values of the test simulator and CIE metamer samples.

(3) Reflectance values for the five CIE metamers, which are used to calculate the CIE metamerism index for the visible range (from 400nm to 700 nm at 5 nm interval, provided in CIE publication 51.2, 1999).

(4) SPDs (5nm interval) of CIE illuminants D65 and D50 for calculating the BS 950 band values for the CIE illuminants.

(5) Mean and standard deviations of relative spectral power (5nm interval) for the representative F7 and F8 lamps respectively.

The representative lamps in (5) were described in Chapter 3 (see Section 3.3.2.2). Each representative lamp was selected from a lamp group (made by the same manufacturer) to show the closest chromaticities to the group mean. The mean of the relative spectral power of the representative lamps was used to reflect the average SPD of the daylight simulators investigated, and the standard deviation to reflect the variation range of SPD for the simulators investigated. Note the SPDs of CIE illuminants D65 and D50, and those of representative F7 (or F8) lamps were normalised according to the CIE recommendations (CIE 1986, see Section 3.3.2.2), which also applies to the following sections where the SPD of a test lamp is concerned.

7.2.2 Results Generated by the Software

Once the SPD of a test simulator has been entered, the software calculates several types of results instantly, which are:

(1) Band values and band-value deviations for the six BS 950 bands (see Appendix A for a worked example).

(2) Chromaticity co-ordinates (u'_{10}, v'_{10}) and chromaticity deviation $\Delta u'_{10}v'_{10}$.

(3) Colour difference (ΔE^*_{ab}) for a reference white illuminated under the test simulator and the corresponding CIE daylight illuminant (CIE D65 or D50).

(4) CIE metamerism index for the visible range (MI_{vis}).

The band values, particularly the band-value deviations, provide an indication for judging whether the spectral power of a test simulator is adequately distributed. According to the findings in Chapter 4 (see Section 4.2.1.5), a daylight simulator with band-value deviations well within the BS 950 tolerance (±15%) corresponds to a good metamerism index rating and therefore is of good quality. Conversely, the quality of a test simulator is significantly degraded if its band-value deviations exceed the BS tolerance at one or more of the six BS 950 bands.

Both the chromaticity deviations and colour differences of a reference white can be used to represent the correctness of the colour of the test simulator. The larger these two values, the further the test simulator departing from the CIE daylight illuminant in CIE 1976 UCS chromaticity diagram. The CIE chromaticity tolerance for daylight simulators was specified as 0.0150 in $\Delta u'_{10}v'_{10}$ units (see Section 2.5.4.2), which was proved to be quite tolerant as all the investigated simulators in Chapter 3 have chromaticities well within this tolerance (see Section 3.3.2.1). The CIE metamerism index is another measure for quantifying the quality of a daylight simulator, represented by the average colour differences of five CIE metamers (perfect matches under CIE daylight illuminant) illuminated under the test simulator.

7.2.3 Optimisation Objective

The optimisation objective to be minimised in this software is a linear combination of the colour difference (ΔE^*_{ab}) of a reference white and CIE metamerism index (MI_{vis}) for the visible range, expressed as below.

$$\text{Optimisation Objective} = 0.3\ \Delta E^*_{ab} + 0.7 \times (10\ MI_{vis}) \qquad 7.2.1$$

where ΔE^*_{ab} is the colour difference of a reference white when the illumination is changed from a CIE daylight illuminant to a test simulator. This measure was used as an alternative of chromaticity deviation for the test simulator. The CIE metamerism index (MI_{vis}) is represented the average colour difference of the five CIE metamers illuminated under the test simulator. Hence, the two measures included in the optimisation objective are all in ΔE^*_{ab} unit.

An analysis on the F7 and F8 lamps accumulated revealed that these two colour difference results are not on the same scale. Therefore, the CIE metamerism index (MI_{vis}) in Equation 7.2.1 is first multiplied by 10 to be directly compared with the colour difference (ΔE^*_{ab}) of a reference illuminant. Trials on a number of F7 and F8 lamps also showed that to achieve the best quality for the test simulator, different weights should be applied to these two colour difference results. As the F7 and F8 lamps investigated generally did not show large chromaticity deviations, it was found more weight should be given to the CIE metamerism index. The weighting factors 0.3 and 0.7 in Equation 7.2.1 were thus defined empirically through a large number of trials on F7 or F8 lamps.

It worth noting that CRI was not included in the optimisation objective because a simulator having a high CRI does not necessarily have good quality. For instance, the CIE A illuminant has CRI of 100, but it is not a good daylight simulator. Furthermore, the surface colour industries are more concerned about metamerism for the application of daylight simulators. Hence, the optimisation objective employs a linear combination of the colour difference of a reference white and CIE metamerism index as these two measures reflect the main features with respect to the quality of daylight simulators. It was found in Chapter 3 (see Section 3.3.2) that a simulator has a good quality as long as it has small values of chromaticity deviation and CIE metamerism index.

7.2.4 Optimisation Coefficients

Ten optimisation coefficients were assigned in the software for optimising the SPD of a F7 or F8 test simulator, including four (k1 to k4) for the four peak wavelengths and six (k5 to k10) for the six BS 950 bands (denoted as Bands 1 to 6). Coefficients k1 to k4 represent the relative power values for peak wavelengths at 405nm, 435nm, 545nm and 580nm respectively. Coefficients k5 to k10 are the factors used to multiply the practical standard deviations (σ_λ) of relative power (calculated from the representative F7 or F8 lamps, see Section 7.2.1) for each reported wavelength within each of the six BS 950 bands respectively. For instance, the original relative power of a test simulator was modified by a factor $k5 \cdot \sigma_\lambda$ for each reported wavelength within Band 1, and those within Bands 2 to 6 were modified by factors $k6 \cdot \sigma_\lambda$, $k7 \cdot \sigma_\lambda$, $k8 \cdot \sigma_\lambda$, $k9 \cdot \sigma_\lambda$ and $k10 \cdot \sigma_\lambda$ respectively. Note that these modifications on power values apply to each reported wavelength except the peak wavelengths. The power values at the peak wavelengths, represented by coefficients k1 to k4, were optimised separately. The reason for this is that the power values at the peak wavelengths are much larger than those at other wavelengths. Hence, optimisation of the power at peak wavelengths is extremely important for improving the quality of a test lamp. The flow chart for the optimisation procedure is shown in Figure 7.2.1. It indicates that the optimisation of SPD of the test simulator is completed when the optimisation objective reaches convergence to a minimum value.

According to Chapter 3 (see Section 3.3.2.2), the practical variation range of F7 or F8 lamps was expressed in terms of the mean power with a range of 2 times the standard deviation at each reported wavelength for the 6 representative F7 (or F8) lamps. It was desirable to set proper constraints to the optimisation coefficients to ensure that the optimised SPD of a test lamp lies within the practical variation range. However, some poor quality lamps have at least one BS 950 band showing large band-value deviation, which is close or above the tolerance (±15%) specified by BS 950. It was also found impossible to effectively improve the quality of these lamps by just optimising their SPDs within the practical variation range. Therefore, based on the band-value deviation results, the constraints for coefficients k5 to k10 were defined with more flexibility. For example, if the band-value deviation for Band 2 is –22.4%, it can be judged that the power of this band is seriously deficient and a large boost of power is needed. Constraint for k6 is then decided to be positive and much larger than 2, say 8. For a band with band-value deviation less than ±10%, the optimisation coefficient for this band is set to zero, which means no modification of power is needed for the band.

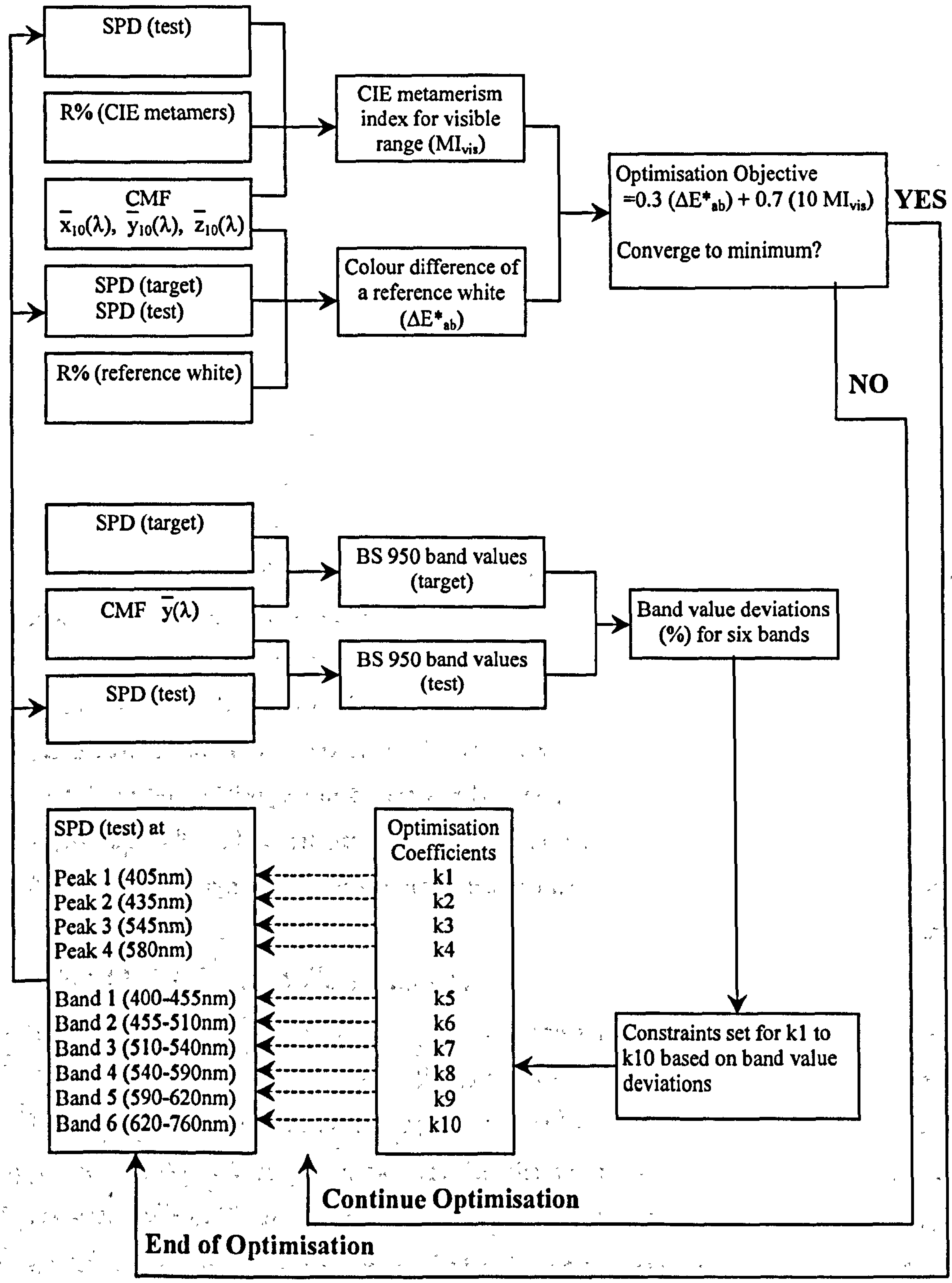


Figure 7.2.1 Flow chart of optimisation procedure

7.3 Results

The performance of the optimisation software was tested using a large number of F7 and F8 lamps chosen from those accumulated in Chapter 3 (see Section 3.3.1). It was found all the test lamps significantly improved their quality after optimisation. For simplicity, this chapter only reports the results for two F7 and two F8 lamps, which show poor quality amongst the lamps tested. The results for these two F7 and two F8 lamps demonstrate the best performance which the software can achieve to improve the quality of F7 and F8 lamps.

The two F7 lamps reported here were made by GE and GretagMacbeth, denoted as GE(F7) and GM(F7) respectively, and the two F8 lamps were made by GE and MEGA, denoted as GE(F8) and MEGA(F8) respectively. The band value results for these test lamps are given in Table 7.3.1. The colorimetric results for these two lamps in terms of chromaticity deviation ($\Delta u'_{10}v'_{10}$), colour difference (ΔE^*_{ab}) of a reference white illuminated from the CIE daylight illuminant to a test simulator, CIE metamerism index for the visible range (MI_{vis}), CRI and CCT are reported in Table 7.3.3.

7.3.1 Optimised SPDs of the Test Lamps

Table 7.3.1 reveals that the two F7 lamps show considerable power deficiency for Band 2 (from 455 to 510nm), and the two F8 lamps show inadequate band values for four BS 950 bands, with power deficiency for Band 2 (from 455 to 510nm), Band 3 (from 510 to 540nm) and Band 6 (from 620 to 760nm), and power surplus for Band 4 (from 540 to 590nm). Based on this finding, measures of simplicity were taken for optimising coefficients k5 to k10. For instance, for the F7 lamps, only coefficient k6 for Band 2 was optimised while the other coefficients set to zero. For the F8 lamps, coefficients k6, k7, k8 and k10 for Bands 2, 3, 4 and 6 respectively, were optimised while the other two coefficients were set to zero.

The first stage of optimisation was to input the SPD of the test lamp. Coefficients k1 to k10 were then optimised using the 'Solver' function until the optimisation objective (see Equation 7.2.1) reached a minimum value. The SPDs of the original and optimised lamps were plotted in the spreadsheet for comparison. For test lamps GM(F7), GE(F8) and MEGA(F8), their optimised SPDs exhibited an unnatural feature for wavelength range between peaks 435 nm and 545 nm. Hence, a point averaging smoothing technique, named McMaster's slide averaging algorithm (Chrisman 1997), was applied to the optimised SPDs of these test lamps to remove the serious perturbations on the SPDs. The method calculates an average for each point based on the values of seven neighbouring points.

Figures 7.3.1 and 7.3.2 show the original and optimised SPDs (with and without smoothing) for the F7 and F8 lamps respectively. It can be seen from these two figures that in addition to the power modifications for the peak wavelengths, both the F7 and F8 test lamps need a increase of power for the range between peaks 435nm and 545nm. Figure 7.3.2 also revealed that the F8 test lamps show power deficiency at the longer wavelength, and a boost of power such as an additional peak of power was proved to be useful for improving the quality of the lamps.

7.3.2 Optimised Power for the Peak Wavelengths and Different BS 950 Bands

Table 7.3.2 lists the power values at the peak wavelengths for the original and optimised test lamps, as well as the power change in percentage for the optimised lamps. The optimised coefficients (k5 to k10) for the six BS 950 bands are also reported in the table. The power values at the peak wavelengths, represented by coefficients k1 to k4, were optimised within the practical variation range. The results show that the power changes for each peak wavelength vary with the test lamps, and they are generally within a range of ±30% with the maximum change of 46% found at peak 405 nm for test lamp GM(F7). It also shows the power increase for Band 2 is within the practical variation range for the F7 lamps with optimised coefficient k6 less than 2.0 for both F7 lamps, while the power increase for the F8 lamps is much larger with optimised coefficient k6 reaching 8.0 for both lamps. For the other BS 950 bands, the power modifications to the F8 test lamps are more or less within the practical variation range with optimised coefficients k7, k8 and k10 being 1.0 or 2.0.

7.3.3 Improved Band Value Results

Table 7.3.1 lists the band values and band-value deviations for the original and optimised (without and with smoothing to the optimised SPDs) test lamps. The results show that after optimisation, the test lamps achieved adequate band values for the six BS 950 bands with maximum band-value deviations within a range of ±10%. For test lamps GM(F7), GE(F8) and MEGA(F8), applying smoothing to the optimised SPDs slightly altered the band values, with the maximum change of band-value deviations about 5%, which has little impact on the quality of the test lamps (see Table 7.3.3).

7.3.4 Improved Colorimetric Results

Table 7.3.3 reports the colorimetric results for the original and optimised (without and with smoothing to the optimised SPDs) test lamps. The results show that all the test lamps have significantly improved their quality after the optimisation. The CIE metermism index results of all test lamps were reduced by more than half of their original values and all the test lamps increased the metamerism index ratings from the original categories 'D' or 'C' to 'B'. The CRI of the test lamps were also improved, with 4 units increased for the F7 lamps and 7 units for the F8 lamps, and all the test lamps achieved CRI above 95. The CCT of the test lamps were made closer to the specified ones of 6500K (F7 lamps) or 5000K (F8 lamps) after the optimisation, particularly in the case of F8 test lamps. The two F8 test lamps also showed improvement on chromaticity results. However, the chromaticities of the two F7 lamps have barely changed, as the original chromaticities of the lamps are already very close to the correct ones.

Table 7.3.1 Band value results for the original and optimised test lamps (without and with smoothing to the optimised SPDs)

	Band value						Band-value deviation (%)						
	Band 1 400-455nm	Band 2 455-510nm	Band 3 510-540nm	Band 4 540-590nm	Band 5 590-620nm	Band 6 620-760nm	Band 1 400-455nm	Band 2 455-510nm	Band 3 510-540nm	Band 4 540-590nm	Band 5 590-620nm	Band 6 620-760nm	Sum (abs.)
(Before optimization)													
GE (F7)	0.85	9.55	21.12	47.41	14.50	6.56	7.75	-14.70	-8.58	8.49	0.70	-3.46	43.69
GM (F7)	0.82	9.49	21.97	47.00	13.53	7.18	4.04	-15.22	-4.87	7.55	-6.05	5.60	43.35
GE (F8)	0.57	7.44	18.21	50.61	16.07	7.08	0.24	-22.45	-16.46	14.61	1.73	-11.57	66.96
MEGA (F8)	0.58	7.87	19.09	49.55	15.77	7.15	0.68	-18.00	-12.43	12.10	-0.22	-10.75	54.19
(After optimization)													
GE (F7)	0.78	10.70	22.08	45.35	14.52	6.57	-1.84	-4.43	-4.44	3.77	0.85	-3.32	18.45
GM (F7)	0.82	11.06	22.73	45.44	13.04	6.92	3.94	-1.27	-1.61	3.97	-9.47	1.77	22.02
GE (F8)	0.56	9.43	20.31	46.54	15.46	7.70	-3.05	-1.81	-6.82	5.30	-2.15	-3.88	23.00
MEGA (F8)	0.57	9.52	20.29	46.30	15.36	7.97	-0.47	-0.64	-6.92	4.74	-2.80	-0.53	16.31
(After optimization and smoothing)													
GE (F7)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GM (F7)	0.82	11.01	22.98	45.30	13.00	6.90	3.62	-1.71	-0.52	3.65	-9.74	1.45	20.71
GE (F8)	0.55	9.11	21.49	45.97	15.27	7.61	-4.24	-5.06	-1.42	4.01	-3.35	-5.06	23.15
MEGA (F8)	0.57	9.21	21.16	45.92	15.23	7.90	-1.27	-4.07	-2.92	3.90	-3.58	-1.32	17.07

Table 7.3.2 Power values at the peak wavelengths for the original and optimised test lamps, and the optimised coefficients (k5 to k10) for the six BS 950 bands respectively.

	Relative power				Optimised coefficients for change of relative power (x standard deviation)					
	Peak 1 405nm	Peak 2 435nm	Peak 3 545nm	Peak 4 580nm	Band 1 400-455nm	Band 2 455-510nm	Band 3 510-540nm	Band 4 540-590nm	Band 5 590-620nm	Band 6 620-760nm
(Before optimization)										
GE (F7)	131	381	249	135						
GM (F7)	102	296	237	122						
GE (F8)	86	221	238	136						
MEGA (F8)	84	211	207	130						
(After optimization)	(k1)[a]	(k2)	(k3)	(k4)	(k5)	(k6)	(k7)	(k8)	(k9)	(k10)
GE (F7)	96 (-27%)	264 (-31%)	203 (-18%)	121 (-10%)	0.00	0.78	0.78	0.00	0.00	0.00
GM (F7)	149 (46%)	322 (9%)	203 (-14%)	156 (28%)	0.00	1.33	1.33	0.00	0.00	0.00
GE (F8)	80 (-7%)	195 (-12%)	180 (-24%)	123 (-10%)	0.00	8.00	2.00	1.00	0.00	2.00
MEGA (F8)	80 (-5%)	195 (-8%)	180 (-13%)	123 (-5%)	0.00	6.00	1.00	-1.00	0.00	2.00

a The values in bracket are the power change in percentage

Table 7.3.3 Colorimetric results for the original and optimised test lamps (with smoothing to the optimised SPDs)

	$\Delta u'v'_{10}$	ΔE^*_{ab}	MI_{vis}	R_a	CCT (K)
(Before Optimization)					
GE (F7)	0.0038	3.29	0.82 (C)	93	6326
GM (F7)	0.0033	2.39	0.70 (C)	93	6296
GE (F8)	0.0072	6.13	1.09 (D)	88	4707
MEGA (F8)	0.0054	4.86	0.94 (C)	89	4807
(After optimization and smoothing)					
GE (F7)	0.0038	3.26	0.37 (B)	97	6334
GM (F7)	0.0031	2.70	0.27 (B)	97	6757
GE (F8)	0.0050	5.26	0.46 (B)	95	5014
MEGA (F8)	0.0032	3.40	0.47 (B)	96	5006

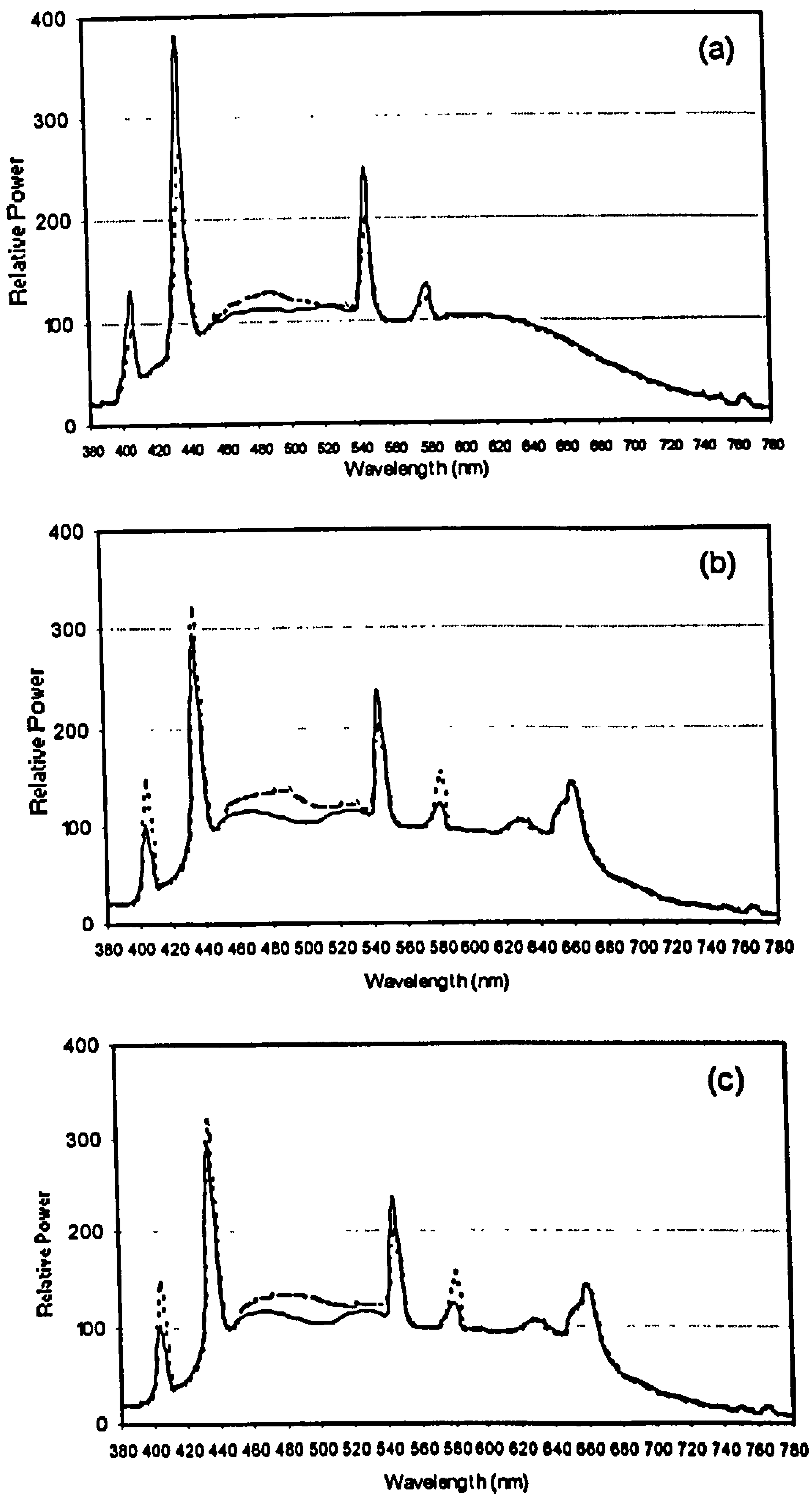


Figure 7.3.1 SPDs for the original (in solid line) and optimised (in dotted line) F7 test lamps: (a) GE(F7), (b) GM(F7), (c) GM(F7) with smoothing to the optimised SPD

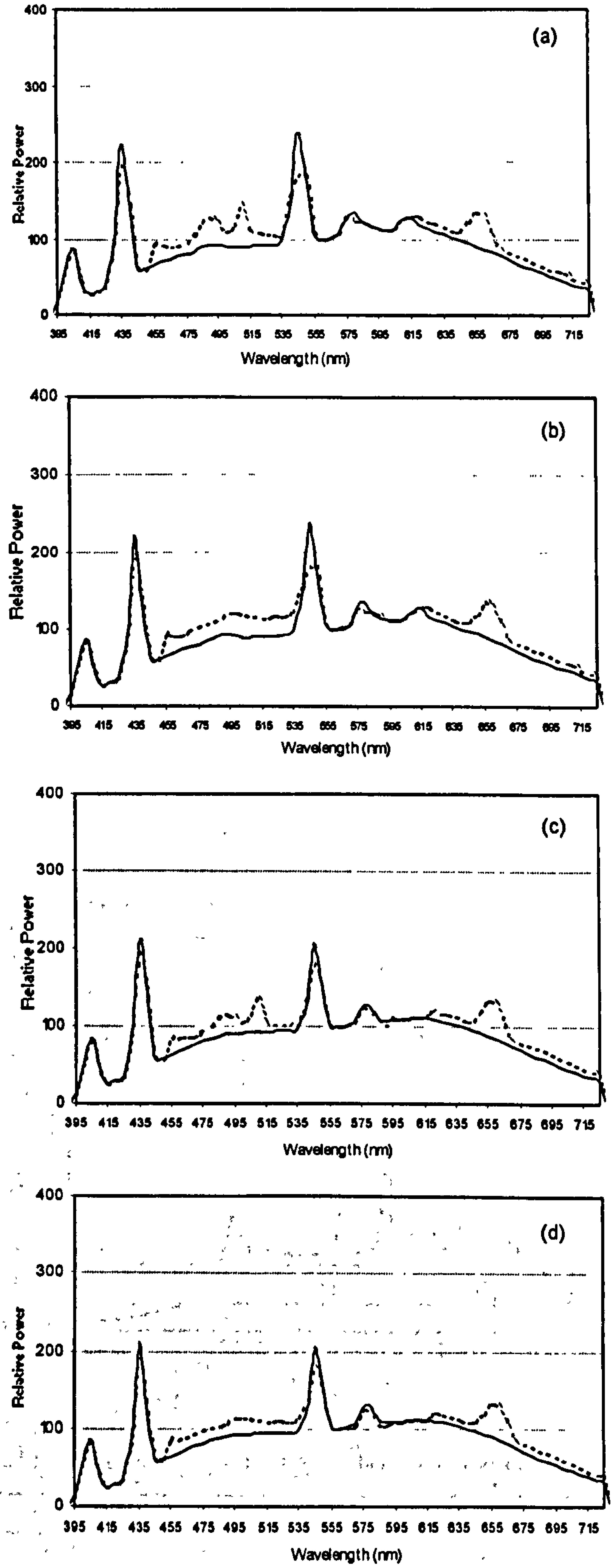


Figure 7.3.2 SPDs for the original (in solid line) and optimised (in dotted line) F8 test lamps: (a) GE(F8), (b) GE(F8) with smoothing to the optimised SPD, (c) MEGA(F8), (d) MEGA(F8) with smoothing to the optimised SPD

7.4 Conclusions

An optimisation method was designed to improve the quality of fluorescent daylight simulators. The method uses a linear combination of chromaticity deviation and CIE metamerism index as the optimisation objective and optimises the power at the peak wavelengths and that at each reported wavelength (except the peak wavelength) for the six BS 950 bands. The performance of the method was illustrated using two F7 lamps and two F7 lamps, selected by showing poor quality amongst the test simulators accumulated. The test lamps significantly improved their qualities in terms of CIE metamerism index and CRI results after optimisation. For the CIE metamerism index results, an increase of one or two category grades (e.g. from categories 'D' or 'C' to 'B') was observed for all the test lamps. For the CRI results, in increase of 4 and 7 units were achieved by the F7 and F8 test lamps respectively. The two F8 test lamps also showed improvement for the chromaticity results, though that did not occur on the F7 test lamps as their original chromaticities were already very close to the reference illuminant.

The band value analysis on the original and optimised test lamps revealed that in addition to the power adjustment for the peak wavelengths, both the F7 and F8 test lamps require a sufficient power increase for the range between the peaks at 435 nm and 545 nm. The F8 test lamps showed power deficiency for the longer wavelengths, and a boost of power such as an additional peak of power was proved to be useful for improving the quality of the lamps. It was also found that to effectively improve the quality of F8 test lamps, the optimisation has to be exercised to such an extent that the optimised SPDs for the range within BS 950 Band 2 are out of the practical variation range of F8 lamps. However, the power modifications to the F7 test lamps were more moderate, and the power change for each reported wavelength was within the practical variation range.

Although the optimisation method proposed here is purely theoretical, the method could be extended if the phosphor formulation data are available from the lamp manufacturer.

CHAPTER 8
CONCLUSIONS

8.1 Overview of Findings

As the thesis title states, the aim of this thesis is to investigate the impact of practical daylight simulators for industrial colour control. It can be divided into three specific tasks. The first task is to investigate the performances of standard methods including the BS950 band value method, CIE metamerism index method and CIE colour rendering index method, for evaluating daylight simulators. The second task is to evaluate the impact of different daylight simulators on industrial colour quality control, e.g. visual assessments on colour difference, metamerism and colour appearance. The final task is to develop new methods for improving the quality of daylight simulators and the provision of a practical guide for manufacturing viewing cabinets. The findings from this study are summarised below.

8.1.1 Variations of Practical D65 and D50 Simulators

The quality variations of the D50 and D65 simulators accumulated were investigated for the colorimetric and spectral results in Chapter 3. The chromaticity results show that all the D65 and D50 simulators investigated are within the CIE specification of 0.0150 in $\Delta u'_{10}v'_{10}$ unit, however, the chromaticity deviations for a considerable number of D50 simulators exceed the ISO 3664 specification of 0.0050 in $\Delta u'_{10}v'_{10}$ unit. This indicates that there is a significant difference between the CIE and ISO for specifying the chromaticities of daylight simulators (Note that the CIE specification is for D50, D55, D65 and D75 simulators while the ISO specification is only for D50 simulators). It was therefore speculated that both the CIE and ISO specifications may not be appropriate, i.e. too lenient for the former and too strict for the latter.

The results in Chapter 3 also revealed that for all the D65 simulators investigated, the CIE metamerism index ratings for the visible range are B, C or better, and the CRI ratings are all above 93, except for the three-band fluorescent lamp. All the investigated D50 simulators performed slightly worse than the D65 simulators, i.e. majority of them have CIE metamerism index ratings of C or D, and a narrow range of CRI between 85 to 91. For both D65 and D50 simulators, the filtered tungsten lamps exhibit the best qualities by giving the best CIE metamerism index ratings, better than average chromaticities and CIE colour rendering index (CRI) ratings, while the three-band fluorescent lamps show the worst qualities with the worst metamerism index and colour rendering index ratings. However, it was found the D65 filtered tungsten lamps do not give the best CRI ratings despite the fact that they have a closer chromaticities and CCT to the target, and a better metamerism index comparing to most of the fluorescent lamps. It was also found that a lamp with a large chromaticity deviation also gives a poor metamerism index rating.

The spectral results for F8 and F7 lamps show that these two types of fluorescent lamps have similar SPDs with exactly the same peak wavelengths. The lamps from the same manufacturer show less spread of SPD comparing to the lamps from different manufactures. It was also found that peak power, especially that at wavelength of 435 nm and 545 nm, plays an important role in determining the qualities of daylight simulators. An investigation in the power ratio between the main peak wavelength and other peak wavelengths revealed that different lamp manufacturers may adopt more or less the same phosphor formulation for the same type of fluorescent lamps.

8.1.2 Experimental Assessment on the Quality of D65 Simulators

In Chapter 4, a psychophysical experiment using real metameric pairs was described for evaluating the quality of six daylight simulators from different manufacturers. The visual results were firstly used to test four colour difference formulae, CIELAB, CIE94, CMC, CIEDE2000. It was found that the last three formulae gave a similar degree of performance in predicting visual data and all outperform the CIELAB formula. In general, all the simulators studied agreed well with each other in terms of visual results, except for one simulator having a three-band SPD, unlike broad-band for the others. Finally, the visual results in terms of Performance Factor (PF/3) were used to test the CIE metamerism index and BS 950 band value methods. The results show that these two standard methods are equally reliable for evaluating the quality of daylight simulators. It was also revealed that a simulator having band-value deviation well below the BS 950 tolerance corresponds to a high CIE metamerism index rating and therefore is therefore judged as good quality.

8.1.3 Generating New Sets of Metamers for Evaluating D65 Simulators

In Chapter 4, seven metamer sets including four general sets and three effective sets were generated for evaluating the qualities of 15 D65 simulators. The general sets include two normal sets, which were generated through normal match prediction procedure on physical samples and, two special sets, which were deliberately made with built-in spectral characteristics. The effective sets were selected from the general sets, which are representatives for evaluating the metamerism quality of daylight simulators. The four general sets were used to compare different metamerism indices. It was found an illuminant-dependent metamerism index such as the CIE special index of metamerism gives very different results from the general metamerism indices such as those developed by Nimeroff-Yurow, Moradian and Viggiano, which are illuminant-independent. An investigation into the crossovers of metamers shows that the number of crossovers has no obvious connections with the metamerism degree of metamers, and a large proportion of crossovers occurs at or near Thornton's three prime wavelengths at 450 nm, 540 nm and 610 nm.

The average and maximum colour differences of each of the seven generated metamer sets were used to evaluate 15 D65 simulators. It was found that the GretagMacbeth filter tungsten lamp shows the best quality while the Toshiba three-band fluorescent lamp shows the worst quality. The results show that the CIE metamer set gives smaller colour differences for the test simulators because it exhibits lower metamerism degree comparing to the generated metamer sets. It was also revealed that simulators with the same CIE metamerism index category may give very different colour differences for metamers, implying that the category of the CIE metamerism index does not differentiate the quality of different daylight simulators in a great detail.

The performance of the measure based on goodness-of-fit of SPD was also investigated for evaluating D65 simulators. It was found that this measure is not sensitive in differentiating daylight simulators of same type, e.g. broad band fluorescent lamps. The rankings of the test simulators based on this method do not agree well with those based on the average colour differences of metamer sets. This suggests that this measure is somewhat different from the CIE metamerism index method, which uses metamers for evaluating daylight simulators.

It was revealed that metamer sets selected from a large database based upon the same material may have a similar performance for evaluating daylight simulators. On average, the

CIE set agrees best with the general sets for evaluating the test simulators, indicating the CIE metamers are representatives of real metamers. It was also found that a limited number of metamers could be selected from a range of real metamers to perform as effective as the CIE set for evaluating daylight simulators.

8.1.4 Investigating the CIE Colour Rendering Index Method for Evaluating D65 Simulators

The CIE colour rendering index method for evaluating daylight simulators was investigated in Chapter 6. In addition to the CIE test colours, new sets of test colours of different material were used. It was found that the CIE test colour sets agreed better with the paint sample sets than with the textile or thread sample sets, which is expected because the CIE test colours are based upon Munsell painted chips. The average colour differences of the total 14 CIE test colours instead of the first 8t test colours give better agreement with those of the normal colours. This suggesting that it might be more appropriate to adopt the total CIE test colours instead of the first eight colours for calculating CRI. It was also found that a simulator with CIE general colour rendering index (CRI) lower than 90 may render colours, particularly for colours showing high colour inconstancy, poorly. Two simulators having a CRI difference of 10 units may be a significant difference in colour rendering properties.

The four colour difference formulae, CIELAB, CMC, CIE94 and CIEDE2000, exhibit a similar performance for calculating CIE colour rendering index, and they all outperform CIEU*V*W*. No significant difference was found for the performance between two CATs, von Kries and CMCCAT2000. A new set of test colours, selected from the CIE test colours and normal colours for showing medium to large colour inconstancy as well as covering a large colour gamut, was generated. These selected test colours exhibit a better agreement with the textile samples than the CIE test colours. The results showed that that the performances of the CIE method could be improved by replacing the current CIE test colours with these selected colours.

8.1.5 Methods to Improve the Quality of Daylight Simulators

Chapter 7 demonstrated how the quality of a daylight simulator (F7 or F8 lamps) can be significantly improved by optimising its SPD. A band value analysis on the original and optimised F7 and F8 test lamps revealed that in addition to the modifications to the power at peak wavelengths, both types of test lamps require a power increase for the wavelength range between peaks at 435nm and 545nm. The F8 test lamps showed power deficiency at the longer wavelengths, and a boost of power, such as an additional peak of power, was proved to be useful for improving the quality of the lamps. It was also found that to improve the quality of F8 test lamps effectively, the optimisation has to be exercised to such an extent that the optimised SPDs for a wavelength range within BS 950 Band 2 exceed the practical variation range. However, modifications of SPDs to the F7 test lamps were more moderate with the power change of each reported wavelength within the practical variation range.

The test lamps significantly improved their qualities in terms of CIE metamerism index and CRI results after optimisation. For the CIE metamerism index results, an upgrade of one to two category ratings (e.g. from categories 'D' or 'C' to 'B') was achieved for all the test lamps. The F7 and F8 test lamps also improved their CRI results by an increment of 4 and 7 units respectively. The chromaticities of F8 test lamps were also improved.

8.2 Guidelines for Viewing Cabinet Design

Chapter 3 reported an industrial survey on viewing cabinets. It was revealed that a considerable variation exists between the viewing cabinets used in practice in terms of the quality of light sources, illumination level and uniformity, interior colour, and some other aspects of the cabinets. The results from the survey (see Section 3.2) provided sufficient information for proposing a guideline for designing high quality viewing cabinets. This is necessary because it was found due to the different requirements from different industries, large variations exist between different standards in specifying the light sources used in viewing cabinets (e.g. daylight simulator). Hence, a draft version of guideline was proposed to the Colour Measurement Committee (CMC) of the Society of Dyers and Colourists (SDC). The guideline is based on relevant ISO standards (3664, 3668, see Section 2.5.5), CIE recommendations (CIE 13.3, 15.2, 17.4 and 51.2) and an Australian standard (AS 40004, see Section 2.6.2). The drafted guideline is provided in Appendix G. It is possible that the guideline will be revised to become a British Standard for the surface colour industry. The main contents of the guideline are summarised below.

Section One *General* provides the general information for this guideline in three parts. Part 1 *Scope* sets out the main principles used for viewing cabinet design. Part 2 *Normative Reference* lists the references used for proposing the guideline. Part 3 *Terms and Definitions* describes the key concepts related to viewing cabinet design, including chromaticity, colour rendering index, CCT, illuminance, illuminant, Lux and relative SPD.

Section Two *Design and Construction* is the main part of this guideline, covering seven aspects relating to viewing cabinet design, which are:

- Viewing area
- Light sources including daylight simulators and incandescent lights
- Additional light sources, such as UV source
- Cabinet interior colour
- Electrical safety
- Recommended life of sources
- Heat generation and dissipation

Section Three *Maintenance* lists the basic requirements for maintaining the quality of a viewing cabinet, such as regular services, change of lamps after a certain period of use.

8.3 Future Work

The current study investigates D65 and D50 daylight simulators with focus on evaluating standard methods for assessing daylight simulators and revealing the impact of different daylight simulators on industrial colour quality control, e.g. visual assessments on colour difference, metamerism and colour appearance. To strengthen the conclusions drawn from the present study as well as to implement practical measures to improve the quality of daylight simulators, future work should be carried out in the following six aspects.

1) To evaluate more test simulators

The current study used a number of D65 and D50 simulators as test lamps for variation analysis and assessment work. The number of the test simulators, particularly D65 test simulators, is however not comprehensive. Lamps of some international leading brands, such as National and Osram, were not included. It is therefore desirable to accumulate more simulators for further evaluation.

2) To conduct visual assessments for evaluating CIE colour rendering index method
Chapter 6 investigated the performance of *CIE colour rendering index* method for evaluating daylight simulators, and a new set of test colours was also developed in this chapter. As the test colours in this set were generated based on theoretical results, visual assessments should be conducted to test the effectiveness of these new test colours.

3) To improve the quality of daylight simulators on a practical basis
The optimisation method described in Chapter 7 was proposed on a theoretical basis for improving the quality of daylight simulators. To optimise the SPDs of test simulators on a practical basis, phosphor formulation data are needed from lamp manufacturers.

4) To receive feedback from the manufacturers for designing viewing cabinets
A guideline for viewing cabinet designed was proposed in this thesis. It was purely based on available standards such as ISO standards, CIE recommendations and an Australian standard. To make the guideline more applicable for industrial use, some feedback from cabinet manufactures are important. It has been proposed to extend the guideline to become a British standard.

5) To test and develop methods for evaluating LED sources.
The development of LED sources has advanced rapidly. It has the great potential to replace the current light sources with lower energy consumption and a longer life. In addition, it is capable of varying colour by adjusting the intensity of red, green and blue in a white LED. Further investigations of the metamerism and colour rendering properties of LED sources can be conducted using the methods and data sets developed in this study.

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APPENDICES

Appendix A1: A worked example for calculating BS 950 band values for CIE D65 illuminant

BS 950 Band	Wav. (nm)	V(λ)	SPD (λ)	V(λ)*SPD (λ)
UV A (300-340)	300		0.03	
	305		1.66	
	310		3.29	
	315		11.77	
	320		20.24	
	325		28.64	
	330		37.05	
	335		38.50	
UV B (340-400)	340		39.95	
	345		42.43	
	350		44.91	
	355		45.78	
	360		46.64	
	365		49.36	
	370		52.09	
	375		51.03	
	380		49.98	
	385		52.31	
	390		54.65	
	395		68.70	
VIS1 (400-455)	400	0.0004	82.75	0.03277
	405	0.0006	87.12	0.05576
	410	0.0012	91.49	0.11070
	415	0.0022	92.46	0.20156
	420	0.0040	93.43	0.37373
	425	0.0073	90.06	0.65742
	430	0.0116	86.68	1.00551
	435	0.0168	95.77	1.61283
	440	0.0230	104.87	2.41190
	445	0.0298	110.94	3.30589
	450	0.0380	117.01	4.44630
VIS2 (455-510)	455	0.0480	117.41	5.63568
	460	0.0600	117.81	7.06872
	465	0.0739	116.34	8.59723
	470	0.0910	114.86	10.45005
	475	0.1126	115.39	12.99314
	480	0.1390	115.92	16.11562
	485	0.1693	112.37	19.02373
	490	0.2080	108.81	22.63486
	495	0.2586	109.08	28.20861
	500	0.3230	109.35	35.32134
	505	0.4073	108.58	44.22382
VIS3 (510-540)	510	0.5030	107.80	54.22441
	515	0.6082	106.30	64.64923
	520	0.7100	104.79	74.40090
	525	0.7932	106.24	84.26877
	530	0.8620	107.69	92.82792
	535	0.9149	106.05	97.01711

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VIS4 (540-590)	540	0.9540	104.41	99.60237
	545	0.9803	104.23	102.17177
	550	0.9950	104.05	103.52058
	555	1.0000	102.02	102.02300
	560	0.9950	100.00	99.50000
	565	0.9786	98.17	96.06632
	570	0.9520	96.33	91.71016
	575	0.9154	96.06	87.93433
	580	0.8700	95.79	83.33556
	585	0.8163	92.24	75.29290
VIS5 (590-620)	590	0.7570	88.69	67.13500
	595	0.6949	89.35	62.08647
	600	0.6310	90.01	56.79391
	605	0.5668	89.80	50.90011
	610	0.5030	89.60	45.06835
	615	0.4412	88.65	39.11189
VIS6 (620-760)	620	0.3810	87.70	33.41320
	625	0.3210	85.49	27.44345
	630	0.2650	83.29	22.07148
	635	0.2170	83.49	18.11818
	640	0.1750	83.70	14.64736
	645	0.1382	81.86	11.31347
	650	0.1070	80.03	8.56287
	655	0.0816	80.12	6.53785
	660	0.0610	80.21	4.89309
	665	0.0446	81.25	3.62196
	670	0.0320	82.28	2.63289
	675	0.0232	80.28	1.86252
	680	0.0170	78.28	1.33083
	685	0.0119	74.00	0.88211
	690	0.0082	69.72	0.57241
	695	0.0057	70.67	0.40442
	700	0.0041	71.61	0.29374
	705	0.0029	72.98	0.21376
	710	0.0021	74.35	0.15546
	715	0.0015	67.98	0.10088
	720	0.0010	61.60	0.06450
	725	0.0007	65.74	0.04865
	730	0.0005	69.89	0.03634
	735	0.0004	72.49	0.02617
	740	0.0002	75.09	0.01871
	745	0.0002	69.34	0.01192
	750	0.0001	63.59	0.00763
	755	0.0001	55.01	0.00466
	760	0.0001	46.42	0.00279

Band	**Band Value**		
	Unscaled	BS 950 specified	Scaled
UVA (300-340)	161.16	11.20	10.67
UVB (340-400)	660.61	43.20	43.73
VIS1(400-455)	17.03	0.79	0.81
VIS2 (455-510)	234.57	11.20	11.10
VIS3 (510-540)	490.08	23.10	23.19
VIS4 (540-590)	924.92	43.70	43.76
VIS5 (590-620)	304.23	14.40	14.39
VIS6 (620-760)	142.59	6.80	6.75
	Sum of Band Value		
	Unscaled	BS 950 specified	
(UVA-UVB)	821.76	54.40	
(VIS1-VIS6)	2113.42	99.99	
	Scaling Factor *		
(UVA-UVB)	0.07		
(VIS1-VIS6)	0.05		

Appendix A2: A worked example for calculating BS 950 band values for CIE D50 illuminant

BS 950 Band	Wav. (nm)	V(λ)	SPD (λ)	V(λ)*SPD (λ)
UV A (300-340)	300		0.02	
	305		1.03	
	310		2.05	
	315		4.91	
	320		7.78	
	325		11.26	
	330		14.75	
	335		16.35	
UV B (340-400)	340		17.95	
	345		19.48	
	350		21.01	
	355		22.48	
	360		23.94	
	365		25.45	
	370		26.96	
	375		25.72	
	380		24.49	
	385		27.18	
	390		29.87	
	395		39.59	
VIS1 (400-455)	400	0.0004	49.31	0.01953
	405	0.0006	52.91	0.03386
	410	0.0012	56.51	0.06838
	415	0.0022	58.27	0.12703
	420	0.0040	60.03	0.24012
	425	0.0073	58.93	0.43019
	430	0.0116	57.82	0.67071
	435	0.0168	66.32	1.11683
	440	0.0230	74.82	1.72086
	445	0.0298	81.04	2.41499
	450	0.0380	87.25	3.31550
VIS2 (455-510)	455	0.0480	88.93	4.26864
	460	0.0600	90.61	5.43660
	465	0.0739	90.99	6.72416
	470	0.0910	91.37	8.31284
	475	0.1126	93.24	10.49882
	480	0.1390	95.11	13.22219
	485	0.1693	93.54	15.83632
	490	0.2080	91.96	19.12952
	495	0.2586	93.84	24.26702
	500	0.3230	95.72	30.91756
	505	0.4073	96.17	39.17004
VIS3 (510-540)	510	0.5030	96.61	48.59483
	515	0.6082	96.87	58.91633
	520	0.7100	97.13	68.96230
	525	0.7932	99.61	79.01065
	530	0.8620	102.10	88.01020
	535	0.9149	101.43	92.79325
VIS4 (540-590)	540	0.9540	100.75	96.11550
	545	0.9803	101.54	99.53966
	550	0.9950	102.32	101.80329
	555	1.0000	101.16	101.16000
	560	0.9950	100.00	99.50000
	565	0.9786	98.87	96.75418
	570	0.9520	97.74	93.04848
	575	0.9154	98.33	90.01128
	580	0.8700	98.92	86.06040
	585	0.8163	96.21	78.53622

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VIS5 (590-620)	590	0.7570	93.50	70.77950
	595	0.6949	95.59	66.42549
	600	0.6310	97.69	61.64239
	605	0.5668	98.48	55.81846
	610	0.5030	99.27	49.93281
	615	0.4412	99.16	43.74939
VIS6 (620-760)	620	0.3810	99.04	37.73424
	625	0.3210	97.38	31.25898
	630	0.2650	95.72	25.36580
	635	0.2170	97.29	21.11193
	640	0.1750	98.86	17.30050
	645	0.1382	97.26	13.44133
	650	0.1070	95.67	10.23669
	655	0.0816	96.93	7.90949
	660	0.0610	98.19	5.98959
	665	0.0446	100.60	4.48475
	670	0.0320	103.00	3.29600
	675	0.0232	101.07	2.34482
	680	0.0170	99.13	1.68521
	685	0.0119	93.26	1.11166
	690	0.0082	87.38	0.71739
	695	0.0057	89.49	0.51215
	700	0.0041	91.60	0.37574
	705	0.0029	92.25	0.27020
	710	0.0021	92.89	0.19423
	715	0.0015	84.87	0.12595
	720	0.0010	76.85	0.08046
	725	0.0007	81.68	0.06044
	730	0.0005	86.51	0.04499
	735	0.0004	89.55	0.03234
	740	0.0002	92.58	0.02307
	745	0.0002	85.40	0.01468
	750	0.0001	78.23	0.00939
	755	0.0001	67.96	0.00576
	760	0.0001	57.69	0.00346

Band	Band Value		
	Unscaled	BS 950 specified	Scaled
UVA (300-340)	67.13	4.70	4.42
UVB (340-400)	344.46	22.40	22.68
VIS1(400-455)	12.29	0.57	0.59
VIS2 (455-510)	199.95	9.60	9.52
VIS3 (510-540)	460.05	21.80	21.89
VIS4 (540-590)	929.86	44.20	44.25
VIS5 (590-620)	331.83	15.80	15.79
VIS6 (620-760)	166.87	8.01	7.94

	Sum of Band Value	
	Unscaled	BS 950 specified
(UVA-UVB)	411.58	27.10
(VIS1-VIS6)	2100.85	99.98

	Scaling Factor *
(UVA-UVB)	0.07
(VIS1-VIS6)	0.05

* Note that the scaling factor in the above tables was calculated as the ratio between the sum of band values specified in BS 950 and that calculated (denoted as 'Unscaled' in the tables). As the band values for the UV and visible ranges are calculated in a different way (the former is the integration result of the spectral power values of the source while the latter is the integration result between the spectral power values and CIE standard photometric observer $V(\lambda)$),

individual scaling factors were applied for the UV and visible ranges. The band values of a test simulator (denoted as 'Scaled' in the tables, see the shaded area) are the unscaled band values multiplied by the scaling factors for the UV and visible ranges respectively. A slight difference was observed for the scaled band values and those specified by BS 950 for both CIE D65 and D50 illuminants, which may be caused by the different way in dealing with the border wavelength for calculating the band values (see Section 2.5.1). The band values of a D65 (or D50) test simulator can be obtained by replacing the SPD values in Appendix A1 (or A2) with those of the test simulator.

Appendix B: A technical report for a viewing cabinet surveyed

A. General Information

Date of survey	29 November 2000
Business	Research Institute
Contact	Hong Xu
Address	Colour & Imaging Institute (CII) University of Derby Kingsway House, Kingsway Derby DE22 3HL Tel: 01332 593108

B. Cabinet Details

Manufacturer / Model	GretagMacbeth/SpectraLight II
Age	About two years
Dimensions of viewing	900 (W) by 640 (H) by 580 (D) mm^3
Number of sources	4

	Make	Simulator	Burned Marks	Over 100 hours	Flickering
Source 1	GretagMacbeth	D65	No	Yes	No
Source 2	GretagMacbeth	A	No	Not Known	No
Source 3	GretagMacbeth	CWF	No	Not Known	No
Source 4	GretagMacbeth	Horizon	No	Not Known	No
	GretagMacbeth	UV*	No	Not Known	No

* UV source is used in conjunction with the other sources and was not investigated.

Status	Excellent	Good	Fair	Bad	Description
Cabinet Interior	√				

Dimmer control	No
Diffuser	Yes
Elapsed-time meter	Yes (only count for D65 source)

Location	CII laboratory with room lighting control

C. Assessment Results (Each measure is described in Appendix)

Source 1: GretagMacbeth D65						
	x x10^4	y x10^4	u' x10^4	v' x10^4	L(cd/m^2)	CCT(K)
Mean	3124	3310	1969	4694	377	6507
Max. Dif.	8	4	4	4	34	46
CV(%)	0.14	0.08	0.11	0.04	6.05	0.40
					Δu'v' x10^4	CIE MI_{vis}
Target	3127	3290	1978	4683		
Centre	3127	3311	1970	4694	14	A

Source 2: GretagMacbeth A						
	x x10^4	y x10^4	u' x10^4	v' x10^4	L(cd/m^2)	CCT(K)
Mean	4533	4123	2575	5270	363	2799
Max. Dif.	2	1	1	1	43	2
CV(%)	0.03	0.02	0.03	0.01	9.30	0.06
					Δu'v' x10^4	
Target	4476	4074	2560	5243		
Centre	4531	4122	2575	5269	30	

Source 3: GretagMacbeth CWF						
	x x10^4	y x10^4	u' x10^4	v' x10^4	L(cd/m^2)	CCT(K)
Mean	3806	3917	2194	5080	279	4090
Max. Dif.	9	10	2	5	65	16
CV(%)	0.15	0.16	0.08	0.06	14	0.29
					Δu'v' x10^4	
Target	3779	3882	2190	5062		
Centre	3797	3907	2192	5075	13	

Source 4: GretagMacbeth Horizon						
	x x10^4	y x10^4	u' x10^4	v' x10^4	L(cd/m^2)	CCT(K)
Mean	5014	4172	2864	5361	249	N/A
Max. Dif.	3	1	2	1	32	N/A
CV(%)	0.06	0.01	0.06	0.01	9.46	
					Δu'v' x10^4	
Target	N/A	N/A	N/A	N/A		
Centre	5011	4172	2862	5361	N/A	

D. Overall Comments

This is a viewing cabinet of high quality in terms of illumination uniformity and agreement with the CIE specification for the colours of the sources investigated.

Appendix

1. Measures used in this survey report

• Instrument

A spectroradiometer traceable to the NPL was used in the survey. The wavelength measured is ranged from 380 to 780 nm with a 5 nm resolution. The measurement accuracy is: +4%, 0.0015 and 0.0010 for luminance, x and y chromaticities respectively for a standard light source A.

• Sampling

A PTFE tile was placed and measured at centre and four corners of the viewing cabinet floor for each test source. The measuring geometry was 0/45 with room lighting off.

• Technical features

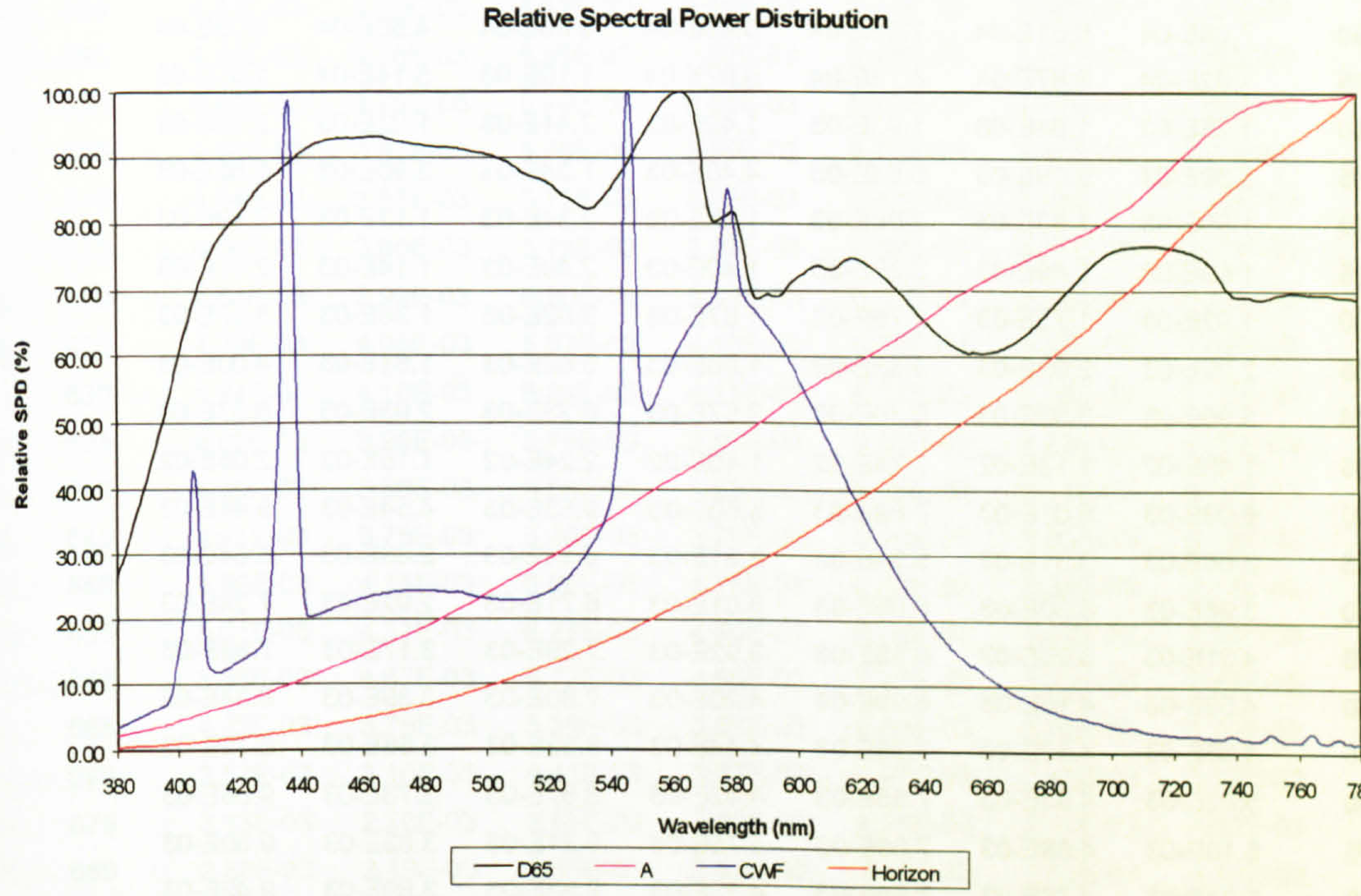
Mean:	The average from the five positions measured in terms of x, y, u', v' chromaticities, Luminance (L(cd/m^2)) and correlated colour temperature (CCT(K)).
Max. Dif.:	The maximum difference between the 'mean' and the most deviate position from five positions. Note that the variation across the most frequently used parts of the cabinet will generally be considerably less.
CV(%):	Coefficient of variation (CV) is calculated by multiplying 100 to the standard deviation dividing by the mean. It represents the uniformity of the viewing cabinet. It is particular important for the luminance uniformity and should normally be within 20%.
Target:	The CIE specification [1] in terms of x and y chromaticities and correlated colour temperature. TL84 and CWF sources correspond to F11 and F6.
Centre:	The measured values from the centre position, which is the most frequently used position.
Δu'v':	The chromatic difference between the 'target' and 'centre'. It is expected to be less than 0.005 [2].
MI_{vis}:	The special metamerism index (only for the visual range from 400 to 700 nm) for evaluating the quality of daylight sources [3]. It is expected that the rating should be at least C with A being the highest grade.

• Reference

1) CIE Technical Report (CIE 15.2 -1986), Colorimetry, 2nd Edition.
2) ISO 3664: 1998 (E). Viewing Conditions – for Graphic Technology and Photography.
3) CIE Publication No. 51 (1981), A Method for Assessing the Quality of Daylight Simulators for Colorimetry.

2. Plots of relative spectral power distribution

The maximum radiance for each source is scaled to 100 in the following diagram.



Appendix C1: SPDs for the 15 D65 simulators accumulated

D65 simulators (VV1 to VV7)

Wav. (nm)	VV1	VV2	VV3	VV4	VV5	VV6	VV7
380	6.95E-04	3.53E-04	4.43E-04	5.37E-04	9.52E-04	4.63E-04	5.14E-04
385	6.74E-04	4.47E-04	5.64E-04	5.22E-04	9.23E-04	4.52E-04	6.20E-04
390	7.03E-04	5.51E-04	7.03E-04	5.45E-04	9.80E-04	4.66E-04	8.03E-04
395	7.82E-04	6.87E-04	8.73E-04	6.07E-04	1.10E-03	5.14E-04	1.01E-03
400	1.76E-03	1.64E-03	1.93E-03	1.40E-03	2.41E-03	1.22E-03	2.26E-03
405	5.39E-03	5.09E-03	5.64E-03	4.40E-03	7.24E-03	3.90E-03	6.65E-03
410	1.60E-03	1.50E-03	2.08E-03	1.35E-03	2.34E-03	1.13E-03	2.49E-03
415	1.63E-03	1.48E-03	2.29E-03	1.40E-03	2.49E-03	1.14E-03	2.77E-03
420	1.92E-03	1.73E-03	2.79E-03	1.67E-03	3.02E-03	1.36E-03	3.37E-03
425	2.25E-03	2.02E-03	3.32E-03	1.98E-03	3.62E-03	1.61E-03	4.00E-03
430	3.96E-03	3.33E-03	5.30E-03	3.57E-03	6.23E-03	2.93E-03	6.37E-03
435	1.49E-02	1.13E-02	1.74E-02	1.40E-02	2.24E-02	1.15E-02	2.08E-02
440	6.06E-03	5.01E-03	7.89E-03	5.50E-03	9.53E-03	4.54E-03	9.44E-03
445	3.66E-03	3.31E-03	5.54E-03	3.31E-03	6.14E-03	2.68E-03	6.64E-03
450	3.98E-03	3.60E-03	6.05E-03	3.61E-03	6.71E-03	2.92E-03	7.24E-03
455	4.31E-03	3.90E-03	6.55E-03	3.92E-03	7.29E-03	3.17E-03	7.83E-03
460	4.59E-03	4.16E-03	6.99E-03	4.20E-03	7.80E-03	3.39E-03	8.34E-03
465	4.83E-03	4.38E-03	7.36E-03	4.44E-03	8.22E-03	3.58E-03	8.76E-03
470	5.02E-03	4.55E-03	7.65E-03	4.62E-03	8.57E-03	3.73E-03	9.08E-03
475	5.16E-03	4.68E-03	7.86E-03	4.75E-03	8.81E-03	3.83E-03	9.30E-03
480	5.24E-03	4.76E-03	7.98E-03	4.83E-03	8.93E-03	3.89E-03	9.42E-03
485	5.27E-03	4.78E-03	8.01E-03	4.86E-03	8.96E-03	3.91E-03	9.44E-03
490	5.30E-03	4.80E-03	8.00E-03	4.88E-03	8.96E-03	3.93E-03	9.41E-03
495	5.24E-03	4.73E-03	7.87E-03	4.81E-03	8.80E-03	3.87E-03	9.24E-03
500	5.16E-03	4.64E-03	7.69E-03	4.73E-03	8.58E-03	3.80E-03	9.02E-03
505	5.10E-03	4.53E-03	7.48E-03	4.65E-03	8.34E-03	3.74E-03	8.77E-03
510	5.04E-03	4.41E-03	7.25E-03	4.59E-03	8.08E-03	3.68E-03	8.48E-03
515	4.99E-03	4.28E-03	7.00E-03	4.52E-03	7.80E-03	3.62E-03	8.18E-03
520	4.93E-03	4.15E-03	6.76E-03	4.45E-03	7.52E-03	3.56E-03	7.89E-03
525	4.85E-03	4.03E-03	6.54E-03	4.36E-03	7.27E-03	3.49E-03	7.63E-03
530	4.76E-03	3.93E-03	6.34E-03	4.26E-03	7.05E-03	3.41E-03	7.38E-03
535	4.64E-03	3.84E-03	6.16E-03	4.14E-03	6.85E-03	3.32E-03	7.17E-03
540	4.76E-03	4.00E-03	6.25E-03	4.22E-03	7.01E-03	3.40E-03	7.26E-03
545	1.19E-02	1.10E-02	1.39E-02	1.03E-02	1.68E-02	8.53E-03	1.60E-02
550	5.44E-03	4.77E-03	6.94E-03	4.77E-03	7.99E-03	3.87E-03	8.03E-03
555	4.33E-03	3.67E-03	5.74E-03	3.83E-03	6.45E-03	3.06E-03	6.67E-03
560	4.29E-03	3.65E-03	5.68E-03	3.79E-03	6.39E-03	3.03E-03	6.60E-03
565	4.29E-03	3.65E-03	5.66E-03	3.78E-03	6.38E-03	3.02E-03	6.58E-03
570	4.30E-03	3.67E-03	5.66E-03	3.79E-03	6.39E-03	3.03E-03	6.59E-03
575	4.87E-03	4.22E-03	6.24E-03	4.30E-03	7.18E-03	3.49E-03	7.27E-03

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Wav. (nm)	W1	W2	W3	W4	W5	W6	W7
580	5.76E-03	5.15E-03	7.16E-03	5.07E-03	8.40E-03	4.21E-03	8.34E-03
585	4.40E-03	3.75E-03	5.69E-03	3.85E-03	6.48E-03	3.09E-03	6.65E-03
590	4.41E-03	3.75E-03	5.67E-03	3.85E-03	6.46E-03	3.08E-03	6.63E-03
595	4.45E-03	3.78E-03	5.69E-03	3.87E-03	6.48E-03	3.11E-03	6.66E-03
600	4.48E-03	3.79E-03	5.69E-03	3.88E-03	6.49E-03	3.12E-03	6.66E-03
605	4.50E-03	3.81E-03	5.69E-03	3.89E-03	6.49E-03	3.13E-03	6.67E-03
610	4.54E-03	3.85E-03	5.72E-03	3.92E-03	6.52E-03	3.15E-03	6.70E-03
615	4.56E-03	3.85E-03	5.72E-03	3.93E-03	6.52E-03	3.17E-03	6.72E-03
620	4.64E-03	3.92E-03	5.80E-03	3.99E-03	6.59E-03	3.22E-03	6.81E-03
625	4.79E-03	4.05E-03	5.97E-03	4.10E-03	6.77E-03	3.32E-03	7.02E-03
630	4.84E-03	4.10E-03	6.04E-03	4.15E-03	6.83E-03	3.36E-03	7.10E-03
635	4.65E-03	3.96E-03	5.78E-03	3.97E-03	6.55E-03	3.22E-03	6.79E-03
640	4.49E-03	3.80E-03	5.56E-03	3.83E-03	6.30E-03	3.11E-03	6.54E-03
645	4.41E-03	3.75E-03	5.46E-03	3.76E-03	6.18E-03	3.05E-03	6.42E-03
650	4.86E-03	4.15E-03	6.06E-03	4.18E-03	6.80E-03	3.38E-03	7.11E-03
655	5.01E-03	4.31E-03	6.25E-03	4.30E-03	6.99E-03	3.49E-03	7.34E-03
660	5.36E-03	4.67E-03	6.72E-03	4.60E-03	7.47E-03	3.73E-03	7.89E-03
665	4.32E-03	3.76E-03	5.38E-03	3.69E-03	6.01E-03	3.00E-03	6.31E-03
670	3.57E-03	3.10E-03	4.41E-03	3.03E-03	4.97E-03	2.47E-03	5.18E-03
675	3.13E-03	2.70E-03	3.86E-03	2.66E-03	4.36E-03	2.16E-03	4.52E-03
680	2.88E-03	2.49E-03	3.55E-03	2.45E-03	4.01E-03	1.99E-03	4.16E-03
685	2.66E-03	2.31E-03	3.28E-03	2.26E-03	3.71E-03	1.84E-03	3.85E-03
690	2.51E-03	2.17E-03	3.07E-03	2.13E-03	3.49E-03	1.74E-03	3.60E-03
695	2.25E-03	1.97E-03	2.79E-03	1.92E-03	3.16E-03	1.56E-03	3.26E-03
700	2.07E-03	1.80E-03	2.55E-03	1.75E-03	2.88E-03	1.42E-03	2.97E-03
705	1.90E-03	1.66E-03	2.36E-03	1.62E-03	2.67E-03	1.31E-03	2.75E-03
710	1.75E-03	1.53E-03	2.16E-03	1.48E-03	2.44E-03	1.21E-03	2.50E-03
715	1.59E-03	1.39E-03	1.96E-03	1.34E-03	2.22E-03	1.09E-03	2.26E-03
720	1.46E-03	1.28E-03	1.78E-03	1.22E-03	2.02E-03	1.00E-03	2.05E-03
725	1.34E-03	1.17E-03	1.65E-03	1.11E-03	1.85E-03	9.16E-04	1.88E-03
730	1.22E-03	1.08E-03	1.51E-03	1.01E-03	1.71E-03	8.35E-04	1.71E-03
735	1.11E-03	9.84E-04	1.37E-03	9.21E-04	1.55E-03	7.64E-04	1.55E-03
740	1.03E-03	9.34E-04	1.31E-03	8.81E-04	1.49E-03	7.09E-04	1.49E-03
745	9.26E-04	8.23E-04	1.15E-03	7.63E-04	1.28E-03	6.33E-04	1.28E-03
750	8.64E-04	8.15E-04	1.17E-03	7.67E-04	1.31E-03	6.06E-04	1.32E-03
755	7.56E-04	6.95E-04	9.62E-04	6.40E-04	1.06E-03	5.17E-04	1.08E-03
760	6.93E-04	6.19E-04	8.56E-04	5.65E-04	9.50E-04	4.77E-04	9.62E-04
765	6.74E-04	6.98E-04	9.68E-04	6.78E-04	1.13E-03	4.93E-04	1.12E-03
770	5.77E-04	5.21E-04	7.56E-04	5.00E-04	8.36E-04	3.99E-04	8.34E-04
775	5.45E-04	5.02E-04	6.96E-04	4.67E-04	7.82E-04	3.67E-04	7.78E-04
780	4.67E-04	4.43E-04	6.21E-04	4.01E-04	6.82E-04	3.32E-04	6.83E-04

D65 simulators (GE to GM(FT)2)

Wav. (nm)	GE	GM	PH	BYK	TO	TO(3B)	GM(FT)1	GM(FT)2
380	1.43E-03	1.41E-03	5.90E-04	4.68E-04	2.04E-03	1.27E-04	1.58E-03	1.79E-03
385	1.38E-03	1.40E-03	7.35E-04	4.67E-04	2.18E-03	9.73E-05	2.00E-03	2.28E-03
390	1.44E-03	1.42E-03	9.56E-04	5.38E-04	2.32E-03	6.41E-05	2.49E-03	2.80E-03
395	1.60E-03	1.49E-03	1.21E-03	6.40E-04	2.45E-03	5.10E-05	3.02E-03	3.38E-03
400	3.07E-03	2.62E-03	2.83E-03	1.72E-03	3.35E-03	1.32E-03	3.59E-03	3.99E-03
405	8.42E-03	6.92E-03	8.56E-03	5.73E-03	6.59E-03	6.70E-03	4.13E-03	4.58E-03
410	3.16E-03	2.53E-03	3.00E-03	1.65E-03	3.13E-03	1.20E-03	4.55E-03	5.02E-03
415	3.29E-03	2.67E-03	3.16E-03	1.71E-03	2.96E-03	1.99E-03	4.81E-03	5.30E-03
420	3.75E-03	3.18E-03	3.69E-03	2.03E-03	2.99E-03	3.87E-03	4.96E-03	5.47E-03
425	4.20E-03	3.78E-03	4.21E-03	2.38E-03	3.07E-03	6.84E-03	5.17E-03	5.69E-03
430	6.80E-03	6.13E-03	6.56E-03	4.08E-03	5.00E-03	1.29E-02	5.33E-03	5.83E-03
435	2.44E-02	2.00E-02	2.18E-02	1.46E-02	1.90E-02	3.56E-02	5.46E-03	5.96E-03
440	9.77E-03	9.27E-03	9.43E-03	6.45E-03	7.50E-03	2.13E-02	5.58E-03	6.09E-03
445	5.77E-03	6.63E-03	6.30E-03	4.49E-03	4.55E-03	1.74E-02	5.69E-03	6.20E-03
450	6.05E-03	7.15E-03	6.84E-03	5.13E-03	5.11E-03	1.71E-02	5.75E-03	6.25E-03
455	6.36E-03	7.54E-03	7.43E-03	5.76E-03	5.75E-03	1.59E-02	5.78E-03	6.26E-03
460	6.61E-03	7.76E-03	7.97E-03	6.29E-03	6.36E-03	1.44E-02	5.81E-03	6.26E-03
465	6.81E-03	7.82E-03	8.45E-03	6.69E-03	6.91E-03	1.28E-02	5.83E-03	6.27E-03
470	6.95E-03	7.76E-03	8.85E-03	6.95E-03	7.39E-03	1.15E-02	5.82E-03	6.24E-03
475	7.05E-03	7.63E-03	9.17E-03	7.08E-03	7.74E-03	1.04E-02	5.80E-03	6.21E-03
480	7.09E-03	7.46E-03	9.46E-03	7.18E-03	7.96E-03	1.08E-02	5.78E-03	6.18E-03
485	7.10E-03	7.28E-03	1.00E-02	7.55E-03	8.08E-03	1.90E-02	5.77E-03	6.16E-03
490	7.16E-03	7.17E-03	1.01E-02	7.54E-03	8.11E-03	2.23E-02	5.77E-03	6.16E-03
495	7.10E-03	7.03E-03	9.70E-03	7.06E-03	7.96E-03	1.61E-02	5.75E-03	6.13E-03
500	7.07E-03	6.99E-03	9.23E-03	6.62E-03	7.72E-03	1.02E-02	5.73E-03	6.10E-03
505	7.09E-03	7.06E-03	8.73E-03	6.28E-03	7.46E-03	6.31E-03	5.70E-03	6.05E-03
510	7.15E-03	7.23E-03	8.31E-03	5.99E-03	7.17E-03	5.26E-03	5.63E-03	5.96E-03
515	7.22E-03	7.48E-03	7.88E-03	5.70E-03	6.86E-03	4.65E-03	5.55E-03	5.86E-03
520	7.27E-03	7.72E-03	7.48E-03	5.44E-03	6.56E-03	3.99E-03	5.50E-03	5.81E-03
525	7.25E-03	7.83E-03	7.10E-03	5.21E-03	6.29E-03	3.42E-03	5.38E-03	5.68E-03
530	7.16E-03	7.80E-03	6.77E-03	5.04E-03	6.06E-03	3.18E-03	5.29E-03	5.58E-03
535	7.00E-03	7.65E-03	6.70E-03	5.07E-03	5.86E-03	5.19E-03	5.25E-03	5.55E-03
540	7.11E-03	7.70E-03	8.33E-03	6.92E-03	6.01E-03	2.99E-02	5.37E-03	5.73E-03
545	1.60E-02	1.60E-02	2.00E-02	1.68E-02	1.47E-02	8.01E-02	5.55E-03	5.97E-03
550	7.88E-03	8.30E-03	9.29E-03	7.63E-03	6.85E-03	2.55E-02	5.78E-03	6.23E-03
555	6.49E-03	6.89E-03	6.47E-03	5.23E-03	5.51E-03	8.32E-03	6.02E-03	6.50E-03
560	6.41E-03	6.76E-03	6.15E-03	5.04E-03	5.49E-03	2.42E-03	6.20E-03	6.70E-03
565	6.40E-03	6.68E-03	6.17E-03	5.07E-03	5.53E-03	1.57E-03	6.23E-03	6.70E-03
570	6.44E-03	6.65E-03	6.27E-03	5.16E-03	5.62E-03	1.38E-03	5.77E-03	5.98E-03
575	7.31E-03	7.27E-03	7.31E-03	5.91E-03	6.47E-03	3.42E-03	5.38E-03	5.42E-03

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Wav. (nm)	GE	GM	PH	BYK	TO	TO(3B)	GM(FT)1	GM(FT)2
580	8.64E-03	8.27E-03	9.08E-03	7.19E-03	7.76E-03	1.16E-02	5.31E-03	5.49E-03
585	6.59E-03	6.57E-03	7.34E-03	6.10E-03	6.02E-03	1.74E-02	4.74E-03	4.80E-03
590	6.61E-03	6.50E-03	7.46E-03	5.95E-03	6.10E-03	1.43E-02	4.54E-03	4.67E-03
595	6.66E-03	6.48E-03	7.34E-03	5.96E-03	6.22E-03	7.35E-03	4.48E-03	4.68E-03
600	6.69E-03	6.42E-03	7.48E-03	6.02E-03	6.32E-03	5.58E-03	4.55E-03	4.84E-03
605	6.70E-03	6.37E-03	7.70E-03	6.06E-03	6.40E-03	3.63E-03	4.60E-03	4.95E-03
610	6.69E-03	6.31E-03	7.92E-03	6.44E-03	6.55E-03	4.32E-02	4.57E-03	4.93E-03
615	6.65E-03	6.31E-03	8.07E-03	6.35E-03	6.56E-03	3.01E-02	4.59E-03	5.01E-03
620	6.58E-03	6.52E-03	8.21E-03	6.22E-03	6.52E-03	1.46E-02	4.56E-03	5.02E-03
625	6.50E-03	6.96E-03	8.01E-03	6.08E-03	6.47E-03	1.00E-02	4.45E-03	4.92E-03
630	6.38E-03	7.13E-03	7.56E-03	5.60E-03	6.41E-03	9.83E-03	4.31E-03	4.78E-03
635	6.23E-03	6.67E-03	7.09E-03	5.16E-03	6.28E-03	2.91E-03	4.15E-03	4.61E-03
640	6.06E-03	6.32E-03	6.64E-03	4.79E-03	6.14E-03	1.38E-03	3.98E-03	4.43E-03
645	5.86E-03	6.18E-03	6.16E-03	4.42E-03	5.97E-03	1.75E-03	3.83E-03	4.27E-03
650	5.65E-03	7.67E-03	5.64E-03	4.06E-03	5.81E-03	3.40E-03	3.73E-03	4.15E-03
655	5.40E-03	8.41E-03	5.10E-03	3.67E-03	5.59E-03	1.93E-03	3.66E-03	4.07E-03
660	5.17E-03	9.71E-03	4.66E-03	3.30E-03	5.38E-03	1.90E-03	3.67E-03	4.08E-03
665	4.89E-03	6.91E-03	4.19E-03	2.95E-03	5.08E-03	2.18E-03	3.71E-03	4.11E-03
670	4.61E-03	4.90E-03	3.73E-03	2.61E-03	4.78E-03	1.67E-03	3.79E-03	4.19E-03
675	4.34E-03	3.85E-03	3.33E-03	2.31E-03	4.49E-03	1.29E-03	3.93E-03	4.33E-03
680	4.05E-03	3.42E-03	2.97E-03	2.05E-03	4.20E-03	1.50E-03	4.07E-03	4.49E-03
685	3.78E-03	3.08E-03	2.64E-03	1.80E-03	3.92E-03	1.17E-03	4.22E-03	4.66E-03
690	3.61E-03	2.83E-03	2.43E-03	1.63E-03	3.72E-03	1.35E-03	4.37E-03	4.84E-03
695	3.32E-03	2.53E-03	2.07E-03	1.39E-03	3.42E-03	1.16E-03	4.49E-03	5.00E-03
700	3.01E-03	2.24E-03	1.84E-03	1.22E-03	3.11E-03	4.39E-04	4.56E-03	5.10E-03
705	2.82E-03	2.06E-03	1.66E-03	1.12E-03	2.90E-03	2.53E-03	4.57E-03	5.15E-03
710	2.56E-03	1.84E-03	1.51E-03	1.03E-03	2.64E-03	4.97E-03	4.56E-03	5.16E-03
715	2.32E-03	1.64E-03	1.34E-03	8.85E-04	2.37E-03	1.50E-03	4.53E-03	5.16E-03
720	2.10E-03	1.48E-03	1.22E-03	7.92E-04	2.14E-03	3.18E-04	4.49E-03	5.14E-03
725	1.93E-03	1.34E-03	1.11E-03	7.25E-04	1.96E-03	2.62E-04	4.44E-03	5.11E-03
730	1.76E-03	1.23E-03	1.03E-03	6.69E-04	1.78E-03	2.74E-04	4.37E-03	5.04E-03
735	1.61E-03	1.11E-03	9.48E-04	6.18E-04	1.60E-03	1.80E-04	4.24E-03	4.86E-03
740	1.63E-03	1.14E-03	8.74E-04	5.77E-04	1.59E-03	3.29E-04	4.10E-03	4.65E-03
745	1.33E-03	9.08E-04	8.15E-04	5.26E-04	1.30E-03	2.72E-04	4.07E-03	4.64E-03
750	1.54E-03	1.12E-03	7.88E-04	5.31E-04	1.46E-03	4.83E-04	4.03E-03	4.62E-03
755	1.13E-03	7.83E-04	7.26E-04	4.57E-04	1.10E-03	2.12E-04	4.03E-03	4.67E-03
760	1.01E-03	7.02E-04	1.24E-03	8.96E-04	9.55E-04	1.88E-04	4.01E-03	4.68E-03
765	1.43E-03	1.11E-03	6.93E-04	4.80E-04	1.34E-03	5.29E-04	3.97E-03	4.68E-03
770	8.94E-04	6.40E-04	7.11E-04	4.76E-04	8.46E-04	2.21E-04	3.95E-03	4.67E-03
775	8.87E-04	6.29E-04	5.89E-04	3.87E-04	8.00E-04	3.32E-04	3.92E-03	4.64E-03
780	7.26E-04	4.92E-04	5.34E-04	3.32E-04	6.34E-04	1.92E-04	3.90E-03	4.63E-03

Appendix C2: SPDs for the 58 D50 simulators accumulated

D50 simulators (GTI-1 to GTI-8)

Wav. (nm)	GTI-1	GTI-2	GTI-3	GTI-4	GTI-5	GTI-6	GTI-7	GTI-8
395	1.39E-03	7.96E-04	1.17E-03	1.25E-03	8.22E-04	1.13E-03	8.22E-04	3.67E-04
400	4.40E-03	2.48E-03	3.60E-03	4.19E-03	2.99E-03	3.54E-03	2.66E-03	1.07E-03
405	7.16E-03	4.01E-03	5.81E-03	6.85E-03	4.94E-03	5.70E-03	4.34E-03	1.71E-03
410	3.94E-03	2.22E-03	3.21E-03	3.66E-03	2.55E-03	3.19E-03	2.27E-03	1.06E-03
415	2.87E-03	1.63E-03	2.32E-03	2.58E-03	1.73E-03	2.39E-03	1.53E-03	8.73E-04
420	3.26E-03	1.87E-03	2.63E-03	2.94E-03	2.00E-03	2.75E-03	1.71E-03	1.00E-03
425	3.74E-03	2.16E-03	3.01E-03	3.41E-03	2.34E-03	3.18E-03	1.96E-03	1.15E-03
430	8.19E-03	4.88E-03	6.66E-03	7.94E-03	5.50E-03	6.96E-03	4.50E-03	2.49E-03
435	1.82E-02	1.10E-02	1.49E-02	1.81E-02	1.26E-02	1.54E-02	1.03E-02	5.48E-03
440	1.18E-02	7.12E-03	9.65E-03	1.16E-02	8.08E-03	1.01E-02	6.56E-03	3.56E-03
445	5.44E-03	3.21E-03	4.36E-03	5.07E-03	3.56E-03	4.70E-03	2.82E-03	1.63E-03
450	5.53E-03	3.26E-03	4.40E-03	5.06E-03	3.58E-03	4.72E-03	2.82E-03	1.65E-03
455	5.86E-03	3.46E-03	4.63E-03	5.28E-03	3.75E-03	4.93E-03	2.98E-03	1.74E-03
460	6.18E-03	3.66E-03	4.87E-03	5.47E-03	3.91E-03	5.11E-03	3.12E-03	1.82E-03
465	6.48E-03	3.84E-03	5.07E-03	5.61E-03	4.03E-03	5.24E-03	3.25E-03	1.89E-03
470	6.73E-03	3.99E-03	5.25E-03	5.71E-03	4.13E-03	5.34E-03	3.36E-03	1.95E-03
475	6.97E-03	4.14E-03	5.42E-03	5.79E-03	4.21E-03	5.43E-03	3.47E-03	2.00E-03
480	7.17E-03	4.27E-03	5.58E-03	5.87E-03	4.29E-03	5.52E-03	3.57E-03	2.05E-03
485	7.36E-03	4.38E-03	5.72E-03	5.97E-03	4.38E-03	5.63E-03	3.67E-03	2.10E-03
490	7.53E-03	4.47E-03	5.86E-03	6.12E-03	4.52E-03	5.79E-03	3.79E-03	2.16E-03
495	7.62E-03	4.52E-03	5.96E-03	6.31E-03	4.68E-03	6.00E-03	3.89E-03	2.21E-03
500	7.66E-03	4.54E-03	6.03E-03	6.66E-03	4.99E-03	6.38E-03	4.00E-03	2.27E-03
505	7.73E-03	4.58E-03	6.17E-03	7.31E-03	5.51E-03	7.03E-03	4.18E-03	2.37E-03
510	7.79E-03	4.61E-03	6.35E-03	8.04E-03	6.09E-03	7.75E-03	4.41E-03	2.50E-03
515	7.84E-03	4.64E-03	6.54E-03	8.46E-03	6.43E-03	8.15E-03	4.66E-03	2.65E-03
520	7.88E-03	4.65E-03	6.71E-03	8.36E-03	6.39E-03	8.05E-03	4.89E-03	2.77E-03
525	7.93E-03	4.68E-03	6.84E-03	8.08E-03	6.19E-03	7.76E-03	5.04E-03	2.86E-03
530	7.99E-03	4.72E-03	6.93E-03	7.83E-03	6.00E-03	7.51E-03	5.11E-03	2.89E-03
535	8.08E-03	4.77E-03	7.00E-03	7.65E-03	5.87E-03	7.30E-03	5.13E-03	2.89E-03
540	1.04E-02	6.05E-03	8.90E-03	9.63E-03	7.65E-03	8.99E-03	6.54E-03	3.46E-03
545	1.64E-02	9.42E-03	1.39E-02	1.53E-02	1.27E-02	1.39E-02	1.04E-02	5.03E-03
550	1.27E-02	7.37E-03	1.08E-02	1.17E-02	9.47E-03	1.07E-02	7.93E-03	3.97E-03
555	8.52E-03	5.04E-03	7.29E-03	7.55E-03	5.84E-03	7.12E-03	5.08E-03	2.79E-03
560	8.43E-03	5.00E-03	7.20E-03	7.44E-03	5.74E-03	7.02E-03	4.96E-03	2.73E-03
565	8.52E-03	5.07E-03	7.28E-03	7.54E-03	5.82E-03	7.12E-03	4.98E-03	2.74E-03
570	8.85E-03	5.26E-03	7.55E-03	7.88E-03	6.10E-03	7.40E-03	5.17E-03	2.82E-03
575	1.03E-02	6.10E-03	8.75E-03	9.34E-03	7.32E-03	8.60E-03	6.12E-03	3.22E-03
580	1.06E-02	6.30E-03	9.04E-03	9.73E-03	7.67E-03	8.95E-03	6.35E-03	3.32E-03

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Wav. (nm)	GTI-1	GTI-2	GTI-3	GTI-4	GTI-5	GTI-6	GTI-7	GTI-8
585	9.29E-03	5.54E-03	7.91E-03	8.49E-03	6.61E-03	7.95E-03	5.45E-03	2.95E-03
590	9.02E-03	5.39E-03	7.68E-03	8.29E-03	6.45E-03	7.80E-03	5.27E-03	2.88E-03
595	9.09E-03	5.43E-03	7.72E-03	8.42E-03	6.57E-03	7.92E-03	5.32E-03	2.92E-03
600	9.12E-03	5.45E-03	7.73E-03	8.53E-03	6.66E-03	8.02E-03	5.36E-03	2.94E-03
605	9.13E-03	5.46E-03	7.73E-03	8.59E-03	6.74E-03	8.10E-03	5.39E-03	2.97E-03
610	9.11E-03	5.44E-03	7.72E-03	8.62E-03	6.78E-03	8.17E-03	5.40E-03	2.97E-03
615	9.04E-03	5.38E-03	7.65E-03	8.57E-03	6.76E-03	8.18E-03	5.37E-03	2.96E-03
620	8.93E-03	5.31E-03	7.52E-03	8.47E-03	6.70E-03	8.14E-03	5.31E-03	2.94E-03
625	8.80E-03	5.22E-03	7.39E-03	8.36E-03	6.63E-03	8.08E-03	5.25E-03	2.90E-03
630	8.63E-03	5.11E-03	7.24E-03	8.20E-03	6.53E-03	7.99E-03	5.15E-03	2.85E-03
635	8.42E-03	4.99E-03	7.05E-03	8.00E-03	6.40E-03	7.82E-03	5.03E-03	2.78E-03
640	8.17E-03	4.83E-03	6.80E-03	7.76E-03	6.23E-03	7.59E-03	4.88E-03	2.70E-03
645	7.87E-03	4.65E-03	6.54E-03	7.50E-03	6.04E-03	7.32E-03	4.71E-03	2.60E-03
650	7.56E-03	4.45E-03	6.26E-03	7.20E-03	5.81E-03	7.03E-03	4.51E-03	2.50E-03
655	7.22E-03	4.25E-03	5.98E-03	6.90E-03	5.56E-03	6.72E-03	4.30E-03	2.40E-03
660	6.84E-03	4.04E-03	5.66E-03	6.57E-03	5.27E-03	6.35E-03	4.08E-03	2.28E-03
665	6.43E-03	3.82E-03	5.35E-03	6.18E-03	4.95E-03	5.96E-03	3.85E-03	2.14E-03
670	6.03E-03	3.58E-03	5.01E-03	5.79E-03	4.63E-03	5.57E-03	3.61E-03	2.00E-03
675	5.63E-03	3.34E-03	4.67E-03	5.42E-03	4.33E-03	5.19E-03	3.38E-03	1.87E-03
680	5.24E-03	3.12E-03	4.35E-03	5.06E-03	4.04E-03	4.84E-03	3.15E-03	1.75E-03
685	4.92E-03	2.92E-03	4.07E-03	4.75E-03	3.78E-03	4.52E-03	2.95E-03	1.63E-03
690	4.61E-03	2.73E-03	3.81E-03	4.45E-03	3.55E-03	4.24E-03	2.77E-03	1.53E-03
695	4.26E-03	2.53E-03	3.52E-03	4.10E-03	3.29E-03	3.91E-03	2.57E-03	1.43E-03
700	3.88E-03	2.32E-03	3.21E-03	3.73E-03	3.01E-03	3.58E-03	2.35E-03	1.31E-03
705	3.56E-03	2.12E-03	2.94E-03	3.42E-03	2.76E-03	3.31E-03	2.16E-03	1.21E-03
710	3.26E-03	1.94E-03	2.69E-03	3.12E-03	2.52E-03	3.03E-03	1.97E-03	1.10E-03
715	2.96E-03	1.75E-03	2.45E-03	2.82E-03	2.30E-03	2.76E-03	1.78E-03	9.98E-04
720	2.66E-03	1.58E-03	2.23E-03	2.56E-03	2.09E-03	2.51E-03	1.61E-03	9.04E-04
725	2.41E-03	1.44E-03	2.01E-03	2.32E-03	1.90E-03	2.30E-03	1.47E-03	8.27E-04

D50 simulators (GTI-9 to GTI-16)

Wav. (nm)	GTI-9	GTI-10	GTI-11	GTI-12	GTI-13	GTI-14	GTI-15	GTI-16
395	1.41E-03	9.22E-04	9.52E-04	1.14E-03	1.68E-03	1.69E-03	8.71E-04	1.30E-03
400	4.37E-03	3.26E-03	3.17E-03	3.78E-03	5.58E-03	5.68E-03	2.78E-03	4.36E-03
405	7.00E-03	5.34E-03	5.16E-03	6.10E-03	9.04E-03	9.22E-03	4.48E-03	7.10E-03
410	3.85E-03	2.82E-03	2.79E-03	3.26E-03	4.75E-03	4.83E-03	2.48E-03	3.85E-03
415	2.81E-03	1.99E-03	2.01E-03	2.32E-03	3.25E-03	3.30E-03	1.83E-03	2.79E-03
420	3.19E-03	2.29E-03	2.30E-03	2.65E-03	3.70E-03	3.74E-03	2.11E-03	3.22E-03
425	3.70E-03	2.68E-03	2.67E-03	3.08E-03	4.29E-03	4.34E-03	2.46E-03	3.76E-03
430	9.07E-03	6.39E-03	5.91E-03	7.21E-03	9.68E-03	9.84E-03	5.66E-03	8.71E-03
435	2.11E-02	1.45E-02	1.31E-02	1.63E-02	2.16E-02	2.20E-02	1.27E-02	1.96E-02
440	1.33E-02	9.28E-03	8.52E-03	1.05E-02	1.39E-02	1.42E-02	8.18E-03	1.26E-02
445	5.53E-03	4.05E-03	3.96E-03	4.60E-03	6.30E-03	6.40E-03	3.65E-03	5.62E-03
450	5.51E-03	4.04E-03	3.98E-03	4.60E-03	6.29E-03	6.41E-03	3.66E-03	5.62E-03
455	5.78E-03	4.22E-03	4.16E-03	4.82E-03	6.55E-03	6.69E-03	3.82E-03	5.89E-03
460	6.04E-03	4.37E-03	4.32E-03	5.00E-03	6.76E-03	6.92E-03	3.97E-03	6.12E-03
465	6.26E-03	4.49E-03	4.44E-03	5.14E-03	6.93E-03	7.08E-03	4.10E-03	6.30E-03
470	6.43E-03	4.57E-03	4.52E-03	5.24E-03	7.06E-03	7.21E-03	4.19E-03	6.43E-03
475	6.58E-03	4.65E-03	4.59E-03	5.33E-03	7.17E-03	7.31E-03	4.26E-03	6.55E-03
480	6.72E-03	4.78E-03	4.65E-03	5.41E-03	7.27E-03	7.41E-03	4.34E-03	6.65E-03
485	6.86E-03	5.04E-03	4.73E-03	5.51E-03	7.40E-03	7.54E-03	4.43E-03	6.77E-03
490	7.03E-03	5.23E-03	4.84E-03	5.66E-03	7.61E-03	7.75E-03	4.56E-03	6.95E-03
495	7.24E-03	5.30E-03	4.99E-03	5.86E-03	7.88E-03	7.99E-03	4.71E-03	7.20E-03
500	7.63E-03	5.51E-03	5.29E-03	6.23E-03	8.38E-03	8.49E-03	5.01E-03	7.65E-03
505	8.30E-03	5.99E-03	5.79E-03	6.87E-03	9.23E-03	9.34E-03	5.53E-03	8.43E-03
510	9.04E-03	6.59E-03	6.36E-03	7.60E-03	1.02E-02	1.03E-02	6.10E-03	9.31E-03
515	9.48E-03	6.96E-03	6.70E-03	8.02E-03	1.08E-02	1.08E-02	6.43E-03	9.83E-03
520	9.42E-03	6.92E-03	6.65E-03	7.97E-03	1.07E-02	1.07E-02	6.37E-03	9.73E-03
525	9.15E-03	6.69E-03	6.43E-03	7.73E-03	1.03E-02	1.04E-02	6.14E-03	9.39E-03
530	8.90E-03	6.52E-03	6.22E-03	7.51E-03	1.00E-02	1.01E-02	5.92E-03	9.08E-03
535	8.70E-03	6.55E-03	6.06E-03	7.33E-03	9.75E-03	9.82E-03	5.76E-03	8.83E-03
540	1.07E-02	8.92E-03	7.62E-03	9.22E-03	1.24E-02	1.25E-02	7.13E-03	1.11E-02
545	1.65E-02	1.41E-02	1.20E-02	1.45E-02	1.98E-02	2.02E-02	1.10E-02	1.74E-02
550	1.27E-02	1.05E-02	9.17E-03	1.11E-02	1.50E-02	1.53E-02	8.44E-03	1.32E-02
555	8.61E-03	6.56E-03	5.97E-03	7.27E-03	9.56E-03	9.69E-03	5.59E-03	8.62E-03
560	8.54E-03	6.34E-03	5.91E-03	7.20E-03	9.43E-03	9.55E-03	5.51E-03	8.51E-03
565	8.68E-03	6.41E-03	6.00E-03	7.32E-03	9.56E-03	9.70E-03	5.58E-03	8.65E-03
570	9.07E-03	6.73E-03	6.30E-03	7.67E-03	1.00E-02	1.02E-02	5.83E-03	9.06E-03
575	1.06E-02	8.02E-03	7.47E-03	9.04E-03	1.19E-02	1.21E-02	6.86E-03	1.07E-02
580	1.10E-02	8.52E-03	7.78E-03	9.39E-03	1.23E-02	1.26E-02	7.14E-03	1.12E-02

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Wav. (nm)	GTI-9	GTI-10	GTI-11	GTI-12	GTI-13	GTI-14	GTI-15	GTI-16
585	9.75E-03	7.64E-03	6.79E-03	8.23E-03	1.07E-02	1.09E-02	6.29E-03	9.75E-03
590	9.57E-03	7.48E-03	6.63E-03	8.05E-03	1.05E-02	1.07E-02	6.16E-03	9.55E-03
595	9.72E-03	7.45E-03	6.73E-03	8.17E-03	1.06E-02	1.08E-02	6.27E-03	9.71E-03
600	9.83E-03	7.41E-03	6.79E-03	8.26E-03	1.08E-02	1.10E-02	6.34E-03	9.83E-03
605	9.91E-03	7.50E-03	6.83E-03	8.32E-03	1.09E-02	1.11E-02	6.41E-03	9.93E-03
610	9.96E-03	8.26E-03	6.84E-03	8.35E-03	1.09E-02	1.11E-02	6.50E-03	1.00E-02
615	9.95E-03	8.44E-03	6.79E-03	8.32E-03	1.09E-02	1.11E-02	6.50E-03	9.99E-03
620	9.86E-03	7.67E-03	6.72E-03	8.25E-03	1.08E-02	1.09E-02	6.42E-03	9.91E-03
625	9.77E-03	7.38E-03	6.64E-03	8.17E-03	1.07E-02	1.08E-02	6.36E-03	9.82E-03
630	9.61E-03	7.21E-03	6.51E-03	8.04E-03	1.05E-02	1.06E-02	6.26E-03	9.68E-03
635	9.40E-03	6.91E-03	6.36E-03	7.88E-03	1.03E-02	1.04E-02	6.11E-03	9.48E-03
640	9.12E-03	6.60E-03	6.17E-03	7.66E-03	1.00E-02	1.01E-02	5.93E-03	9.20E-03
645	8.78E-03	6.36E-03	5.95E-03	7.40E-03	9.67E-03	9.74E-03	5.73E-03	8.90E-03
650	8.39E-03	6.12E-03	5.71E-03	7.11E-03	9.31E-03	9.38E-03	5.50E-03	8.56E-03
655	7.99E-03	5.82E-03	5.46E-03	6.81E-03	8.92E-03	9.01E-03	5.27E-03	8.20E-03
660	7.57E-03	5.52E-03	5.17E-03	6.47E-03	8.48E-03	8.58E-03	5.00E-03	7.81E-03
665	7.13E-03	5.19E-03	4.88E-03	6.11E-03	8.00E-03	8.10E-03	4.71E-03	7.36E-03
670	6.69E-03	4.84E-03	4.57E-03	5.74E-03	7.50E-03	7.61E-03	4.41E-03	6.89E-03
675	6.25E-03	4.52E-03	4.26E-03	5.37E-03	7.03E-03	7.14E-03	4.11E-03	6.43E-03
680	5.85E-03	4.21E-03	3.98E-03	5.02E-03	6.57E-03	6.66E-03	3.84E-03	6.03E-03
685	5.47E-03	3.95E-03	3.73E-03	4.70E-03	6.16E-03	6.23E-03	3.60E-03	5.63E-03
690	5.15E-03	3.69E-03	3.50E-03	4.41E-03	5.77E-03	5.83E-03	3.36E-03	5.28E-03
695	4.77E-03	3.38E-03	3.23E-03	4.07E-03	5.31E-03	5.37E-03	3.10E-03	4.87E-03
700	4.39E-03	3.11E-03	2.95E-03	3.73E-03	4.86E-03	4.89E-03	2.85E-03	4.47E-03
705	4.09E-03	2.94E-03	2.71E-03	3.42E-03	4.43E-03	4.52E-03	2.62E-03	4.10E-03
710	3.72E-03	2.74E-03	2.46E-03	3.12E-03	4.04E-03	4.13E-03	2.39E-03	3.76E-03
715	3.38E-03	2.42E-03	2.24E-03	2.83E-03	3.66E-03	3.73E-03	2.15E-03	3.39E-03
720	3.08E-03	2.16E-03	2.05E-03	2.58E-03	3.33E-03	3.40E-03	1.95E-03	3.08E-03
725	2.83E-03	1.95E-03	1.84E-03	2.30E-03	2.97E-03	3.05E-03	1.80E-03	2.82E-03

D50 simulators (GTI-17 to MEGA-7)

Wav. (nm)	GTI-17	MEGA-1	MEGA-2	MEGA-3	MEGA-4	MEGA-5	MEGA-6	MEGA-7
395	1.30E-03	8.87E-04	8.15E-04	1.00E-03	9.98E-04	1.39E-03	8.46E-04	8.59E-04
400	4.22E-03	3.79E-03	3.18E-03	4.18E-03	4.24E-03	5.97E-03	3.49E-03	3.46E-03
405	6.84E-03	6.35E-03	5.26E-03	7.03E-03	7.12E-03	1.00E-02	5.87E-03	5.81E-03
410	3.75E-03	3.01E-03	2.60E-03	3.38E-03	3.43E-03	4.88E-03	2.84E-03	2.82E-03
415	2.75E-03	1.83E-03	1.69E-03	2.11E-03	2.13E-03	3.08E-03	1.77E-03	1.77E-03
420	3.17E-03	2.12E-03	1.96E-03	2.46E-03	2.49E-03	3.59E-03	2.05E-03	2.05E-03
425	3.68E-03	2.51E-03	2.35E-03	2.92E-03	2.96E-03	4.26E-03	2.44E-03	2.44E-03
430	8.49E-03	6.31E-03	5.87E-03	7.50E-03	7.62E-03	1.10E-02	6.23E-03	6.27E-03
435	1.91E-02	1.47E-02	1.37E-02	1.77E-02	1.79E-02	2.60E-02	1.47E-02	1.49E-02
440	1.23E-02	9.37E-03	8.78E-03	1.12E-02	1.14E-02	1.65E-02	9.43E-03	9.46E-03
445	5.49E-03	4.13E-03	3.89E-03	4.83E-03	4.93E-03	7.01E-03	4.07E-03	4.03E-03
450	5.51E-03	4.24E-03	4.00E-03	4.97E-03	5.09E-03	7.22E-03	4.20E-03	4.15E-03
455	5.76E-03	4.55E-03	4.29E-03	5.36E-03	5.50E-03	7.82E-03	4.55E-03	4.49E-03
460	5.98E-03	4.85E-03	4.57E-03	5.75E-03	5.91E-03	8.43E-03	4.88E-03	4.82E-03
465	6.15E-03	5.11E-03	4.81E-03	6.12E-03	6.29E-03	9.01E-03	5.19E-03	5.14E-03
470	6.27E-03	5.35E-03	5.01E-03	6.46E-03	6.63E-03	9.55E-03	5.48E-03	5.43E-03
475	6.38E-03	5.58E-03	5.21E-03	6.77E-03	6.95E-03	1.01E-02	5.75E-03	5.71E-03
480	6.48E-03	5.86E-03	5.50E-03	7.05E-03	7.23E-03	1.05E-02	5.98E-03	5.96E-03
485	6.60E-03	6.28E-03	5.95E-03	7.31E-03	7.50E-03	1.10E-02	6.19E-03	6.18E-03
490	6.77E-03	6.56E-03	6.21E-03	7.54E-03	7.71E-03	1.14E-02	6.36E-03	6.38E-03
495	6.99E-03	6.51E-03	6.13E-03	7.67E-03	7.81E-03	1.16E-02	6.46E-03	6.50E-03
500	7.41E-03	6.37E-03	5.94E-03	7.72E-03	7.83E-03	1.17E-02	6.49E-03	6.53E-03
505	8.15E-03	6.31E-03	5.85E-03	7.80E-03	7.88E-03	1.18E-02	6.54E-03	6.60E-03
510	8.98E-03	6.33E-03	5.85E-03	7.86E-03	7.92E-03	1.19E-02	6.59E-03	6.67E-03
515	9.46E-03	6.36E-03	5.88E-03	7.90E-03	7.94E-03	1.19E-02	6.62E-03	6.72E-03
520	9.37E-03	6.37E-03	5.91E-03	7.92E-03	7.96E-03	1.20E-02	6.64E-03	6.75E-03
525	9.05E-03	6.40E-03	5.93E-03	7.94E-03	7.97E-03	1.20E-02	6.65E-03	6.76E-03
530	8.76E-03	6.46E-03	5.99E-03	7.99E-03	8.02E-03	1.20E-02	6.68E-03	6.79E-03
535	8.53E-03	6.71E-03	6.27E-03	8.07E-03	8.10E-03	1.21E-02	6.74E-03	6.85E-03
540	1.06E-02	9.91E-03	9.20E-03	1.07E-02	1.08E-02	1.58E-02	8.83E-03	8.85E-03
545	1.66E-02	1.62E-02	1.44E-02	1.73E-02	1.76E-02	2.55E-02	1.43E-02	1.41E-02
550	1.27E-02	1.17E-02	1.06E-02	1.32E-02	1.34E-02	1.95E-02	1.09E-02	1.08E-02
555	8.38E-03	7.12E-03	6.68E-03	8.48E-03	8.58E-03	1.27E-02	7.11E-03	7.14E-03
560	8.30E-03	6.83E-03	6.37E-03	8.37E-03	8.48E-03	1.25E-02	7.02E-03	7.03E-03
565	8.42E-03	6.88E-03	6.41E-03	8.48E-03	8.60E-03	1.27E-02	7.11E-03	7.10E-03
570	8.81E-03	7.19E-03	6.68E-03	8.84E-03	9.00E-03	1.32E-02	7.42E-03	7.36E-03
575	1.04E-02	8.63E-03	7.84E-03	1.05E-02	1.07E-02	1.57E-02	8.76E-03	8.63E-03
580	1.08E-02	9.18E-03	8.36E-03	1.09E-02	1.11E-02	1.63E-02	9.12E-03	8.95E-03

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Wav. (nm)	GTI-17	MEGA-1	MEGA-2	MEGA-3	MEGA-4	MEGA-5	MEGA-6	MEGA-7
585	9.50E-03	8.14E-03	7.62E-03	9.38E-03	9.59E-03	1.41E-02	7.88E-03	7.80E-03
590	9.30E-03	7.81E-03	7.35E-03	9.09E-03	9.30E-03	1.37E-02	7.63E-03	7.58E-03
595	9.45E-03	7.66E-03	7.14E-03	9.16E-03	9.37E-03	1.39E-02	7.70E-03	7.65E-03
600	9.57E-03	7.60E-03	7.03E-03	9.21E-03	9.42E-03	1.40E-02	7.74E-03	7.71E-03
605	9.66E-03	7.68E-03	7.13E-03	9.26E-03	9.46E-03	1.41E-02	7.77E-03	7.76E-03
610	9.70E-03	8.45E-03	8.03E-03	9.35E-03	9.53E-03	1.42E-02	7.82E-03	7.82E-03
615	9.65E-03	8.64E-03	8.28E-03	9.32E-03	9.47E-03	1.42E-02	7.78E-03	7.80E-03
620	9.56E-03	7.96E-03	7.51E-03	9.17E-03	9.28E-03	1.40E-02	7.65E-03	7.70E-03
625	9.47E-03	7.64E-03	7.15E-03	9.05E-03	9.12E-03	1.38E-02	7.53E-03	7.60E-03
630	9.31E-03	7.38E-03	6.89E-03	8.88E-03	8.92E-03	1.35E-02	7.39E-03	7.46E-03
635	9.10E-03	7.06E-03	6.56E-03	8.67E-03	8.68E-03	1.32E-02	7.20E-03	7.29E-03
640	8.82E-03	6.76E-03	6.26E-03	8.42E-03	8.41E-03	1.28E-02	6.97E-03	7.08E-03
645	8.51E-03	6.53E-03	6.04E-03	8.12E-03	8.11E-03	1.23E-02	6.72E-03	6.84E-03
650	8.17E-03	6.28E-03	5.82E-03	7.78E-03	7.79E-03	1.18E-02	6.45E-03	6.58E-03
655	7.82E-03	5.98E-03	5.54E-03	7.44E-03	7.46E-03	1.12E-02	6.16E-03	6.28E-03
660	7.44E-03	5.69E-03	5.26E-03	7.07E-03	7.09E-03	1.06E-02	5.86E-03	5.97E-03
665	7.01E-03	5.36E-03	4.98E-03	6.68E-03	6.69E-03	1.00E-02	5.55E-03	5.63E-03
670	6.57E-03	5.02E-03	4.66E-03	6.26E-03	6.30E-03	9.37E-03	5.22E-03	5.27E-03
675	6.17E-03	4.69E-03	4.37E-03	5.89E-03	5.92E-03	8.75E-03	4.90E-03	4.93E-03
680	5.76E-03	4.37E-03	4.09E-03	5.51E-03	5.54E-03	8.21E-03	4.58E-03	4.61E-03
685	5.39E-03	4.10E-03	3.85E-03	5.17E-03	5.22E-03	7.71E-03	4.29E-03	4.31E-03
690	5.05E-03	3.83E-03	3.59E-03	4.85E-03	4.91E-03	7.22E-03	4.03E-03	4.04E-03
695	4.67E-03	3.51E-03	3.29E-03	4.48E-03	4.53E-03	6.66E-03	3.75E-03	3.73E-03
700	4.29E-03	3.24E-03	3.02E-03	4.12E-03	4.18E-03	6.13E-03	3.43E-03	3.42E-03
705	3.94E-03	3.05E-03	2.89E-03	3.78E-03	3.85E-03	5.70E-03	3.15E-03	3.14E-03
710	3.58E-03	2.84E-03	2.68E-03	3.47E-03	3.52E-03	5.22E-03	2.89E-03	2.88E-03
715	3.26E-03	2.53E-03	2.34E-03	3.15E-03	3.20E-03	4.75E-03	2.62E-03	2.62E-03
720	2.96E-03	2.28E-03	2.10E-03	2.88E-03	2.90E-03	4.36E-03	2.39E-03	2.37E-03
725	2.66E-03	2.07E-03	1.90E-03	2.60E-03	2.65E-03	3.97E-03	2.18E-03	2.15E-03

D50 simulators (MEGA-8 to GE-3)

Wav. (nm)	MEGA-8	MEGA-9	MEGA-10	MEGA-11	MEGA-12	GE-1	GE-2	GE-3
395	7.35E-04	4.43E-04	8.86E-04	8.67E-04	9.32E-04	7.87E-04	1.03E-03	9.41E-04
400	2.83E-03	1.83E-03	3.64E-03	3.54E-03	3.75E-03	3.01E-03	3.90E-03	3.72E-03
405	4.71E-03	3.06E-03	6.08E-03	5.93E-03	6.26E-03	4.98E-03	6.49E-03	6.21E-03
410	2.33E-03	1.50E-03	2.94E-03	2.89E-03	3.03E-03	2.44E-03	3.25E-03	3.07E-03
415	1.51E-03	9.69E-04	1.84E-03	1.82E-03	1.91E-03	1.56E-03	2.13E-03	1.99E-03
420	1.76E-03	1.12E-03	2.12E-03	2.10E-03	2.22E-03	1.79E-03	2.45E-03	2.29E-03
425	2.08E-03	1.34E-03	2.50E-03	2.49E-03	2.63E-03	2.12E-03	2.89E-03	2.71E-03
430	5.42E-03	3.69E-03	6.43E-03	6.37E-03	6.60E-03	5.43E-03	7.62E-03	7.14E-03
435	1.28E-02	8.91E-03	1.51E-02	1.50E-02	1.54E-02	1.28E-02	1.82E-02	1.70E-02
440	8.12E-03	5.57E-03	9.57E-03	9.54E-03	9.79E-03	8.08E-03	1.14E-02	1.07E-02
445	3.45E-03	2.26E-03	4.08E-03	4.08E-03	4.25E-03	3.44E-03	4.67E-03	4.40E-03
450	3.56E-03	2.32E-03	4.20E-03	4.20E-03	4.37E-03	3.51E-03	4.77E-03	4.50E-03
455	3.86E-03	2.52E-03	4.53E-03	4.54E-03	4.72E-03	3.75E-03	5.14E-03	4.85E-03
460	4.15E-03	2.71E-03	4.86E-03	4.87E-03	5.06E-03	3.99E-03	5.52E-03	5.20E-03
465	4.43E-03	2.90E-03	5.18E-03	5.17E-03	5.35E-03	4.21E-03	5.86E-03	5.52E-03
470	4.69E-03	3.06E-03	5.46E-03	5.46E-03	5.60E-03	4.40E-03	6.17E-03	5.82E-03
475	4.92E-03	3.22E-03	5.74E-03	5.71E-03	5.84E-03	4.57E-03	6.46E-03	6.09E-03
480	5.15E-03	3.36E-03	5.98E-03	5.94E-03	6.06E-03	4.80E-03	6.73E-03	6.34E-03
485	5.35E-03	3.49E-03	6.21E-03	6.17E-03	6.26E-03	5.15E-03	6.97E-03	6.57E-03
490	5.52E-03	3.60E-03	6.41E-03	6.35E-03	6.44E-03	5.37E-03	7.18E-03	6.77E-03
495	5.62E-03	3.66E-03	6.51E-03	6.44E-03	6.54E-03	5.32E-03	7.31E-03	6.88E-03
500	5.67E-03	3.69E-03	6.55E-03	6.48E-03	6.57E-03	5.20E-03	7.37E-03	6.94E-03
505	5.73E-03	3.73E-03	6.62E-03	6.53E-03	6.61E-03	5.16E-03	7.47E-03	7.02E-03
510	5.78E-03	3.77E-03	6.68E-03	6.59E-03	6.64E-03	5.18E-03	7.56E-03	7.10E-03
515	5.81E-03	3.78E-03	6.72E-03	6.62E-03	6.67E-03	5.22E-03	7.63E-03	7.17E-03
520	5.83E-03	3.80E-03	6.74E-03	6.63E-03	6.72E-03	5.25E-03	7.70E-03	7.24E-03
525	5.84E-03	3.80E-03	6.75E-03	6.66E-03	6.81E-03	5.28E-03	7.77E-03	7.30E-03
530	5.86E-03	3.82E-03	6.79E-03	6.70E-03	6.96E-03	5.35E-03	7.86E-03	7.39E-03
535	5.91E-03	3.85E-03	6.85E-03	6.77E-03	7.15E-03	5.59E-03	7.98E-03	7.51E-03
540	7.52E-03	4.91E-03	8.95E-03	8.84E-03	9.48E-03	8.36E-03	1.03E-02	9.84E-03
545	1.17E-02	7.65E-03	1.44E-02	1.42E-02	1.53E-02	1.38E-02	1.64E-02	1.59E-02
550	9.07E-03	5.94E-03	1.10E-02	1.09E-02	1.19E-02	1.00E-02	1.28E-02	1.22E-02
555	6.13E-03	4.03E-03	7.19E-03	7.14E-03	8.05E-03	6.04E-03	8.59E-03	8.09E-03
560	6.06E-03	3.99E-03	7.11E-03	7.06E-03	8.07E-03	5.79E-03	8.54E-03	8.03E-03
565	6.12E-03	4.04E-03	7.20E-03	7.16E-03	8.27E-03	5.83E-03	8.67E-03	8.15E-03
570	6.35E-03	4.20E-03	7.51E-03	7.45E-03	8.66E-03	6.10E-03	9.03E-03	8.51E-03
575	7.37E-03	4.90E-03	8.82E-03	8.73E-03	1.01E-02	7.39E-03	1.06E-02	1.00E-02
580	7.61E-03	5.07E-03	9.15E-03	9.05E-03	1.04E-02	7.87E-03	1.10E-02	1.04E-02

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Wav. (nm)	MEGA-8	MEGA-9	MEGA-10	MEGA-11	MEGA-12	GE-1	GE-2	GE-3
585	6.70E-03	4.44E-03	7.98E-03	7.88E-03	9.12E-03	6.91E-03	9.58E-03	9.00E-03
590	6.53E-03	4.32E-03	7.76E-03	7.66E-03	8.80E-03	6.63E-03	9.30E-03	8.73E-03
595	6.59E-03	4.35E-03	7.84E-03	7.73E-03	8.77E-03	6.53E-03	9.39E-03	8.81E-03
600	6.63E-03	4.38E-03	7.91E-03	7.77E-03	8.70E-03	6.48E-03	9.44E-03	8.86E-03
605	6.67E-03	4.40E-03	7.96E-03	7.80E-03	8.60E-03	6.56E-03	9.48E-03	8.90E-03
610	6.72E-03	4.42E-03	8.00E-03	7.84E-03	8.49E-03	7.22E-03	9.48E-03	8.91E-03
615	6.70E-03	4.40E-03	7.97E-03	7.81E-03	8.30E-03	7.39E-03	9.44E-03	8.85E-03
620	6.61E-03	4.33E-03	7.86E-03	7.69E-03	8.04E-03	6.81E-03	9.32E-03	8.73E-03
625	6.54E-03	4.27E-03	7.76E-03	7.57E-03	7.79E-03	6.55E-03	9.21E-03	8.62E-03
630	6.43E-03	4.20E-03	7.61E-03	7.43E-03	7.55E-03	6.35E-03	9.06E-03	8.47E-03
635	6.28E-03	4.11E-03	7.42E-03	7.26E-03	7.29E-03	6.10E-03	8.86E-03	8.28E-03
640	6.11E-03	3.98E-03	7.19E-03	7.03E-03	7.01E-03	5.86E-03	8.60E-03	8.05E-03
645	5.89E-03	3.85E-03	6.93E-03	6.78E-03	6.72E-03	5.66E-03	8.30E-03	7.77E-03
650	5.65E-03	3.70E-03	6.64E-03	6.50E-03	6.42E-03	5.46E-03	7.97E-03	7.47E-03
655	5.40E-03	3.54E-03	6.34E-03	6.21E-03	6.10E-03	5.20E-03	7.62E-03	7.14E-03
660	5.13E-03	3.36E-03	6.01E-03	5.89E-03	5.77E-03	4.95E-03	7.24E-03	6.78E-03
665	4.84E-03	3.17E-03	5.67E-03	5.56E-03	5.41E-03	4.68E-03	6.84E-03	6.41E-03
670	4.54E-03	2.97E-03	5.31E-03	5.22E-03	5.06E-03	4.40E-03	6.43E-03	6.03E-03
675	4.24E-03	2.78E-03	4.96E-03	4.89E-03	4.71E-03	4.12E-03	6.04E-03	5.66E-03
680	3.96E-03	2.60E-03	4.62E-03	4.58E-03	4.37E-03	3.87E-03	5.65E-03	5.31E-03
685	3.69E-03	2.44E-03	4.33E-03	4.31E-03	4.09E-03	3.63E-03	5.30E-03	4.97E-03
690	3.46E-03	2.29E-03	4.07E-03	4.03E-03	3.83E-03	3.43E-03	4.99E-03	4.68E-03
695	3.20E-03	2.11E-03	3.77E-03	3.71E-03	3.53E-03	3.15E-03	4.62E-03	4.33E-03
700	2.94E-03	1.94E-03	3.46E-03	3.40E-03	3.24E-03	2.90E-03	4.24E-03	4.00E-03
705	2.70E-03	1.79E-03	3.19E-03	3.14E-03	2.97E-03	2.76E-03	3.92E-03	3.68E-03
710	2.47E-03	1.63E-03	2.95E-03	2.89E-03	2.71E-03	2.56E-03	3.60E-03	3.38E-03
715	2.25E-03	1.48E-03	2.66E-03	2.61E-03	2.45E-03	2.28E-03	3.28E-03	3.06E-03
720	2.04E-03	1.34E-03	2.42E-03	2.37E-03	2.23E-03	2.04E-03	2.97E-03	2.81E-03
725	1.85E-03	1.22E-03	2.20E-03	2.16E-03	2.01E-03	1.86E-03	2.69E-03	2.55E-03

D50 simulators (GE-4 to SYLV-4)

Wav. (nm)	GE-4	GE-5	GE-6	GE-7	SYLV-1	SYLV-2	SYLV-3	SYLV-4
395	1.07E-03	9.35E-04	9.42E-04	9.87E-04	1.23E-03	1.17E-03	1.13E-03	8.92E-04
400	3.76E-03	3.34E-03	3.54E-03	3.74E-03	4.49E-03	4.36E-03	4.44E-03	3.34E-03
405	6.17E-03	5.48E-03	5.88E-03	6.19E-03	7.37E-03	7.18E-03	7.45E-03	5.53E-03
410	3.25E-03	2.76E-03	2.91E-03	3.05E-03	3.65E-03	3.55E-03	3.74E-03	2.74E-03
415	2.25E-03	1.82E-03	1.84E-03	1.94E-03	2.32E-03	2.27E-03	2.42E-03	1.76E-03
420	2.56E-03	2.08E-03	2.10E-03	2.21E-03	2.64E-03	2.60E-03	2.79E-03	2.02E-03
425	2.96E-03	2.46E-03	2.46E-03	2.58E-03	3.08E-03	3.06E-03	3.32E-03	2.37E-03
430	6.87E-03	6.26E-03	5.98E-03	6.25E-03	7.61E-03	7.44E-03	8.00E-03	5.88E-03
435	1.56E-02	1.47E-02	1.39E-02	1.45E-02	1.77E-02	1.71E-02	1.83E-02	1.37E-02
440	1.00E-02	9.33E-03	8.92E-03	9.30E-03	1.13E-02	1.10E-02	1.18E-02	8.71E-03
445	4.40E-03	3.96E-03	3.92E-03	4.08E-03	4.88E-03	4.90E-03	5.36E-03	3.79E-03
450	4.45E-03	4.07E-03	4.03E-03	4.18E-03	4.99E-03	5.05E-03	5.55E-03	3.90E-03
455	4.72E-03	4.38E-03	4.33E-03	4.49E-03	5.38E-03	5.43E-03	5.99E-03	4.21E-03
460	4.99E-03	4.69E-03	4.63E-03	4.80E-03	5.76E-03	5.82E-03	6.40E-03	4.53E-03
465	5.22E-03	4.99E-03	4.91E-03	5.08E-03	6.11E-03	6.18E-03	6.81E-03	4.81E-03
470	5.44E-03	5.26E-03	5.17E-03	5.33E-03	6.43E-03	6.52E-03	7.19E-03	5.07E-03
475	5.64E-03	5.51E-03	5.39E-03	5.56E-03	6.72E-03	6.85E-03	7.53E-03	5.32E-03
480	5.83E-03	5.71E-03	5.59E-03	5.76E-03	6.98E-03	7.12E-03	7.81E-03	5.55E-03
485	6.02E-03	5.91E-03	5.77E-03	5.94E-03	7.21E-03	7.35E-03	8.06E-03	5.74E-03
490	6.21E-03	6.08E-03	5.91E-03	6.09E-03	7.42E-03	7.54E-03	8.29E-03	5.91E-03
495	6.35E-03	6.16E-03	5.98E-03	6.16E-03	7.54E-03	7.63E-03	8.43E-03	6.02E-03
500	6.48E-03	6.19E-03	6.00E-03	6.18E-03	7.61E-03	7.68E-03	8.47E-03	6.07E-03
505	6.67E-03	6.26E-03	6.05E-03	6.23E-03	7.71E-03	7.76E-03	8.55E-03	6.14E-03
510	6.91E-03	6.33E-03	6.08E-03	6.28E-03	7.80E-03	7.82E-03	8.63E-03	6.20E-03
515	7.18E-03	6.37E-03	6.10E-03	6.31E-03	7.86E-03	7.87E-03	8.69E-03	6.25E-03
520	7.40E-03	6.42E-03	6.12E-03	6.33E-03	7.90E-03	7.91E-03	8.72E-03	6.30E-03
525	7.56E-03	6.49E-03	6.15E-03	6.37E-03	7.94E-03	7.95E-03	8.74E-03	6.34E-03
530	7.67E-03	6.59E-03	6.20E-03	6.43E-03	7.99E-03	8.01E-03	8.80E-03	6.40E-03
535	7.75E-03	6.73E-03	6.27E-03	6.51E-03	8.07E-03	8.09E-03	8.90E-03	6.47E-03
540	9.92E-03	8.80E-03	8.10E-03	8.45E-03	1.03E-02	1.04E-02	1.16E-02	8.36E-03
545	1.57E-02	1.40E-02	1.29E-02	1.35E-02	1.61E-02	1.64E-02	1.86E-02	1.33E-02
550	1.21E-02	1.09E-02	1.00E-02	1.04E-02	1.25E-02	1.26E-02	1.42E-02	1.02E-02
555	7.92E-03	7.44E-03	6.69E-03	6.92E-03	8.45E-03	8.42E-03	9.28E-03	6.83E-03
560	7.77E-03	7.41E-03	6.63E-03	6.85E-03	8.35E-03	8.30E-03	9.15E-03	6.74E-03
565	7.82E-03	7.57E-03	6.72E-03	6.93E-03	8.41E-03	8.36E-03	9.22E-03	6.80E-03
570	8.09E-03	7.90E-03	7.00E-03	7.22E-03	8.69E-03	8.65E-03	9.53E-03	7.06E-03
575	9.45E-03	9.16E-03	8.26E-03	8.51E-03	1.01E-02	1.00E-02	1.12E-02	8.25E-03
580	9.77E-03	9.48E-03	8.56E-03	8.81E-03	1.04E-02	1.03E-02	1.16E-02	8.51E-03

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Wav. (nm)	GE-4	GE-5	GE-6	GE-7	SYLV-1	SYLV-2	SYLV-3	SYLV-4
585	8.48E-03	8.32E-03	7.37E-03	7.59E-03	9.01E-03	8.96E-03	9.97E-03	7.35E-03
590	8.23E-03	8.10E-03	7.12E-03	7.33E-03	8.72E-03	8.66E-03	9.61E-03	7.11E-03
595	8.30E-03	8.11E-03	7.16E-03	7.38E-03	8.76E-03	8.70E-03	9.64E-03	7.15E-03
600	8.37E-03	8.04E-03	7.19E-03	7.39E-03	8.78E-03	8.71E-03	9.66E-03	7.17E-03
605	8.41E-03	8.00E-03	7.20E-03	7.39E-03	8.79E-03	8.70E-03	9.65E-03	7.17E-03
610	8.47E-03	7.99E-03	7.17E-03	7.38E-03	8.76E-03	8.64E-03	9.58E-03	7.15E-03
615	8.44E-03	7.90E-03	7.11E-03	7.32E-03	8.67E-03	8.54E-03	9.43E-03	7.08E-03
620	8.33E-03	7.71E-03	7.01E-03	7.20E-03	8.56E-03	8.40E-03	9.28E-03	6.98E-03
625	8.23E-03	7.55E-03	6.91E-03	7.10E-03	8.42E-03	8.24E-03	9.15E-03	6.87E-03
630	8.09E-03	7.36E-03	6.76E-03	6.96E-03	8.25E-03	8.05E-03	8.95E-03	6.74E-03
635	7.91E-03	7.14E-03	6.58E-03	6.78E-03	8.05E-03	7.82E-03	8.72E-03	6.56E-03
640	7.68E-03	6.90E-03	6.37E-03	6.57E-03	7.79E-03	7.56E-03	8.43E-03	6.34E-03
645	7.43E-03	6.64E-03	6.14E-03	6.33E-03	7.49E-03	7.28E-03	8.15E-03	6.10E-03
650	7.15E-03	6.36E-03	5.88E-03	6.07E-03	7.18E-03	6.97E-03	7.81E-03	5.84E-03
655	6.86E-03	6.07E-03	5.61E-03	5.80E-03	6.86E-03	6.65E-03	7.42E-03	5.57E-03
660	6.53E-03	5.78E-03	5.34E-03	5.51E-03	6.51E-03	6.31E-03	7.01E-03	5.29E-03
665	6.17E-03	5.46E-03	5.04E-03	5.21E-03	6.14E-03	5.94E-03	6.60E-03	5.00E-03
670	5.79E-03	5.14E-03	4.74E-03	4.89E-03	5.76E-03	5.58E-03	6.21E-03	4.68E-03
675	5.43E-03	4.82E-03	4.45E-03	4.58E-03	5.39E-03	5.21E-03	5.80E-03	4.37E-03
680	5.08E-03	4.51E-03	4.17E-03	4.29E-03	5.03E-03	4.88E-03	5.40E-03	4.08E-03
685	4.77E-03	4.24E-03	3.92E-03	4.01E-03	4.71E-03	4.56E-03	5.08E-03	3.82E-03
690	4.48E-03	4.00E-03	3.69E-03	3.77E-03	4.40E-03	4.26E-03	4.82E-03	3.58E-03
695	4.14E-03	3.69E-03	3.41E-03	3.50E-03	4.05E-03	3.95E-03	4.47E-03	3.29E-03
700	3.79E-03	3.39E-03	3.14E-03	3.21E-03	3.71E-03	3.62E-03	4.06E-03	3.03E-03
705	3.50E-03	3.12E-03	2.89E-03	2.96E-03	3.40E-03	3.33E-03	3.70E-03	2.79E-03
710	3.20E-03	2.86E-03	2.65E-03	2.71E-03	3.11E-03	3.06E-03	3.44E-03	2.57E-03
715	2.91E-03	2.59E-03	2.40E-03	2.48E-03	2.83E-03	2.79E-03	3.17E-03	2.33E-03
720	2.68E-03	2.38E-03	2.19E-03	2.28E-03	2.58E-03	2.56E-03	2.86E-03	2.13E-03
725	2.44E-03	2.17E-03	1.99E-03	2.07E-03	2.37E-03	2.34E-03	2.55E-03	1.93E-03

D50 simulators (SYLV-5 to GM-5)

Wav. (nm)	SYLV-5	SYLV-6	SYLV-7	GM-1	GM-2	GM-3	GM-4	GM-5
395	1.09E-03	7.48E-04	8.00E-04	4.55E-04	1.46E-03	1.06E-03	1.01E-03	1.06E-03
400	4.21E-03	2.82E-03	2.86E-03	1.08E-03	3.64E-03	2.77E-03	2.65E-03	2.88E-03
405	6.98E-03	4.66E-03	4.64E-03	1.66E-03	5.60E-03	4.30E-03	4.12E-03	4.52E-03
410	3.41E-03	2.31E-03	2.35E-03	1.03E-03	3.05E-03	2.29E-03	2.19E-03	2.39E-03
415	2.16E-03	1.50E-03	1.58E-03	8.47E-04	2.16E-03	1.59E-03	1.53E-03	1.64E-03
420	2.50E-03	1.75E-03	1.83E-03	9.60E-04	2.45E-03	1.80E-03	1.73E-03	1.87E-03
425	2.96E-03	2.07E-03	2.17E-03	1.10E-03	2.87E-03	2.11E-03	2.03E-03	2.18E-03
430	7.71E-03	5.45E-03	5.50E-03	2.41E-03	6.75E-03	4.87E-03	4.71E-03	5.09E-03
435	1.83E-02	1.29E-02	1.27E-02	5.35E-03	1.54E-02	1.10E-02	1.07E-02	1.16E-02
440	1.15E-02	8.18E-03	8.05E-03	3.52E-03	1.01E-02	7.21E-03	6.98E-03	7.54E-03
445	4.86E-03	3.45E-03	3.54E-03	1.68E-03	4.73E-03	3.38E-03	3.26E-03	3.51E-03
450	4.99E-03	3.53E-03	3.64E-03	1.73E-03	4.87E-03	3.47E-03	3.34E-03	3.59E-03
455	5.37E-03	3.80E-03	3.92E-03	1.84E-03	5.19E-03	3.67E-03	3.53E-03	3.81E-03
460	5.74E-03	4.06E-03	4.19E-03	1.94E-03	5.45E-03	3.84E-03	3.69E-03	3.98E-03
465	6.07E-03	4.29E-03	4.44E-03	2.02E-03	5.64E-03	3.97E-03	3.81E-03	4.12E-03
470	6.37E-03	4.50E-03	4.66E-03	2.09E-03	5.77E-03	4.07E-03	3.90E-03	4.22E-03
475	6.64E-03	4.70E-03	4.86E-03	2.14E-03	5.88E-03	4.15E-03	3.96E-03	4.30E-03
480	6.97E-03	4.95E-03	5.09E-03	2.19E-03	5.96E-03	4.21E-03	4.01E-03	4.36E-03
485	7.43E-03	5.30E-03	5.38E-03	2.22E-03	6.05E-03	4.27E-03	4.06E-03	4.42E-03
490	7.73E-03	5.53E-03	5.58E-03	2.26E-03	6.16E-03	4.35E-03	4.13E-03	4.50E-03
495	7.73E-03	5.51E-03	5.60E-03	2.29E-03	6.24E-03	4.41E-03	4.18E-03	4.57E-03
500	7.61E-03	5.41E-03	5.55E-03	2.32E-03	6.35E-03	4.49E-03	4.25E-03	4.65E-03
505	7.59E-03	5.39E-03	5.56E-03	2.37E-03	6.57E-03	4.64E-03	4.39E-03	4.80E-03
510	7.64E-03	5.44E-03	5.61E-03	2.46E-03	6.88E-03	4.85E-03	4.59E-03	5.02E-03
515	7.70E-03	5.51E-03	5.66E-03	2.55E-03	7.24E-03	5.09E-03	4.83E-03	5.26E-03
520	7.77E-03	5.57E-03	5.71E-03	2.63E-03	7.56E-03	5.31E-03	5.05E-03	5.48E-03
525	7.83E-03	5.63E-03	5.76E-03	2.69E-03	7.78E-03	5.45E-03	5.19E-03	5.62E-03
530	7.94E-03	5.70E-03	5.84E-03	2.71E-03	7.89E-03	5.51E-03	5.25E-03	5.68E-03
535	8.23E-03	5.92E-03	6.01E-03	2.72E-03	7.92E-03	5.51E-03	5.25E-03	5.68E-03
540	1.16E-02	8.43E-03	8.18E-03	3.34E-03	9.89E-03	7.04E-03	6.73E-03	7.32E-03
545	1.82E-02	1.33E-02	1.27E-02	5.04E-03	1.52E-02	1.12E-02	1.08E-02	1.18E-02
550	1.37E-02	9.87E-03	9.63E-03	3.93E-03	1.17E-02	8.40E-03	8.06E-03	8.83E-03
555	8.83E-03	6.32E-03	6.42E-03	2.68E-03	7.83E-03	5.24E-03	5.02E-03	5.45E-03
560	8.52E-03	6.08E-03	6.26E-03	2.62E-03	7.66E-03	5.07E-03	4.86E-03	5.27E-03
565	8.56E-03	6.11E-03	6.30E-03	2.63E-03	7.68E-03	5.06E-03	4.84E-03	5.27E-03
570	8.88E-03	6.36E-03	6.53E-03	2.70E-03	7.93E-03	5.23E-03	5.01E-03	5.46E-03
575	1.04E-02	7.50E-03	7.60E-03	3.09E-03	9.30E-03	6.26E-03	6.00E-03	6.58E-03
580	1.10E-02	7.94E-03	7.92E-03	3.17E-03	9.58E-03	6.47E-03	6.19E-03	6.81E-03

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Wav. (nm)	SYLV-5	SYLV-6	SYLV-7	GM-1	GM-2	GM-3	GM-4	GM-5
585	9.77E-03	7.14E-03	7.06E-03	2.75E-03	8.20E-03	5.40E-03	5.15E-03	5.65E-03
590	9.43E-03	6.90E-03	6.82E-03	2.65E-03	7.89E-03	5.13E-03	4.89E-03	5.36E-03
595	9.29E-03	6.78E-03	6.74E-03	2.64E-03	7.90E-03	5.12E-03	4.87E-03	5.35E-03
600	9.20E-03	6.72E-03	6.69E-03	2.63E-03	7.88E-03	5.10E-03	4.84E-03	5.33E-03
605	9.23E-03	6.78E-03	6.71E-03	2.61E-03	7.88E-03	5.08E-03	4.82E-03	5.30E-03
610	9.90E-03	7.40E-03	7.07E-03	2.59E-03	7.90E-03	5.06E-03	4.80E-03	5.29E-03
615	1.00E-02	7.55E-03	7.14E-03	2.57E-03	7.94E-03	5.08E-03	4.80E-03	5.30E-03
620	9.35E-03	6.97E-03	6.73E-03	2.59E-03	8.18E-03	5.26E-03	4.97E-03	5.47E-03
625	8.98E-03	6.68E-03	6.52E-03	2.65E-03	8.61E-03	5.58E-03	5.27E-03	5.79E-03
630	8.71E-03	6.47E-03	6.33E-03	2.66E-03	8.82E-03	5.74E-03	5.43E-03	5.95E-03
635	8.37E-03	6.20E-03	6.10E-03	2.55E-03	8.50E-03	5.51E-03	5.21E-03	5.72E-03
640	8.03E-03	5.94E-03	5.87E-03	2.40E-03	8.00E-03	5.15E-03	4.88E-03	5.36E-03
645	7.76E-03	5.73E-03	5.66E-03	2.41E-03	8.18E-03	5.32E-03	5.05E-03	5.51E-03
650	7.45E-03	5.51E-03	5.44E-03	2.64E-03	9.40E-03	6.28E-03	5.96E-03	6.45E-03
655	7.09E-03	5.25E-03	5.18E-03	2.92E-03	1.08E-02	7.37E-03	7.01E-03	7.51E-03
660	6.71E-03	4.99E-03	4.92E-03	2.82E-03	1.05E-02	7.21E-03	6.87E-03	7.34E-03
665	6.33E-03	4.71E-03	4.63E-03	2.23E-03	8.16E-03	5.47E-03	5.21E-03	5.61E-03
670	5.92E-03	4.41E-03	4.34E-03	1.72E-03	6.04E-03	3.92E-03	3.74E-03	4.07E-03
675	5.51E-03	4.14E-03	4.06E-03	1.43E-03	4.89E-03	3.09E-03	2.95E-03	3.23E-03
680	5.15E-03	3.88E-03	3.80E-03	1.29E-03	4.34E-03	2.73E-03	2.60E-03	2.87E-03
685	4.82E-03	3.64E-03	3.56E-03	1.17E-03	3.94E-03	2.48E-03	2.37E-03	2.62E-03
690	4.51E-03	3.43E-03	3.34E-03	1.08E-03	3.59E-03	2.26E-03	2.16E-03	2.40E-03
695	4.15E-03	3.15E-03	3.07E-03	9.77E-04	3.23E-03	2.04E-03	1.95E-03	2.15E-03
700	3.82E-03	2.91E-03	2.83E-03	8.80E-04	2.89E-03	1.84E-03	1.76E-03	1.95E-03
705	3.60E-03	2.74E-03	2.64E-03	8.06E-04	2.62E-03	1.69E-03	1.61E-03	1.78E-03
710	3.32E-03	2.53E-03	2.44E-03	7.23E-04	2.35E-03	1.54E-03	1.46E-03	1.64E-03
715	2.97E-03	2.25E-03	2.18E-03	6.52E-04	2.12E-03	1.38E-03	1.31E-03	1.48E-03
720	2.66E-03	2.03E-03	1.95E-03	5.97E-04	1.92E-03	1.26E-03	1.19E-03	1.34E-03
725	2.45E-03	1.85E-03	1.77E-03	5.46E-04	1.72E-03	1.15E-03	1.09E-03	1.21E-03

D50 simulators (GM-6 to PH(3B)-2)

Wav. (nm)	GM-6	PH-1	PH-2	PH-3	PH-4	PH-5	PH (3B)-1	PH (3B)-2
395	1.08E-03	4.84E-04	4.34E-04	6.87E-04	1.09E-03	1.05E-03	3.70E-04	2.40E-04
400	2.90E-03	1.96E-03	1.76E-03	2.84E-03	4.11E-03	3.96E-03	2.44E-03	1.38E-03
405	4.54E-03	3.26E-03	2.92E-03	4.75E-03	6.76E-03	6.57E-03	4.36E-03	2.46E-03
410	2.41E-03	1.59E-03	1.43E-03	2.28E-03	3.35E-03	3.28E-03	2.29E-03	1.39E-03
415	1.67E-03	1.01E-03	9.09E-04	1.42E-03	2.17E-03	2.14E-03	1.91E-03	1.32E-03
420	1.89E-03	1.17E-03	1.06E-03	1.65E-03	2.51E-03	2.49E-03	2.68E-03	1.93E-03
425	2.21E-03	1.39E-03	1.26E-03	1.97E-03	2.97E-03	2.95E-03	3.69E-03	2.70E-03
430	5.16E-03	3.54E-03	3.35E-03	5.21E-03	7.51E-03	7.59E-03	7.46E-03	5.92E-03
435	1.17E-02	8.31E-03	8.00E-03	1.24E-02	1.76E-02	1.80E-02	1.49E-02	1.24E-02
440	7.65E-03	5.31E-03	5.05E-03	7.84E-03	1.12E-02	1.15E-02	1.09E-02	8.79E-03
445	3.55E-03	2.31E-03	2.12E-03	3.28E-03	4.87E-03	4.91E-03	6.68E-03	5.11E-03
450	3.63E-03	2.39E-03	2.18E-03	3.37E-03	5.02E-03	5.04E-03	6.60E-03	5.04E-03
455	3.85E-03	2.60E-03	2.37E-03	3.64E-03	5.43E-03	5.44E-03	6.42E-03	4.93E-03
460	4.02E-03	2.79E-03	2.56E-03	3.91E-03	5.83E-03	5.82E-03	6.01E-03	4.63E-03
465	4.16E-03	2.98E-03	2.73E-03	4.17E-03	6.21E-03	6.18E-03	5.47E-03	4.25E-03
470	4.26E-03	3.15E-03	2.90E-03	4.40E-03	6.55E-03	6.51E-03	4.87E-03	3.80E-03
475	4.34E-03	3.31E-03	3.05E-03	4.63E-03	6.87E-03	6.83E-03	4.35E-03	3.41E-03
480	4.41E-03	3.45E-03	3.19E-03	4.85E-03	7.16E-03	7.11E-03	5.60E-03	4.34E-03
485	4.48E-03	3.59E-03	3.33E-03	5.06E-03	7.42E-03	7.37E-03	9.45E-03	7.20E-03
490	4.56E-03	3.69E-03	3.43E-03	5.21E-03	7.64E-03	7.58E-03	9.96E-03	7.58E-03
495	4.63E-03	3.75E-03	3.48E-03	5.29E-03	7.77E-03	7.68E-03	6.77E-03	5.23E-03
500	4.71E-03	3.77E-03	3.51E-03	5.32E-03	7.83E-03	7.70E-03	3.88E-03	3.11E-03
505	4.87E-03	3.80E-03	3.55E-03	5.37E-03	7.91E-03	7.76E-03	2.19E-03	1.85E-03
510	5.10E-03	3.84E-03	3.58E-03	5.42E-03	7.98E-03	7.83E-03	1.53E-03	1.35E-03
515	5.35E-03	3.85E-03	3.60E-03	5.45E-03	8.02E-03	7.88E-03	1.22E-03	1.13E-03
520	5.57E-03	3.86E-03	3.61E-03	5.47E-03	8.04E-03	7.93E-03	1.07E-03	1.03E-03
525	5.73E-03	3.87E-03	3.61E-03	5.47E-03	8.05E-03	7.97E-03	1.06E-03	1.03E-03
530	5.80E-03	3.89E-03	3.63E-03	5.50E-03	8.08E-03	8.03E-03	1.69E-03	1.52E-03
535	5.80E-03	3.93E-03	3.68E-03	5.57E-03	8.14E-03	8.11E-03	6.70E-03	5.26E-03
540	7.46E-03	5.11E-03	4.76E-03	7.45E-03	1.03E-02	1.03E-02	2.76E-02	2.05E-02
545	1.20E-02	8.05E-03	7.46E-03	1.21E-02	1.60E-02	1.59E-02	4.16E-02	3.08E-02
550	8.98E-03	6.18E-03	5.75E-03	9.13E-03	1.25E-02	1.24E-02	2.38E-02	1.79E-02
555	5.56E-03	4.07E-03	3.81E-03	5.82E-03	8.43E-03	8.36E-03	7.14E-03	5.76E-03
560	5.37E-03	4.00E-03	3.75E-03	5.70E-03	8.31E-03	8.23E-03	2.99E-03	2.78E-03
565	5.37E-03	4.03E-03	3.79E-03	5.75E-03	8.39E-03	8.29E-03	2.11E-03	2.20E-03
570	5.57E-03	4.19E-03	3.94E-03	5.99E-03	8.69E-03	8.60E-03	2.12E-03	2.25E-03
575	6.69E-03	4.93E-03	4.63E-03	7.12E-03	1.01E-02	9.97E-03	3.87E-03	3.59E-03
580	6.91E-03	5.11E-03	4.82E-03	7.41E-03	1.04E-02	1.03E-02	7.56E-03	6.29E-03

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Wav. (nm)	GM-6	PH-1	PH-2	PH-3	PH-4	PH-5	PH (3B)-1	PH (3B)-2
585	5.76E-03	4.44E-03	4.21E-03	6.40E-03	9.15E-03	9.06E-03	1.00E-02	8.08E-03
590	5.46E-03	4.31E-03	4.09E-03	6.20E-03	8.91E-03	8.81E-03	9.08E-03	7.41E-03
595	5.45E-03	4.33E-03	4.12E-03	6.25E-03	9.00E-03	8.85E-03	7.04E-03	5.84E-03
600	5.42E-03	4.34E-03	4.13E-03	6.29E-03	9.05E-03	8.87E-03	5.32E-03	4.48E-03
605	5.39E-03	4.37E-03	4.17E-03	6.36E-03	9.10E-03	8.90E-03	6.30E-03	5.16E-03
610	5.38E-03	4.52E-03	4.32E-03	6.62E-03	9.17E-03	8.98E-03	2.22E-02	1.68E-02
615	5.39E-03	4.54E-03	4.34E-03	6.65E-03	9.15E-03	8.91E-03	2.63E-02	1.97E-02
620	5.56E-03	4.35E-03	4.17E-03	6.35E-03	9.00E-03	8.68E-03	1.19E-02	9.01E-03
625	5.88E-03	4.26E-03	4.08E-03	6.24E-03	8.88E-03	8.52E-03	8.46E-03	6.46E-03
630	6.06E-03	4.18E-03	4.02E-03	6.15E-03	8.73E-03	8.38E-03	7.42E-03	5.70E-03
635	5.82E-03	4.06E-03	3.89E-03	5.97E-03	8.54E-03	8.18E-03	3.86E-03	3.08E-03
640	5.45E-03	3.91E-03	3.76E-03	5.77E-03	8.28E-03	7.97E-03	1.77E-03	1.53E-03
645	5.63E-03	3.78E-03	3.62E-03	5.57E-03	8.00E-03	7.74E-03	1.76E-03	1.47E-03
650	6.59E-03	3.64E-03	3.49E-03	5.35E-03	7.68E-03	7.48E-03	2.24E-03	1.79E-03
655	7.68E-03	3.49E-03	3.33E-03	5.12E-03	7.34E-03	7.19E-03	1.93E-03	1.57E-03
660	7.52E-03	3.32E-03	3.18E-03	4.87E-03	6.98E-03	6.87E-03	1.62E-03	1.33E-03
665	5.75E-03	3.14E-03	3.00E-03	4.59E-03	6.59E-03	6.51E-03	1.38E-03	1.11E-03
670	4.17E-03	2.94E-03	2.82E-03	4.32E-03	6.19E-03	6.12E-03	1.07E-03	8.81E-04
675	3.32E-03	2.75E-03	2.64E-03	4.05E-03	5.78E-03	5.73E-03	9.67E-04	7.84E-04
680	2.94E-03	2.56E-03	2.48E-03	3.79E-03	5.42E-03	5.36E-03	1.08E-03	8.50E-04
685	2.67E-03	2.40E-03	2.32E-03	3.58E-03	5.08E-03	5.02E-03	1.31E-03	1.02E-03
690	2.45E-03	2.26E-03	2.17E-03	3.37E-03	4.76E-03	4.70E-03	1.12E-03	8.88E-04
695	2.20E-03	2.07E-03	2.00E-03	3.11E-03	4.41E-03	4.31E-03	6.70E-04	5.52E-04
700	1.99E-03	1.91E-03	1.84E-03	2.85E-03	4.05E-03	3.95E-03	8.27E-04	6.53E-04
705	1.84E-03	1.78E-03	1.72E-03	2.65E-03	3.72E-03	3.65E-03	2.33E-03	1.82E-03
710	1.66E-03	1.64E-03	1.59E-03	2.46E-03	3.42E-03	3.32E-03	2.99E-03	2.27E-03
715	1.50E-03	1.49E-03	1.43E-03	2.21E-03	3.08E-03	2.99E-03	1.40E-03	1.08E-03
720	1.38E-03	1.35E-03	1.30E-03	1.99E-03	2.83E-03	2.73E-03	3.49E-04	3.04E-04
725	1.24E-03	1.21E-03	1.18E-03	1.81E-03	2.58E-03	2.48E-03	2.21E-04	2.15E-04

D50 simulators (PH(3B)-3, Solux(FT))

Wav. (nm)	PH (3B)-3	Solux (FT)
395	2.63E-04	7.27E-02
400	1.68E-03	7.97E-02
405	3.00E-03	8.61E-02
410	1.68E-03	9.23E-02
415	1.56E-03	9.83E-02
420	2.29E-03	1.05E-01
425	3.20E-03	1.13E-01
430	6.78E-03	1.17E-01
435	1.39E-02	1.22E-01
440	1.00E-02	1.27E-01
445	6.01E-03	1.32E-01
450	5.94E-03	1.37E-01
455	5.78E-03	1.41E-01
460	5.43E-03	1.44E-01
465	4.95E-03	1.47E-01
470	4.39E-03	1.49E-01
475	3.95E-03	1.51E-01
480	5.07E-03	1.53E-01
485	8.56E-03	1.54E-01
490	9.03E-03	1.55E-01
495	6.16E-03	1.55E-01
500	3.58E-03	1.55E-01
505	2.07E-03	1.56E-01
510	1.46E-03	1.56E-01
515	1.20E-03	1.57E-01
520	1.07E-03	1.57E-01
525	1.06E-03	1.58E-01
530	1.64E-03	1.58E-01
535	6.23E-03	1.59E-01
540	2.52E-02	1.59E-01
545	3.80E-02	1.59E-01
550	2.19E-02	1.59E-01
555	6.75E-03	1.59E-01
560	2.98E-03	1.59E-01
565	2.21E-03	1.60E-01
570	2.23E-03	1.60E-01
575	3.82E-03	1.60E-01
580	7.19E-03	1.61E-01
585	9.49E-03	1.61E-01
590	8.64E-03	1.62E-01
595	6.72E-03	1.63E-01
600	5.10E-03	1.64E-01
605	5.97E-03	1.66E-01
610	2.06E-02	1.67E-01
615	2.43E-02	1.67E-01
620	1.10E-02	1.66E-01
625	7.89E-03	1.66E-01
630	6.94E-03	1.66E-01
635	3.64E-03	1.67E-01
640	1.73E-03	1.67E-01
645	1.69E-03	1.66E-01
650	2.13E-03	1.66E-01
655	1.87E-03	1.66E-01
660	1.57E-03	1.66E-01
665	1.34E-03	1.64E-01
670	1.05E-03	1.63E-01
675	9.13E-04	1.61E-01
680	1.01E-03	1.61E-01
685	1.20E-03	1.60E-01
690	1.02E-03	1.59E-01
695	6.64E-04	1.57E-01
700	8.02E-04	1.55E-01
705	2.21E-03	1.54E-01
710	2.78E-03	1.52E-01
715	1.31E-03	1.49E-01
720	3.30E-04	1.48E-01
725	1.84E-04	1.46E-01

Appendix C3: Colorimetric results for the 58 D50 and 15 D65 simulators accumulated

Simulators (D50)	L(cd/m2)	x	y	u'_{10}	v'_{10}	$\Delta u'v'_{10}$	CCT (K)	ΔE^*_{ab}	R_a	MI_{vis}
GTI-1	671.4	0.3463	0.3592	0.2126	0.4882	0.0025	4979	0.4	90	1.09 (D)
GTI-2	396.6	0.3467	0.3578	0.2132	0.4877	0.0032	4957	0.8	90	1.11 (D)
GTI-3	567.7	0.3505	0.3655	0.2137	0.4914	0.0043	4854	4.1	88	1.15 (D)
GTI-4	625.8	0.3469	0.3606	0.2127	0.4886	0.0025	4965	1.2	90	1.36 (D)
GTI-5	489.2	0.3547	0.3717	0.2143	0.4947	0.0071	4739	7.6	89	1.20 (D)
GTI-6	589.0	0.3500	0.3650	0.2130	0.4913	0.0037	4868	3.7	91	1.19 (D)
GTI-7	401.5	0.3539	0.3739	0.2135	0.4953	0.0072	4772	8.7	86	1.21 (D)
GTI-8	217.3	0.3520	0.3694	0.2132	0.4935	0.0055	4820	6.2	89	1.12 (D)
GTI-9	709.5	0.3495	0.3597	0.2145	0.4887	0.0043	4864	1.9	91	1.36 (D)
GTI-10	546.5	0.3553	0.3690	0.2157	0.4936	0.0072	4709	6.5	89	1.32 (D)
GTI-11	496.4	0.3496	0.3649	0.2130	0.4911	0.0036	4881	3.7	90	1.21 (D)
GTI-12	601.0	0.3523	0.3660	0.2145	0.4918	0.0052	4788	4.6	90	1.27 (D)
GTI-13	796.4	0.3493	0.3652	0.2128	0.4910	0.0033	4888	3.8	90	1.29 (D)
GTI-14	808.1	0.3493	0.3645	0.2130	0.4907	0.0033	4894	3.4	89	1.29 (D)
GTI-15	465.2	0.3497	0.3642	0.2132	0.4908	0.0036	4877	3.3	91	1.26 (D)
GTI-16	720.4	0.3505	0.3648	0.2136	0.4912	0.0041	4850	3.7	90	1.25 (D)
GTI-17	696.3	0.3501	0.3636	0.2137	0.4906	0.0039	4864	3.1	90	1.26 (D)
MEGA-1	578.9	0.3527	0.3695	0.2135	0.4939	0.0060	4796	6.3	88	1.02 (D)
MEGA-2	535.5	0.3529	0.3675	0.2141	0.4932	0.0058	4780	5.4	89	1.01 (D)
MEGA-3	681.3	0.3520	0.3680	0.2133	0.4933	0.0054	4807	5.5	89	0.94 (C)
MEGA-4	691.0	0.3519	0.3673	0.2135	0.4930	0.0053	4814	5.1	89	0.95 (C)
MEGA-5	1021.9	0.3542	0.3696	0.2141	0.4944	0.0067	4743	6.6	90	0.92 (C)
MEGA-6	569.1	0.3516	0.3672	0.2132	0.4929	0.0050	4823	5.0	89	0.93 (C)
MEGA-7	568.9	0.3514	0.3673	0.2130	0.4930	0.0050	4827	5.1	90	0.93 (C)
MEGA-8	487.1	0.3514	0.3666	0.2131	0.4927	0.0048	4825	4.7	90	0.92 (C)
MEGA-9	319.9	0.3509	0.3644	0.2137	0.4916	0.0044	4835	3.6	90	1.00 (D)
MEGA-10	577.1	0.3527	0.3671	0.2140	0.4929	0.0055	4787	5.1	90	0.97 (C)
MEGA-11	569.7	0.3515	0.3664	0.2135	0.4925	0.0049	4820	4.6	90	0.96 (C)
MEGA-12	619.8	0.3565	0.3721	0.2156	0.4954	0.0085	4677	8.1	85	1.07 (D)
GE-1	489.5	0.3552	0.3690	0.2154	0.4939	0.0072	4707	6.5	88	1.09 (D)
GE-2	677.7	0.3565	0.3672	0.2167	0.4933	0.0078	4659	6.1	89	1.04 (D)
GE-3	639.8	0.3561	0.3681	0.2162	0.4937	0.0077	4677	6.3	89	1.03 (D)
GE-4	621.3	0.3545	0.3722	0.2141	0.4950	0.0072	4745	7.9	87	1.08 (D)
GE-5	576.7	0.3566	0.3700	0.2161	0.4946	0.0082	4664	7.2	87	1.02 (D)
GE-6	527.7	0.3499	0.3644	0.2132	0.4913	0.0038	4873	3.4	89	0.99 (C)
GE-7	545.6	0.3490	0.3642	0.2128	0.4910	0.0033	4895	3.2	89	1.01 (D)

Continued...

...Continued

Simulators	L(cd/m2)	x	y	u'_{10}	v'_{10}	$\Delta u'v'_{10}$	CCT (K)	ΔE^*_{ab}	R_a	MI_{vis}
(D50)										
SYLV-1	658.5	0.3465	0.3651	0.2108	0.4911	0.0023	4993	3.9	88	1.03 (D)
SYLV-2	657.3	0.3450	0.3666	0.2094	0.4917	0.0029	5044	5.1	88	0.99 (C)
SYLV-3	730.2	0.3465	0.3691	0.2095	0.4930	0.0042	5004	6.3	87	0.93 (C)
SYLV-4	533.8	0.3500	0.3692	0.2118	0.4935	0.0049	4887	6.0	88	0.96 (C)
SYLV-5	692.8	0.3520	0.3690	0.2133	0.4936	0.0056	4815	6.0	88	1.06 (D)
SYLV-6	502.0	0.3556	0.3706	0.2151	0.4948	0.0077	4698	7.3	88	1.05 (D)
SYLV-7	500.7	0.3526	0.3699	0.2133	0.4942	0.0061	4802	6.5	88	0.99 (C)
GM-1	207.3	0.3426	0.3642	0.2086	0.4901	0.0020	5131	4.4	89	0.92 (C)
GM-2	616.2	0.3532	0.3674	0.2144	0.4928	0.0057	4766	5.4	90	1.00 (D)
GM-3	420.4	0.3444	0.3655	0.2094	0.4907	0.0020	5066	4.6	88	0.99 (C)
GM-4	401.3	0.3435	0.3646	0.2092	0.4901	0.0016	5095	4.3	88	1.01 (D)
GM-5	438.1	0.3446	0.3654	0.2097	0.4906	0.0018	5056	4.5	88	0.99 (C)
GM-6	445.9	0.3451	0.3662	0.2098	0.4910	0.0021	5047	4.8	88	1.00 (D)
PH-1	324.6	0.3503	0.3679	0.2121	0.4932	0.0047	4866	5.3	90	0.91 (C)
PH-2	305.0	0.3526	0.3678	0.2136	0.4934	0.0056	4792	5.5	90	0.94 (C)
PH-3	468.9	0.3520	0.3679	0.2133	0.4933	0.0054	4812	5.4	89	0.97 (C)
PH-4	668.0	0.3496	0.3652	0.2124	0.4918	0.0036	4885	3.8	91	0.93 (C)
PH-5	659.5	0.3472	0.3636	0.2115	0.4907	0.0022	4963	2.9	90	0.98 (C)
PH(3B)-1	676.7	0.3574	0.3698	0.2183	0.4933	0.0092	4638	7.3	80	2.74 (E)
PH(3B)-2	529.2	0.3584	0.3689	0.2194	0.4931	0.0101	4605	7.3	80	2.66 (E)
PH(3B)-3	630.5	0.3603	0.3723	0.2195	0.4948	0.0110	4557	9.0	80	2.72 (E)
Solux(FT)	11666.0	0.3485	0.3532	0.2136	0.4866	0.0041	4869	4.12	98	0.28 (B)
(D65)										
VV1	369.3	0.3206	0.3359	0.2015	0.4746	0.0062	6058	4.2	95	0.62 (C)
VV2	319.1	0.3189	0.3372	0.1997	0.4753	0.0061	6129	4.4	96	0.49 (B)
VV3	482.5	0.3098	0.3291	0.1955	0.4707	0.0027	6660	1.7	98	0.25 (B)
VV4	325.9	0.3153	0.3321	0.1990	0.4722	0.0029	6340	1.7	96	0.51 (C)
VV5	549.0	0.3093	0.3263	0.1963	0.4690	0.0017	6713	1.7	98	0.32 (B)
VV6	263.2	0.3150	0.3311	0.1992	0.4716	0.0025	6362	1.2	95	0.54 (C)
VV7	562.8	0.3087	0.3259	0.1956	0.4689	0.0024	6751	2.0	98	0.26 (B)
GE	534.8	0.3160	0.3287	0.2016	0.4694	0.0037	6326	2.0	93	0.82 (C)
GM	550.8	0.3161	0.3328	0.2000	0.4720	0.0033	6296	2.1	93	0.70 (C)
PH	590.6	0.3154	0.3309	0.1990	0.4721	0.0028	6341	1.3	98	0.55 (C)
BYK	465.2	0.3220	0.3428	0.2001	0.4791	0.0098	5963	7.3	94	0.92 (C)
TO	491.9	0.3202	0.3328	0.2012	0.4738	0.0054	6090	3.5	97	0.34 (B)
TO(3B)	985.2	0.3135	0.3212	0.2025	0.4654	0.0062	6529	4.89	88	2.31 (E)
GM(FT)1	386.6	0.3131	0.3341	0.1972	0.4718	0.0024	6440	3.15	94	0.23 (A)
GM(FT)2	410.7	0.3127	0.3311	0.1978	0.4701	0.0006	6486	1.37	96	0.18 (A)

Appendix D: Mean ΔV (20 observations) for assessing 70 metameric pairs under the six D65 simulators investigated

Pair No. \Simulator	GM (FT)	VV (F7)	GM (F7)	GE (F7)	TO (F7)	TO (3B)
1	4.12	4.08	4.61	4.43	4.38	3.78
2	4.14	4.37	4.81	5.97	4.61	4.52
3	2.14	2.03	2.03	2.52	2.35	3.57
4	2.91	2.54	3.05	3.58	3.30	5.50
5	3.56	3.15	3.80	4.02	4.00	3.70
6	2.56	3.07	3.01	3.78	3.34	3.60
7	3.05	3.30	3.38	4.08	3.70	4.16
8	3.09	2.57	3.11	3.12	3.13	2.49
9	2.66	2.55	3.05	3.24	2.91	4.96
10	3.58	4.01	3.92	4.35	3.96	3.38
11	3.07	2.79	3.26	3.56	3.22	6.24
12	3.31	3.08	3.30	3.86	3.14	4.41
13	1.95	1.95	1.81	2.36	1.97	2.73
14	1.49	1.24	1.25	1.62	1.61	4.90
15	3.03	2.39	2.74	3.58	3.00	5.84
16	3.20	3.18	3.70	4.23	3.45	4.89
17	3.42	3.14	3.38	3.69	3.35	3.94
18	1.92	1.79	2.10	2.17	1.95	4.68
19	2.87	2.44	3.68	3.21	2.84	5.66
20	2.55	2.34	3.43	2.89	2.78	4.97
21	2.51	2.18	2.51	2.43	2.56	5.67
22	2.00	1.68	1.85	2.11	1.86	2.94
23	1.64	1.68	1.80	1.72	1.94	3.92
24	3.10	2.58	3.73	3.42	3.13	4.66
25	2.51	2.18	2.97	2.92	2.75	4.11
26	3.80	3.48	3.93	4.11	3.89	4.45
27	3.88	3.70	4.79	4.66	4.30	6.44
28	3.50	3.11	3.93	3.92	3.61	5.74
29	3.92	3.55	4.29	4.43	4.04	5.40
30	2.99	2.69	3.09	3.08	2.96	2.97
31	2.23	1.92	2.58	2.30	2.54	2.64
32	4.38	4.25	4.65	5.60	4.33	3.96
33	2.41	2.71	2.66	2.82	2.93	2.59
34	2.54	2.21	2.46	2.48	2.63	2.44
35	3.07	2.79	2.56	3.11	2.91	2.28
36	3.49	3.28	3.31	3.47	3.36	2.69
37	1.81	1.41	1.61	1.74	1.71	1.89
38	3.24	2.80	3.29	3.05	3.22	2.92
39	2.85	2.54	2.78	2.73	2.79	2.42
40	2.97	2.95	3.34	3.38	3.27	3.66
41	3.03	2.76	3.51	3.13	3.14	2.77
42	3.63	3.36	3.72	3.40	3.64	3.13
43	2.57	1.81	1.87	2.52	2.70	3.92
44	2.38	1.73	2.27	2.06	2.20	1.83
45	3.31	3.73	3.42	4.25	3.72	3.33
46	2.51	2.26	2.76	2.78	2.92	2.96
47	2.63	2.76	3.17	3.04	3.07	2.76
48	3.31	3.13	4.17	3.19	3.51	3.82
49	2.39	2.14	2.17	2.24	2.51	3.88
50	2.81	2.63	2.59	2.96	2.76	3.18
51	3.38	2.95	2.89	3.43	3.03	3.05
52	4.59	3.45	2.99	3.62	3.50	5.88
53	3.51	2.87	2.40	2.77	3.00	1.63
54	4.33	3.60	2.76	4.09	3.81	4.46
55	4.72	4.47	3.54	4.87	4.32	4.82
56	5.10	4.14	4.79	4.81	4.57	7.81
57	3.28	2.93	2.38	3.33	3.02	3.82
58	4.23	2.93	3.44	3.28	3.60	2.81
59	3.96	3.33	3.60	4.37	4.09	4.10
60	2.73	2.06	2.32	2.68	2.45	5.39
61	4.10	3.65	2.84	3.64	3.34	3.96
62	2.24	1.79	1.48	1.72	1.97	2.10
63	2.68	2.20	1.81	2.36	2.21	1.71
64	2.99	2.68	2.32	2.47	2.74	3.04
65	3.55	3.21	2.83	3.19	3.38	2.99
66	3.38	2.13	3.11	2.27	2.81	4.98
67	2.11	1.52	1.75	1.67	1.99	2.28
68	3.27	2.99	3.46	3.30	3.57	2.69
69	3.42	2.52	2.35	2.89	3.01	2.50
70	3.47	2.14	2.13	3.16	2.96	5.26

Appendix E1: Spectral reflectance values for the 70 metameric pairs measured in Chapter 4

Pair No.	1		2		3		4		5		6		7		8		9		10	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	21.21	15.27	12.40	7.54	15.55	18.16	7.11	9.67	21.42	15.66	4.61	8.55	7.78	13.10	26.31	24.14	20.94	12.74	10.48	18.56
410	22.54	16.37	12.21	8.08	16.26	19.69	7.30	10.69	23.13	16.44	4.67	8.60	8.10	13.49	28.78	26.42	22.18	13.25	10.90	19.33
420	24.18	17.57	13.15	8.76	17.03	20.82	7.58	11.44	24.52	17.39	4.77	8.47	8.50	13.60	31.22	28.54	23.03	13.90	11.48	19.76
430	26.20	19.08	15.46	9.78	17.90	21.50	8.03	11.53	25.54	18.70	5.10	8.23	9.18	13.42	33.80	30.68	23.58	15.02	12.47	20.02
440	26.94	21.07	16.64	11.19	18.75	21.52	8.51	10.56	25.62	20.48	5.68	7.47	10.15	12.58	35.28	32.70	23.19	16.74	14.01	19.62
450	26.20	23.60	15.93	13.05	19.35	20.76	8.96	8.92	24.67	22.80	6.45	6.41	11.27	11.27	35.43	34.64	21.94	19.16	16.23	18.63
460	24.66	26.66	14.27	15.36	19.54	19.03	9.17	7.19	23.07	25.68	7.43	5.37	12.38	9.81	34.51	36.54	20.28	22.51	19.35	17.25
470	22.99	29.64	12.51	17.48	19.06	16.89	8.94	5.70	21.43	28.52	8.28	4.51	13.13	8.51	33.26	38.29	18.70	26.48	23.04	15.69
480	21.98	32.02	11.32	18.89	17.92	14.85	8.24	4.72	20.39	30.77	8.69	4.07	13.16	7.63	32.34	40.03	17.92	30.65	27.00	15.04
490	21.56	32.87	10.61	18.91	16.50	13.12	7.37	4.10	19.95	31.71	8.52	3.87	12.55	7.14	31.93	41.58	17.88	33.84	29.91	14.72
500	21.10	31.37	9.91	16.98	15.13	11.69	6.46	3.55	19.66	30.96	7.97	3.67	11.58	6.62	31.47	42.50	17.98	35.48	30.59	14.51
510	21.36	28.84	9.76	14.55	14.02	10.86	5.72	3.26	20.20	29.40	7.40	3.75	10.66	6.52	31.86	42.64	19.24	35.73	29.53	15.13
520	24.24	27.28	10.89	13.08	13.35	10.73	5.33	3.39	23.14	28.54	7.04	4.73	10.00	7.52	34.78	43.05	24.53	35.60	28.82	18.14
530	27.68	25.52	12.30	11.62	13.23	10.84	5.17	3.55	27.34	27.75	6.95	6.35	9.69	8.92	38.49	42.82	34.44	35.64	27.76	22.79
540	27.83	22.46	12.57	9.52	13.58	11.24	5.06	3.53	30.31	26.16	7.16	7.46	9.70	9.53	40.43	40.80	45.17	35.77	25.26	26.99
550	26.54	20.35	12.59	8.12	14.44	12.99	5.24	3.83	31.75	25.26	7.72	8.52	10.01	10.37	41.93	39.19	52.38	36.48	23.62	31.08
560	26.73	20.60	13.18	8.10	16.31	17.77	6.03	5.32	32.87	26.70	8.89	11.07	10.85	13.04	44.96	40.16	56.45	38.74	24.66	36.34
570	26.70	21.30	13.29	8.36	20.03	26.78	7.65	9.26	34.21	29.18	11.25	15.67	12.43	17.61	48.21	41.65	58.19	42.69	26.49	40.70
580	24.26	20.05	11.86	7.59	26.28	37.87	9.48	15.31	35.34	29.56	14.99	19.59	14.46	20.53	48.56	40.42	57.36	46.57	25.74	40.67
590	21.71	18.58	10.09	6.79	35.24	47.34	11.09	21.34	36.26	28.87	19.32	20.71	16.38	20.30	46.91	38.62	55.45	49.59	24.27	37.62
600	21.65	20.12	8.69	7.47	46.63	53.42	14.31	25.88	37.25	32.06	22.96	20.11	18.11	18.78	44.95	41.08	54.75	54.54	27.05	34.54
610	22.85	24.77	7.47	9.70	56.94	55.96	20.94	27.88	38.20	40.70	24.61	19.09	19.37	17.39	42.66	47.87	55.04	61.78	35.39	32.35
620	22.32	30.17	5.95	12.36	65.05	55.73	31.44	27.30	38.78	53.01	23.84	17.15	20.06	15.37	39.04	55.54	54.10	68.87	48.02	29.49
630	20.12	34.01	4.62	14.22	70.51	53.01	44.26	24.50	39.06	64.83	21.06	14.27	20.36	12.59	35.07	61.06	51.03	73.96	61.28	25.57
640	19.03	36.82	4.20	15.63	74.37	50.06	56.53	21.81	40.09	73.36	18.43	11.97	21.10	10.42	33.33	64.93	47.96	77.56	71.61	22.49
650	21.00	40.31	4.98	17.80	77.12	49.75	65.61	21.42	42.89	78.31	18.04	11.65	23.23	10.14	35.74	68.52	47.71	80.00	77.75	22.20
660	27.20	46.05	7.51	21.87	79.40	54.18	71.62	24.73	48.29	81.43	21.09	14.16	27.60	12.47	43.33	72.90	52.22	81.94	81.27	25.92
670	37.12	53.90	12.46	28.19	81.17	62.26	75.32	31.56	56.01	83.21	27.56	19.52	34.52	17.51	54.79	77.32	60.42	83.30	83.00	33.35
680	49.70	63.00	20.16	36.98	82.66	71.34	77.80	41.25	64.91	84.39	36.93	27.55	43.95	25.21	67.30	81.06	69.73	84.32	83.92	43.72
690	63.66	71.64	31.08	47.95	83.78	78.93	79.67	53.52	72.93	85.32	49.01	38.70	55.04	36.01	77.90	83.77	77.73	85.13	84.63	56.64
700	76.80	78.44	44.74	59.65	84.65	84.36	81.22	66.84	78.81	86.28	62.45	52.58	65.71	49.67	85.54	85.70	83.59	85.83	85.50	70.35

Pair No.	11		12		13		14		15		16		17		18		19		20	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	10.52	5.64	6.08	12.02	5.30	2.19	2.67	5.34	6.47	12.42	7.03	12.43	10.71	3.86	3.88	6.32	7.89	5.09	8.91	5.66
410	10.66	5.67	6.17	12.18	5.16	2.19	2.66	5.17	6.71	12.53	7.14	12.76	10.62	3.87	3.88	6.37	8.00	5.15	9.10	5.72
420	10.68	5.82	6.37	12.22	4.91	2.15	2.66	4.91	7.01	12.55	7.39	12.89	10.48	3.98	3.99	6.50	8.20	5.29	9.38	5.89
430	10.59	6.24	6.86	12.12	4.74	2.24	2.80	4.71	7.61	12.39	7.99	12.86	10.32	4.32	4.33	6.88	8.79	5.80	10.00	6.47
440	9.91	6.83	7.75	11.57	4.31	2.36	3.04	4.22	8.48	11.57	8.86	12.40	9.57	5.01	4.99	7.40	9.61	6.71	10.87	7.48
450	8.68	7.62	9.04	10.53	3.74	2.70	3.45	3.58	9.63	10.26	10.10	11.48	8.36	6.12	6.13	7.98	10.64	8.25	11.91	9.16
460	7.38	8.55	10.73	9.24	3.16	3.38	4.03	3.03	10.92	8.82	11.57	10.14	7.11	8.03	8.05	8.49	11.85	10.84	13.02	11.88
470	6.30	9.51	12.49	7.99	2.74	4.50	4.56	2.64	11.86	7.60	12.84	8.80	6.07	10.80	10.81	8.84	12.95	14.72	14.04	15.91
480	5.79	10.65	13.88	7.18	2.54	6.09	4.92	2.46	12.28	6.95	13.58	7.83	5.58	14.41	14.40	9.29	14.18	20.39	15.15	21.74
490	5.65	11.99	14.31	6.77	2.48	7.49	4.91	2.40	11.99	6.75	13.48	7.23	5.48	17.85	17.86	9.82	15.42	27.22	16.28	28.66
500	5.61	13.27	14.00	6.43	2.43	8.20	4.70	2.37	10.93	6.60	12.82	6.73	5.48	20.20	20.19	10.17	16.33	33.90	17.17	35.23
510	6.14	14.34	13.35	6.60	2.52	8.23	4.53	2.52	10.00	7.04	12.07	6.70	6.03	20.99	21.00	11.14	17.97	38.28	18.80	39.11
520	8.82	15.52	12.86	7.95	3.24	8.17	4.54	3.43	9.89	9.49	11.60	7.56	8.87	21.04	21.06	14.98	23.40	40.56	24.20	40.89
530	14.25	16.23	12.78	10.01	4.86	8.18	4.64	5.87	9.91	13.80	11.52	8.79	15.24	21.10	21.10	21.93	33.63	40.95	34.16	40.70
540	19.87	15.53	13.07	12.13	7.05	8.37	5.03	9.16	9.64	17.14	11.80	10.15	23.71	21.26	21.26	27.99	45.40	39.10	45.17	37.94
550	22.66	14.83	13.86	15.24	9.92	9.00	6.39	11.94	10.25	18.96	12.61	12.67	31.39	21.92	21.91	30.92	53.59	37.85	52.46	35.81
560	23.10	15.71	15.65	21.26	15.17	10.72	10.00	14.62	13.33	21.79	14.45	18.17	38.26	23.91	23.90	33.76	57.08	39.74	55.29	36.91
570	22.32	16.95	19.19	30.75	24.03	14.36	17.48	18.23	20.00	24.82	18.14	27.63	44.11	27.63	27.63	36.34	57.00	42.73	54.74	38.82
580	21.07	16.16	24.82	40.26	34.72	20.18	28.22	22.50	28.34	24.59	24.24	38.71	46.44	31.95	31.94	35.43	54.40	42.46	51.74	37.54
590	20.16	14.83	32.33	45.49	43.33	28.49	39.18	26.79	35.27	23.10	32.94	47.29	45.96	36.00	36.01	33.53	50.90	40.85	47.99	35.49
600	19.98	16.43	41.89	46.75	47.99	39.43	47.54	32.90	39.61	25.69	44.16	51.80	44.52	42.01	41.99	36.30	47.92	43.80	44.84	38.41
610	20.25	21.62	51.73	46.15	49.30	50.16	51.64	42.07	41.18	33.93	54.57	53.12	42.46	50.96	50.94	44.81	45.76	52.28	42.59	47.28
620	20.46	28.70	60.78	43.86	48.20	59.48	52.46	53.39	40.15	46.76	63.05	52.06	39.10	61.09	61.08	56.44	42.83	62.98	39.63	59.19
630	20.51	34.83	67.46	39.81	44.98	66.40	50.44	63.58	36.82	60.58	69.00	48.84	35.38	69.16	69.16	66.80	38.60	71.59	35.45	69.58
640	21.15	39.32	72.15	36.30	41.91	71.46	47.89	70.90	33.66	71.47	73.27	45.63	33.82	74.54	74.54	73.87	35.14	77.02	32.10	76.58
650	23.24	43.67	75.35	35.82	41.62	75.00	47.67	75.44	33.26	77.93	76.27	45.22	36.14	77.84	77.86	77.93	34.79	80.09	31.76	80.49
660	27.67	49.75	77.79	40.11	45.99	77.68	51.93	78.47	37.36	81.68	78.69	49.63	43.48	80.15	80.17	80.56	39.14	82.34	36.02	82.97
670	34.71	57.57	79.62	48.57	54.25	79.65	59.79	80.50	45.50	83.62	80.52	57.94	54.38	81.69	81.71	82.07	47.63	83.81	44.32	84.24
680	44.47	66.20	81.13	59.44	64.28	81.25	68.88	82.00	56.24	84.76	82.04	67.75	66.11	82.92	82.94	83.16	58.48	84.80	55.17	85.01
690	56.02	73.96	82.29	70.61	73.74	82.47	76.76	83.15	67.80	85.59	83.24	76.52	75.80	83.86	83.86	83.98	69.82	85.50	67.00	85.65
700	67.12	79.83	83.22	80.11	81.20	83.41	82.56	84.12	78.09	86.45	84.11	83.06	82.67	84.64	84.68	84.85	79.66	86.21	77.73	86.35

Pair No	21		22		23		24		25		26		27		28		29		30	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	8.80	5.84	11.95	10.21	5.32	5.92	23.97	18.22	14.58	10.36	5.02	11.64	11.23	9.39	12.32	4.83	9.03	3.35	14.52	17.48
410	9.00	5.98	12.39	10.49	5.39	5.98	25.80	19.39	15.08	10.72	5.20	11.41	11.00	9.06	12.14	4.94	8.65	3.42	15.22	17.75
420	9.32	6.18	12.92	11.00	5.54	6.16	27.41	20.64	15.65	11.29	5.39	11.09	11.28	8.76	11.75	5.19	8.13	3.55	16.47	19.18
430	9.95	6.74	13.93	11.98	6.04	6.67	28.98	22.34	16.51	12.35	5.93	10.75	12.12	8.60	11.46	5.72	7.80	3.89	18.67	22.45
440	10.76	7.79	15.41	13.55	6.99	7.65	29.82	24.65	17.63	14.01	6.81	10.01	12.03	8.59	10.88	6.62	7.39	4.48	21.37	25.58
450	11.67	9.44	17.54	15.98	8.62	9.22	29.84	27.74	19.02	16.51	8.12	9.01	10.96	8.79	10.10	8.11	6.93	5.54	24.51	27.79
460	12.51	11.97	20.46	19.64	11.28	11.69	29.32	31.83	20.68	20.24	9.85	8.01	9.54	9.50	9.30	10.49	6.54	7.30	28.35	29.22
470	13.13	15.48	23.95	24.63	15.27	15.11	28.59	36.67	22.36	25.22	11.76	7.10	8.33	10.68	8.56	13.71	6.18	9.77	32.63	30.05
480	13.84	19.81	28.04	31.31	21.27	19.76	28.44	41.91	24.21	31.62	13.35	6.61	7.67	12.15	8.23	17.67	6.04	12.90	37.01	30.91
490	14.62	23.86	32.04	38.76	28.93	24.91	28.79	46.12	25.98	38.12	13.99	6.46	7.56	14.43	8.28	21.06	6.13	15.47	40.21	31.79
500	15.16	26.60	35.35	45.75	37.73	29.78	29.24	48.27	27.31	43.15	13.69	6.28	7.52	17.31	8.31	22.13	6.13	16.02	41.54	32.36
510	16.43	27.56	38.61	50.29	45.33	34.25	30.85	48.27	29.29	45.18	12.94	6.59	8.16	18.40	9.02	21.04	6.61	14.88	40.90	33.51
520	20.86	27.46	44.46	51.89	50.25	40.83	36.41	47.51	34.84	44.57	12.19	8.56	11.27	17.49	12.20	19.77	8.76	13.59	38.87	36.86
530	28.33	27.18	51.89	51.62	52.31	49.02	44.86	45.96	42.96	42.51	11.63	11.75	17.10	16.13	17.90	18.05	12.32	12.06	36.04	40.02
540	34.77	27.14	57.04	50.44	51.80	54.54	51.25	43.28	48.44	40.03	11.31	13.88	22.10	15.14	22.55	15.44	14.78	10.04	32.93	39.47
550	37.28	27.38	58.71	49.06	50.56	55.85	53.04	41.12	48.99	37.77	11.28	15.10	23.25	14.32	23.92	13.63	14.91	8.62	30.02	36.08
560	37.14	28.33	58.12	47.67	50.36	54.56	51.64	40.63	46.53	35.85	11.59	16.95	21.59	13.51	23.17	13.43	13.75	8.28	27.22	31.63
570	35.87	30.00	55.94	46.24	49.83	51.54	48.21	40.37	42.35	33.98	12.29	18.57	18.66	12.95	20.87	13.52	11.90	8.19	24.31	26.68
580	34.10	31.77	52.14	44.61	46.85	46.97	43.39	38.72	36.98	32.11	12.95	17.51	15.41	12.76	17.26	12.47	9.50	7.39	21.32	21.87
590	32.61	33.31	48.02	43.57	43.34	42.30	38.91	37.18	32.05	30.91	13.49	14.89	12.96	12.99	13.90	11.36	7.37	6.67	19.01	18.34
600	31.63	34.71	44.70	43.45	41.84	38.74	35.59	38.08	28.55	30.65	14.08	12.67	11.36	13.32	11.60	12.08	5.95	7.00	17.52	15.99
610	31.16	35.88	42.36	43.91	41.79	36.38	33.11	40.87	26.31	30.96	14.65	11.25	10.10	13.59	10.18	14.49	5.09	8.28	16.32	14.06
620	30.93	36.59	39.31	44.24	40.41	33.43	29.94	43.33	23.61	31.22	15.00	9.58	8.39	13.84	8.61	17.07	4.24	9.62	14.54	11.63
630	30.80	36.89	35.11	44.38	36.86	29.44	26.11	44.62	20.10	31.27	15.12	7.51	6.72	13.92	6.73	18.64	3.34	10.45	12.58	9.37
640	31.09	37.91	31.76	45.38	33.57	26.26	23.67	46.11	17.44	32.09	15.68	6.02	6.07	13.81	5.47	19.98	2.82	11.23	11.63	8.56
650	32.07	40.68	31.52	48.15	33.21	25.92	24.31	49.17	17.24	34.69	17.48	5.90	7.02	13.84	5.43	22.34	2.86	12.86	13.29	9.91
660	34.12	46.09	35.86	53.45	37.52	29.80	29.11	54.75	20.60	39.98	21.34	7.53	10.22	14.64	7.07	26.81	3.64	16.21	17.93	14.24
670	37.26	53.98	44.25	60.78	45.95	37.57	37.60	62.26	27.33	47.94	27.62	11.21	16.18	16.62	10.61	33.73	5.46	21.69	25.72	21.74
680	41.70	63.33	55.24	68.77	56.96	48.20	48.75	70.25	36.92	57.95	36.58	17.26	24.94	20.37	16.38	43.10	8.93	29.60	36.34	32.13
690	47.35	72.00	67.23	75.48	68.80	60.93	61.67	76.82	49.39	68.02	47.84	26.41	36.85	26.18	25.17	54.34	15.08	40.05	49.52	45.66
700	53.88	78.48	78.22	80.14	79.40	73.77	74.47	81.39	63.72	76.17	59.67	38.57	51.16	33.63	36.92	65.48	24.02	52.02	63.76	61.29

Pair No.	31		32		33		34		35		36		37		38		39		40	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	18.05	15.54	7.92	12.48	19.22	20.59	20.99	18.44	13.44	14.89	7.80	7.85	12.37	10.44	11.58	10.60	7.34	5.80	5.73	5.90
410	18.38	16.78	8.61	11.81	21.11	20.53	21.99	20.65	15.65	14.65	7.01	8.84	12.26	12.98	12.04	13.01	7.13	7.46	5.34	6.50
420	19.54	18.16	9.39	12.66	23.25	22.56	24.31	22.98	18.20	16.45	8.04	10.10	14.21	16.19	14.18	15.97	8.47	9.67	6.13	7.24
430	21.90	19.90	10.58	15.47	25.79	27.89	28.71	25.59	21.16	21.69	12.38	11.84	19.87	20.11	18.92	19.01	12.94	12.41	9.15	8.17
440	24.10	22.20	12.27	17.29	29.07	32.69	32.20	28.50	24.57	26.71	17.61	14.25	25.77	24.84	22.51	21.73	17.58	15.40	12.13	9.23
450	25.83	25.07	14.41	16.96	32.92	34.57	33.40	31.55	27.70	28.55	20.04	16.97	28.23	28.38	22.62	23.03	18.80	16.84	12.54	10.02
460	27.06	28.51	16.95	15.44	36.76	33.95	32.76	34.40	29.51	27.39	19.18	18.66	27.11	28.58	20.28	22.27	16.84	15.63	10.84	9.94
470	27.80	32.02	19.43	13.79	39.39	32.32	31.13	36.38	29.71	24.94	16.93	18.39	24.03	26.22	16.97	19.88	13.74	13.12	8.74	8.99
480	28.18	35.03	21.20	12.78	40.39	30.83	29.50	37.21	28.49	22.44	14.76	16.94	20.90	22.97	14.13	17.11	11.10	10.67	7.04	7.64
490	28.27	36.38	21.49	12.32	39.59	29.68	28.10	36.49	26.26	20.28	12.97	15.12	18.17	19.62	11.88	14.50	9.08	8.64	5.81	6.37
500	28.18	35.45	20.35	11.88	37.32	28.34	26.46	34.12	23.41	18.05	11.20	13.13	14.88	16.31	9.44	11.61	6.99	6.84	4.76	5.30
510	27.93	33.20	18.55	12.14	34.35	27.59	25.35	31.17	20.65	16.42	9.89	11.33	12.10	13.54	7.54	9.22	5.42	5.56	4.10	4.54
520	27.69	31.10	16.68	14.26	31.31	28.25	25.55	28.76	18.25	15.76	9.28	9.89	10.74	11.36	6.77	7.91	4.76	4.72	3.90	3.99
530	27.57	28.73	14.84	16.93	28.22	28.59	25.72	26.25	15.98	15.12	8.63	8.47	9.41	9.44	6.03	6.76	4.16	4.03	3.72	3.62
540	27.57	25.72	13.25	17.55	25.20	27.35	24.95	23.30	13.95	13.99	7.60	7.07	7.41	7.76	4.82	5.34	3.32	3.45	3.42	3.34
550	27.49	23.51	12.01	16.75	22.65	25.72	24.53	21.08	12.41	13.42	6.82	5.92	6.10	6.58	4.13	4.49	2.84	3.10	3.36	3.17
560	27.41	22.77	11.08	15.65	20.72	24.38	25.14	20.23	11.32	13.58	6.33	5.04	5.92	5.83	4.26	4.35	2.81	2.90	3.64	3.08
570	26.90	22.23	10.31	13.69	19.10	22.08	25.12	19.58	10.34	13.20	5.53	4.36	5.76	5.25	4.53	4.37	2.84	2.77	3.84	3.06
580	25.22	20.76	9.47	10.93	17.40	18.59	22.91	18.13	9.35	11.32	4.28	3.80	4.76	4.61	3.96	3.93	2.48	2.58	3.37	3.00
590	23.10	19.48	8.96	8.69	16.05	15.58	20.21	16.95	8.70	9.33	3.34	3.37	3.90	4.20	3.37	3.53	2.20	2.45	2.80	2.89
600	21.19	20.01	8.84	7.26	15.35	13.52	18.06	17.34	8.52	7.90	2.80	3.15	3.81	4.16	3.47	3.79	2.17	2.40	2.45	2.81
610	19.26	21.89	9.01	6.16	15.11	11.80	16.12	18.86	8.65	6.71	2.43	3.03	4.05	4.34	4.06	4.71	2.25	2.41	2.17	2.76
620	16.47	23.52	9.14	4.84	15.02	9.63	13.55	20.17	8.77	5.32	2.12	2.97	3.83	4.50	4.18	5.76	2.19	2.44	1.96	2.74
630	13.62	24.35	9.18	3.77	14.92	7.61	11.09	20.82	8.79	4.16	1.92	2.94	3.24	4.57	3.71	6.47	2.04	2.46	1.84	2.71
640	12.43	25.41	9.57	3.44	15.06	6.84	10.19	21.73	9.17	3.80	1.91	2.94	3.03	4.82	3.47	7.10	2.01	2.54	1.84	2.74
650	13.94	27.86	10.96	4.02	15.72	7.96	11.65	24.02	10.51	4.52	2.07	3.09	3.59	5.65	4.08	8.34	2.22	2.90	1.97	2.85
660	19.03	32.75	14.03	6.05	17.16	11.62	16.36	28.62	13.46	6.84	2.64	3.48	5.36	7.59	6.12	10.97	2.88	3.89	2.35	3.18
670	27.61	40.28	19.22	10.19	19.47	18.29	24.35	35.82	18.48	11.42	4.02	4.14	9.04	11.19	10.25	15.45	4.50	6.02	3.33	3.79
680	39.09	50.23	26.92	17.13	22.80	27.84	35.17	45.59	25.94	18.70	7.25	5.29	15.33	17.01	17.04	22.20	8.04	9.94	5.82	4.81
690	53.10	61.44	37.23	27.46	27.35	40.65	48.88	57.00	36.06	29.25	13.63	7.12	24.99	25.41	27.06	31.55	14.75	16.37	11.30	6.50
700	67.98	71.62	49.20	40.75	33.12	55.93	64.12	67.95	47.99	42.63	23.11	9.81	37.58	35.98	39.88	42.84	24.52	25.10	19.82	9.03

Pair No.	41		42		43		44		45		46		47		48		49		50	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	23.61	20.85	22.54	19.37	23.81	20.43	9.71	9.28	8.63	5.75	8.40	7.68	26.54	23.19	20.51	24.58	3.52	3.45	25.49	23.21
410	25.80	22.93	24.42	21.42	26.22	23.42	11.62	11.48	8.45	6.08	8.36	8.97	29.23	25.54	22.65	27.15	3.98	3.75	28.16	25.59
420	28.74	25.11	27.23	23.54	29.55	26.61	13.84	14.18	9.24	6.60	9.49	10.29	32.28	27.83	24.76	30.08	4.29	3.96	31.03	27.84
430	32.85	27.36	31.38	25.70	33.96	29.64	16.10	17.01	11.29	7.46	12.40	11.51	35.69	30.05	26.83	33.16	4.31	4.10	34.21	30.10
440	35.69	29.67	34.23	27.94	36.71	32.22	18.22	19.53	12.22	8.52	14.27	12.51	37.74	32.03	28.65	34.49	3.90	4.14	36.21	32.07
450	36.36	32.06	34.69	30.21	36.94	34.02	19.60	20.16	11.34	9.78	13.62	12.65	38.08	33.82	30.33	33.79	3.30	3.91	36.63	33.84
460	35.24	34.29	33.28	32.32	35.19	34.63	19.66	18.41	9.59	11.12	11.57	11.54	37.00	35.35	31.69	31.52	2.73	3.40	35.74	35.37
470	33.06	35.59	30.92	33.50	32.25	33.67	18.18	15.69	7.91	11.94	9.34	9.90	35.20	36.36	32.00	28.56	2.34	2.87	34.09	36.38
480	30.73	35.81	28.48	33.69	29.31	31.76	16.07	13.15	6.74	12.00	7.59	8.29	33.46	37.12	31.38	25.61	2.09	2.50	32.47	37.10
490	28.59	34.82	26.32	32.71	26.66	29.37	13.86	11.00	5.97	11.22	6.31	6.98	32.02	37.48	30.01	23.52	1.95	2.23	31.03	37.46
500	26.28	32.11	24.04	30.09	23.63	25.83	11.13	9.06	5.26	9.26	5.18	5.92	30.39	36.74	27.38	21.22	1.87	2.06	29.40	36.70
510	24.60	29.02	22.40	27.10	21.11	22.45	8.82	7.64	4.90	7.34	4.47	5.25	29.40	35.30	24.65	19.60	1.83	1.97	28.35	35.26
520	24.24	27.34	21.99	25.39	20.09	20.64	7.62	6.84	5.21	6.51	4.32	4.86	30.10	34.65	23.31	19.33	1.83	1.95	28.89	34.61
530	24.06	25.55	21.75	23.59	19.14	18.82	6.54	6.10	5.60	5.74	4.19	4.52	30.97	33.54	22.00	19.27	1.80	1.93	29.59	33.50
540	23.39	22.55	21.05	20.68	17.18	16.02	5.15	5.37	5.53	4.44	3.92	4.32	30.97	30.73	19.54	18.85	1.77	1.94	29.52	30.68
550	23.79	20.50	21.32	18.68	16.09	14.16	4.31	4.97	5.67	3.73	4.01	4.40	31.82	28.70	17.91	19.54	1.80	2.05	30.35	28.65
560	26.51	20.87	23.62	18.67	17.22	14.28	4.26	4.95	6.60	3.88	4.82	4.73	35.37	29.44	18.78	22.95	1.92	2.33	33.88	29.38
570	30.12	21.77	26.50	19.51	18.86	14.77	4.36	4.96	7.70	4.24	5.93	4.91	40.31	30.75	20.43	28.73	2.42	2.79	38.88	30.70
580	30.77	20.58	26.65	18.32	18.03	13.68	3.93	4.72	7.39	3.85	5.94	4.72	42.16	29.45	19.70	32.93	3.28	3.04	41.11	29.41
590	29.11	19.12	24.90	16.96	16.37	12.47	3.52	4.48	6.32	3.37	5.18	4.45	41.05	27.68	18.37	34.07	3.79	3.06	40.42	27.64
600	27.09	20.74	22.93	18.38	17.01	13.69	3.86	4.44	5.37	3.88	4.43	4.40	39.15	30.01	20.83	33.55	3.77	3.08	38.78	29.97
610	24.87	25.67	20.86	22.68	19.31	17.38	5.00	4.52	4.56	5.74	3.78	4.46	36.82	36.90	28.59	31.93	3.51	3.15	36.61	36.86
620	21.72	31.57	18.07	27.66	20.11	21.64	6.42	4.59	3.61	8.23	3.02	4.52	33.14	45.60	41.10	28.79	3.08	3.22	33.09	45.55
630	18.49	35.94	15.34	31.16	18.57	24.60	7.44	4.61	2.88	9.38	2.47	4.56	29.15	52.57	55.73	25.20	2.55	3.22	29.31	52.50
640	17.20	39.13	14.33	33.81	17.58	26.80	8.30	4.83	2.67	9.63	2.31	4.76	27.43	57.48	68.52	23.58	2.21	3.36	27.68	57.42
650	19.04	42.83	16.09	37.10	19.36	29.77	9.72	5.66	3.10	11.08	2.64	5.59	29.58	61.78	76.67	25.53	2.20	3.90	29.89	61.75
660	24.99	48.71	21.55	42.64	25.26	34.99	12.60	7.61	4.55	15.36	3.75	7.52	36.73	67.14	81.37	32.13	2.56	5.28	36.99	67.12
670	34.73	56.60	30.47	50.35	34.85	42.67	17.43	11.17	7.73	22.68	6.26	11.09	47.98	72.87	83.58	42.72	3.45	8.01	48.08	72.86
680	47.29	65.54	42.02	59.50	47.16	52.53	24.56	16.94	13.42	32.76	11.06	16.87	61.24	78.06	84.65	55.73	5.41	12.73	60.96	78.07
690	61.58	73.82	55.68	68.46	61.34	63.35	34.38	25.27	22.45	45.60	19.08	25.28	73.92	82.00	85.43	69.15	9.53	19.95	73.07	82.04
700	75.23	80.19	69.72	75.72	75.22	73.10	46.11	35.73	34.38	59.95	30.05	35.93	83.98	84.79	86.41	80.59	16.11	29.32	82.56	84.85

Pair No.	51		52		53		54		55		56		57		58		59		60	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	13.98	18.08	12.16	4.84	4.92	5.93	17.91	15.25	8.97	7.50	10.55	9.64	17.71	15.60	4.56	8.53	7.87	13.07	5.86	5.65
410	15.04	18.46	11.82	4.94	4.95	5.97	18.58	16.33	8.86	8.05	10.92	10.68	18.54	16.41	4.56	8.58	8.20	13.48	5.87	5.68
420	16.27	19.61	11.33	5.17	5.12	6.13	19.66	17.56	9.32	8.75	11.07	11.40	19.44	17.33	4.67	8.45	8.58	13.57	6.04	5.83
430	17.88	21.97	10.93	5.71	5.61	6.67	21.51	19.06	10.62	9.73	10.94	11.48	20.59	18.64	5.06	8.21	9.30	13.41	6.52	6.25
440	20.08	24.18	10.22	6.63	6.53	7.61	23.43	21.05	12.03	11.12	10.01	10.52	21.83	20.42	5.64	7.46	10.30	12.57	7.14	6.83
450	22.94	25.90	9.31	8.12	8.06	9.19	25.30	23.57	13.20	13.03	8.61	8.90	23.07	22.76	6.39	6.40	11.46	11.24	7.84	7.64
460	26.48	27.18	8.39	10.47	10.64	11.63	26.86	26.65	13.98	15.31	7.21	7.17	24.14	25.61	7.28	5.35	12.62	9.82	8.53	8.59
470	30.22	27.90	7.59	13.68	14.60	15.06	27.80	29.61	14.17	17.44	6.02	5.68	24.75	28.46	7.95	4.50	13.40	8.50	9.06	9.53
480	33.54	28.28	7.20	17.66	20.57	19.67	27.81	31.97	13.69	18.84	5.38	4.72	25.01	30.72	8.13	4.04	13.41	7.62	9.60	10.68
490	35.10	28.36	7.25	21.05	28.43	24.84	26.97	32.86	12.71	18.87	5.09	4.10	25.02	31.65	7.81	3.85	12.77	7.14	10.13	12.01
500	34.27	28.27	7.26	22.14	37.73	29.70	25.74	31.37	11.58	16.95	4.81	3.54	24.85	30.93	7.20	3.67	11.76	6.59	10.51	13.29
510	31.99	27.99	7.96	21.05	46.11	34.16	24.53	28.84	10.60	14.54	4.83	3.26	24.61	29.40	6.59	3.76	10.77	6.49	10.84	14.34
520	29.68	27.76	11.20	19.76	51.10	40.75	23.69	27.29	9.96	13.05	5.99	3.39	24.53	28.52	6.22	4.69	10.09	7.51	11.60	15.52
530	27.15	27.63	17.60	18.07	52.70	48.92	23.37	25.52	9.69	11.61	7.62	3.55	24.81	27.73	6.13	6.31	9.75	8.88	12.34	16.25
540	24.19	27.62	23.75	15.48	52.27	54.43	23.54	22.47	9.67	9.49	7.87	3.53	25.47	26.15	6.30	7.45	9.71	9.52	12.66	15.54
550	21.97	27.55	26.06	13.64	50.91	55.77	24.15	20.38	9.93	8.11	7.57	3.84	26.60	25.23	6.78	8.51	9.98	10.37	13.63	14.84
560	20.95	27.47	25.45	13.44	49.03	54.49	25.41	20.59	10.49	8.08	8.45	5.32	28.59	26.64	7.83	11.03	10.77	13.01	16.68	15.70
570	20.13	26.94	22.86	13.53	46.56	51.47	27.32	21.30	11.35	8.32	9.83	9.25	32.01	29.14	9.93	15.60	12.27	17.54	21.63	16.95
580	18.65	25.26	18.77	12.48	43.43	46.91	28.78	20.07	11.69	7.58	9.52	15.24	36.44	29.52	13.13	19.54	14.09	20.48	25.12	16.17
590	17.49	23.14	15.00	11.37	40.74	42.27	29.05	18.59	11.34	6.77	8.61	21.26	40.74	28.81	16.81	20.67	15.84	20.26	25.87	14.83
600	17.74	21.20	12.45	12.11	38.95	38.69	28.43	20.09	10.57	7.44	10.11	25.81	44.06	31.99	19.72	20.08	17.36	18.77	25.19	16.42
610	19.02	19.28	10.92	14.52	37.41	36.34	26.85	24.73	9.47	9.66	15.43	27.85	45.90	40.55	20.51	19.06	18.50	17.39	23.66	21.58
620	20.11	16.47	9.27	17.07	34.89	33.38	23.81	30.12	7.72	12.31	25.10	27.27	46.64	52.63	18.99	17.14	19.12	15.37	20.79	28.62
630	20.62	13.63	7.23	18.65	31.85	29.40	20.45	33.97	6.02	14.16	38.40	24.48	47.24	64.65	16.38	14.25	19.37	12.59	17.60	34.78
640	21.51	12.43	5.77	19.99	30.51	26.22	18.95	36.81	5.31	15.59	52.85	21.79	47.89	73.18	15.03	11.97	20.07	10.42	16.09	39.27
650	23.75	13.93	5.64	22.34	32.65	25.85	20.74	40.28	6.15	17.75	64.61	21.37	49.14	78.16	16.37	11.61	22.16	10.09	17.62	43.63
660	28.30	18.99	7.23	26.82	39.46	29.70	26.82	45.98	9.13	21.80	72.74	24.63	51.51	81.28	21.43	14.07	26.47	12.40	23.16	49.70
670	35.45	27.56	10.85	33.69	49.99	37.43	36.80	53.79	14.79	28.09	77.60	31.39	54.93	83.10	30.01	19.37	33.35	17.39	32.37	57.48
680	45.16	38.99	16.85	43.07	61.95	48.01	49.51	62.85	23.37	36.83	80.52	41.03	59.31	84.25	41.43	27.33	42.77	25.03	44.34	66.09
690	56.54	52.98	26.04	54.29	72.70	60.70	63.52	71.50	35.08	47.78	82.51	53.24	64.37	85.20	54.85	38.40	53.90	35.75	58.17	73.84
700	67.48	67.83	38.34	65.40	80.75	73.51	76.41	78.28	49.26	59.42	84.22	66.47	69.53	86.15	68.22	52.16	64.61	49.31	71.66	79.70

Pair No.	61		62		63		64		65		66		67		68		69		70	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	8.51	5.10	12.14	10.21	21.38	18.18	13.88	10.35	5.15	3.34	10.47	12.49	18 82	20.54	22.76	20.88	22.90	19.36	24.52	24.56
410	8 61	5.18	12.42	10.47	22.59	19.37	14.08	10.71	5.26	3.42	11.13	11.81	20.57	20.52	25 45	22.95	25.74	21.42	27.36	27.15
420	8 87	5.30	12 93	10.97	23.75	20.62	14 44	11.28	5.47	3.57	12.00	12.64	23.00	22.50	28 12	25.11	28 50	23.52	29.98	30.02
430	9 47	5 80	13 89	11.94	25.11	22.32	15.15	12.31	5.91	3.88	13 24	15.45	26.53	27.81	30 54	27.37	30.95	25 67	31.82	33.08
440	10 32	6.72	15 39	13.52	26.61	24.61	16.07	14.01	6.50	4 48	14.80	17.28	30.29	32 62	32 18	29 71	32 64	27.92	32.16	34.41
450	11.34	8 28	17.58	15.90	28.34	27.70	17 20	16.46	7.15	5.51	16.59	16.97	33.36	34 49	32 47	32.08	32.97	30 20	31.24	33.71
460	12.48	10 84	20.62	19.55	30.33	31.76	18.58	20.20	7.70	7.26	18.12	15.44	35.45	33 91	31.42	34 29	32 08	32.29	29.49	31.45
470	13 45	14 72	24.46	24 53	32.32	36.62	20.02	25.18	7.99	9.74	18.97	13.80	36.52	32.29	29.72	35.59	30.48	33.51	27.42	28.50
480	14 51	20.38	29.17	31.20	34.44	41.83	21.78	31.58	8.23	12.83	19.27	12.78	36.79	30.81	27.99	35 84	28 80	33.67	25.90	25.80
490	15 64	27.21	34 34	38.62	36.52	46.07	23.90	38.10	8.51	15.39	19.14	12.32	36.26	29 66	26 44	34 85	27.30	32 71	24.86	23.49
500	16.47	33 91	39 72	45.58	38.33	48.23	26 26	43.13	8.56	15.96	18.45	11.89	34.97	28 35	24 92	32.15	25.79	30.10	23.39	21.22
510	18 08	38.24	44 68	50.10	39 80	48.23	29.07	45.18	8.95	14.62	17.46	12.14	33 03	27.56	23.82	29.04	24.69	27.11	22.31	19.62
520	23.50	40.55	48.98	51.75	41.51	47.47	33 65	44.58	10.81	13.53	16.53	14.25	30.63	28.23	23 60	27.36	24.40	25 39	23.11	19.35
530	33.95	40 95	52 61	51.47	42.96	45.92	39.26	42.51	13.18	12.00	15.36	16.90	27.89	28.58	23.51	25 58	24 26	23.60	23.74	19.30
540	46 22	39.12	55 50	50.29	43 62	43.27	43.36	40.04	13.73	10.00	13.94	17.54	25.17	27.33	23.06	22.57	23.79	20.69	21.84	18.92
550	55.18	37.89	57.20	48.92	44.59	41.11	44.76	37.77	12.78	8.59	12.80	16.75	22 82	25.75	22 61	20 52	23.31	18 69	20.09	19.61
560	59 43	39.75	57.63	47.56	46.84	40.58	43.75	35 84	11.40	8.25	12.05	15.65	20.77	24.37	22.51	20.87	23.13	18 86	20.68	23.01
570	60.13	42 75	56 67	46 11	48.81	40.34	40.70	33.99	10.14	8.14	11.39	13.70	18.78	22.09	22 66	21.77	23.18	19.50	21.83	28.75
580	58.45	42.49	53 86	44.49	47.58	38.72	35.94	32.10	8.93	7.36	10.48	10.93	16.76	18 59	22.53	20.62	23 00	18.32	20.68	32.93
590	56.26	40 87	50.32	43.45	44.32	37.17	31.26	30.89	8.01	6.65	9.63	8.70	15.25	15 57	22.41	19.12	22 86	16.95	19.04	34.06
600	54.36	43.77	47 29	43.33	41.20	38.06	27 81	30.63	7.45	6.96	9.03	7.26	14.48	13.49	22 67	20.76	23.12	18 37	21.00	33.52
610	52.41	52.19	45.13	43.79	38 99	40.84	25.63	30.98	7.15	8.24	8.73	6.15	14.01	11.81	23.18	25.66	23 61	22 64	27.16	31.91
620	49.14	62 87	42.22	44.12	36.00	43.27	22.97	31.21	7.00	9.58	8.56	4.87	13.13	9 63	23.48	31.57	23.93	27.62	35.57	28.77
630	45.22	71 43	38 02	44 27	31.84	44.58	19 50	31.26	6 91	10.39	8.48	3.77	11.95	7.60	23.60	35 96	24.03	31.15	43.03	25.20
640	43.39	76.89	34.54	45.24	28.44	46.08	16.75	32 09	6.95	11.16	8 53	3.44	11.50	6.84	24.30	39 14	24.76	33.78	48.44	23.57
650	45.71	80.01	34.13	47.99	28.00	49.09	16 46	34 67	7.31	12.79	8.96	4.02	12.64	7.92	26 59	42 84	27 01	37.10	53.24	25.52
660	53.23	82.26	38 35	53.28	32.03	54.68	19 66	39.94	8.18	16.10	9.94	6.00	16 89	11 56	31.32	48.73	31.69	42 60	59.44	32.09
670	63 87	83.72	46.66	60.55	40.07	62.17	26.20	47.89	9.61	21.54	11.57	10.14	23 82	18.19	38.79	56 62	39 00	50.28	66.61	42.67
680	74.12	84.68	57.43	68.51	50.94	70.12	35.56	57.86	11.83	29.40	14.03	17.02	33.46	27.69	48 80	65.60	48 80	59 42	73.77	55.66
690	81.45	85.40	68 87	75.26	63.54	76.69	47.83	67.94	15.05	39.81	17.53	27.31	45 68	40.41	60.04	73.89	59 87	68 39	79.55	69 04
700	86.21	86 11	78 98	79.93	75.79	81.26	62.10	76 08	19.32	51.76	22.12	40.47	59.14	55 61	70.17	80 29	69.96	75.64	83.72	80.44

Appendix E2: Spectral reflectance values for the 70-pair set generated in Chapter 5

Pair No.	1		2		3		4		5		6		7		8		9		10	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	21.21	15.29	12.40	7.57	15.55	18.13	7.11	9.68	21.42	15.64	4.61	8.57	7.78	13.11	26.31	24.09	20.94	12.74	10.48	18.57
410	22.54	16.43	12.21	8.24	16.26	19.54	7.30	10.76	23.13	18.34	4.67	8.70	8.10	13.53	28.78	26.18	22.18	13.24	10.90	19.38
420	24.18	17.74	13.15	9.15	17.03	20.46	7.58	11.59	24.52	17.16	4.77	8.72	8.50	13.69	31.22	27.95	23.03	13.88	11.48	19.87
430	26.20	19.37	15.46	10.39	17.90	20.91	8.03	11.74	25.54	18.39	5.10	8.61	9.18	13.58	33.80	29.79	23.58	15.00	12.47	20.16
440	26.94	21.50	16.64	12.07	18.75	20.66	8.51	10.82	25.62	20.10	5.68	8.00	10.15	12.64	35.28	31.43	23.19	16.74	14.01	19.78
450	26.20	24.12	15.93	14.06	19.35	19.77	8.96	9.14	24.67	22.49	6.45	6.98	11.27	11.59	35.43	33.22	21.94	19.21	16.23	18.75
460	24.66	27.16	14.27	16.27	19.54	18.14	9.17	7.28	23.07	25.57	7.43	5.85	12.38	10.17	34.51	35.30	20.28	22.66	19.35	17.27
470	22.99	30.06	12.51	18.17	19.06	16.21	8.94	5.61	21.43	28.69	8.28	4.83	13.13	8.90	33.26	37.38	18.70	26.75	23.04	15.79
480	21.98	32.36	11.32	19.32	17.92	14.42	8.24	4.45	20.39	31.21	8.69	4.22	13.16	8.04	32.34	39.44	17.92	31.07	27.00	14.85
490	21.56	33.13	10.61	19.16	16.50	12.87	7.37	3.72	19.95	32.29	8.52	3.92	12.55	7.59	31.93	41.12	17.88	34.37	29.91	14.51
500	21.10	31.61	9.91	17.15	15.13	11.53	6.46	3.13	19.66	31.62	7.97	3.72	11.58	7.16	31.47	41.96	17.98	36.18	30.59	14.33
510	21.36	29.05	9.76	14.67	14.02	10.75	5.72	2.86	20.20	30.02	7.40	3.86	10.66	7.16	31.86	41.84	19.24	36.60	29.53	15.08
520	24.24	27.45	10.89	13.17	13.35	10.66	5.33	3.11	23.14	28.97	7.04	4.97	10.00	8.27	34.78	41.86	24.53	36.62	28.82	18.30
530	27.68	25.62	12.30	11.69	13.23	10.81	5.17	3.50	27.34	27.81	6.95	6.79	9.69	9.73	38.49	41.12	34.44	36.78	27.76	23.28
540	27.83	22.46	12.57	9.56	13.58	11.25	5.06	3.80	30.31	25.75	7.16	8.11	9.70	10.35	40.43	38.62	45.17	36.89	25.26	27.85
550	26.54	20.23	12.59	8.13	14.44	13.05	5.24	4.47	31.75	24.27	7.72	9.39	10.01	11.14	41.93	36.54	52.38	37.52	23.62	32.34
560	26.73	20.33	13.18	8.07	16.31	17.89	6.03	6.36	32.87	25.07	8.89	12.15	10.85	13.70	44.96	37.09	56.45	39.64	24.66	38.01
570	26.70	20.89	13.29	8.29	20.03	26.95	7.65	10.71	34.21	26.93	11.25	16.95	12.43	18.14	48.21	38.24	58.19	43.40	26.49	42.77
580	24.26	19.52	11.86	7.50	26.28	38.09	9.48	17.11	35.34	26.75	14.99	21.01	14.46	20.91	48.56	36.78	57.36	47.07	25.74	43.06
590	21.71	17.97	10.09	6.67	35.24	47.59	11.09	23.33	36.26	25.77	19.32	22.19	16.38	20.54	46.91	34.99	55.45	49.89	24.27	40.13
600	21.65	19.48	8.69	7.33	46.63	53.68	14.31	27.96	37.25	26.83	22.96	21.58	18.11	18.91	44.95	37.55	54.75	54.69	27.05	37.08
610	22.85	24.15	7.47	9.58	56.94	56.21	20.94	29.83	38.20	37.68	24.61	20.42	19.37	17.45	42.66	44.72	55.04	61.83	35.39	34.69
620	22.32	29.66	5.95	12.25	65.05	55.93	31.44	28.91	38.78	50.51	23.84	18.23	20.06	15.38	39.04	53.01	54.10	68.86	48.02	31.39
630	20.12	33.63	4.62	14.14	70.51	53.15	44.26	25.68	39.06	63.01	21.06	15.06	20.36	12.59	35.07	59.25	51.03	73.93	61.28	26.95
640	19.03	36.57	4.20	15.57	74.37	50.16	56.53	22.60	40.09	72.14	18.43	12.49	21.10	10.41	33.33	63.74	47.96	77.53	71.61	23.41
650	21.00	40.16	4.98	17.77	77.12	49.81	65.61	21.89	42.89	77.58	18.04	11.96	23.23	10.13	35.74	67.80	47.71	79.98	77.75	22.75
660	27.20	45.96	7.51	21.86	79.40	54.21	71.62	25.00	48.29	81.01	21.09	14.34	27.60	12.46	43.33	72.50	52.22	81.93	81.27	26.23
670	37.12	53.85	12.46	28.18	81.17	62.28	75.32	31.71	56.01	82.99	27.56	19.62	34.52	17.51	54.79	77.10	60.42	83.29	83.00	33.52
680	49.70	62.98	20.16	36.97	82.66	71.35	77.80	41.32	64.91	84.28	36.93	27.60	43.95	25.21	67.30	80.96	69.73	84.32	83.92	43.81
690	63.66	71.63	31.08	47.95	83.78	78.93	79.67	53.55	72.93	85.28	49.01	38.72	55.04	36.01	77.90	83.72	77.73	85.13	84.63	56.67
700	76.80	78.43	44.74	59.64	84.65	84.36	81.22	66.87	78.81	86.24	62.45	52.60	65.71	49.67	85.54	85.65	83.59	85.83	85.50	70.38

Pair No.	11		12		13		14		15		16		17		18		19		20	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	10.52	5.65	6.08	12.03	5.30	2.20	2.67	5.35	6.47	12.37	7.03	12.40	10.71	3.85	3.88	6.31	7.89	5.08	8.91	5.66
410	10.66	5.71	6.17	12.20	5.16	2.23	2.66	5.19	6.71	12.33	7.14	12.65	10.62	3.84	3.88	6.32	8.00	5.09	9.10	5.70
420	10.68	5.93	6.37	12.26	4.91	2.25	2.66	4.95	7.01	12.10	7.39	12.61	10.48	3.93	3.99	6.38	8.20	5.14	9.38	5.87
430	10.59	6.42	6.86	12.14	4.74	2.39	2.80	4.77	7.61	11.76	7.99	12.43	10.32	4.28	4.33	6.71	8.79	5.61	10.00	6.46
440	9.91	7.11	7.75	11.50	4.31	2.58	3.04	4.30	8.48	10.80	8.86	11.80	9.57	5.02	4.99	7.16	9.61	6.50	10.87	7.53
450	8.68	7.96	9.04	10.32	3.74	2.96	3.45	3.65	9.63	9.60	10.10	10.83	8.36	6.25	6.13	7.74	10.64	8.10	11.91	9.30
460	7.38	8.91	10.73	8.84	3.16	3.63	4.03	3.08	10.92	8.54	11.57	9.62	7.11	8.32	8.05	8.30	11.85	10.85	13.02	12.15
470	6.30	9.86	12.49	7.36	2.74	4.71	4.56	2.65	11.86	7.88	12.84	8.50	6.07	11.29	10.81	8.75	12.95	14.96	14.04	16.34
480	5.79	10.98	13.88	6.33	2.54	6.28	4.92	2.44	12.28	7.77	13.58	7.77	5.58	15.06	14.40	9.27	14.18	20.83	15.15	22.33
490	5.65	12.31	14.31	5.78	2.48	7.66	4.91	2.37	11.99	7.87	13.48	7.33	5.46	18.59	17.86	9.84	15.42	27.78	16.28	29.37
500	5.61	13.61	14.00	5.30	2.43	8.41	4.70	2.36	10.93	7.90	12.82	6.93	5.48	21.01	20.19	10.19	16.33	34.55	17.17	36.08
510	6.14	14.70	13.35	5.40	2.52	8.50	4.53	2.54	10.00	8.31	12.07	6.95	6.03	21.78	21.00	11.10	17.97	38.94	18.80	40.09
520	8.82	15.89	12.86	6.81	3.24	8.51	4.54	3.52	9.89	10.45	11.60	7.80	8.87	21.67	21.06	14.84	23.40	41.10	24.20	41.92
530	14.25	16.58	12.78	9.12	4.86	8.59	4.64	6.06	9.91	14.11	11.52	8.98	15.24	21.42	21.10	21.65	33.63	41.25	34.16	41.68
540	19.87	15.80	13.07	11.66	7.05	8.84	5.03	9.45	9.64	16.59	11.80	10.23	23.71	21.15	21.26	27.54	45.40	39.04	45.17	38.74
550	22.66	14.99	13.88	15.32	9.92	9.51	6.39	12.34	10.25	17.36	12.61	12.61	31.39	21.25	21.91	30.29	53.59	37.35	52.46	36.34
560	23.10	15.74	15.65	21.99	15.17	11.25	10.00	15.14	13.33	19.02	14.45	17.94	38.26	22.64	23.90	32.96	57.08	38.75	55.29	37.09
570	22.32	16.83	19.19	32.18	24.03	14.89	17.48	18.85	20.00	20.87	18.14	27.22	44.11	25.73	27.63	35.37	57.00	41.23	54.74	38.60
580	21.07	15.89	24.82	42.31	34.72	20.70	28.22	23.20	28.34	19.62	24.24	38.15	46.44	29.50	31.94	34.33	54.40	40.51	51.74	36.94
590	20.16	14.47	32.33	47.95	43.33	28.97	39.18	27.52	35.27	17.57	32.94	46.63	45.96	33.24	36.01	32.39	50.90	38.64	47.99	34.62
600	19.98	16.00	41.89	49.43	47.99	39.87	47.54	33.64	39.61	19.86	44.16	51.08	44.52	39.09	41.99	35.16	47.92	41.46	44.84	37.36
610	20.25	21.19	51.73	48.74	49.30	50.53	51.64	42.74	41.18	28.48	54.57	52.42	42.46	48.21	50.94	43.76	45.76	50.07	42.59	46.22
620	20.46	28.33	60.78	46.03	48.20	59.77	52.46	53.94	40.15	42.25	63.05	51.48	39.10	58.81	61.08	55.59	42.83	61.15	39.63	58.27
630	20.51	34.55	67.46	41.41	44.98	66.60	50.44	63.97	36.82	57.28	69.00	48.42	35.38	67.49	69.16	66.18	38.60	70.24	35.45	68.89
640	21.15	39.14	72.15	37.37	41.91	71.59	47.89	71.16	33.66	69.27	73.27	45.35	33.82	73.42	74.54	73.46	35.14	76.11	32.10	76.11
650	23.24	43.55	75.35	36.47	41.62	75.08	47.67	75.59	33.26	76.80	76.27	45.04	36.14	77.16	77.86	77.69	34.79	79.54	31.76	80.21
660	27.67	49.69	77.79	40.48	45.99	77.73	51.93	78.56	37.36	80.92	78.69	49.53	43.48	79.77	80.17	80.42	39.14	82.03	36.02	82.81
670	34.71	57.54	79.62	48.77	54.25	79.67	59.79	80.55	45.50	83.21	80.52	57.89	54.38	81.48	81.71	81.99	47.63	83.64	44.32	84.15
680	44.47	66.19	81.13	59.54	64.28	81.26	68.88	82.03	56.24	84.57	82.04	67.72	66.11	82.82	82.94	83.12	58.48	84.72	55.17	84.97
690	56.02	73.95	82.29	70.65	73.74	82.48	76.76	83.16	67.80	85.51	83.24	76.51	75.80	83.81	83.86	83.97	69.82	85.47	67.00	85.63
700	67.12	79.82	83.22	80.14	81.20	83.42	82.56	84.13	78.09	86.37	84.11	83.05	82.67	84.60	84.68	84.84	79.66	86.18	77.73	86.33

Pair No.	21		22		23		24		25		26		27		28		29		30	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	8.80	5.85	11.95	10.22	5.32	5.92	23.97	18.18	14.58	10.37	5.02	11.63	11.23	9.42	12.32	4.84	9.03	3.35	14.52	17.44
410	9.00	6.03	12.39	10.56	5.39	5.99	25.80	19.22	15.08	10.81	5.20	11.41	11.00	9.18	12.14	4.97	8.65	3.44	15.22	17.54
420	9.32	6.31	12.92	11.14	5.54	6.17	27.41	20.22	15.65	11.49	5.39	11.07	11.28	9.02	11.75	5.27	8.13	3.61	16.47	18.68
430	9.95	6.95	13.93	12.19	6.04	6.68	28.98	21.68	16.51	12.66	5.93	10.71	12.12	9.01	11.46	5.63	7.80	3.98	18.67	21.66
440	10.76	8.10	15.41	13.84	6.99	7.67	29.82	23.69	17.63	14.44	6.81	9.96	12.03	9.18	10.88	6.77	7.39	4.59	21.37	24.44
450	11.67	9.81	17.54	16.29	8.62	9.27	29.84	26.62	19.02	16.96	8.12	8.97	10.96	9.45	10.10	8.26	6.93	5.64	24.51	26.52
460	12.51	12.32	20.46	19.91	11.28	11.82	29.32	30.77	20.68	20.57	9.85	7.99	9.54	10.07	9.30	10.58	6.54	7.33	28.35	28.13
470	13.13	15.79	23.95	24.84	15.27	15.36	28.59	35.75	22.36	25.36	11.76	7.11	8.33	11.08	8.56	13.70	6.18	9.70	32.63	29.30
480	13.84	20.05	28.04	31.48	21.27	20.18	28.44	41.13	24.21	31.53	13.35	6.67	7.67	12.36	8.23	17.55	6.04	12.72	37.01	30.53
490	14.62	24.06	32.04	38.94	28.93	25.52	28.79	45.38	25.98	37.86	13.99	6.56	7.56	14.52	8.28	20.86	6.13	15.17	40.21	31.68
500	15.16	26.79	35.35	46.03	37.73	30.67	29.24	47.37	27.31	42.75	13.69	6.44	7.52	17.35	8.31	21.85	6.13	15.60	41.54	32.39
510	16.43	27.75	38.61	50.74	45.33	35.48	30.85	47.11	29.29	44.66	12.94	6.81	8.16	18.44	9.02	20.68	6.61	14.32	40.90	33.59
520	20.86	27.64	44.46	52.59	50.25	42.45	36.41	46.02	34.84	43.96	12.19	8.85	11.27	17.57	12.20	19.34	8.76	12.90	38.87	36.96
530	28.33	27.36	51.89	52.62	52.31	51.02	44.86	44.11	42.96	41.86	11.63	12.11	17.10	16.29	17.90	17.59	12.32	11.26	36.04	40.08
540	34.77	27.27	57.04	51.71	51.80	56.83	51.25	41.17	48.44	39.40	11.31	14.29	22.10	15.39	22.55	14.98	14.78	9.19	32.93	39.46
550	37.28	27.47	58.71	50.60	50.56	58.34	53.04	38.81	48.99	37.22	11.28	15.55	23.25	14.67	23.92	13.21	14.91	7.76	30.02	35.98
560	37.14	28.35	58.12	49.45	50.36	57.14	51.64	38.20	46.53	35.42	11.59	17.42	21.59	13.95	23.17	13.07	13.75	7.46	27.22	31.42
570	35.87	29.94	55.94	48.20	49.83	54.13	48.21	37.92	42.35	33.70	12.29	19.04	18.66	13.49	20.87	13.25	11.90	7.43	24.31	26.36
580	34.10	31.65	52.14	46.69	46.85	49.49	43.39	36.32	36.98	31.99	12.95	17.97	15.41	13.36	17.26	12.29	9.50	6.73	21.32	21.44
590	32.61	33.14	48.02	45.64	43.34	44.63	38.91	34.94	32.05	30.92	13.49	15.31	12.96	13.62	13.90	11.27	7.37	6.12	19.01	17.85
600	31.63	34.51	44.70	45.45	41.84	40.87	35.59	36.02	28.55	30.76	14.08	13.06	11.36	13.95	11.60	12.06	5.95	6.55	17.52	15.47
610	31.16	35.68	42.36	45.70	41.79	38.20	33.11	39.09	26.31	31.12	14.65	11.58	10.10	14.16	10.18	14.52	5.09	7.93	16.32	13.57
620	30.93	36.41	39.31	45.67	40.41	34.84	29.94	41.95	23.61	31.38	15.00	9.84	8.39	14.31	8.61	17.11	4.24	9.37	14.54	11.22
630	30.80	36.76	35.11	45.41	36.86	30.43	26.11	43.64	20.10	31.40	15.12	7.69	6.72	14.26	6.73	18.68	3.34	10.28	12.58	9.07
640	31.09	37.82	31.76	46.06	33.57	26.90	23.67	45.47	17.44	32.18	15.68	6.14	6.07	14.04	5.47	20.01	2.82	11.12	11.83	8.36
650	32.07	40.63	31.52	48.55	33.21	26.30	24.31	48.79	17.24	34.75	17.48	5.97	7.02	13.97	5.43	22.35	2.86	12.79	13.29	9.79
660	34.12	46.06	35.86	53.68	37.52	30.01	29.11	54.54	20.60	40.01	21.34	7.57	10.22	14.71	7.07	26.82	3.64	16.18	17.93	14.17
670	37.26	53.97	44.25	60.90	45.95	37.69	37.60	62.15	27.33	47.96	27.62	11.23	16.18	16.67	10.61	33.74	5.46	21.67	25.72	21.70
680	41.70	63.32	55.24	68.82	56.96	48.26	48.75	70.19	36.92	57.96	36.58	17.27	24.94	20.39	16.38	43.10	8.93	29.60	36.34	32.11
690	47.35	72.00	67.23	75.51	68.80	60.96	61.67	76.79	49.39	68.03	47.84	26.41	36.85	26.19	25.17	54.34	15.08	40.05	49.52	45.65
700	53.88	78.47	78.22	80.17	79.40	73.79	74.47	81.36	63.72	76.17	59.67	38.57	51.16	33.64	36.92	65.48	24.02	52.02	63.76	61.29

Pair No.	31		32		33		34		35		36		37		38		39		40	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	18.05	15.50	7.92	12.47	19.22	20.65	20.99	18.42	13.44	14.94	7.80	7.88	12.37	10.41	11.58	10.55	7.34	5.85	5.73	5.95
410	18.38	16.57	8.61	11.76	21.11	20.82	21.99	20.56	15.65	14.89	7.01	9.00	12.26	12.81	12.04	12.76	7.13	7.69	5.34	6.72
420	19.54	17.66	9.39	12.55	23.25	23.27	24.31	22.74	18.20	17.06	8.04	10.49	14.21	15.79	14.18	15.37	8.47	10.22	6.13	7.79
430	21.90	19.12	10.58	15.30	25.79	29.04	28.71	25.21	21.16	22.67	12.38	12.44	19.87	19.46	18.92	18.06	12.94	13.29	9.15	9.03
440	24.10	21.07	12.27	17.06	29.07	34.39	32.20	27.94	24.57	28.16	17.61	15.11	25.77	23.90	22.51	20.35	17.58	16.67	12.13	10.48
450	25.83	23.78	14.41	16.73	32.92	36.57	33.40	30.88	27.70	30.26	20.04	17.90	28.23	27.29	22.62	21.44	18.80	18.29	12.54	11.44
460	27.06	27.36	16.95	15.28	36.76	35.86	32.76	33.74	29.51	29.03	19.18	19.44	27.11	27.56	20.28	20.82	16.84	16.93	10.84	11.20
470	27.80	31.15	19.43	13.77	39.39	33.96	31.13	35.79	29.71	26.34	16.93	18.88	24.03	25.40	16.97	18.72	13.74	14.11	8.74	9.91
480	28.18	34.48	21.20	12.91	40.39	32.16	29.50	36.70	28.49	23.58	14.76	17.11	20.90	22.36	14.13	16.28	11.10	11.28	7.04	8.17
490	28.27	36.04	21.49	12.57	39.59	30.83	28.10	36.03	26.26	21.26	12.97	15.05	18.17	19.15	11.88	13.88	9.08	8.99	5.81	6.63
500	28.18	35.18	20.35	12.25	37.32	29.56	26.46	33.62	23.41	19.08	11.20	12.90	14.88	15.86	9.44	11.00	6.99	7.05	4.76	5.42
510	27.93	32.92	18.55	12.62	34.35	28.98	25.35	30.60	20.65	17.58	9.89	11.00	12.10	13.04	7.54	8.53	5.42	5.69	4.10	4.56
520	27.69	30.78	16.68	14.83	31.31	29.84	25.55	28.13	18.25	17.06	9.28	9.52	10.74	10.80	6.77	7.10	4.76	4.80	3.90	3.97
530	27.57	28.34	14.84	17.57	28.22	30.35	25.72	25.57	15.98	16.52	8.63	8.09	9.41	8.81	6.03	5.80	4.16	4.05	3.72	3.56
540	27.57	25.27	13.25	18.20	25.20	29.14	24.95	22.63	13.95	15.39	7.60	6.73	7.41	7.11	4.82	4.29	3.32	3.40	3.42	3.25
550	27.49	23.00	12.01	17.37	22.65	27.47	24.53	20.47	12.41	14.73	6.82	5.68	6.10	5.93	4.13	3.37	2.84	2.99	3.36	3.08
560	27.41	22.22	11.08	16.20	20.72	25.97	25.14	19.72	11.32	14.72	6.33	4.91	5.92	5.23	4.26	3.22	2.81	2.72	3.64	2.97
570	26.90	21.65	10.31	14.14	19.10	23.43	25.12	19.20	10.34	14.10	5.53	4.38	5.76	4.71	4.53	3.26	2.84	2.54	3.84	2.96
580	25.22	20.17	9.47	11.26	17.40	19.68	22.91	17.89	9.35	11.98	4.28	3.95	4.76	4.15	3.96	2.88	2.48	2.29	3.37	2.90
590	23.10	18.92	8.96	8.91	16.05	16.39	20.21	16.83	8.70	9.75	3.34	3.63	3.90	3.84	3.37	2.59	2.20	2.14	2.80	2.80
600	21.19	19.48	8.84	7.39	15.35	14.11	18.06	17.32	8.52	8.13	2.80	3.47	3.81	3.87	3.47	2.94	2.17	2.07	2.45	2.72
610	19.26	21.42	9.01	6.23	15.11	12.20	16.12	18.89	8.65	6.81	2.43	3.36	4.05	4.12	4.06	4.00	2.25	2.10	2.17	2.69
620	16.47	23.15	9.14	4.87	15.02	9.89	13.55	20.23	8.77	5.34	2.12	3.26	3.83	4.34	4.18	5.21	2.19	2.19	1.96	2.68
630	13.62	24.09	9.18	3.78	14.92	7.77	11.09	20.87	8.79	4.15	1.92	3.17	3.24	4.47	3.71	6.08	2.04	2.27	1.84	2.67
640	12.43	25.24	9.57	3.44	15.06	6.93	10.19	21.78	9.17	3.78	1.91	3.09	3.03	4.75	3.47	6.86	2.01	2.42	1.84	2.71
650	13.94	27.76	10.96	4.02	15.72	8.01	11.65	24.05	10.51	4.50	2.07	3.18	3.59	5.61	4.08	8.19	2.22	2.82	1.97	2.84
660	19.03	32.69	14.03	6.04	17.16	11.64	16.36	28.63	13.46	6.83	2.64	3.53	5.36	7.57	6.12	10.88	2.88	3.85	2.35	3.17
670	27.61	40.25	19.22	10.19	19.47	18.30	24.35	35.83	18.48	11.41	4.02	4.17	9.04	11.18	10.25	15.41	4.50	6.00	3.33	3.78
680	39.09	50.22	26.92	17.13	22.80	27.85	35.17	45.59	25.94	18.70	7.25	5.30	15.33	17.01	17.04	22.18	8.04	9.93	5.82	4.81
690	53.10	61.43	37.23	27.46	27.35	40.65	48.88	57.01	36.06	29.25	13.63	7.13	24.99	25.40	27.06	31.54	14.75	16.37	11.30	6.50
700	67.98	71.61	49.20	40.75	33.12	55.94	64.12	67.95	47.99	42.63	23.11	9.81	37.58	35.98	39.88	42.83	24.52	25.09	19.82	9.03

Pair No	41		42		43		44		45		46		47		48		49		50	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	23 61	20.94	22 54	19 45	23.81	20.51	9.71	9.29	8.63	5.76	8.40	7.70	26 54	23 29	20 51	24 53	3.52	3 43	25.49	23.26
410	25 80	23 33	24 42	21 85	26.22	23 80	11.62	11.56	8 45	6 13	8 36	9 04	29 23	26 02	22 65	26 88	3.98	3 68	28 16	25 82
420	28 74	26 08	27.23	24 59	29 55	27.55	13.84	14.39	9 24	6.71	9 49	10 48	32 28	29 01	24 76	29 39	4 29	3.79	31.03	28.40
430	32 85	28 90	31.38	27.37	33.96	31.11	16.10	17 35	11.29	7.64	12.40	11.80	35 69	31.93	26 83	32 04	4.31	3 83	34.21	30.98
440	35 69	31 92	34 23	30 36	36.71	34.34	18.22	20 03	12 22	8.77	14.27	12 94	37.74	34.77	28 65	32 80	3 90	3.75	36 21	33.34
450	36 36	34 64	34 69	32.97	36.94	36 40	19.60	20.74	11.34	10.06	13.62	13.14	38 08	36.97	30 33	31.76	3.30	3.47	36.63	35.26
460	35.24	36 63	33 28	34.79	35.19	36 73	19 66	18 95	9.59	11.36	11 57	11.98	37 00	38.23	31.69	29 54	2.73	3 00	35.74	36.59
470	33 06	37.39	30 92	35.34	32 25	35.20	18.18	16.14	7.91	12.10	9 34	10.22	35.20	38 59	32.00	26 82	2.34	2 57	34 09	37.21
480	30 73	37 01	28 48	34.79	29.31	32.66	16 07	13.50	6.74	12.06	7.59	8 48	33 46	38 63	31 38	24 38	2.09	2.30	32.47	37.48
490	28 59	35 61	26 32	33.30	26.66	29.86	13.86	11.29	5 97	11.21	6.31	7.06	32 02	38.49	30.01	22.31	1 95	2.10	31.03	37.51
500	26 28	32 76	24 04	30.42	23 63	26.16	11.13	9.36	5.26	9.20	5.18	5.92	30.39	37 58	27.38	20 03	1.87	1.96	29 40	36.54
510	24 60	29 67	22 40	27.29	21.11	22.77	8.82	7.98	4 90	7.25	4.47	5.19	29 40	36.11	24 65	18.39	1.83	1 87	28.35	34.94
520	24 24	28 05	21.99	25.49	20.09	21.05	7.62	7.25	5.21	6 39	4.32	4.73	30.10	35 50	23.31	18.15	1.83	1.83	28 89	34.19
530	24 06	26.33	21.75	23 62	19.14	19.39	6 54	6.57	5.60	5 60	4.19	4 32	30.97	34 44	22.00	18 24	1.80	1.79	29.59	32.99
540	23.39	23.36	21.05	20.65	17.18	16.77	5.15	5.87	5.53	4.31	3 92	4 06	30.97	31.62	19 54	18.09	1.77	1.79	29 52	30.14
550	23.79	21.32	21.32	18 60	16 09	15.09	4.31	5.47	5.67	3 60	4 01	4 08	31 82	29 54	17 91	19 16	1.80	1.88	30.35	28.12
560	26.51	21.66	23.62	18.74	17.22	15.38	4.26	5.44	6.60	3 76	4.82	4 36	35.37	30.18	18 78	23 04	1.92	2.15	33.88	28 89
570	30.12	22 50	26.50	19.34	18 86	16.02	4.36	5.41	7.70	4.15	5 93	4 50	40.31	31.37	20 43	29 33	2.42	2.61	38.88	30.28
580	30.77	21.23	26.65	18.11	18.03	15.04	3 93	5.13	7.39	3.78	5.94	4.29	42.16	29 93	19 70	34 00	3.28	2 86	41.11	29.07
590	29.11	19 67	24.90	16.72	16.37	13 85	3.52	4 82	6.32	3 32	5 18	4.02	41.05	28.01	18 37	35 47	3.79	2.90	40.42	27.38
600	27 09	21.21	22.93	18.14	17.01	15.04	3 86	4.73	5.37	3.86	4.43	3.98	39 15	30.22	20 83	35 16	3.77	2.93	38.78	29.78
610	24 87	26 04	20 86	22.45	19 31	18 59	5.00	4.75	4 56	5 73	3.78	4 09	36 82	37 03	28 59	33 52	3 51	3.02	36.61	36.72
620	21.72	31.85	18 07	27.47	20.11	22.62	6.42	4.76	3 61	8.22	3.02	4 22	33.14	45 67	41.10	30 15	3.08	3.12	33.09	45.46
630	18 49	36 13	15.34	31 02	18.57	25.31	7 44	4.73	2.88	9.38	2.47	4.35	29.15	52 60	55.73	26.21	2.55	3.15	29.31	52.44
640	17.20	39 25	14 33	33.72	17.58	27.27	8 30	4 90	2.67	9 64	2.31	4.62	27.43	57.50	68.52	24 26	2.21	3.32	27.68	57.39
650	19 04	42 90	16 09	37.04	19.36	30.05	9.72	5.70	3.10	11.08	2.64	5 51	29 58	61.79	76 67	25 94	2.20	3 87	29.89	61.73
660	24 99	48.75	21.55	42.61	25.26	35.15	12.60	7.63	4.55	15.36	3.75	7.47	36.73	67.14	81.37	32.36	2.56	5.27	36 99	67.11
670	34 73	56.62	30 47	50.33	34 85	42.75	17.43	11.18	7.73	22.68	6.26	11.07	47.98	72.87	83 58	42 85	3.45	8 00	48.08	72.86
680	47 29	65 55	42.02	59.50	47.16	52.57	24.56	16 94	13.42	32.76	11.06	16 86	61.24	78.06	84 65	55.79	5 41	12.72	60.96	78.07
690	61 58	73 83	55 68	68.46	61.34	63.36	34.38	25 27	22.45	45.60	19 08	25.28	73 92	82.00	85 43	69 18	9.53	19.95	73.07	82.04
700	75.23	80.19	69.72	75.72	75.22	73.12	46.11	35.73	34 38	59.95	30 05	35 93	83 98	84.79	86.41	80.62	16.11	29 32	82.56	84.85

Pair No	51		52		53		54		55		56		57		58		59		60	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	13.98	18.02	12.16	4.81	4.92	5.88	17.91	15.28	8 97	7.47	10.55	9 62	17.71	15.58	4 56	8 53	7.87	13.08	5.86	5 64
410	15.04	18.18	11.82	4.83	4 95	5.75	18.58	16.45	8.86	7 88	10.92	10.60	18.54	16.31	4.56	8 58	8 20	13.53	5.87	5.64
420	16.27	18.94	11.33	4.88	5.12	5.62	19.66	17.85	9.32	8 31	11.07	11.21	19 44	17.05	4 67	8 48	8.58	13.71	6.04	5.74
430	17 88	20.94	10.93	5.22	5 61	5.92	21.51	19.50	10.62	9 01	10.94	11.22	20.59	18.17	5 06	8.28	9.30	13.65	6.52	6.11
440	20.08	22.72	10.22	5.88	6.53	6.63	23.43	21.63	12.03	10.03	10.01	10 20	21 83	19 68	5 64	7.59	10.30	12 97	7.14	6.63
450	22.94	24.30	9 31	7.21	8.06	8.28	25.30	24.16	13.20	11.72	8 61	8 63	23.07	21.82	6.39	6 62	11.46	11.78	7.84	7.40
460	26 48	25.82	8.39	9.57	10 64	11.16	26 86	27.09	13.98	14 04	7.21	7.11	24.14	24 61	7.28	5 63	12.62	10 43	8.53	8.35
470	30.22	26.99	7.59	12.87	14.60	15.26	27.80	29.78	14.17	16.31	6 02	5.94	24.75	27.47	7 95	4 84	13.40	9.17	9.06	9.32
480	33 54	27.82	7.20	16.98	20.57	20.60	27.81	31.88	13.69	17.88	5 38	5.30	25.01	29 75	8.13	4.42	13.41	8.33	9 60	10.49
490	35.10	28.17	7.25	20.48	28.43	26.31	26.97	32.63	12.71	18 03	5 09	4 94	25.02	30 69	7 81	4 23	12.77	7.90	10.13	11.83
500	34 27	28.15	7.26	21.62	37.73	31.67	25.74	31.07	11.58	16.07	4 81	4 65	24.85	29 88	7.20	4 04	11.76	7.47	10 51	13.07
510	31.99	27.78	7.96	20.57	46.11	36.54	24.53	28.58	10.60	13 57	4 83	4 61	24.61	28.24	6.59	4.07	10.77	7.50	10.84	14.07
520	29.68	27.32	11.20	19.38	51.10	43.34	23.69	27.17	9.96	12.01	5.99	4 88	24.53	27.31	6 22	4 88	10.09	8.58	11.60	15.18
530	27.15	26 84	17.60	17 86	52.70	51.50	23.37	25.66	9 69	10.56	7.62	5.07	24 81	26.58	6.13	6.27	9.75	9.94	12.34	15.84
540	24.19	26.44	23.75	15.50	52.27	56.69	23.54	22.94	9.67	8.53	7.87	4.93	25.47	25.20	6.30	7.13	9.71	10.45	12.66	15.10
550	21.97	25.97	26.06	13.96	50.91	57.47	24 15	21.23	9 93	7.32	7.57	4.98	26.60	24 58	6 78	7.86	9 98	11.07	13.63	14.37
560	20.95	25.48	25.45	14 09	49.03	55.41	25.41	21.85	10 49	7.53	8.45	6.08	28 59	26.39	7.83	10.02	10.77	13 41	16.68	15.23
570	20.13	24 59	22.86	14.51	46.56	51.52	27.32	22.97	11.35	8.05	9.83	9 58	32 01	29.32	9.93	14.24	12.27	17.59	21.63	16.51
580	18 65	22.62	18 77	13.75	43.43	46.11	28.78	22.07	11 69	7.58	9 52	15.13	36 44	30.13	13.13	17.87	14.09	20.20	25.12	15.76
590	17.49	20.41	15.00	12.81	40.74	40.81	29.05	20.75	11.34	7.00	8.61	20 82	40.74	29.73	16 81	18 85	15 84	19.71	25.87	14.47
600	17.74	18.47	12.45	13.63	38.95	36.80	28.43	22.33	10.57	7.83	10.11	25.12	44.06	33.11	19.72	18.19	17.36	18 06	25.19	16 09
610	19.02	16 80	10.92	15.96	37.41	34.34	26.85	26.81	9.47	10.11	15.43	27.07	45 90	41.70	20.51	17.30	18 50	16 62	23 66	21.31
620	20.11	14.45	9.27	18.27	34 89	31.63	23 81	31.82	7.72	12.73	25.10	26.56	46 84	53.82	18 99	15 69	19.12	14 70	20.79	28.42
630	20 62	12.17	7.23	19.53	31 85	28.07	20 45	35.21	6.02	14.46	38 40	23.94	47.24	65.40	16.38	13.20	19.37	12.07	17.60	34.64
640	21.51	11.46	5.77	20.57	30.51	25.31	18.95	37.64	5.31	15.82	52.85	21.41	47.89	73 69	15 03	11 27	20.07	10.07	16.09	39.16
650	23.75	13.35	5.64	22.70	32.65	25.29	20.74	40.78	6.15	17.89	64.61	21.14	49 14	78.47	16.37	11.19	22.16	9 88	17.62	43.57
660	28.30	18 66	7.23	27.02	39.46	29 38	26.82	46.26	9.13	21.88	72.74	24.49	51.51	81.45	21.43	13.83	26 47	12.28	23.16	49.67
670	35.45	27.39	10.85	33.80	49.99	37.25	36.80	53.94	14.79	28.13	77.60	31.32	54 93	83 20	30 01	19.24	33 35	17.33	32.37	57.47
680	45.16	38 91	16 85	43.12	61.95	47.93	49.51	62.92	23.37	36.85	80.52	40.99	59.31	84.30	41.43	27.26	42.77	24 99	44.34	66.08
690	56 54	52 94	26.04	54 31	72.70	60 66	63.52	71.53	35.08	47.78	82.51	53.23	64 37	85 22	54 85	38 37	53.90	35.74	58.17	73.84
700	67.48	67.79	38.34	65.42	80.75	73.48	76.41	78.31	49.26	59.43	84.22	66.46	69 53	86.17	68 22	52.13	64.61	49.29	71.66	79.70

Pair No	61		62		63		64		65		66		67		68		69		70	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	8 51	5 15	12.14	10.24	21.38	18 16	13 88	10.30	5.15	3.36	10.47	12.54	18.82	20.57	22 76	20 83	22 90	19 43	24 52	24 49
410	8 61	5 44	12.42	10 62	22.59	19 26	14 08	10.50	5 26	3 48	11.13	12 07	20.57	20.70	25.45	22.71	25.74	21.73	27.36	26 82
420	8 87	5 90	12 93	11 32	23.75	20.34	14 44	10 73	5 47	3.72	12.00	13.26	23.00	22.93	28 12	24 54	28 50	24 29	29 98	29 22
430	9.47	6 68	13 89	12.48	25.11	21.84	15.15	11.42	5.91	4.12	13.24	16.43	26.53	28 50	30 54	26.47	30 95	26 87	31.82	31 84
440	10.32	7 87	15 39	14 28	26 61	23.84	16.07	12.63	6 50	4 79	14.80	18.71	30.29	33.64	32.18	28.40	32.64	29 63	32.16	32 67
450	11.34	9 40	17.58	16 78	28.34	26.73	17.20	14.74	7.15	5.82	16 59	18 60	33.36	35.70	32.47	30.58	32 97	32.11	31 24	31.79
460	12.48	11 58	20 62	20 39	30.33	30.72	18.58	18.38	7.70	7.46	18.12	16.92	35.45	35.06	31.42	32.90	32.08	33 96	29 49	29 84
470	13.45	14 86	24 46	25 28	32.32	35 55	20.02	23.35	7.99	9.75	18 97	14.92	36.52	33.26	29.72	34.46	30.48	34 69	27 42	27.47
480	14.51	19 93	29 17	31.90	34 44	40.77	21.78	29.73	8.23	12.65	19.27	13.52	36.79	31.59	27 99	34.96	28 80	34 34	25 90	25.38
490	15 64	26 41	34 34	39 39	36.52	44.99	23 90	36.16	8 51	15 06	19.14	12.79	36.26	30.31	26.44	34 09	27.30	33.06	24 86	23.49
500	16 47	32.94	39 72	46 63	38.33	47.02	26 26	40 82	8.56	15 50	18 45	12.26	34.97	29 00	24.92	31.29	25.79	30.35	23.39	21.41
510	18 08	37.31	44 68	51.60	39.80	46.87	29.07	42.38	8 95	14 27	17.46	12.51	33.03	28.26	23.82	27.95	24 69	27.40	22.31	19 85
520	23.50	39.93	48 98	53.80	41.51	46.04	33.65	41.33	10.81	12.93	16.53	14.66	30.63	28.98	23.60	25.95	24 40	25.83	23.11	19.48
530	33.95	40.91	52 61	54.15	42.96	44.52	39.26	38.92	13.18	11.41	15.36	17.36	27.89	29.36	23 51	23.83	24.26	24 28	23.74	19.19
540	46.22	39.87	55 50	53.51	43.62	42.05	43.36	36.38	13.73	9.49	13.94	18.04	25.17	28.07	23.06	20.54	23.79	21 62	21.84	18 51
550	55.18	39 57	57.20	52 59	44 59	40.20	44.76	34.27	12.78	8.22	12.80	17.27	22.82	26.39	22.61	18.28	23.31	19 89	20.09	18.83
560	59.43	42.46	57 63	51 56	46.84	40 09	43.75	32.72	11.40	8.08	12.05	16.17	20.77	24 87	22.51	18.48	23.13	20.33	20 68	21 82
570	60.13	46.48	56 67	50.34	48 81	40.32	40.70	31.40	10.14	8.18	11.39	14.20	18.78	22.41	22.66	19.32	23.18	21.20	21.83	27.16
580	58.45	47.11	53 86	48 80	47.58	39.16	35.94	30.10	8 93	7.61	10.48	11.41	16.76	18.73	22.53	18.18	23.00	20 20	20 68	31.00
590	56.26	45.96	50.32	47.59	44.32	37.96	31.26	29.49	8.01	7.05	9.63	9.12	15.25	15.55	22.41	16.83	22.86	18 87	19 04	31 95
600	54.36	49 06	47 29	47 24	41.20	39.08	27.81	29.69	7.45	7.47	9.03	7.64	14.48	13.35	22.67	18.62	23.12	20 27	21 00	31.34
610	52 41	57.15	45 13	47.22	38 99	41.91	25.63	30.40	7.15	8.77	8.73	6.47	14.01	11.62	23.18	23 81	23.61	24.36	27.16	29.88
620	49.14	66.95	42.22	46 83	36.00	44 21	22.97	30.89	7.00	10.04	8.56	5.11	13.13	9.44	23.48	30.12	23.93	29 01	35 57	27.10
630	45.22	74 42	38.02	46.20	31 84	45.30	19.50	31.09	6.91	10.73	8.48	3.94	11.95	7.44	23 60	34 93	24.03	32.15	43 03	23 98
640	43 39	78 89	34 54	46 50	28 44	46 57	16.75	32.01	6.95	11.40	8.53	3.55	11.50	6.73	24.30	38.47	24.76	34 44	48 44	22.76
650	45 71	81.22	34 13	48 75	28.00	49.40	16.46	34.64	7.31	12.94	8.96	4.08	12.84	7.85	26 59	42.45	27.01	37 50	53 24	25 03
660	53 23	82.94	38.35	53.71	32.03	54.86	19 66	39 92	8.18	16.18	9.94	6.04	16.89	11.52	31.32	48 51	31.69	42 83	59.44	31.82
670	63 87	84.09	46 66	60.78	40.07	62.27	26 20	47.89	9 61	21.59	11.57	10.15	23.82	18.16	38.79	56 50	39 00	50 41	66 61	42.52
680	74.12	84.86	57.43	68 62	50 94	70.16	35.56	57.85	11.83	29 42	14.03	17.03	33.46	27.68	48 80	65 54	48 80	59 48	73.77	55.58
690	81.45	85.48	68 87	75.31	63.54	76.71	47.83	67.94	15.05	39.82	17.53	27.32	45.68	40.40	60.04	73.86	59 87	68 41	79 55	69 01
700	86 21	86.18	78 98	79 98	75.79	81.27	62.10	76.08	19 32	51.77	22.12	40.47	59.14	55 61	70 17	80 27	69 96	75 66	83.72	80 41

Appendix E3: Spectral reflectance values for the 88-pair set generated in Chapter 5

Pair No.	1		2		3		4		5		6		7		8		9		10	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	11.12	15.75	14.49	17.72	15.84	20.57	14.60	18.62	13.62	19.66	13.81	16.43	13.83	16.04	15.31	17.15	16.23	18.19	17.65	20.98
410	12.08	15.25	14.26	17.49	15.62	20.05	14.36	18.13	13.31	16.46	13.52	16.12	13.54	15.82	14.95	17.00	15.90	18.19	17.38	20.99
420	13.04	14.70	14.02	17.26	15.41	19.52	14.13	17.64	13.00	13.18	13.23	15.82	13.24	15.60	14.59	16.85	15.57	18.20	17.12	20.99
430	13.27	13.42	14.00	16.32	15.36	18.14	14.09	16.52	12.94	11.36	13.17	15.09	13.17	14.96	14.47	16.22	15.47	17.48	17.04	19.80
440	13.49	12.14	13.98	15.38	15.31	16.75	14.05	15.39	12.88	9.51	13.12	14.35	13.10	14.33	14.36	15.59	15.37	16.76	16.96	18.61
450	11.81	10.78	14.34	14.40	15.55	15.42	14.37	14.33	13.29	10.43	13.54	13.69	13.54	13.74	14.76	14.98	15.73	15.93	17.19	17.22
460	10.12	9.53	14.70	13.42	15.79	14.10	14.68	13.28	13.70	11.51	13.96	13.01	13.99	13.14	15.16	14.36	16.08	15.08	17.42	15.82
470	8.13	8.49	15.01	12.99	15.86	13.49	14.91	12.81	14.19	17.63	14.48	12.78	14.56	12.96	15.74	14.18	16.52	14.73	17.52	15.13
480	6.13	7.46	15.32	12.55	15.93	12.89	15.14	12.35	14.69	23.77	14.99	12.55	15.14	12.78	16.31	13.99	16.95	14.39	17.62	14.45
490	5.07	6.64	15.47	12.63	15.80	12.86	15.18	12.41	15.13	22.59	15.43	12.79	15.69	13.07	16.88	14.30	17.31	14.55	17.50	14.37
500	4.00	5.79	15.62	12.70	15.67	12.83	15.23	12.47	15.57	21.34	15.88	13.04	16.25	13.37	17.45	14.61	17.68	14.72	17.38	14.29
510	3.57	5.17	15.56	13.26	15.46	13.33	15.17	13.04	15.83	18.89	16.11	13.78	16.55	14.15	17.80	15.43	17.77	15.37	17.09	14.73
520	3.14	4.50	15.50	13.82	15.25	13.85	15.11	13.63	16.09	16.40	16.35	14.54	16.85	14.95	18.14	16.26	17.87	16.03	16.80	15.19
530	3.06	4.03	15.06	14.67	14.97	14.78	14.87	14.59	15.91	15.00	16.08	15.56	16.51	15.93	17.84	17.24	17.36	16.85	16.24	15.94
540	2.98	3.53	14.62	15.53	14.69	15.73	14.63	15.57	15.73	13.57	15.81	16.59	16.17	16.93	17.54	18.24	16.84	17.68	15.68	16.71
550	3.21	3.30	14.32	16.15	14.84	16.73	14.75	16.54	15.65	13.12	15.60	17.35	15.75	17.52	16.96	18.72	16.12	17.98	15.17	17.17
560	3.43	3.05	14.02	16.78	14.99	17.73	14.87	17.53	15.58	12.66	15.39	18.12	15.33	18.11	16.38	19.22	15.40	18.29	14.66	17.64
570	4.87	2.99	14.26	16.88	16.12	18.48	15.86	18.20	16.16	12.68	15.74	18.36	15.38	18.10	16.32	19.05	15.17	17.93	14.81	17.55
580	6.31	2.94	14.50	16.97	17.25	19.21	16.85	18.87	16.74	12.71	16.10	18.60	15.43	18.07	16.25	18.88	14.94	17.57	14.95	17.44
590	7.66	3.31	14.35	15.65	17.55	18.54	17.06	18.12	16.73	13.56	16.00	17.35	15.21	16.60	15.96	17.26	14.58	15.84	14.77	15.93
600	9.02	3.73	14.21	14.31	17.84	17.86	17.27	17.35	16.72	14.43	15.90	16.09	14.98	15.10	15.67	15.62	14.21	14.10	14.59	14.41
610	8.90	6.45	14.17	13.73	17.86	17.64	17.27	17.07	16.67	18.97	15.85	15.56	14.91	14.47	15.53	14.94	14.06	13.39	14.47	13.77
620	8.78	9.24	14.13	13.11	17.88	17.39	17.27	16.76	16.63	23.53	15.80	14.99	14.83	13.80	15.39	14.24	13.91	12.64	14.35	13.10
630	8.39	13.94	15.00	13.10	18.82	17.56	18.19	16.90	17.52	26.91	16.71	15.00	15.65	13.77	16.06	14.20	14.56	12.58	15.05	13.07
640	8.01	18.64	15.87	13.09	19.77	17.73	19.11	17.04	18.41	30.29	17.62	15.02	16.47	13.75	16.72	14.17	15.21	12.52	15.75	13.04
650	8.61	24.44	19.14	10.96	23.39	15.17	22.66	14.53	21.92	30.76	21.17	12.67	19.77	11.53	19.66	11.89	18.09	10.45	18.74	10.91
660	9.22	30.21	22.42	8.85	27.01	12.62	26.21	12.04	25.43	31.22	24.72	10.33	23.06	9.33	22.59	9.63	20.97	8.39	21.73	8.80
670	12.07	37.18	29.18	7.98	34.43	11.49	33.51	10.94	32.69	30.92	32.03	9.35	30.08	8.42	29.01	8.70	27.37	7.56	28.25	7.94
680	14.93	44.13	35.93	7.12	41.86	10.37	40.81	9.85	39.95	30.61	39.34	8.37	37.10	7.61	35.43	7.77	33.77	6.73	34.77	7.08
690	20.29	50.73	44.32	12.86	50.69	17.32	49.57	16.66	48.70	31.99	48.13	14.67	45.83	13.45	43.77	13.82	42.21	12.28	43.19	12.80
700	25.65	57.31	52.71	18.61	59.52	24.26	58.33	23.46	57.45	33.36	56.92	20.97	54.55	19.39	52.11	19.88	50.65	17.83	51.61	18.53

Pair No.	11		12		13		14		15		16		17		18		19		20	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	18.26	21.51	17.43	21.30	15.73	23.73	13.83	22.66	11.49	16.66	11.40	16.72	12.75	18.15	16.18	16.61	20.54	21.79	22.27	23.15
410	18.05	21.59	17.19	21.11	15.57	20.29	13.59	19.78	11.21	13.79	11.07	13.64	12.34	14.95	15.78	16.88	20.40	22.62	22.25	24.13
420	17.83	21.66	16.95	20.93	15.41	16.78	13.34	16.84	10.93	10.86	10.73	10.47	11.94	11.66	15.39	17.16	20.25	23.46	22.22	25.11
430	17.75	20.49	16.86	19.63	15.36	14.80	13.29	14.69	10.89	9.54	10.67	8.87	11.83	9.95	15.28	16.82	20.22	22.74	22.20	24.53
440	17.67	19.31	16.76	18.33	15.32	12.79	13.24	12.52	10.85	8.20	10.61	7.23	11.73	8.21	15.18	16.48	20.18	22.03	22.18	23.95
450	17.81	17.81	16.92	16.87	15.38	13.20	13.48	11.97	11.26	9.08	11.12	8.10	12.22	9.14	15.63	16.00	20.30	20.51	22.03	22.21
460	17.96	16.32	17.07	15.41	15.43	13.78	13.71	11.57	11.67	10.10	11.63	9.16	12.71	10.26	16.08	15.49	20.41	18.97	21.88	20.45
470	17.87	15.51	17.02	14.65	15.16	16.88	13.80	12.73	12.18	14.72	12.44	16.09	13.59	17.44	16.78	15.38	20.26	18.02	21.20	19.12
480	17.78	14.70	16.97	13.89	14.89	20.00	13.88	13.92	12.69	19.36	13.25	23.05	14.46	24.63	17.47	15.26	20.11	17.06	20.52	17.78
490	17.46	14.48	16.70	13.73	14.38	19.10	13.77	16.21	13.14	19.17	14.24	22.90	15.61	24.33	18.22	15.60	19.69	16.67	19.58	16.98
500	17.13	14.26	16.42	13.57	13.87	18.13	13.65	18.45	13.58	18.93	15.24	22.66	16.76	23.95	18.96	15.96	19.27	16.28	18.64	16.19
510	16.71	14.53	16.07	13.93	13.43	16.48	13.52	17.46	13.93	17.37	16.11	20.01	17.76	21.16	19.32	16.73	18.67	16.34	17.78	15.88
520	16.28	14.81	15.71	14.29	12.99	14.79	13.39	16.42	14.28	15.78	16.97	17.31	18.77	18.33	19.69	17.53	18.06	16.42	16.92	15.58
530	15.76	15.46	15.32	15.05	12.74	13.46	13.28	14.91	14.32	14.43	17.02	15.82	18.61	16.68	18.85	18.19	17.14	16.76	16.21	15.78
540	15.24	16.11	14.93	15.83	12.50	12.09	13.17	13.36	14.36	13.06	17.07	14.29	18.45	15.01	18.01	18.87	16.21	17.12	15.50	16.01
550	14.90	16.69	14.76	16.60	12.93	11.68	13.67	12.80	14.70	12.66	16.82	13.72	17.53	14.25	16.65	18.55	15.34	17.16	15.12	16.43
560	14.55	17.28	14.59	17.37	13.37	11.24	14.17	12.22	15.04	12.25	16.57	13.12	16.61	13.49	15.29	18.23	14.46	17.20	14.74	16.86
570	15.02	17.67	15.41	17.97	15.18	11.30	16.01	12.15	16.35	12.34	16.75	12.94	15.91	13.06	14.28	17.14	14.12	16.94	15.23	17.85
580	15.49	18.06	16.22	18.56	16.99	11.37	17.84	12.10	17.67	12.44	16.92	12.77	15.21	12.64	13.26	16.04	13.79	16.67	15.73	18.83
590	15.47	16.73	16.38	17.50	17.76	12.34	18.60	12.95	18.07	13.43	16.73	13.46	14.66	12.99	12.62	13.94	13.41	14.80	15.71	17.39
600	15.44	15.39	16.54	16.44	18.53	13.35	19.36	13.84	18.48	14.44	16.53	14.17	14.11	13.36	11.98	11.81	13.02	12.92	15.69	15.94
610	15.35	14.77	16.46	15.95	18.65	19.18	19.47	19.01	18.52	19.94	16.46	18.09	13.93	15.76	11.80	10.97	12.89	12.11	15.60	15.14
620	15.26	14.12	16.38	15.43	18.78	25.07	19.59	24.25	18.56	25.47	16.39	22.06	13.76	18.21	11.62	10.10	12.75	11.26	15.50	14.31
630	15.97	14.10	17.10	15.46	19.82	31.47	20.62	30.51	19.51	30.66	17.26	25.16	14.39	19.74	12.19	9.98	13.40	11.16	16.22	14.21
640	16.69	14.08	17.82	15.50	20.86	37.86	21.65	36.77	20.45	35.83	18.12	28.29	15.01	21.27	12.76	9.86	14.06	11.06	16.94	14.11
650	19.77	11.82	20.94	13.10	24.73	39.46	25.51	41.59	24.01	36.91	21.57	33.42	17.78	25.59	15.40	8.19	16.92	9.19	20.03	11.81
660	22.85	9.58	24.07	10.72	28.60	41.04	29.36	46.38	27.56	37.97	25.02	38.53	20.56	29.89	18.04	6.52	19.79	7.34	23.12	9.53
670	29.58	8.65	30.98	9.71	36.35	40.84	37.08	52.09	34.79	37.72	32.22	48.63	26.74	40.08	24.12	5.88	26.20	6.61	29.81	8.59
680	36.31	7.73	37.89	8.70	44.10	40.63	44.79	57.79	42.01	37.46	39.43	58.73	32.92	50.26	30.20	5.24	32.61	5.89	36.51	7.67
690	45.00	13.76	46.78	15.13	52.93	42.03	53.58	63.63	50.56	38.87	48.19	66.94	41.14	60.37	38.40	9.76	41.13	10.89	45.10	13.68
700	53.68	19.80	55.68	21.56	61.76	43.43	62.37	69.46	59.11	40.27	56.96	75.15	49.35	70.47	46.61	14.29	49.65	15.90	53.69	19.69

Pair No.	21		22		23		24		25		26		27		28		29		30	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	19.07	21.30	16.05	27.93	9.47	6.28	25.20	33.37	10.76	16.61	6.10	3.62	6.23	8.70	18.73	27.19	9.09	16.74	5.51	8.03
410	18.99	21.72	15.94	25.11	9.09	6.03	25.63	30.77	10.53	13.72	5.83	3.43	6.04	8.55	19.06	24.43	8.90	14.11	5.27	6.15
420	18.92	22.16	15.82	22.25	8.71	5.76	26.06	28.10	10.30	10.75	5.55	3.22	5.85	8.43	19.38	21.58	8.72	11.42	5.04	4.20
430	18.87	21.25	15.77	19.42	8.60	5.93	26.15	25.45	10.21	9.11	5.47	3.26	5.98	8.49	19.40	19.03	8.64	9.65	4.97	3.40
440	*18.83*	*20.34*	*15.72*	*16.56*	8.49	6.10	26.23	22.78	10.12	7.45	5.39	3.28	6.12	8.55	19.42	16.45	8.57	7.86	4.91	2.58
450	18.67	18.67	15.70	14.86	8.95	7.89	25.35	*22.84*	*10.19*	*8.03*	*5.74*	*4.40*	*7.70*	9.06	18.48	16.23	8.59	7.39	5.13	3.02
460	18.51	16.97	15.67	13.24	9.42	9.72	24.46	23.06	10.26	8.80	6.08	5.58	9.28	9.47	17.54	16.21	8.61	7.06	6.36	3.65
470	17.82	15.76	15.27	12.41	10.38	13.49	22.65	24.94	10.15	12.40	6.91	9.52	13.15	10.34	15.79	17.40	8.43	7.73	5.81	8.28
480	17.13	14.55	14.87	11.60	11.35	17.27	20.83	26.84	10.03	16.01	7.73	13.48	17.02	11.20	14.04	18.60	8.24	8.40	6.26	12.92
490	16.23	13.87	14.25	11.19	12.89	18.89	19.04	23.98	9.73	15.17	9.32	16.21	19.91	12.84	12.49	16.72	7.92	9.48	6.89	14.02
500	15.33	13.20	13.63	10.75	14.43	20.49	17.25	21.07	9.44	14.27	10.92	18.92	22.81	14.53	10.95	14.77	7.59	10.51	7.52	15.06
510	14.59	12.98	13.14	10.72	16.27	19.16	16.03	18.75	9.22	12.77	13.51	18.07	22.51	17.12	10.04	13.24	7.36	10.19	8.36	13.54
520	13.84	12.78	12.65	10.71	18.10	17.82	14.81	16.39	9.00	11.19	16.11	17.21	22.20	19.74	9.13	11.62	7.13	9.79	9.19	11.94
530	13.42	13.10	12.40	11.50	18.61	16.85	14.25	14.84	9.08	10.65	17.95	16.53	20.52	21.43	8.94	10.87	7.21	9.41	9.96	11.27
540	13.00	13.44	12.14	12.30	19.12	15.89	13.69	13.24	9.16	10.03	19.79	15.85	18.84	23.16	8.76	10.03	7.30	8.95	10.73	10.51
550	13.06	14.19	12.59	14.44	18.25	15.01	13.80	12.67	10.01	9.74	19.68	15.20	17.22	21.87	9.45	9.66	8.18	9.27	11.91	10.54
560	13.11	14.94	13.03	16.57	17.38	14.13	13.91	12.07	10.85	9.41	19.57	14.56	15.60	20.59	10.15	9.23	9.05	9.54	13.10	10.52
570	14.48	16.73	14.89	18.45	16.42	14.65	15.58	11.95	14.90	10.22	18.78	15.85	14.51	18.30	14.03	9.73	13.94	11.07	17.20	11.43
580	15.84	18.52	16.75	20.31	15.46	15.18	17.24	11.84	18.95	11.06	17.99	17.14	13.43	16.00	17.91	10.25	18.82	12.61	21.31	12.37
590	16.39	17.90	17.53	19.91	14.78	15.40	18.01	12.66	22.80	12.80	17.32	18.02	12.76	13.38	21.65	11.67	25.37	15.51	24.87	14.46
600	16.93	17.27	18.31	19.48	14.11	15.63	18.77	13.53	26.65	14.61	16.65	18.89	12.09	10.73	25.40	13.18	31.91	18.49	28.43	16.64
610	16.93	16.72	18.41	17.88	13.92	15.63	18.61	18.59	27.69	23.06	16.46	18.99	11.92	9.80	26.38	21.20	34.52	28.24	29.35	25.71
620	16.92	16.12	18.50	16.24	13.73	15.64	18.85	23.73	28.73	31.65	16.27	19.08	11.74	8.82	27.37	29.37	37.12	38.12	30.27	34.92
630	17.64	16.10	19.45	15.20	14.40	16.48	19.62	28.80	29.83	46.76	16.98	19.98	12.33	8.64	28.39	44.49	38.62	53.51	31.36	50.04
640	18.36	16.08	20.39	14.16	15.07	17.32	20.40	33.86	30.94	61.85	17.69	20.88	12.93	8.47	29.41	59.59	40.13	68.87	32.46	65.15
650	21.46	13.59	24.07	13.77	17.98	20.99	23.67	39.67	34.85	71.38	20.79	24.76	15.60	7.01	33.11	69.63	44.31	79.27	36.36	74.31
660	24.55	11.11	27.75	13.40	20.90	24.65	26.93	45.44	38.77	80.84	23.89	28.65	18.28	5.57	36.82	79.60	48.48	89.61	40.27	83.40
670	31.37	10.07	35.32	13.15	27.39	32.48	34.05	54.80	46.51	81.88	30.71	36.72	24.41	5.01	44.34	80.98	55.87	89.37	47.90	83.61
680	38.20	9.03	42.90	12.92	33.89	40.31	41.17	64.15	54.26	82.88	37.53	44.78	30.55	4.47	51.87	82.33	63.25	89.10	55.52	83.80
690	46.94	15.57	51.80	13.87	42.44	50.99	50.02	70.59	62.26	82.56	46.24	55.23	38.87	8.37	60.01	82.12	69.80	86.66	63.36	83.01
700	55.69	22.12	60.70	14.82	51.00	61.66	58.86	77.01	70.26	82.21	54.96	65.69	47.19	12.27	68.15	81.90	76.36	84.20	71.20	82.20

Pair No.	31		32		33		34		35		36		37		38		39		40	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	4.25	2.49	3.58	2.06	3.31	2.04	3.71	4.68	4.96	5.26	7.61	9.66	8.77	10.38	20.14	31.06	15.85	27.44	13.37	25.90
410	4.08	2.38	3.47	1.96	3.20	1.95	3.58	4.53	4.81	5.07	7.46	9.82	9.02	10.86	21.12	29.28	16.99	25.86	13.92	23.14
420	3.91	2.26	3.36	1.81	3.10	1.83	3.46	4.43	4.66	4.89	7.31	10.04	9.27	11.37	22.10	27.43	18.13	24.20	14.47	20.31
430	3.86	2.26	3.33	1.78	3.09	1.81	3.49	4.52	4.79	5.08	7.52	10.36	9.71	11.90	22.27	24.29	18.30	20.74	14.53	17.17
440	3.82	2.25	3.31	1.72	3.09	1.77	3.53	4.63	4.92	5.28	7.74	10.71	10.15	12.44	22.44	21.15	18.48	17.27	14.60	14.02
450	4.02	2.92	3.46	2.22	3.38	2.26	4.24	5.04	6.52	6.85	9.84	11.63	12.51	13.73	20.44	18.57	16.27	14.41	13.32	11.75
460	4.22	3.62	3.62	2.80	3.67	2.80	4.94	5.35	8.11	8.41	11.94	12.42	14.88	14.95	18.44	16.20	14.06	11.74	12.04	9.65
470	4.67	6.68	4.04	5.84	4.44	5.88	7.13	6.07	13.08	12.76	17.35	13.91	20.00	17.22	15.60	14.58	11.41	10.13	10.16	8.45
480	5.13	9.75	4.45	8.88	5.21	8.96	9.31	6.79	18.05	17.12	22.76	15.39	25.13	19.48	12.77	12.98	8.77	8.54	8.29	7.27
490	5.98	11.26	5.42	11.45	6.71	12.29	12.62	8.61	22.88	21.25	26.81	18.01	28.26	22.42	10.83	11.97	7.26	7.74	7.04	6.66
500	6.83	12.74	6.38	13.97	8.21	15.59	15.92	10.46	27.71	25.39	30.87	20.68	31.40	25.38	8.88	10.89	5.76	6.88	5.79	6.00
510	8.25	11.71	8.45	13.59	10.90	15.90	18.81	14.54	26.99	25.45	29.21	24.19	29.99	27.90	7.92	10.22	5.10	6.38	5.19	5.76
520	9.66	10.69	10.53	13.19	13.58	16.21	21.71	18.63	26.26	25.51	27.55	27.70	28.59	30.42	6.95	9.46	4.45	5.81	4.60	5.48
530	11.07	10.55	13.00	12.97	16.17	15.81	22.22	22.48	23.43	23.72	24.23	27.66	25.63	28.61	6.78	9.14	4.37	5.85	4.54	5.60
540	12.47	10.43	15.47	12.73	18.77	15.43	22.74	26.33	20.59	21.93	20.91	27.60	22.67	26.80	6.61	8.72	4.28	5.82	4.47	5.66
550	13.84	10.39	17.05	12.51	19.40	14.91	21.08	24.78	18.13	19.30	18.17	23.06	19.36	21.80	7.34	8.68	4.87	6.14	5.07	6.65
560	15.20	10.37	18.63	12.28	20.04	14.39	19.43	23.23	15.66	16.66	15.43	18.50	16.06	16.79	8.06	8.97	5.45	6.41	5.66	7.60
570	18.36	14.53	19.93	15.27	19.54	16.00	17.28	19.90	13.75	14.57	13.31	14.94	13.36	13.41	12.68	10.13	10.02	9.06	10.43	10.83
580	21.51	18.68	21.22	18.26	19.03	17.61	15.13	16.57	11.84	12.49	11.20	11.37	10.65	10.02	17.29	11.31	14.59	11.76	15.20	14.09
590	23.61	24.53	21.53	21.81	18.41	18.84	13.67	13.44	10.70	10.84	9.99	8.90	8.79	7.83	23.42	13.59	24.66	17.93	25.93	20.09
600	25.71	30.37	21.84	25.37	17.79	20.07	12.22	10.31	9.55	9.19	8.78	6.45	6.93	5.65	29.56	15.96	34.73	24.16	36.66	26.14
610	26.14	31.34	21.83	25.79	17.60	20.25	11.39	9.32	8.95	8.46	8.14	5.73	6.14	5.03	31.89	25.01	41.92	36.24	44.77	38.23
620	26.56	32.28	21.83	26.24	17.42	20.41	10.57	8.33	8.34	7.72	7.49	5.04	5.34	4.42	34.22	34.19	49.11	48.42	52.88	50.40
630	27.52	32.20	22.67	26.67	18.15	21.37	10.06	8.22	8.04	7.53	7.12	5.01	5.25	4.39	35.59	49.76	52.18	63.88	56.26	67.04
640	28.48	32.13	23.51	27.10	18.88	22.32	9.56	8.12	7.73	7.34	6.75	4.98	5.16	4.37	36.95	65.30	55.25	79.32	59.64	83.67
650	32.20	28.27	26.97	30.45	22.03	26.34	10.27	6.74	8.52	6.74	7.35	4.21	4.70	3.72	40.99	76.51	59.37	80.89	63.52	83.06
660	35.92	24.43	30.42	33.78	25.17	30.37	10.98	5.37	9.30	6.14	7.95	3.43	4.24	3.06	45.02	87.65	63.48	82.41	67.41	82.43
670	43.43	22.61	37.67	40.52	31.99	38.52	14.16	4.86	12.43	5.95	10.71	3.18	3.90	2.86	52.52	88.03	69.03	86.66	72.32	82.47
680	50.95	20.80	44.92	47.24	38.80	46.68	17.33	4.35	15.55	5.77	13.47	2.93	3.57	2.66	60.03	88.39	74.59	90.89	77.23	82.50
690	59.20	30.24	53.50	54.97	47.41	56.91	23.09	8.17	21.20	8.79	18.61	5.56	5.29	4.94	67.13	86.19	78.49	87.47	80.50	83.74
700	67.44	39.68	62.08	62.69	56.02	67.15	28.86	11.99	26.85	11.81	24.15	8.19	7.01	7.22	74.24	83.97	82.40	84.04	83.77	84.98

Pair No.	41		42		43		44		45		46		47		48		49		50	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	9.78	21.02	7.25	15.53	4.60	9.88	2.84	1.71	3.51	2.99	26.28	34.59	23.69	32.16	23.87	32.19	23.43	26.12	25.24	33.23
410	9.86	18.05	7.14	12.96	4.44	7.88	2.75	1.63	3.47	2.87	26.04	30.68	23.67	28.20	23.58	28.02	23.12	26.03	24.85	29.08
420	9.95	15.01	7.03	10.35	4.28	5.83	2.66	1.51	3.43	2.73	25.81	26.68	23.44	24.14	23.29	23.74	22.80	25.95	24.46	24.83
430	9.91	12.42	6.98	8.59	4.23	4.77	2.64	1.48	3.53	2.78	25.76	23.98	23.39	21.55	23.21	21.12	22.74	25.16	24.33	22.18
440	9.86	9.81	6.93	6.82	4.19	3.70	2.61	1.43	3.62	2.83	25.71	21.23	23.35	18.92	23.14	18.45	22.68	24.35	24.20	19.48
450	9.40	8.25	6.85	6.03	4.31	3.51	2.70	1.78	4.58	3.80	26.01	22.37	23.76	20.09	23.63	19.70	23.23	23.47	24.67	20.77
460	8.93	6.83	6.77	5.35	4.44	3.44	2.79	2.20	5.53	4.82	26.30	23.74	24.17	21.48	24.12	21.19	23.78	22.56	25.14	22.29
470	7.99	6.17	6.45	5.25	4.64	4.18	3.04	4.40	8.71	9.56	26.38	30.61	24.52	28.84	24.70	29.42	24.43	22.26	25.82	30.64
480	7.05	5.51	6.13	5.15	4.84	4.92	3.28	6.60	11.89	14.30	26.47	37.50	24.86	36.24	25.27	37.67	25.08	21.96	26.49	39.02
490	6.24	5.24	5.72	5.22	5.04	6.41	3.78	8.09	16.69	20.60	26.28	35.03	25.01	33.96	25.76	35.66	25.66	22.31	27.14	37.03
500	5.44	4.92	5.32	5.26	5.23	7.86	4.27	9.54	21.49	26.89	26.09	32.47	25.16	31.59	26.24	33.56	26.23	22.66	27.79	34.94
510	5.00	4.86	5.06	5.25	5.48	7.94	5.24	9.02	24.64	27.55	25.80	29.53	25.12	28.69	26.49	30.55	26.51	23.64	28.15	31.81
520	4.56	4.76	4.81	5.19	5.73	7.95	6.21	8.47	27.79	28.20	25.52	26.56	25.09	25.74	26.74	27.49	26.79	24.64	28.52	28.63
530	4.54	5.05	4.84	5.48	6.06	7.84	7.36	8.33	26.60	25.07	25.13	24.68	24.74	23.93	26.44	25.55	26.36	25.84	28.10	26.56
540	4.51	5.30	4.88	5.72	6.39	7.65	8.56	8.16	25.42	21.92	24.75	22.77	24.40	22.10	26.15	23.56	25.93	27.06	27.68	24.46
550	5.12	6.82	5.57	7.22	7.34	8.28	10.14	8.04	21.06	18.48	24.88	22.15	24.39	21.49	26.00	22.75	25.50	27.71	26.92	23.51
560	5.74	8.31	6.27	8.69	8.29	8.86	11.72	7.91	16.74	15.02	25.02	21.52	24.38	20.87	25.85	21.92	25.06	28.37	26.16	22.53
570	10.44	12.26	11.17	12.39	13.52	11.32	16.65	11.63	13.29	12.63	26.39	21.59	25.37	20.92	26.51	21.69	25.26	28.39	26.02	22.09
580	15.15	16.23	16.07	16.10	18.75	13.80	21.59	15.37	9.84	10.24	27.76	21.68	26.36	20.99	27.17	21.48	25.46	28.40	25.88	21.65
590	25.68	21.17	26.10	20.55	27.30	18.48	27.07	24.06	7.76	8.37	28.09	22.94	26.54	22.17	27.14	22.47	25.22	26.75	25.50	22.32
600	36.21	26.15	36.12	25.05	35.85	23.23	32.55	32.77	5.69	6.51	28.42	24.22	26.73	23.37	27.10	23.51	24.97	25.08	25.12	23.01
610	44.17	36.83	42.91	35.52	40.29	34.36	34.50	37.58	4.90	5.92	28.41	30.79	26.73	29.45	27.05	29.09	24.88	24.50	24.93	27.07
620	52.13	47.60	49.69	46.08	44.74	45.61	36.45	42.45	4.11	5.37	28.40	37.41	26.74	35.55	27.01	34.74	24.80	23.88	24.75	31.17
630	55.49	61.76	52.56	60.52	46.78	60.45	37.81	44.56	4.02	5.43	29.46	42.44	27.88	39.88	28.13	38.97	25.90	23.90	25.55	33.75
640	58.85	75.92	55.44	74.95	48.82	75.26	39.17	46.65	3.92	5.48	30.51	47.46	29.01	44.21	29.25	43.20	26.99	23.93	26.34	36.33
650	62.83	83.43	59.55	83.15	53.02	84.54	43.28	51.28	3.51	4.73	34.58	48.25	33.31	44.80	33.56	48.51	31.19	20.72	29.82	41.37
660	66.80	90.91	63.65	91.31	57.22	93.76	47.39	55.89	3.09	3.97	38.64	49.02	37.60	45.38	37.86	53.78	35.38	17.53	33.29	46.40
670	71.89	88.62	69.28	89.14	63.84	92.01	54.85	62.83	2.86	3.69	46.47	48.64	45.77	44.99	46.05	62.05	43.42	16.07	40.62	55.74
680	76.98	86.31	74.90	86.95	70.45	90.22	62.31	69.76	2.63	3.40	54.30	48.26	53.93	44.59	54.23	70.30	51.46	14.63	47.95	65.06
690	80.41	84.46	78.86	85.00	75.59	87.33	69.11	75.95	3.73	6.59	62.29	49.59	62.08	45.96	62.34	75.22	59.76	22.79	56.40	71.70
700	83.85	82.59	82.81	83.04	80.73	84.42	75.91	82.12	4.82	9.78	70.27	50.91	70.23	47.33	70.46	80.12	68.05	30.97	64.88	78.33

Pair No.	51		52		53		54		55		56		57		58		59		60	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	26.40	34.55	27.79	36.45	29.17	38.02	28.13	36.84	26.36	37.52	23.11	34.19	22.68	30.82	20.94	28.76	21.67	29.86	23.27	30.89
410	26.24	30.54	27.82	32.56	29.31	34.23	28.16	32.95	26.25	34.26	22.83	30.73	22.34	26.59	20.56	24.56	21.18	25.52	22.80	26.61
420	26.08	26.43	27.85	28.57	29.46	30.34	28.19	28.96	26.15	30.92	22.55	27.19	21.99	22.25	20.19	20.25	20.69	20.99	22.32	22.23
430	25.92	23.75	27.76	25.80	29.41	27.52	28.11	26.15	26.11	27.94	22.47	24.32	21.93	19.68	20.11	17.77	20.57	18.29	22.18	19.68
440	25.77	21.04	27.67	23.00	29.36	24.66	28.03	23.30	26.06	24.93	22.38	21.43	21.87	17.07	20.04	15.26	20.45	15.50	22.04	17.09
450	26.12	22.33	27.88	24.19	29.44	25.79	28.12	24.43	26.12	24.03	22.69	20.69	22.41	18.34	20.64	16.55	21.07	16.72	22.70	18.47
460	26.48	23.83	26.09	25.61	29.52	27.17	28.21	25.81	26.18	23.32	22.99	20.15	22.95	19.89	21.24	18.10	21.70	18.36	23.36	20.10
470	26.99	31.73	28.24	32.65	29.40	33.68	28.07	32.42	25.84	24.62	23.14	21.76	23.59	28.47	22.09	27.06	22.76	27.93	24.54	29.93
480	27.51	39.65	28.40	39.71	29.29	40.22	27.93	39.06	25.50	25.95	23.29	23.39	24.22	37.09	22.94	36.04	23.62	37.54	25.72	39.79
490	27.91	37.50	28.32	37.29	28.92	37.66	27.53	36.53	24.87	28.23	23.21	26.53	24.74	35.32	23.83	34.75	25.09	36.40	27.24	38.58
500	28.30	35.28	28.24	34.79	28.55	35.00	27.13	33.91	24.24	30.44	23.12	29.59	25.26	33.45	24.71	33.34	26.36	35.07	28.76	37.27
510	28.36	32.08	27.91	31.64	28.02	31.89	26.63	30.89	23.72	28.79	23.02	28.30	25.63	30.48	25.42	30.32	27.49	31.90	30.08	34.00
520	28.42	28.83	27.58	28.45	27.49	28.72	26.14	27.80	23.19	27.09	22.93	26.94	25.99	27.43	26.14	27.23	28.62	28.69	31.39	30.69
530	27.97	26.62	27.11	26.26	27.02	26.53	25.84	25.72	22.93	25.04	22.83	24.90	25.96	25.59	26.19	25.38	28.66	26.73	31.13	28.58
540	27.51	24.37	26.63	24.04	26.56	24.30	25.54	23.59	22.68	22.95	22.73	22.79	25.93	23.68	26.24	23.47	28.69	24.76	30.86	26.44
550	26.81	23.26	26.25	23.05	26.36	23.35	25.65	22.75	23.36	22.27	23.39	22.09	26.26	22.98	26.38	22.77	28.05	23.96	29.53	25.36
560	26.12	22.13	25.87	22.04	26.16	22.38	25.76	21.88	24.08	21.57	24.04	21.36	26.60	22.24	26.51	22.04	27.41	23.16	28.21	24.26
570	25.45	21.45	25.84	21.54	26.59	21.96	26.90	21.64	26.73	21.60	26.46	21.32	28.11	22.21	27.56	21.93	27.22	22.86	27.09	23.57
580	24.78	20.78	25.81	21.06	27.01	21.56	28.05	21.41	29.38	21.65	28.88	21.30	29.63	22.19	28.61	21.84	27.02	22.57	25.98	22.89
590	23.99	21.17	25.30	21.65	26.76	22.31	28.19	22.40	30.56	22.96	29.81	22.56	30.06	23.43	28.73	23.01	26.57	23.37	25.16	23.27
600	23.19	21.59	24.79	22.28	26.50	23.10	28.33	23.45	31.74	24.32	30.75	23.88	30.49	24.73	28.85	24.22	26.13	24.18	24.35	23.67
610	22.61	24.66	24.23	26.09	25.99	27.63	27.86	29.17	31.92	31.66	30.84	30.96	30.53	31.90	28.82	30.81	25.96	28.56	24.10	26.74
620	22.03	27.80	23.67	29.94	25.47	32.24	27.40	34.98	32.10	39.08	30.94	38.14	30.57	39.16	28.79	37.49	25.79	32.95	23.85	29.86
630	22.19	29.60	23.86	32.33	25.67	35.30	27.59	39.41	33.30	46.95	32.08	44.68	31.72	46.66	29.95	43.07	26.69	35.73	24.66	31.58
640	22.35	31.40	24.06	34.72	25.87	38.36	27.78	43.83	34.50	54.82	33.22	51.20	32.88	54.15	31.11	48.65	27.60	38.50	25.46	33.29
650	25.11	36.27	27.01	39.73	28.89	43.51	30.82	49.18	38.89	59.29	37.53	56.66	37.19	58.52	35.56	54.05	31.37	43.55	28.97	38.14
660	27.87	41.11	29.96	44.72	31.90	48.64	33.87	54.49	43.29	63.73	41.64	62.07	41.49	62.86	40.01	59.42	35.13	48.58	32.48	42.96
670	33.77	51.03	36.25	54.26	38.38	57.69	40.35	62.65	51.30	67.67	49.91	68.62	49.45	66.96	48.32	66.69	42.76	57.66	39.91	52.60
680	39.66	60.94	42.54	63.79	44.86	66.72	46.84	70.78	59.31	71.60	57.99	75.14	57.41	71.04	56.63	73.94	50.38	66.75	47.34	62.23
690	46.34	68.81	49.51	70.81	51.94	72.84	53.78	75.54	66.76	74.83	65.71	78.26	65.03	74.48	64.58	77.65	58.68	72.94	55.96	69.65
700	53.02	76.67	56.47	77.82	59.02	78.94	60.72	80.27	74.20	78.05	73.42	81.37	72.65	77.91	72.53	81.36	66.99	79.14	64.59	77.06

Pair No.	61		62		63		64		65		66		67		68		69		70	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	26.41	34.50	31.44	40.14	33.80	42.39	26.64	35.66	17.75	25.99	15.79	10.89	18.99	20.53	26.16	20.73	32.29	41.58	36.84	46.64
410	26.17	30.32	31.81	36.72	34.26	39.23	26.75	32.04	17.24	21.78	15.27	10.62	18.76	20.79	26.01	21.14	33.16	38.52	38.61	44.60
420	25.94	26.03	32.18	33.22	34.72	35.99	26.87	28.30	16.74	17.48	14.75	10.35	18.53	21.09	25.86	21.54	34.03	35.36	40.38	42.47
430	25.76	23.34	32.14	30.44	34.71	33.15	26.89	25.49	16.59	15.41	14.60	10.73	18.66	21.17	25.79	22.28	34.18	32.69	40.93	39.86
440	25.59	20.60	32.10	27.64	34.70	30.28	26.91	22.65	16.45	13.32	14.44	11.11	18.80	21.26	25.73	23.02	34.33	29.98	41.48	37.22
450	26.13	22.01	32.12	28.73	34.39	31.12	26.58	23.32	16.99	14.14	15.05	13.75	20.62	21.60	26.44	25.74	34.52	31.13	40.58	37.60
460	26.67	23.67	32.14	30.02	34.08	32.18	26.25	24.26	17.54	15.18	15.65	16.41	22.45	21.88	27.15	28.47	34.72	32.48	39.67	38.18
470	27.65	32.89	31.98	35.96	33.24	36.93	25.21	28.56	18.42	20.96	16.82	21.24	25.44	22.70	28.43	32.39	34.86	38.64	38.10	41.09
480	28.64	42.15	31.81	41.92	32.40	41.70	24.17	32.87	19.31	26.75	17.98	26.08	28.43	23.52	29.72	36.30	35.00	44.81	36.53	44.01
490	29.77	40.52	31.34	39.26	31.26	38.74	22.89	30.28	20.30	27.86	19.62	27.45	30.36	25.07	31.12	36.47	34.81	42.57	34.80	40.86
500	30.91	38.78	30.87	36.51	30.13	35.70	21.60	27.59	21.30	28.89	21.26	28.82	32.28	26.64	32.52	36.63	34.63	40.25	33.07	37.62
510	31.61	35.41	30.13	33.21	29.04	32.53	20.63	25.12	22.29	27.59	23.11	26.87	32.54	28.88	33.06	34.67	33.86	36.63	31.52	34.24
520	32.31	31.99	29.39	29.86	27.96	29.30	19.66	22.55	23.27	26.23	24.97	24.91	32.80	31.14	33.61	32.71	33.10	32.97	29.96	30.81
530	31.79	29.58	28.45	27.40	27.25	27.00	19.41	20.97	23.83	24.62	25.87	24.09	31.74	32.33	32.24	30.50	31.51	29.95	28.70	28.15
540	31.27	27.14	27.52	24.90	26.53	24.65	19.16	19.29	24.39	22.96	26.77	23.28	30.69	33.53	30.87	28.29	29.93	26.90	27.44	25.45
550	29.91	25.72	26.61	23.65	26.27	23.66	19.97	18.65	24.98	22.45	26.80	22.56	29.08	32.18	28.59	26.40	27.96	24.94	26.47	24.10
560	28.54	24.28	25.70	22.37	26.00	22.68	20.78	18.35	25.57	21.90	26.84	21.85	27.47	30.83	26.30	24.51	26.00	22.96	25.51	22.74
570	26.77	23.23	24.88	21.52	26.43	22.23	24.85	18.77	27.82	22.02	27.31	24.16	25.55	28.64	23.92	22.66	23.86	21.31	24.72	21.79
580	24.99	22.18	24.05	20.68	26.86	21.79	28.92	19.22	30.06	22.17	27.79	26.46	23.64	26.44	21.54	20.81	21.72	19.68	23.94	20.85
590	23.74	22.22	23.19	20.88	26.62	22.47	31.83	21.06	31.09	23.57	27.65	28.22	22.36	23.26	19.94	19.79	20.10	19.14	23.12	20.94
600	22.49	22.28	22.33	21.10	26.37	23.18	34.74	22.98	32.12	25.03	27.52	29.98	21.09	20.06	18.33	18.79	18.48	18.62	22.30	21.06
610	21.84	24.26	21.74	23.52	25.86	27.33	35.35	32.65	32.19	32.64	27.40	30.24	20.44	18.92	17.37	18.29	17.66	19.10	21.74	23.13
620	21.18	26.30	21.14	25.99	25.34	31.53	35.96	42.47	32.27	40.33	27.28	30.49	19.79	17.76	16.41	17.81	16.84	19.63	21.18	25.25
630	21.32	27.34	21.32	27.32	25.56	34.20	37.15	56.70	33.20	48.48	28.20	31.63	19.94	17.56	15.98	18.17	16.85	19.91	21.36	26.35
640	21.46	28.37	21.51	28.65	25.78	36.86	38.33	70.91	34.14	56.62	29.11	32.76	20.09	17.36	15.55	18.52	16.85	20.18	21.53	27.44
650	24.20	33.00	24.37	33.34	28.83	41.92	42.66	78.25	37.98	60.84	32.90	37.28	22.79	14.67	16.98	21.52	17.57	24.13	24.21	32.04
660	26.94	37.61	27.22	38.01	31.88	46.96	46.99	85.53	41.81	65.02	36.70	41.78	25.50	11.99	18.41	24.51	18.29	28.05	26.89	36.61
670	32.82	47.71	33.36	48.08	38.24	56.23	54.74	85.19	49.35	68.46	44.30	49.71	31.34	10.87	22.93	30.82	19.55	38.06	32.65	46.78
680	38.70	57.80	39.49	58.14	44.60	65.49	62.50	84.83	56.88	71.87	51.90	57.63	37.18	9.76	27.44	37.12	20.81	48.07	38.41	56.94
690	45.39	66.40	46.43	66.65	51.50	72.00	69.41	84.02	64.46	74.90	59.99	66.21	43.87	16.54	34.41	45.15	26.19	58.55	44.97	65.76
700	52.08	74.99	53.37	75.15	58.41	78.50	76.32	83.18	72.04	77.91	68.08	74.60	50.57	23.33	41.38	53.18	31.57	69.02	51.53	74.59

Pair No.	71		72		73		74		75		76		77		78		79		80	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	25.55	35.60	14.60	20.93	11.67	7.37	11.95	14.04	19.47	28.77	25.82	23.08	29.59	26.60	33.50	31.79	40.82	36.65	27.86	24.19
410	25.62	32.07	14.16	17.21	11.19	7.09	11.60	13.77	19.16	24.56	25.83	24.63	30.93	29.43	36.26	36.04	42.91	39.06	28.68	25.00
420	25.68	28.44	13.71	13.37	10.72	6.80	11.25	13.54	18.86	20.24	25.84	26.22	32.27	32.30	39.02	40.36	44.99	41.51	29.51	25.82
430	25.66	25.45	13.58	11.41	10.59	7.04	11.36	13.52	19.00	17.81	26.18	27.49	33.09	33.97	40.69	42.93	45.58	43.31	29.65	26.81
440	25.64	22.44	13.44	9.41	10.47	7.26	11.47	13.50	19.14	15.35	26.53	28.77	33.92	35.66	42.37	45.51	46.18	45.14	29.80	27.80
450	25.16	22.51	13.91	10.43	11.03	9.48	13.13	14.08	20.97	16.82	28.64	29.92	34.98	35.82	43.70	44.75	43.42	43.81	28.14	28.19
460	24.67	22.80	14.38	11.71	11.60	11.75	14.78	14.59	22.81	18.56	30.76	30.98	36.04	35.92	45.03	43.77	40.66	42.36	26.48	28.55
470	23.44	25.20	15.14	19.27	12.80	16.90	17.95	15.68	26.09	30.14	34.03	32.23	37.30	36.16	45.46	42.72	36.59	38.39	23.72	26.32
480	22.21	27.61	15.89	26.85	13.99	22.06	21.13	16.77	29.37	41.76	37.31	33.46	38.56	36.39	45.89	41.64	32.51	34.43	20.97	24.10
490	20.82	25.63	16.74	26.71	15.87	24.56	24.02	18.73	32.30	42.48	38.95	34.70	39.27	36.75	44.45	40.82	29.35	31.04	18.70	21.30
500	19.43	23.56	17.58	26.48	17.74	27.03	26.90	20.73	35.22	43.10	40.59	35.98	39.98	37.14	43.01	40.10	26.20	27.74	16.42	18.52
510	18.47	21.57	18.47	24.18	20.24	25.13	28.49	23.83	36.24	39.32	39.38	36.59	38.93	37.13	40.58	39.25	24.31	25.16	15.10	16.29
520	17.52	19.49	19.37	21.79	22.74	23.24	30.08	26.96	37.25	35.48	38.18	37.23	37.88	37.13	38.16	38.43	22.41	22.59	13.79	14.08
530	17.39	19.10	20.10	20.78	24.49	22.67	29.71	29.44	35.54	32.67	35.15	35.90	34.83	35.41	35.35	36.58	21.88	22.12	13.58	13.86
540	17.27	18.64	20.83	19.68	26.23	22.12	29.34	31.93	33.83	29.83	32.13	34.59	31.78	33.69	32.54	34.72	21.34	21.61	13.38	13.66
550	18.41	18.48	22.09	19.72	26.93	21.74	27.86	31.52	31.00	27.53	29.02	31.32	28.21	29.84	29.49	31.18	22.11	21.26	14.61	13.67
560	19.55	18.28	23.34	19.71	27.63	21.38	26.38	31.12	28.17	25.21	25.90	28.05	24.63	26.00	26.44	27.63	22.87	20.86	15.84	13.69
570	25.15	20.62	27.64	20.89	28.69	24.70	25.10	29.31	25.39	23.13	23.17	25.36	21.56	22.67	23.55	24.47	26.67	24.66	22.69	19.34
580	30.74	22.98	31.95	22.09	29.76	28.02	23.81	27.49	22.61	21.06	20.44	22.67	18.48	19.32	20.67	21.31	30.47	28.45	29.55	24.97
590	36.12	26.28	35.10	24.62	29.93	31.12	22.95	24.43	20.77	20.21	18.69	19.10	16.23	16.08	18.27	18.04	33.00	32.63	38.80	37.59
600	41.50	29.65	38.26	27.22	30.09	34.20	22.09	21.36	18.92	19.38	16.94	15.52	13.98	12.82	15.87	14.76	35.54	36.84	48.06	50.16
610	43.03	39.85	38.97	37.38	30.03	34.25	21.84	20.26	17.80	19.37	15.88	14.28	12.79	11.74	14.67	13.63	35.63	37.13	52.02	56.33
620	44.56	50.16	39.67	47.67	29.97	34.26	21.59	19.12	16.68	19.40	14.83	13.02	11.61	10.63	13.47	12.49	35.72	37.43	55.97	62.44
630	45.84	63.10	40.85	61.42	30.92	34.56	22.38	18.91	16.01	19.46	14.22	12.80	11.19	10.46	13.32	12.29	36.05	37.76	57.81	63.18
640	47.11	76.02	42.04	75.15	31.88	34.86	23.17	18.71	15.34	19.52	13.61	12.59	10.76	10.30	13.16	12.09	36.38	38.09	59.64	63.92
650	51.21	81.19	46.21	81.53	35.76	38.27	26.62	15.88	16.44	23.35	14.65	10.45	10.35	8.54	12.38	10.08	39.69	41.53	63.49	60.61
660	55.31	86.31	50.38	87.84	39.65	41.70	30.08	13.08	17.54	27.16	15.69	8.32	9.94	6.78	11.60	8.08	43.01	44.99	67.34	57.31
670	62.15	85.82	57.61	86.87	47.24	48.28	37.48	11.89	21.81	37.10	19.77	7.48	10.24	6.11	10.97	7.28	49.62	51.42	72.52	55.36
680	68.99	85.31	64.85	85.87	54.83	54.86	44.87	10.71	26.08	47.03	23.85	6.66	10.54	5.44	10.34	6.49	56.24	57.85	77.70	53.42
690	74.49	84.86	71.04	84.88	62.62	61.90	53.66	17.75	33.18	57.59	30.71	12.17	14.99	10.13	14.26	11.90	62.64	64.48	81.14	61.85
700	80.00	84.39	77.24	83.87	70.40	68.95	62.44	24.79	40.28	68.14	37.57	17.69	19.45	14.83	18.19	17.31	69.04	71.12	84.58	70.29

Pair No.	81		82		83		84		85		86		87		88	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	8.21	11.35	15 50	17.28	22 63	21 40	5 44	2 98	4 54	3.22	4.01	5.06	5.02	5.73	41 62	46 39
410	7.99	11.26	15.44	17.96	26.25	24 28	5 19	2 80	4 40	3 03	3 87	4.95	4 86	5.59	41.94	46.72
420	7.78	11.24	15.38	18.68	29 66	27.15	4 94	2 57	4 26	2.79	3.74	4 86	4.69	5.47	42.26	47.05
430	8.00	11.46	15.82	19 40	32 45	29 99	4 87	2 54	4 32	2 78	3.83	5.10	4 83	5 74	42.41	45 92
440	8.22	11.72	16.26	20.13	35 23	32 83	4 80	2.49	4 38	2.77	3.92	5 36	4.97	6 02	42.56	44.78
450	10.53	12.65	19.38	21.49	37.49	36 44	5.12	3.41	5 29	3 84	5.18	6 61	6 64	7.69	42.95	43.09
460	12.83	13.47	22.50	22.76	39 75	40 08	5.43	4.44	6.21	5 01	6.44	7.77	8.30	9 29	43.33	41.38
470	19.01	15.05	29.35	25.02	41.73	44 94	6 18	8.79	8 92	10.34	11.70	10.55	14 47	13.60	43.60	40.48
480	25.20	16.64	36.21	27.27	43.72	49 80	6 94	13.14	11.62	15.67	16 96	13.33	20.65	17.91	43 88	39.59
490	30.68	19 64	40.91	30.67	44 48	49 21	8 48	17.05	15.93	23.57	25.29	17.72	29.93	24.33	43.88	39.56
500	36.17	22.73	45 61	34.12	45.24	48 60	10 03	20.91	20.24	31.44	33.62	22.18	39.22	30.79	43.89	39.53
510	35.44	27.75	43.43	38.15	43.69	44.63	12.90	20.40	25.56	33 85	35.72	27.90	41.20	36.27	43.59	40.28
520	34.70	32.80	41.25	42.20	42.14	40 64	15.76	19 85	30.89	36 20	37.81	33.62	43.18	41.74	43.30	41.05
530	32.07	35.44	37.21	41.33	37.90	35.97	19 00	19.57	34.85	34.57	35.36	36.90	39 62	41.64	42.53	42.20
540	29.44	38.04	33.16	40.45	33 67	31.30	22.23	19.27	38.82	32.87	32.91	40.15	36.07	41.53	41.76	43.36
550	27.08	34.18	29.57	34.79	28.27	26.54	24 86	18.96	37.31	30.94	30.23	36.61	32.12	36.15	41.27	44.05
560	24.72	30.29	25.98	29.12	22 88	21.78	27.48	18.63	35.80	28.97	27.54	33.05	28.16	30.75	40.78	44.74
570	22.77	26.17	23 02	24 81	18 86	18.43	31.20	23.47	31.97	26.72	25.21	28.83	24.88	26.44	41.24	44.82
580	20 82	22.02	20.06	20.49	14.84	15.08	34.92	28.33	28.14	24.48	22.87	24.61	21.60	22.12	41.70	44.88
590	19.28	18.23	17.99	16 84	12.03	12.44	37 08	35.75	24.26	23.21	21.18	20.55	19.11	18.31	41.50	43.09
600	17.74	14.45	15 91	13.18	9 22	9 82	39 24	43 21	20.37	22.00	19.49	16.52	16 63	14.51	41.30	41.28
610	16.70	13.16	14.76	12.02	8.03	8 96	39.72	45 39	18.43	21.37	18.40	15.21	15.31	13.29	41.21	40.63
620	15 67	11.83	13.61	10.84	6 84	8.12	40.19	47.63	16.48	20 84	17.31	13.91	13.98	12.07	41.13	39.95
630	15.04	11.52	13.07	10.67	6 66	8.08	41.33	49.22	16.15	21.26	16.68	13.72	13.50	11.90	42.40	40.00
640	14.41	11.24	12.53	10.50	6.49	8.04	42.46	50.79	15 82	21.67	16.06	13.54	13.01	11.73	43.68	40 06
650	15 43	9 28	12.58	8.71	5.70	6.85	46.55	55 13	13 92	24 89	17.12	11.30	12.38	9.74	48.35	36.00
660	16.45	7.35	12.63	6.92	4.91	5.65	50 63	59.45	12 02	28.07	18.19	9.06	11.75	7.75	53.02	31.97
670	20.49	6.60	13.97	6.23	4 42	5.17	57.81	65.77	10.53	34 43	22.30	8.17	11.77	6 98	60.62	29.90
680	24.53	5 86	15.31	5 55	3 94	4.69	65 00	72 08	9 03	40.78	26.40	7.29	11.80	6.22	68.23	27.84
690	31.36	10.84	20.91	10.33	5 85	8 78	71.25	77.69	12.71	48 41	33.21	13.14	16.42	11.47	74.18	37.87
700	38.20	15.83	26.51	15.11	7.76	12 85	77.51	83.29	16.38	56.02	40.02	18.99	21.04	16.72	80.12	47.90

Appendix E4: Spectral reflectance values for the 36-pair set generated in Chapter 5

Pair No.	1		2		3		4		5		6		7		8		9		10	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	15.84	21.54	14.60	17.93	13.83	8.74	15.31	9.18	16.23	10.51	17.43	31.13	15.73	24.69	13.83	22.13	11.49	20.92	16.18	12.12
410	15.62	20.97	14.36	17.74	13.54	10.02	14.95	10.55	15.90	11.99	17.19	29.20	15.57	23.76	13.59	20.75	11.21	18.91	15.78	11.71
420	15.41	19.98	14.13	17.36	13.24	12.13	14.59	12.82	15.57	14.34	16.95	26.03	15.41	21.94	13.35	19.09	10.93	16.73	15.39	11.52
430	15.36	18.78	14.09	16.77	13.17	14.31	14.48	15.26	15.47	16.67	16.87	22.02	15.36	19.81	13.29	16.93	10.89	14.39	15.28	11.94
440	15.32	17.19	14.05	15.80	13.10	15.84	14.36	17.11	15.37	18.21	16.78	18.91	15.32	17.22	13.24	14.99	10.85	12.61	15.18	13.13
450	15.55	15.66	14.37	14.74	13.54	15.77	14.76	17.21	15.73	18.01	16.93	16.24	15.38	15.02	13.48	13.23	11.26	11.12	15.63	15.26
460	15.79	14.02	14.68	13.46	13.99	14.23	15.16	15.66	16.08	16.28	17.07	13.70	15.44	12.98	13.71	11.50	11.67	9.70	16.08	17.77
470	15.86	12.62	14.91	12.27	14.56	12.47	15.74	13.82	16.52	14.33	17.02	12.12	15.16	11.21	13.80	10.36	12.18	8.80	16.78	20.29
480	15.93	12.05	15.14	11.79	15.14	11.70	16.31	12.99	16.95	13.46	16.97	11.70	14.89	10.27	13.88	10.08	12.69	8.66	17.47	21.60
490	15.80	11.94	15.18	11.74	15.69	11.52	16.88	12.80	17.31	13.23	16.70	11.48	14.38	10.04	13.77	9.93	13.14	8.66	18.22	22.01
500	15.67	11.58	15.23	11.41	16.25	11.11	17.46	12.38	17.68	12.77	16.42	10.84	13.87	9.74	13.65	9.48	13.59	8.40	18.96	21.66
510	15.46	11.48	15.17	11.33	16.55	11.05	17.80	12.32	17.77	12.66	16.07	10.89	13.43	9.45	13.52	9.56	13.94	8.64	19.32	20.63
520	15.25	12.80	15.11	12.65	16.85	12.67	18.14	14.03	17.87	14.27	15.71	12.94	12.99	10.14	13.39	11.23	14.29	10.58	19.69	19.31
530	14.97	15.82	14.87	15.64	16.51	16.68	17.84	18.14	17.36	18.05	15.32	17.15	12.74	12.56	13.28	14.46	14.32	14.72	18.85	17.83
540	14.69	18.56	14.63	18.28	16.17	20.75	17.54	22.11	16.84	21.40	14.93	20.25	12.50	15.97	13.17	17.19	14.36	18.71	18.01	16.36
550	14.84	19.34	14.75	18.94	15.75	21.44	16.96	22.57	16.12	21.30	14.76	19.35	12.93	18.13	13.67	18.13	14.70	19.44	16.65	15.06
560	15.00	18.73	14.87	18.27	15.33	18.71	16.38	19.61	15.40	18.18	14.59	17.89	13.37	18.44	14.17	17.89	15.04	19.00	15.29	14.01
570	16.12	17.68	15.86	17.23	15.38	16.64	16.32	17.42	15.17	15.99	15.41	17.61	15.18	17.79	16.01	17.38	16.35	19.23	14.28	13.14
580	17.25	16.81	16.86	16.38	15.43	16.16	16.25	16.87	14.94	15.43	16.22	17.58	16.99	17.07	17.84	17.08	17.67	19.51	13.26	12.44
590	17.55	16.34	17.06	15.93	15.21	16.07	15.96	16.72	14.58	15.26	16.38	17.59	17.76	16.65	18.60	17.04	18.07	19.77	12.62	12.03
600	17.84	16.21	17.27	15.82	14.98	16.05	15.67	16.68	14.21	15.22	16.54	16.28	18.53	16.53	19.36	17.18	18.48	16.53	11.98	11.84
610	17.86	16.29	17.27	15.89	14.91	14.82	15.53	15.40	14.06	14.01	16.46	12.67	18.65	16.59	19.47	17.52	18.52	14.69	11.80	11.89
620	17.88	16.58	17.27	16.17	14.83	11.46	15.39	11.93	13.91	10.76	16.38	10.24	18.78	16.87	19.59	18.30	18.56	12.00	11.62	12.30
630	18.82	17.33	18.19	16.91	15.65	9.23	16.06	9.64	14.56	8.66	17.10	10.80	19.82	17.60	20.62	19.98	19.51	12.60	12.19	13.55
640	19.77	19.00	19.11	18.56	16.47	9.78	16.72	10.23	15.21	9.21	17.82	15.15	20.88	19.25	21.65	22.68	20.45	17.35	12.76	16.14
650	23.39	21.67	22.66	21.18	19.77	13.87	19.66	14.49	18.09	13.18	20.94	25.05	24.73	21.93	25.51	27.35	24.01	27.88	15.40	20.68
660	27.01	26.29	26.21	25.74	23.06	23.31	22.59	24.18	20.97	22.39	24.07	25.04	28.60	26.55	29.36	27.32	27.56	27.86	18.04	27.18
670	34.43	26.28	33.51	25.74	30.08	23.32	29.01	24.19	27.37	22.41	30.98	25.04	36.35	26.54	37.08	27.32	34.79	27.84	24.12	35.66
680	41.86	26.28	40.81	25.74	37.10	23.34	35.43	24.20	33.77	22.42	37.89	25.04	44.10	26.54	44.79	27.31	42.01	27.84	30.20	44.29
690	50.69	26.28	49.57	25.74	45.83	23.34	43.77	24.21	42.21	22.43	46.78	25.04	52.93	26.53	53.58	27.30	50.56	27.83	38.40	54.28
700	59.52	26.29	58.33	25.74	54.55	23.34	52.11	24.22	50.65	22.43	55.68	25.04	61.76	26.54	62.37	27.31	59.11	27.83	46.61	54.29

Pair No.	11		12		13		14		15		16		17		18		19		20	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	22.27	36.20	16.05	14.48	3.71	2.88	25.24	17.05	28.13	46.03	22.68	15.06	17.75	9.72	26.16	19.25	15.50	18.35	4.54	3.41
410	22.25	34.72	15.94	14.92	3.59	2.79	24.85	19.14	28.16	44.19	22.34	16.06	17.24	10.42	26.01	18.95	15.44	18.92	4.40	3.31
420	22.22	31.62	15.83	15.23	3.46	2.60	24.46	22.39	28.19	40.31	21.99	18.05	16.74	11.94	25.86	18.93	15.38	19.08	4.26	3.08
430	22.20	27.92	15.77	15.47	3.49	2.53	24.33	25.60	28.11	35.74	21.93	21.06	16.59	14.55	25.79	19.84	15.82	19.43	4.32	3.00
440	22.18	23.95	15.72	15.62	3.53	2.70	24.20	27.80	28.03	30.94	21.87	23.93	16.45	17.50	25.73	21.97	16.26	20.02	4.38	3.19
450	22.03	20.94	15.70	15.67	4.24	3.30	24.67	27.78	28.12	27.32	22.41	25.67	16.99	20.07	26.44	25.70	19.38	21.02	5.29	3.91
460	21.88	18.28	15.67	15.56	4.94	4.69	25.14	25.69	28.22	23.92	22.95	25.31	17.54	20.64	27.15	30.17	22.50	22.78	6.21	5.59
470	21.20	16.22	15.27	15.55	7.13	7.13	25.82	23.21	28.07	21.19	23.59	23.10	18.42	19.12	28.43	34.92	29.35	24.93	8.92	8.63
480	20.52	15.35	14.87	15.47	9.32	11.80	26.49	22.07	27.93	20.02	24.23	20.66	19.31	17.09	29.72	37.49	36.21	27.68	11.62	14.79
490	19.58	15.07	14.25	15.01	12.62	17.78	27.14	21.81	27.53	19.81	24.74	19.60	20.30	16.24	31.12	37.74	40.91	30.80	15.93	23.72
500	18.64	14.50	13.63	14.59	15.92	22.70	27.79	21.23	27.13	19.39	25.26	19.39	21.30	16.10	32.52	36.49	45.61	34.69	20.24	32.34
510	17.78	14.23	13.14	14.68	18.81	24.09	28.15	21.15	26.63	19.38	25.63	18.92	22.29	15.71	33.06	34.63	43.43	38.64	25.56	35.72
520	16.92	15.40	12.65	14.82	21.71	23.15	28.52	23.50	26.14	21.65	25.99	18.99	23.27	15.86	33.61	32.49	41.25	41.32	30.69	35.56
530	16.21	18.01	12.40	14.29	22.22	21.43	28.10	28.78	25.84	27.09	25.96	21.63	23.83	18.46	32.24	30.38	37.21	41.68	34.85	34.18
540	15.51	19.82	12.14	13.54	22.74	19.50	27.68	33.44	25.54	32.87	25.93	27.77	24.39	24.80	30.87	28.43	33.16	39.47	38.82	32.44
550	15.12	19.44	12.59	12.97	21.09	17.63	26.92	33.81	25.65	34.61	26.26	34.20	24.98	32.31	28.59	26.38	29.57	35.03	37.31	30.78
560	14.74	17.39	13.03	12.42	19.43	16.02	26.16	30.22	25.76	31.73	26.60	36.34	25.57	35.97	26.30	24.05	25.98	29.54	35.80	28.95
570	15.23	15.89	14.89	11.83	17.28	14.75	26.02	27.47	26.90	29.15	28.11	33.73	27.82	34.44	23.92	21.79	23.02	24.66	31.97	26.78
580	15.73	15.51	16.75	11.51	15.13	13.73	25.88	26.76	28.05	28.48	29.63	31.32	30.07	32.44	21.54	20.18	20.06	20.69	28.14	24.64
590	15.71	15.49	17.53	12.02	13.67	12.97	25.50	26.56	28.19	28.25	30.06	30.75	31.09	32.01	19.94	19.26	17.99	17.01	24.26	23.11
600	15.69	15.80	18.32	13.74	12.22	12.52	25.12	26.50	28.33	28.14	30.49	30.61	32.12	31.95	18.33	18.56	15.92	13.24	20.37	22.24
610	15.60	15.43	18.41	17.06	11.39	12.34	24.94	24.84	27.86	28.37	30.53	30.56	32.19	31.91	17.37	17.92	14.77	11.28	18.43	21.60
620	15.50	13.00	18.50	21.89	10.57	12.43	24.75	20.10	27.40	21.40	30.57	28.74	32.27	30.09	16.41	17.68	13.61	10.82	16.48	20.98
630	16.22	11.02	19.45	28.22	10.06	12.88	25.55	16.75	27.59	17.84	31.73	23.60	33.21	24.83	15.98	18.55	13.07	10.71	16.15	20.76
640	16.95	11.81	20.39	34.67	9.56	14.19	26.34	17.60	27.78	18.64	32.88	19.83	34.14	20.94	15.55	20.92	12.53	10.70	15.82	21.69
650	20.03	16.47	24.07	42.08	10.27	16.84	29.82	23.57	30.83	24.72	37.19	20.66	37.98	21.77	16.98	25.13	12.58	9.84	13.92	24.21
660	23.12	26.72	27.75	42.14	10.98	21.41	33.29	35.51	33.87	36.82	41.49	27.02	41.81	28.22	18.42	30.80	12.63	7.46	12.02	28.57
670	29.81	26.72	35.32	42.18	14.16	27.86	40.62	35.53	40.35	36.82	49.45	39.30	49.35	40.52	22.93	37.74	13.97	5.93	10.53	34.27
680	36.51	26.72	42.90	42.20	17.33	36.11	47.95	35.54	46.84	36.82	57.41	39.30	56.88	40.51	27.44	44.37	15.31	6.30	9.03	41.02
690	45.10	26.72	51.80	42.22	23.09	44.33	56.40	35.56	53.78	36.83	65.03	39.30	64.46	40.51	34.41	51.55	20.91	9.20	12.71	47.26
700	53.69	26.73	60.70	42.23	28.86	53.53	64.86	35.56	60.72	36.83	72.65	39.31	72.04	40.52	41.38	51.56	26.51	16.51	16.39	53.79

Pair No.	21		22		23		24		25		26		27		28		29		30	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	21 21	28.21	2 67	2.34	8 91	9 99	8.80	7.33	11.95	13.02	23.97	28 02	14.58	14 93	5.02	2.85	11 23	8.91	12.32	9.33
410	22 54	26.58	2 66	2 28	9 10	9 58	9 00	7.35	12.39	12.79	25 80	27.26	15.08	14 83	5.20	3 38	11.00	8 67	12 14	9.15
420	24.18	25 43	2 66	2.15	9 38	9 44	9 32	7.69	12.92	12.25	27.41	26 73	15 65	14.33	5.39	4.44	11.28	8.59	11.75	8 92
430	26.20	24 63	2.80	2.12	10 00	9 52	9.95	8 41	13 93	12.12	28 98	26.53	16.51	14 21	5.93	6.11	12.12	8 67	11.46	8 86
440	26.94	24.21	3.04	2 27	10 87	10 03	10.76	9.28	15.41	12.88	29.82	26 69	17 63	14 96	6 81	8 59	12.03	9 04	10 88	8 94
450	26.20	24.16	3 45	2.72	11 91	11 00	11.67	10 57	17.54	14.96	29 84	27.57	19 02	16 81	8.12	10 52	10 96	9.76	10 10	9.33
460	24 66	24.40	4.03	3 65	13 02	12.21	12.51	12.22	20 46	19.07	29 32	29.16	20 68	20.19	9 85	10.79	9.54	10.61	9 30	10.11
470	22.99	24.83	4 56	5 02	14 04	13 95	13.13	14 46	23 95	25.13	28 59	30 98	22.36	24 62	11.76	9 99	8 33	11.62	8.56	10.98
480	21.98	25.39	4 92	6 89	15.15	16 21	13 84	17.11	28.04	34.11	28 44	33.30	24 21	30.11	13.35	9.57	7.67	12.70	8 23	12.01
490	21.56	26.01	4.91	8 27	16.28	19 52	14 62	20 03	32 04	42.73	28 79	35.82	25 98	34 40	13.99	9 48	7.56	13.84	8.28	13.10
500	21.10	26 61	4.70	8.53	17.17	23.91	15.16	22 79	35.35	48.40	29.24	38 85	27.31	37.05	13.69	9.16	7.52	14 54	8.31	14.22
510	21.36	26.94	4.53	7.89	18.80	29 08	16.43	24 67	38.61	50.41	30 85	41.82	29.29	38.38	12.94	9.06	8.16	14.91	9.02	15.16
520	24 24	26.77	4.54	7.42	24 20	34.32	20.86	26.04	44.46	50.81	36.41	44 06	34.84	39.31	12.19	10.13	11.27	15.55	12.20	16.21
530	27.68	26.16	4 64	7.38	34.16	38.70	28 33	28.15	51.89	50.73	44 86	45.27	42.96	40.20	11.63	12.58	17.10	15 83	17.90	17.15
540	27.83	25.24	5 03	7.30	45.17	41.94	34.77	30.80	57.04	50.47	51.25	45.37	48 44	40.89	11.31	14.73	22.10	15.22	22 55	17 26
550	26.54	23.84	6.39	7.16	52 46	44.52	37.28	32.06	58.71	50.22	53.04	44.62	48 99	41.08	11.28	15.24	23.25	14.90	23 92	17.05
560	26.73	22.78	10.00	7.86	55 29	46 24	37.14	31.92	58.12	49.73	51.64	43.28	46.53	40.44	11.59	14.69	21.59	16 04	23.17	17.71
570	26.70	22.35	17.48	10.73	54.74	46 52	35 87	31.45	55.94	48.74	48.21	41 51	42.35	39.14	12.29	13.84	16 66	17.75	20.87	18 97
580	24.26	22.26	28.22	17.60	51.74	46.08	34.10	30.78	52.14	47.45	43.39	39 53	36.98	37.33	12 95	13 17	15.41	17.41	17.26	18.78
590	21.71	22.84	39.18	28.90	47 99	45 63	32 61	29.96	48.02	46.47	38.91	37.89	32.05	34 58	13.49	12.81	12.96	14 68	13 90	16 54
600	21.65	23.40	47.54	42.41	44 84	45 06	31 63	29 58	44.70	45.98	35.59	36.87	28 55	30.35	14 08	12 73	11 36	12.85	11 60	13.13
610	22.85	22.20	51.64	54.18	42.59	44.33	31.16	30.59	42.36	45.59	33.11	36.08	26.31	27.73	14.65	12.81	10.10	12.42	10.18	11.23
620	22.32	20.85	52.46	61.24	39 63	44 00	30.93	33 50	39.31	45.12	29.94	35.32	23 61	27.20	15.00	13.05	8 39	12.30	8 61	10.80
630	20.12	22.78	50.44	64.77	35.45	45.05	30.80	38.41	35.11	45.03	26.11	35.06	20.10	27.18	15.12	13 67	6 72	12.23	6 73	10.70
640	19.03	29.51	47.89	66 90	32.10	47.92	31.09	44.54	31.76	46.26	23.67	36.23	17.44	27.26	15 68	15 06	6 07	11.19	5.47	10.68
650	21.00	41.21	47.67	66 83	31.76	52 57	32 07	51 40	31.52	49.22	24.31	39.26	17.24	25 68	17.48	17.33	7.02	8.46	5.43	9.76
660	27.20	41.29	51.93	70.43	36.02	58.04	34 12	57.44	35.86	53.85	29.11	44.22	20.60	20 91	21.34	21.37	10.22	6.71	7.07	7.34
670	37.12	41.33	59.79	71.81	44 32	63 79	37.26	63 50	44.25	59.19	37.60	50.24	27.33	17.48	27.62	21.36	16.18	7.10	10 61	5 80
680	49.70	41.36	66.88	73.08	55.17	68 60	41.70	63 55	55.24	64.77	48.75	56 83	36.92	18.31	36.58	21.37	24.94	10.28	16 38	6.15
690	63.66	41.38	76.76	74.29	67.00	73.19	47.35	63.59	67.23	69.39	61.67	62.51	49.39	24.34	47.84	21.36	36 85	18.17	25.17	9 00
700	76.80	41.39	82.56	75.17	77.73	73 24	53 88	63 62	78.22	73.74	74.47	68.14	63.72	36.37	59 67	21.36	51.16	18.17	36.92	16.21

Pair No.	31		32		33		34		35		36	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	9 03	6.27	21.42	28.30	25.49	31.13	12.14	12 98	13.88	13.66	5.15	5.49
410	8.65	6.25	23.13	26.45	28.16	31.06	12.42	12.76	14 08	13.53	5.26	5.37
420	8.13	6.14	24.52	24 91	31.03	30.59	12 93	12.23	14 44	13.00	5.47	5.13
430	7.80	6.14	25.54	23.84	34.21	30 62	13 89	12.12	15.15	12.85	5.91	5 04
440	7.39	6.24	25.62	23.12	36.21	31.76	15.39	12.91	16.07	13.50	6.50	5.27
450	6.93	6.54	24.67	22.78	36.63	33 82	17.58	15.07	17.20	15.19	7.15	5 98
460	6.54	7.11	23.07	22.86	35.74	36.49	20 62	19.40	18.58	18.34	7.70	7.32
470	6.18	7.73	21.43	23.25	34.09	38 61	24.46	25.82	20.02	22.47	7.99	9.06
480	6.04	8.43	20.39	23.82	32 47	39.14	29.17	35.47	21.78	27.59	8.23	11.09
490	6.13	9.16	19.95	24.52	31.03	37.92	34 34	44.93	23.90	31.58	8 51	12.40
500	6.13	9.84	19.66	25.33	29.40	35.59	39.72	51.02	26.26	34.09	8.56	12.96
510	6.61	10.34	20.20	26.19	28 35	32.49	44 68	52.61	29.07	35.45	8.95	12.86
520	8.76	10.91	23.14	27.05	28.89	30.21	48.98	52.58	33.65	36.46	10.81	12.31
530	12.32	11.38	27.34	27.82	29.59	29.53	52 61	52.16	39.26	37.46	13.18	11.59
540	14.78	11.21	30.31	28.39	29 52	29 04	55 50	51.22	43.36	38.29	13.73	10.78
550	14.91	10.76	31.75	28 85	30.35	27.97	57.20	50.42	44.76	38.70	12.78	9.99
560	13.75	10.89	32 87	29 35	33 88	27.95	57.63	50.37	43.75	38.33	11.40	9.31
570	11.90	11.27	34.21	29.83	38.88	30.88	56 67	50.46	40.70	37.30	10.14	8.78
580	9.50	10.70	35.34	30.31	41.11	36.10	53.86	49.82	35 94	35.73	8.93	8.37
590	7.37	9.00	36.26	31.15	40.42	39 85	50 32	48.88	31.26	33.19	8.01	8.06
600	5.95	6.79	37.25	33.20	38.78	40.80	47.29	48.17	27.81	29.16	7.45	7.89
610	5.09	5 65	38.20	37.03	36.61	40.18	45.13	47.50	25.63	26.65	7.15	7.86
620	4 24	5.44	38.78	42.93	33.09	39.27	42.22	46.76	22.97	26.20	7.00	7.94
630	3.34	5.44	39.06	50.05	29.31	38 70	38 02	46 49	19.50	26.23	6.91	8.24
640	2.82	5.46	40.09	57.76	27.68	38.57	34.54	47.60	16.75	26.36	6.95	9.15
650	2.86	4.97	42.89	64.39	29.89	38.73	34.13	50.48	16.46	24.85	7.31	11.06
660	3.64	3.66	48.29	70.92	36.99	39.20	38.35	55.00	19.66	20.21	8.18	14 57
670	5.46	2.85	56.01	71.00	48 08	40.30	46 66	60.24	26.20	16 85	9.61	19.92
680	8.93	3.05	64.91	71.08	60.96	42.59	57.43	65.67	35.56	17.67	11.83	27.44
690	15.08	4.59	72.93	71.13	73.07	45 97	68 87	70.17	47.83	23.61	15.05	35.68
700	24.02	8.92	78 81	71.17	82.56	51.17	78.98	74.39	62.10	35.52	19.32	45.85

Appendix E5: Spectral reflectance values for the 54-pair set generated in Chapter 5

Pair No.	1		2		3		4		5		6		7		8		9		10	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	14.49	8.98	15.84	32.67	14.60	31.15	13.62	7.52	13.81	7.02	13.83	8.74	15.31	29.27	16.23	32.01	17.65	12.76	18.26	22.97
410	14.26	11.29	15.62	29.64	14.36	27.91	13.31	9.63	13.52	9.07	13.54	10.03	14.95	26.30	15.90	28.44	17.38	15.50	18.05	24.52
420	14.02	14.11	15.41	25.47	14.13	23.75	13.00	12.37	13.23	11.86	13.24	12.13	14.59	22.77	15.57	24.37	17.12	18.42	17.83	24.68
430	14.00	16.68	15.36	20.79	14.09	19.29	12.94	15.20	13.17	15.02	13.17	14.31	14.48	19.14	15.47	20.31	17.04	20.44	17.75	22.89
440	13.98	17.29	15.32	17.42	14.05	16.10	12.88	16.23	13.12	16.46	13.10	15.85	14.36	16.43	15.37	17.34	16.96	20.35	17.67	20.43
450	14.34	16.02	15.55	14.66	14.37	13.48	13.29	15.24	13.54	15.69	13.54	15.77	14.76	13.97	15.73	14.71	17.19	18.59	17.81	17.74
460	14.70	13.77	15.79	12.19	14.68	11.25	13.70	13.12	13.96	13.60	13.99	14.22	15.16	12.16	16.08	12.79	17.43	16.00	17.96	15.01
470	15.01	12.18	15.86	10.68	14.91	10.00	14.19	11.60	14.48	12.09	14.56	12.48	15.74	11.52	16.52	12.12	17.52	14.21	17.87	13.29
480	15.32	11.74	15.93	10.31	15.14	9.72	14.69	11.19	14.99	11.69	15.14	11.70	16.31	11.49	16.95	12.09	17.62	13.69	17.78	12.84
490	15.47	11.47	15.80	10.11	15.18	9.54	15.13	10.96	15.43	11.47	15.69	11.51	16.88	11.23	17.31	11.80	17.50	13.35	17.46	12.58
500	15.62	10.82	15.67	9.57	15.23	9.15	15.57	10.36	15.88	10.87	16.25	11.11	17.46	11.27	17.68	11.82	17.38	12.60	17.13	11.90
510	15.56	10.82	15.46	9.69	15.17	9.53	15.83	10.43	16.11	10.92	16.55	11.05	17.80	13.02	17.77	13.51	17.09	12.53	16.71	11.89
520	15.50	12.72	15.25	11.79	15.11	11.87	16.09	12.50	16.35	12.97	16.85	12.67	18.14	17.28	17.87	17.51	16.80	14.46	16.28	13.90
530	15.06	16.51	14.97	16.33	14.87	16.45	15.91	16.84	16.08	17.15	16.51	16.68	17.84	21.74	17.36	21.36	16.24	18.14	15.76	17.82
540	14.62	19.03	14.69	20.34	14.63	20.22	15.73	20.35	15.81	20.27	16.17	20.75	17.54	22.69	16.84	21.73	15.68	20.18	15.24	20.28
550	14.32	17.82	14.84	20.26	14.75	19.91	15.66	19.85	15.60	19.44	15.75	21.44	16.96	19.98	16.12	18.78	15.17	18.48	14.90	18.88
560	14.02	16.28	15.00	19.10	14.87	18.66	15.58	18.56	15.39	18.01	15.33	18.70	16.38	17.87	15.40	16.59	14.66	16.73	14.55	17.22
570	14.26	15.92	16.12	18.91	15.86	18.43	16.16	18.33	15.74	17.71	15.38	16.64	16.32	17.38	15.17	16.02	14.81	16.28	15.02	16.83
580	14.50	15.83	17.25	18.90	16.86	18.40	16.74	18.32	16.10	17.64	15.43	16.16	16.25	17.27	14.94	15.82	14.95	16.14	15.49	16.72
590	14.35	15.82	17.55	18.92	17.06	18.42	16.73	18.36	16.00	17.65	15.21	16.06	15.96	17.24	14.58	15.74	14.77	16.10	15.47	16.69
600	14.21	14.59	17.84	17.55	17.27	17.07	16.72	17.05	15.90	16.34	14.98	16.05	15.67	15.93	14.21	14.46	14.59	14.62	15.44	15.40
610	14.17	11.25	17.86	13.74	17.27	13.33	16.67	13.35	15.85	12.74	14.91	14.82	15.53	12.37	14.06	11.10	14.47	11.41	15.35	11.90
620	14.13	9.05	17.88	11.16	17.27	10.80	16.63	10.84	15.80	10.32	14.83	11.46	15.39	9.98	13.91	8.90	14.35	9.19	15.26	9.59
630	15.00	9.61	18.82	11.75	18.19	11.36	17.52	11.43	16.71	10.91	15.65	9.23	16.06	10.49	14.56	9.45	15.05	9.78	15.97	10.16
640	15.87	13.70	19.77	16.37	19.11	15.83	18.41	15.95	17.62	15.33	16.47	9.78	16.72	14.72	15.21	13.48	15.75	13.95	16.69	14.39
650	19.15	23.10	23.39	26.67	22.66	25.94	21.92	26.05	21.17	25.26	19.77	13.87	19.66	24.44	18.09	22.85	18.74	23.51	19.77	24.07
660	22.42	23.13	27.01	26.67	26.21	25.93	25.43	26.05	24.72	25.27	23.06	23.32	22.59	24.43	20.97	22.87	21.73	23.54	22.86	24.09
670	29.18	23.14	34.43	26.66	33.51	25.93	32.69	26.05	32.03	25.28	30.08	23.33	29.01	24.42	27.37	22.88	28.25	23.56	29.58	24.10
680	35.93	23.15	41.86	26.67	40.81	25.92	39.95	26.05	39.34	25.29	37.10	23.33	35.43	24.42	33.77	22.89	34.77	23.57	36.31	24.10
690	44.32	23.16	50.69	26.67	49.57	25.92	48.70	26.06	48.13	25.29	45.83	23.34	43.77	24.42	42.21	22.90	43.19	23.58	45.00	24.11
700	52.71	23.16	59.52	26.67	58.33	25.93	57.45	26.06	56.92	25.29	54.55	23.34	52.11	24.42	50.65	22.90	51.61	23.59	53.68	24.11

Pair No.	11		12		13		14		15		16		17		18		19		20	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	17.43	31.13	15.73	30.19	13.83	23.95	11.49	20.91	11.40	21.01	19.07	24.97	16.05	30.25	10.76	10.25	9.09	9.46	3.71	2.88
410	17.19	29.20	15.57	28.87	13.59	22.31	11.21	18.91	11.07	19.25	18.99	26.07	15.94	29.12	10.53	10.25	8.91	9.43	3.59	2.79
420	16.95	26.02	15.41	25.46	13.35	20.19	10.93	16.73	10.73	16.97	18.92	26.09	15.83	25.83	10.30	10.41	8.72	9.45	3.46	2.60
430	16.87	22.02	15.36	21.40	13.29	17.47	10.89	14.39	10.67	14.51	18.88	24.49	15.77	21.80	10.21	10.72	8.64	9.44	3.49	2.53
440	16.78	18.91	15.32	17.26	13.24	15.11	10.85	12.62	10.61	12.61	18.83	21.34	15.72	17.60	10.12	10.95	8.57	9.34	3.53	2.69
450	16.93	16.24	15.38	14.37	13.48	13.00	11.26	11.12	11.12	10.82	18.67	18.46	15.70	14.66	10.19	10.81	8.59	9.01	4.24	3.29
460	17.07	13.71	15.44	12.00	13.71	11.09	11.67	9.70	11.63	9.47	18.51	15.77	15.67	12.25	10.26	10.23	8.61	8.40	4.94	4.68
470	17.02	12.11	15.16	10.02	13.80	9.95	12.18	8.80	12.44	9.01	17.82	13.17	15.27	10.18	10.15	9.60	8.43	7.61	7.13	7.13
480	16.97	11.70	14.89	8.94	13.88	9.66	12.69	8.66	13.25	9.04	17.13	11.52	14.87	9.01	10.03	8.87	8.24	6.93	9.32	11.81
490	16.70	11.47	14.38	8.68	13.77	9.45	13.14	8.66	14.25	8.87	16.23	11.05	14.25	8.70	9.73	7.89	7.92	6.20	12.62	17.82
500	16.42	10.85	13.87	8.46	13.65	9.04	13.59	8.40	15.24	8.96	15.33	10.76	13.63	8.47	9.44	7.18	7.59	5.57	15.92	22.75
510	16.07	10.89	13.43	8.15	13.52	9.32	13.94	8.64	16.11	10.59	14.59	10.12	13.14	8.11	9.22	7.08	7.36	5.36	18.81	24.11
520	15.71	12.94	12.99	8.70	13.39	11.27	14.29	10.59	16.97	14.78	13.84	10.15	12.65	8.51	9.00	7.06	7.13	5.42	21.71	23.15
530	15.32	17.15	12.74	11.23	13.28	14.75	14.32	14.72	17.02	20.03	13.42	12.14	12.40	10.82	9.08	6.77	7.22	5.35	22.22	21.42
540	14.93	20.25	12.50	16.03	13.17	17.54	14.36	18.71	17.07	22.39	13.00	16.32	12.14	15.47	9.17	7.01	7.30	5.49	22.74	19.46
550	14.76	19.35	12.93	20.13	13.67	18.40	14.70	19.45	16.82	20.55	13.06	19.54	12.59	19.61	10.01	9.02	8.18	6.81	21.09	17.59
560	14.59	17.90	13.37	20.10	14.17	18.03	15.04	19.00	16.58	18.69	13.11	18.81	13.03	19.71	10.85	14.10	9.05	10.68	19.43	15.99
570	15.41	17.61	15.18	18.95	16.01	17.43	16.35	19.23	16.75	18.30	14.48	17.43	14.89	18.64	14.90	21.07	13.94	17.98	17.28	14.75
580	16.22	17.58	16.99	18.76	17.84	17.07	17.67	19.52	16.92	18.25	15.84	17.17	16.75	18.47	18.95	25.31	18.82	26.86	15.13	13.74
590	16.38	17.59	17.76	18.75	18.60	17.00	18.07	19.76	16.73	18.26	16.39	17.13	17.53	18.46	22.80	26.49	25.37	32.24	13.67	12.99
600	16.54	16.28	18.53	18.76	19.36	17.11	18.48	18.53	16.53	16.93	16.93	17.13	18.32	18.48	26.65	27.13	31.91	33.38	12.22	12.54
610	16.46	12.67	18.65	17.39	19.47	17.41	18.52	14.69	16.46	13.24	16.93	15.84	18.41	17.12	27.69	27.37	34.52	33.83	11.39	12.36
620	16.38	10.24	18.78	13.60	19.59	18.15	18.56	12.00	16.39	10.72	16.92	12.29	18.50	13.37	28.73	27.47	37.12	34.01	10.57	12.43
630	17.10	10.80	19.82	11.03	20.62	19.79	19.51	12.60	17.26	11.22	17.64	9.93	19.45	10.63	29.83	25.85	38.63	34.11	10.06	12.88
640	17.82	15.14	20.86	11.62	21.65	22.45	20.45	17.36	18.13	15.57	18.36	10.49	20.39	11.42	30.94	21.04	40.13	32.39	9.56	14.18
650	20.94	25.04	24.73	16.20	25.51	27.08	24.01	27.88	21.57	25.52	21.46	14.78	24.07	15.97	34.85	17.58	44.31	27.11	10.27	16.82
660	24.07	25.04	28.60	26.45	29.36	27.05	27.56	27.86	25.02	25.49	24.55	24.59	27.75	26.15	38.77	18.43	48.49	23.16	10.98	21.39
670	30.98	25.04	36.35	26.45	37.08	27.03	34.79	27.84	32.22	25.47	31.37	24.59	35.32	26.15	46.51	24.50	55.87	24.13	14.16	27.84
680	37.89	25.04	44.10	26.46	44.79	27.02	42.01	27.84	39.43	25.46	38.20	24.60	42.90	26.16	54.26	36.53	63.25	30.93	17.33	36.08
690	46.78	25.04	52.93	26.46	53.58	27.01	50.56	27.83	48.19	25.45	46.94	24.60	51.80	26.16	62.26	36.54	69.80	43.43	23.09	44.31
700	55.68	25.04	61.76	26.46	62.37	27.02	59.11	27.84	56.96	25.46	55.69	24.60	60.70	26.16	70.26	36.55	76.36	43.44	28.86	53.51

Pair No.	21		22		23		24		25		26		27		28		29		30	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	26.28	44.19	23.89	22.32	23.87	15.24	22.68	34.13	20.94	39.89	15.50	18.35	4.54	3.41	21.21	17.45	10.48	6.54	6.08	9.14
410	26.04	41.68	23.67	25.45	23.58	18.69	22.34	32.97	20.56	36.02	15.44	18.92	4.40	3.31	22.54	18.06	10.90	8.63	6.17	8.82
420	25.81	37.71	23.44	28.01	23.29	22.77	21.99	30.76	20.19	31.40	15.38	19.06	4.26	3.08	24.18	19.20	11.48	11.84	6.37	8.69
430	25.76	32.74	23.39	28.78	23.21	26.51	21.93	27.66	20.11	26.60	15.82	19.43	4.32	3.00	26.20	20.58	12.47	16.55	6.88	8.73
440	25.71	28.79	23.35	27.54	23.14	27.65	21.87	25.01	20.04	23.02	16.26	20.02	4.38	3.20	26.94	22.33	14.01	20.23	7.75	9.06
450	26.01	25.29	23.76	24.99	23.63	26.21	22.41	22.45	20.64	19.84	19.38	21.02	5.29	3.91	26.20	24.22	16.23	20.99	9.04	9.60
460	26.30	21.90	24.17	21.76	24.12	23.24	22.95	19.81	21.24	17.28	22.50	22.79	6.21	5.59	24.66	26.64	19.35	19.22	10.73	10.08
470	26.38	19.71	24.52	19.53	24.70	21.04	23.59	18.12	22.09	16.13	29.35	24.92	8.92	8.63	22.99	29.05	23.04	17.59	12.49	10.49
480	26.47	19.14	24.87	18.90	25.27	20.43	24.23	17.72	22.94	15.96	36.21	27.68	11.62	14.79	21.98	30.57	27.00	17.20	13.88	10.84
490	26.28	18.83	25.01	18.54	25.76	20.08	24.74	17.45	23.83	15.68	40.91	30.81	15.93	23.73	21.56	30.87	29.91	17.01	14.31	11.11
500	26.09	18.02	25.16	17.67	26.24	19.19	25.26	16.86	24.71	15.60	45.61	34.69	20.24	32.34	21.10	30.06	30.59	16.38	14.00	10.91
510	25.80	18.21	25.13	17.78	26.49	19.29	25.63	17.46	25.42	17.35	43.43	38.64	25.56	35.71	21.36	28.52	29.53	16.67	13.35	10.68
520	25.52	21.33	25.09	20.74	26.74	22.30	25.99	21.03	26.14	22.35	41.25	41.31	30.89	35.56	24.24	26.74	28.82	19.68	12.86	11.03
530	25.13	27.40	24.74	26.57	26.45	28.08	25.96	27.66	26.19	29.43	37.21	41.67	34.85	34.18	27.68	25.08	27.76	25.73	12.78	11.41
540	24.75	32.07	24.40	30.94	26.15	32.21	25.93	33.09	26.24	33.89	33.16	39.47	38.82	32.44	27.83	23.55	25.26	31.55	13.07	11.37
550	24.88	31.64	24.39	30.36	26.00	31.39	26.26	33.31	26.38	33.00	29.57	35.02	37.31	30.78	26.54	22.23	23.62	34.50	13.88	12.07
560	25.02	30.09	24.38	28.79	25.85	29.68	26.60	32.04	26.51	31.14	25.98	29.54	35.80	28.95	26.73	21.21	24.66	35.03	15.65	15.46
570	26.39	29.82	25.37	28.53	26.51	29.34	28.11	31.92	27.56	30.69	23.02	24.66	31.97	26.78	26.70	20.47	26.49	34.58	19.19	23.44
580	27.76	29.81	26.36	28.54	27.17	29.29	29.63	32.01	28.61	30.56	20.06	20.69	28.14	24.64	24.26	20.05	25.74	34.16	24.82	34.75
590	28.09	29.84	26.54	28.58	27.14	29.31	30.06	32.10	28.73	30.52	17.99	17.01	24.26	23.11	21.71	20.13	24.27	34.08	32.33	44.57
600	28.42	28.11	26.73	26.92	27.10	27.61	30.49	30.37	28.85	28.74	15.92	13.23	20.37	22.24	21.65	21.13	27.05	34.27	41.89	50.31
610	28.41	23.05	26.74	21.99	27.05	22.63	30.53	25.15	28.82	23.61	14.77	11.28	18.43	21.60	22.85	23.26	35.39	34.76	51.73	53.05
620	28.40	19.36	26.74	18.41	27.01	19.02	30.57	21.25	28.79	19.88	13.61	10.82	16.48	20.99	22.32	26.59	48.02	35.86	60.78	53.94
630	29.46	20.19	27.88	19.21	28.13	19.90	31.73	22.05	29.95	20.78	13.07	10.71	16.15	20.78	20.12	30.68	61.28	38.10	67.46	54.17
640	30.51	26.47	29.02	25.32	29.25	26.18	32.88	28.48	31.11	27.22	12.53	10.70	15.82	21.69	19.03	35.57	71.61	41.43	72.15	52.54
650	34.58	38.74	33.31	37.42	33.56	38.40	37.19	40.86	35.56	39.61	12.58	9.83	13.92	24.21	21.00	40.72	77.75	46.59	75.35	47.21
660	38.64	38.73	37.60	37.40	37.86	38.41	41.49	40.81	40.01	39.63	12.63	7.46	12.02	28.57	27.20	47.39	81.27	46.60	77.79	42.78
670	46.47	38.72	45.77	37.39	46.05	38.41	49.45	40.78	48.32	39.64	13.97	5.93	10.53	34.27	37.12	47.42	83.00	46.61	79.62	43.87
680	54.30	38.72	53.93	37.39	54.23	38.42	57.41	40.77	56.63	39.65	15.31	6.30	9.03	41.02	49.70	47.45	83.92	46.62	81.13	51.06
690	62.29	38.73	62.08	37.40	62.34	38.43	65.03	40.76	64.58	39.66	20.91	9.19	12.71	47.28	63.66	47.46	84.63	46.63	82.29	62.15
700	70.27	38.73	70.23	37.40	70.46	38.43	72.65	40.77	72.53	39.67	26.51	16.51	16.39	53.79	76.80	47.48	85.50	46.65	83.22	62.17

Pair No.	31		32		33		34		35		36		37		38		39		40	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	5.30	3.76	2.67	2.35	7.03	11.15	10.71	8.62	3.88	3.48	7.89	5.20	8.91	5.88	8.80	6.05	23.97	24.37	14.58	13.70
410	5.16	3.52	2.66	2.28	7.14	10.92	10.62	8.35	3.88	3.35	8.00	5.43	9.10	6.13	9.00	6.31	25.80	24.07	15.08	13.53
420	4.91	3.35	2.66	2.15	7.39	10.77	10.48	8.10	3.99	3.37	8.20	5.90	9.38	6.64	9.32	6.86	27.41	23.35	15.65	13.01
430	4.74	3.24	2.80	2.12	7.99	10.69	10.32	7.93	4.33	3.69	8.79	6.54	10.00	7.35	9.95	7.58	28.98	23.14	16.51	12.91
440	4.31	3.25	3.04	2.27	8.86	10.68	9.57	7.78	4.99	4.44	9.61	7.53	10.87	8.45	10.76	8.66	29.82	23.99	17.63	13.68
450	3.74	3.41	3.45	2.72	10.10	10.65	8.36	7.65	6.13	5.96	10.64	8.93	11.91	10.02	11.67	10.10	29.84	26.24	19.02	15.80
460	3.16	3.65	4.03	3.65	11.57	10.45	7.11	7.80	8.05	8.44	11.85	11.21	13.02	12.50	12.51	12.26	29.32	30.11	20.68	19.91
470	2.74	4.00	4.56	5.02	12.84	10.09	6.07	8.18	10.81	12.55	12.95	14.50	14.04	16.04	13.13	15.19	28.59	34.66	22.36	25.66
480	2.54	4.41	4.92	6.89	13.58	9.76	5.58	8.44	14.40	16.45	14.18	18.74	15.15	20.46	13.84	18.64	28.44	39.56	24.21	33.44
490	2.48	4.89	4.91	8.26	13.48	9.29	5.48	8.88	17.86	17.67	15.42	23.57	16.28	25.30	14.62	22.14	28.79	42.70	25.98	39.82
500	2.43	5.39	4.70	8.53	12.82	8.76	5.48	10.46	20.19	16.61	16.33	28.55	17.17	30.10	15.16	25.28	29.24	44.25	27.31	42.83
510	2.52	6.00	4.53	7.90	12.07	8.68	6.03	13.85	21.00	16.00	17.97	33.21	18.80	34.40	16.43	27.77	30.85	44.57	29.29	42.76
520	3.24	6.72	4.54	7.42	11.60	8.94	8.87	18.45	21.06	16.03	23.40	37.06	24.20	37.71	20.86	29.35	36.41	44.16	34.84	41.78
530	4.86	7.32	4.64	7.38	11.52	9.00	15.24	22.88	21.10	15.83	33.63	39.69	34.16	39.69	28.33	29.82	44.86	43.43	42.96	40.54
540	7.05	8.04	5.03	7.30	11.80	9.37	23.71	26.27	21.26	16.22	45.40	41.18	45.17	40.50	34.77	29.47	51.25	42.45	48.44	38.98
550	9.92	9.81	6.39	7.16	12.61	11.48	31.39	28.27	21.91	19.25	53.59	42.16	52.46	40.85	37.28	29.03	53.04	41.34	48.99	37.57
560	15.17	13.58	10.00	7.86	14.45	16.88	38.26	29.23	23.90	26.79	57.08	43.03	55.29	41.18	37.14	28.65	51.64	40.27	46.53	36.53
570	24.03	19.47	17.48	10.74	18.14	25.91	44.11	30.01	27.63	37.33	57.00	43.65	54.74	41.32	35.87	28.63	48.21	39.37	42.35	35.33
580	34.72	26.65	28.22	17.60	24.24	36.54	46.44	31.70	31.94	46.01	54.40	43.91	51.74	41.17	34.10	28.25	43.39	38.58	36.98	33.65
590	43.33	34.10	39.18	28.89	32.94	45.29	45.96	34.96	36.01	49.84	50.90	44.33	47.99	41.27	32.61	28.20	38.91	37.91	32.05	32.18
600	47.99	40.92	47.54	42.41	44.16	49.45	44.52	40.00	41.99	50.67	47.92	45.85	44.84	42.61	31.63	29.38	35.59	37.56	28.55	31.25
610	49.30	47.05	51.64	54.18	54.57	50.38	42.46	46.15	50.94	51.14	45.76	48.95	42.59	45.70	31.16	32.34	33.11	37.47	26.31	30.48
620	48.20	52.95	52.46	61.24	63.05	50.53	39.10	52.94	61.08	51.42	42.83	53.60	39.63	50.52	30.93	37.25	29.94	37.65	23.61	29.73
630	44.98	58.82	50.44	64.77	69.00	51.64	35.38	58.84	69.16	51.68	38.60	58.92	35.45	56.16	30.80	43.39	26.11	38.37	20.10	29.44
640	41.91	64.31	47.89	66.91	73.27	54.34	33.82	64.69	74.54	50.55	35.14	64.42	32.10	62.08	31.09	50.28	23.67	40.43	17.44	30.51
650	41.62	69.26	47.67	68.83	76.27	58.57	36.14	64.80	77.86	46.02	34.79	68.98	31.76	67.03	32.07	56.40	24.31	44.33	17.24	33.40
660	45.99	73.26	51.93	70.43	78.69	63.42	43.48	64.88	80.17	42.09	39.14	73.26	36.02	71.72	34.12	62.55	29.11	50.21	20.60	38.25
670	54.25	76.51	59.79	71.81	80.52	68.41	54.38	64.93	81.71	43.25	47.63	73.29	44.32	71.79	37.26	62.59	37.60	57.15	27.33	44.32
680	64.28	78.70	68.88	73.08	82.04	72.45	66.11	64.98	82.94	50.08	58.48	73.34	55.17	71.86	41.70	62.63	48.75	64.47	36.92	51.15
690	73.74	80.46	76.76	74.29	83.24	76.23	75.80	65.02	83.86	60.25	69.82	73.39	67.00	71.91	47.35	62.67	61.67	70.60	49.39	57.19
700	81.20	80.53	82.56	75.17	84.11	76.28	82.67	65.05	84.68	60.27	79.66	73.43	77.73	71.95	53.88	62.69	74.47	76.53	83.72	63.28

Pair No.	41		42		43		44		45		46		47		48		49		50	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	5.02	7.50	11.23	9.13	12 32	6.46	9 03	5 20	15.55	19.92	7.11	12.85	12.16	7.18	4.56	6 24	7 87	13 23	4 61	6 87
410	5.20	7 81	11.00	8.93	12.14	6 58	8 65	5.10	16.26	19.90	7.30	12.36	11 82	6.87	4.56	6.20	8 20	13 39	4 67	6.72
420	5.39	8.27	11.28	8.87	11 75	6.92	8.13	5.07	17.03	19 95	7.58	11.62	11.33	6.73	4.67	6.25	8 58	13.45	4.77	6.66
430	5 93	8 64	12.12	8 95	11.46	7 43	7.80	5.27	17 90	20.06	8 03	10.79	10.93	6 83	5.06	6.45	9.30	13.23	5.10	6 65
440	6.81	8.88	12.03	9.27	10.88	8 18	7.39	5.71	18.75	20.05	8.51	9.76	10.22	7.31	5.64	6 68	10.30	12.68	5.68	6 72
450	8.12	9 07	10.96	9 91	10.10	9.13	6.93	6.30	19 35	19.55	8.96	8 58	9.31	8.26	6.39	6.76	11.46	11.77	6.45	6.83
460	9 85	9.21	9.54	10 60	9.30	10 51	6 54	7.18	19.54	18 42	9.17	7.49	8.39	9 49	7.28	6.63	12.62	10 64	7 43	6.80
470	11.76	8.95	8.33	11.40	8.56	12.22	6.18	8.26	19.06	16.78	8.94	6.43	7.59	11.11	7.95	6.46	13 40	9 71	8 28	6.64
480	13.35	8.68	7.67	12.21	8 23	14 05	6.04	9.76	17.92	15.35	8.24	5.68	7.20	12.86	8.13	6.19	13.41	8.72	8.69	6.45
490	13.99	8.86	7.56	12.95	8.28	15 75	6.13	11.44	16.50	13 89	7.37	5.06	7.25	15.03	7.81	5.66	12.77	7.86	8.52	6.11
500	13.69	8 97	7.52	13.47	8 31	17.11	6.13	12.69	15.13	12.39	6.46	4.45	7.26	17.26	7.20	5.25	11.76	7.60	7.97	5.72
510	12.94	8.64	8.16	14.16	9 02	17.96	6.61	13.12	14.02	11.55	5.72	4 07	7.96	18.86	6.59	5.23	10.77	7.66	7.40	5.66
520	12.19	8.78	11.27	14.90	12 20	18.24	8.76	12.71	13.35	11.48	5.33	4.03	11.20	19.44	6.22	5 24	10.09	7.52	7.04	5 80
530	11.63	10.57	17.10	14.97	17.90	17.97	12.32	11.75	13.23	11.41	5.17	4.08	17.60	19.02	6.13	5.02	9.75	7.57	6 95	5.77
540	11.31	14.25	22.10	14.93	22.55	17.32	14.78	10.64	13.58	11.26	5.06	4.04	23.75	17.98	6.30	5.18	9 71	8.91	7.16	5.94
550	11.28	17.03	23.25	16.08	23 92	16.43	14 91	9.65	14.44	12.34	5.24	4.31	26.06	16.80	6.78	6 66	9.98	12.50	7.72	7.33
560	11.59	16.24	21.59	18.31	23.17	15.40	13.75	8.82	16.31	16.39	6.03	5.66	25.45	15.79	7.83	10.41	10.77	17.41	8 89	11.20
570	12.29	14.94	18.66	19.18	20.87	14 42	11.90	8.10	20.03	25.05	7.65	9.07	22.86	14.96	9.93	15.28	12.27	20.09	11.25	17.24
580	12.95	14.66	15.41	17.47	17.26	13.70	9.50	7.46	26.28	37.08	9.48	14.51	18.77	14.33	13.13	17.45	14.09	18 60	14 99	21 68
590	13.49	14.61	12.96	14.11	13.90	13.32	7.37	7.09	35.24	47.69	11.09	20.33	15.00	13.97	16.81	17.54	15.84	16.79	19.32	21.56
600	14.08	14.60	11.36	12.14	11 60	13 24	5.95	7.04	46.63	53.71	14.31	25.13	12.45	13.82	19.72	17.72	17.36	16.32	22.96	20 23
610	14.65	13.44	10.10	11.68	10.18	13 37	5.09	7.21	56.94	56 47	20.94	28.85	10.92	13.86	20.51	17.81	18.50	16.21	24 61	19.94
620	15.00	10.30	8.39	11.58	8 61	13.73	4.24	7.78	65.05	57.48	31.44	31.56	9.27	14.22	18.99	17.87	19.12	16.25	23.84	19 88
630	15.12	8.25	6.72	11 57	6.73	14 52	3.34	8.64	70.51	57 88	44.26	33.63	7.23	15.46	16.38	16 58	19.37	15.06	21.06	19.88
640	15 68	8.74	6.07	10 59	5 47	16.13	2 82	9.02	74.37	56.48	58.53	33.63	5.77	18.14	15.03	12 94	20 07	11.68	18 43	18.47
650	17.48	12.50	7.02	8 01	5.43	18 64	2.86	9.09	77.12	51.47	65.61	29.62	5.64	22.85	16.37	10.49	22.16	9.45	18 04	14 53
660	21.34	21 42	10.22	6.35	7 07	22 98	3.64	10.58	79.40	47.22	71.62	26.06	7.23	29.55	21.43	11.09	26.47	10.03	21.09	11.83
670	27.62	21.43	16.18	6.74	10.61	23.00	5.46	15.06	81.17	48 35	75.32	27.27	10.85	38.14	30.01	15 55	33.35	14 23	27.56	12.47
680	36.58	21.43	24.94	9 81	16.38	23.02	8 93	24.49	82.66	55.34	77.80	34.34	16.85	46.71	41.43	25.58	42.77	23 85	36 93	17.28
690	47.84	21.43	36.85	17.46	25.17	23.03	15.08	24.49	83 78	65.83	79.67	46.78	26.04	56.42	54 85	25.59	53.90	23.86	49.01	27.83
700	59.67	21.44	51.16	17.46	36.92	23.03	24.02	24.50	84.65	65 86	81.22	46.79	38.34	56.44	68.22	25.60	64.61	23.86	62.45	27 83

Pair No.	51		52		53		54	
(nm)	std	batch	std	batch	std	batch	std	batch
400	13.88	13.24	5.15	4.03	7.78	17.82	20.94	15.09
410	14.08	12.95	5.26	3.85	8.10	16.94	22.18	15.98
420	14.44	12.50	5.47	3.75	8.50	15.59	23.03	17.02
430	15.15	12.44	5.91	3.95	9.18	14.13	23 58	18.17
440	16.07	13.13	6.50	4.55	10.15	12.40	23.19	19.44
450	17.20	14.89	7.15	5.88	11.27	10.98	21.94	20.69
460	18.58	18.14	7.70	7.88	12.38	9.73	20.28	22 22
470	20.02	22.49	7.99	10.60	13.13	8.51	18.70	23.80
480	21.78	28.24	8.23	12.65	13.16	7.72	17.92	24.62
490	23.90	33.38	8.51	13.26	12.55	7.57	17.88	25.36
500	26.26	37.47	8.56	12.82	11 58	7.51	17.98	27.97
510	29.07	39.90	8.95	12.21	10 66	7.24	19.24	32 89
520	33.65	40.60	10 81	11 61	10.00	7.40	24.53	37.84
530	39.26	39 96	13.18	10.88	9.69	8.90	34.44	40.87
540	43.36	38.36	13.73	10.29	9.70	11.98	45.17	42.13
550	44.76	36.28	12.78	10.03	10.01	14.98	52.38	42.40
560	43.75	34.18	11.40	9.77	10.85	16.39	56 45	42.46
570	40.70	32.36	10.14	9.22	12.43	16.49	58.19	42.94
580	35 94	30.80	8.93	8.68	14.46	16.13	57 36	44.75
590	31.26	29.58	8 01	8.33	16.38	15.87	55.45	48.40
600	27.81	28.84	7.45	8 02	18.11	15.84	54.75	53.93
610	25 63	28 53	7.15	7.69	19.37	15.99	55.04	60.41
620	22.97	28.64	7.00	7.54	20.06	16.36	54.10	67.13
630	19.50	29.35	6.91	7.95	20.36	17.19	51.03	72.68
640	16.75	31.38	6.95	9.20	21.10	18 91	47.96	77.87
650	16.46	35.27	7.31	11.62	23.23	21.62	47.71	78.06
660	19.66	41.29	8.18	15.28	27.60	26 26	52.22	78 21
670	26.20	48.70	9.61	20.39	34 52	26.27	60.42	78.31
680	35.56	56.88	11.83	25.96	43 95	26.28	69.73	78.41
690	47.83	64.03	15.05	32.78	55 04	26.29	77.73	78.50
700	62.10	71.18	19.32	32.78	65 71	26.29	83 59	78.56

Appendix E6: Spectral reflectance values for Set 1 generated in Chapter 5

Pair No.	1		2		3		4		5		6		7		8		9		10	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	2 67	5.35	6 47	12.37	9.03	3 35	3 52	3.43	6.10	3 62	4 25	2.49	3.58	2.06	5.44	2.98	15 84	20.57	14 60	18 62
410	2.66	5.19	6.71	12.33	8 65	3 44	3.98	3 68	5 83	3.43	4 08	2.38	3.47	1.96	5.19	2.80	15.62	20.05	14.36	18.13
420	2.66	4.95	7.01	12.10	8.13	3.61	4.29	3 79	5 55	3.22	3.91	2.26	3.36	1.81	4.94	2.57	15.41	19.52	14.13	17.64
430	2.80	4.77	7.61	11.76	7.80	3 98	4 31	3 83	5 47	3 26	3.86	2.26	3.33	1.78	4.87	2.54	15.36	18.14	14 09	16.52
440	3 04	4.30	8 48	10 80	7.39	4 59	3.90	3 75	5.39	3.28	3.82	2.25	3.31	1.72	4.80	2.49	15.31	16.75	14.05	15.39
450	3.45	3.65	9 63	9.60	6.93	5.64	3.30	3.47	5.74	4 40	4.02	2.92	3.46	2.22	5.12	3.41	15.55	15.42	14.37	14 33
460	4.03	3.08	10.92	8.54	6 54	7.33	2.73	3.00	6 08	5.58	4.22	3 62	3.62	2.80	5.43	4.44	15.79	14.10	14 68	13.28
470	4.56	2.65	11.86	7.88	6.18	9.70	2.34	2.57	6.91	9.52	4.67	6.68	4.04	5.84	6.18	8.79	15.86	13.49	14.91	12.81
480	4.92	2.44	12.28	7.77	6 04	12 72	2 09	2 30	7.73	13.48	5.13	9.75	4 45	8.88	6.94	13.14	15.93	12.89	15.14	12.35
490	4.91	2.37	11.99	7.87	6.13	15.17	1.95	2.10	9 32	16.21	5 98	11.26	5.42	11.45	8.48	17.05	15.80	12.86	15.18	12.41
500	4.70	2.36	10.93	7.90	6.13	15 60	1 87	1.96	10.92	18.92	6.83	12.74	6.38	13.97	10.03	20.91	15.67	12 83	15.23	12.47
510	4.53	2.54	10.00	8 31	6 61	14.32	1 83	1 87	13.51	18.07	8.25	11.71	8.45	13.59	12.90	20.40	15.46	13.33	15.17	13.04
520	4.54	3.52	9.89	10.45	8.76	12.90	1 83	1.83	16.11	17.21	9 66	10 69	10.53	13.19	15.76	19.85	15.25	13.85	15.11	13.63
530	4.64	6.06	9.91	14.11	12.32	11.26	1 80	1.79	17.95	16.53	11.07	10.55	13 00	12.97	19.00	19.57	14.97	14.78	14.87	14 59
540	5 03	9.45	9 64	16 59	14 78	9.19	1.77	1.79	19.79	15 85	12.47	10.43	15.47	12.73	22.23	19.27	14.69	15.73	14.63	15.57
550	6.39	12.34	10.25	17.36	14 91	7.76	1 80	1.88	19 68	15.20	13 84	10.39	17.05	12 51	24 86	18.96	14 84	16.73	14.75	16 54
560	10.00	15.14	13.33	19 02	13.75	7.46	1.92	2.15	19.57	14 56	15.20	10.37	16.63	12 28	27.48	18.63	14.99	17.73	14 87	17.53
570	17.48	18.85	20.00	20.87	11.90	7.43	2 42	2 61	18.78	15.85	18.36	14.53	19 93	15.27	31.20	23.47	16.12	18.48	15.86	18 20
580	28.22	23 20	28.34	19 62	9.50	6.73	3 28	2 86	17.99	17.14	21.51	18.68	21.22	18.26	34 92	28 33	17.25	19 21	16 65	18 67
590	39.18	27.52	35.27	17.57	7.37	6 12	3 79	2 90	17.32	18.02	23.61	24.53	21.53	21.81	37.08	35.75	17.55	18.54	17.06	18.12
600	47.54	33 64	39 61	19 88	5.95	6 55	3.77	2 93	16.65	18.89	25.71	30.37	21.84	25.37	39 24	43.21	17.84	17.86	17.27	17.35
610	51.64	42.74	41.18	28.48	5.09	7.93	3 51	3 02	16.46	18 99	26.14	31.34	21.83	25.79	39.72	45.39	17.86	17.64	17.27	17.07
620	52.46	53.94	40.15	42.25	4.24	9.37	3.08	3.12	16.27	19.08	26.56	32.28	21.83	26.24	40 19	47 63	17.88	17.39	17.27	16.76
630	50.44	63.97	36.82	57.28	3.34	10 28	2.55	3.15	16 98	19.98	27.52	32 20	22 67	26 67	41.33	49 22	18 82	17.56	18 19	16.90
640	47 89	71.16	33.66	69.27	2.82	11.12	2 21	3.32	17 69	20.88	28.48	32.13	23 51	27.10	42.46	50.79	19.77	17.73	19.11	17.04
650	47.67	75.59	33.26	76 60	2 86	12.79	2.20	3.87	20 79	24.76	32.20	28 27	26 97	30.45	46.55	55.13	23 39	15 17	22.66	14 53
660	51.93	78.56	37.36	80.92	3.64	16 18	2.56	5.27	23 89	28.65	35 92	24.43	30.42	33.78	50 63	59.45	27.01	12 62	26.21	12.04
670	59.79	80.55	45.50	83.21	5.46	21.67	3 45	8 00	30.71	36 72	43.43	22 61	37.67	40.52	57.81	65.77	34.43	11.49	33 51	10 94
680	68 88	82.03	56.24	84.57	8.93	29 60	5 41	12.72	37.53	44.78	50.95	20 80	44 92	47.24	65 00	72.08	41.86	10.37	40.81	9.85
690	76.76	83.16	67.80	85.51	15.08	40 05	9.53	19.95	46.24	55.23	59.20	30.24	53.50	54.97	71.25	77.69	50.69	17.32	49.57	16 66
700	82.56	84.13	78.09	86.37	24.02	52.02	16.11	29.32	54 96	65 69	67.44	39 68	62.08	62.69	77.51	83.29	59.52	24 26	58.33	23.46

Appendix E7: Spectral reflectance values for Set 2 generated in Chapter 5

Pair No.	1		2		3		4		5		6		7		8		9		10	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	10.48	18.57	6.47	12.37	11.23	9 42	12.32	4 84	9.03	3.35	12.16	4.81	10.55	9 62	5.51	8.03	28.13	36.84	11.23	8 91
410	10.90	19.38	6.71	12.33	11.00	9.18	12.14	4.97	8.65	3.44	11.82	4 83	10.92	10.60	5.27	6.15	28.16	32.95	11.00	8.67
420	11.48	19.87	7.01	12.10	11.28	9.02	11.75	5.27	8.13	3.61	11.33	4.88	11.07	11.21	5.04	4.20	28.19	28.96	11.28	8 59
430	12.47	20.16	7.61	11.76	12.12	9.01	11.46	5.83	7.80	3.98	10.93	5.22	10 94	11.22	4.97	3.40	28.11	26.15	12.12	8 67
440	14.01	19.78	8.48	10 80	12.03	9.18	10.88	6.77	7.39	4.59	10.22	5.88	10.01	10.20	4.91	2.58	28.03	23.30	12.03	9.04
450	16.23	18.75	9.63	9.60	10.96	9.45	10.10	8.26	6.93	5.64	9.31	7.21	8.61	8.63	5.13	3.02	28.12	24.43	10.96	9.76
460	19.35	17.27	10.92	8.54	9.54	10.07	9.30	10.58	6 54	7.33	8.39	9.57	7 21	7.11	5.36	3.65	28.21	25.81	9 54	10.61
470	23.04	15.79	11.86	7.88	8.33	11.08	8.56	13.70	6.18	9.70	7.59	12.87	6 02	5.94	5.81	8.28	28.07	32.42	8.33	11.62
480	27.00	14.85	12.28	7.77	7.67	12.36	8.23	17.55	6.04	12.72	7.20	16.98	5.38	5.30	6.26	12.92	27.93	39.06	7.67	12.70
490	29.91	14.51	11.99	7.87	7.56	14.52	8.28	20.86	6.13	15.17	7.25	20.48	5.09	4.94	6.89	14.02	27.53	36.53	7.56	13.84
500	30.59	14.33	10.93	7.90	7.52	17.35	8.31	21.85	6.13	15 60	7.26	21.62	4 81	4.65	7.52	15.06	27.13	33.91	7.52	14.54
510	29.53	15.08	10.00	8.31	8.16	18.44	9.02	20.68	6.61	14.32	7.96	20.57	4 83	4.61	8.36	13.54	26.63	30.89	8.16	14.91
520	28.82	18.30	9.89	10.45	11.27	17.57	12.20	19 34	8.76	12 90	11.20	19.38	5 99	4.88	9.19	11.94	26.14	27.80	11.27	15.55
530	27.76	23.28	9.91	14.11	17.10	16.29	17 90	17.59	12.32	11.26	17.60	17.86	7.62	5 07	9.96	11.27	25.84	25.72	17.10	15 83
540	25.26	27.85	9 64	16.59	22.10	15.39	22.55	14.98	14 78	9.19	23 75	15.50	7.87	4.93	10.73	10.51	25.54	23.59	22.10	15.22
550	23.62	32.34	10.25	17.36	23.25	14.67	23.92	13.21	14.91	7.76	26.06	13.96	7.57	4.98	11.91	10.54	25.65	22.75	23.25	14.90
560	24.66	38.01	13.33	19.02	21.59	13.95	23.17	13.07	13.75	7 46	25.45	14 09	8.45	6.08	13.10	10.52	25.76	21.88	21.59	16.04
570	26.49	42.77	20.00	20.87	18.66	13.49	20.87	13.25	11.90	7.43	22 86	14 51	9 83	9 58	17.20	11.43	26.90	21.64	18.66	17.75
580	25.74	43.06	28.34	19.62	15.41	13.36	17.26	12.29	9.50	6.73	18.77	13.75	9 52	15.13	21.31	12.37	28.05	21 41	15.41	17.41
590	24.27	40.13	35.27	17.57	12.96	13.62	13.90	11.27	7.37	6.12	15 00	12.81	8 61	20.82	24.87	14.46	28.19	22.40	12.96	14.68
600	27.05	37.08	39.61	19.88	11.36	13.95	11.60	12.06	5 95	6.55	12.45	13 63	10.11	25.12	28.43	16 64	28.33	23 45	11.36	12 85
610	35.39	34 69	41.18	28.48	10.10	14.16	10.18	14.52	5.09	7.93	10.92	15.96	15.43	27.07	29 35	25.71	27.86	29.17	10.10	12.42
620	48.02	31.39	40.15	42.25	8.39	14 31	8.61	17.11	4.24	9.37	9.27	18.27	25.10	26.56	30.27	34.92	27.40	34 98	8.39	12.30
630	61.28	26.95	36.82	57.28	6.72	14.26	6.73	18.68	3.34	10.28	7.23	19.53	38.40	23.94	31.36	50.04	27.59	39 41	6.72	12.23
640	71.61	23.41	33.66	69.27	6 07	14.04	5.47	20 01	2.82	11.12	5.77	20.57	52.85	21.41	32.46	65.15	27.78	43.83	6.07	11.19
650	77.75	22.75	33.26	76.60	7.02	13.97	5 43	22.35	2.86	12.79	5.64	22.70	64 61	21.14	36.36	74.31	30.82	49.18	7.02	8.46
660	81.27	26.23	37.36	80.92	10.22	14.71	7.07	26.82	3.64	16.18	7.23	27.02	72.74	24.49	40.27	83.40	33.87	54 49	10.22	6.71
670	83.00	33.52	45.50	83.21	16.18	16.67	10 61	33.74	5.46	21.67	10.85	33.80	77.60	31.32	47.90	83.61	40.35	62.65	16.18	7.10
680	83.92	43.81	56.24	84.57	24.94	20.39	16 38	43.10	8.93	29.60	16.85	43.12	80.52	40.99	55.52	83 80	46.84	70.78	24.94	10.28
690	84.63	56.67	67.80	85.51	36.85	26.19	25.17	54.34	15.08	40.05	26.04	54.31	82.51	53.23	63.36	83.01	53.78	75.54	36 85	18.17
700	85.50	70.38	78 09	86.37	51.16	33.64	36.92	65.48	24.02	52.02	38.34	65.42	84.22	66.46	71.20	82.20	60.72	80.27	51.16	18.17

Appendix E8: Spectral reflectance values for Set 3 generated in Chapter 5

Pair No.	1		2		3		4		5		6	
(nm)	std	batch	std	batch	std	batch	std	batch	std	batch	std	batch
400	4.54	3.41	2.67	2.35	7.03	11.15	23.97	24.37	12.16	7.18	5.15	4 03
410	4.40	3.31	2.66	2.28	7.14	10.92	25.80	24 07	11 82	6 87	5 26	3 85
420	4.26	3.08	2.66	2.15	7.39	10.77	27.41	23.35	11.33	6.73	5 47	3.75
430	4.32	3.00	2.80	2.12	7.99	10.69	28.98	23.14	10.93	6.83	5 91	3 95
440	4 38	3.20	3.04	2.27	8 86	10.68	29.82	23.99	10.22	7.31	6 50	4 55
450	5.29	3.91	3.45	2.72	10.10	10.65	29.84	26.24	9.31	8 26	7.15	5 88
460	6.21	5.59	4 03	3.65	11 57	10.45	29.32	30.11	8 39	9 49	7.70	7.88
470	8 92	8.63	4.56	6.02	12.84	10.09	28.59	34 66	7.59	11.11	7.99	10 60
480	11.62	14.79	4.92	6.89	13.58	9.76	28.44	39.56	7.20	12.86	8.23	12 65
490	15.93	23.73	4 91	8.26	13 48	9.29	28.79	42.70	7.25	15 03	8.51	13 28
500	20.24	32.34	4.70	8 53	12.82	8.76	29.24	44.25	7.26	17.26	8 56	12.82
510	25.56	35.71	4.53	7 90	12.07	8 68	30.85	44.57	7.96	18 86	8 95	12.21
520	30.89	35.56	4.54	7.42	11.60	8.94	36.41	44.16	11.20	19.44	10 81	11 61
530	34 85	34.16	4.64	7.36	11.52	9 00	44.86	43.43	17.60	19 02	13.18	10.88
540	38 82	32.44	5.03	7 30	11 80	9 37	51.25	42 45	23.75	17 98	13.73	10.29
550	37.31	30.78	6.39	7.16	12.61	11.48	53.04	41.34	26.06	16.80	12.78	10.03
560	35.80	28.95	10.00	7 86	14.45	16.88	51.64	40.27	25.45	15.79	11.40	9 77
570	31.97	26.78	17.48	10.74	18.14	25.91	48.21	39.37	22.86	14.96	10.14	9 22
580	28.14	24.64	28.22	17.60	24.24	36.54	43.39	38.56	18.77	14.33	8 93	8 66
590	24.26	23.11	39.18	28.89	32.94	45 29	38.91	37.91	15.00	13.97	8.01	8 33
600	20.37	22.24	47.54	42.41	44.16	49.45	35.59	37.56	12 45	13.82	7.45	8 02
610	18.43	21.60	51.64	54.18	54.57	50.38	33.11	37.47	10 92	13 86	7.15	7.69
620	16.48	20.99	52.46	61.24	63.05	50.53	29.94	37.65	9.27	14 22	7.00	7.54
630	16.15	20.78	50.44	64.77	69.00	51.64	26.11	38 37	7.23	15 46	6.91	7.95
640	15 82	21.69	47.89	66.91	73.27	54.34	23.67	40.43	5.77	18 14	6 95	9 20
650	13.92	24.21	47 67	68.83	76.27	58 57	24.31	44.33	5 64	22.85	7.31	11.62
660	12.02	28.57	51.93	70.43	78.69	63.42	29.11	50.21	7.23	29 55	8.18	15 28
670	10 53	34.27	59 79	71.81	80.52	68 41	37.60	57.15	10.85	38.14	9 61	20 39
680	9.03	41.02	68 88	73.08	82.04	72.45	48.75	64 47	16 85	46.71	11.83	25 96
690	12.71	47.28	76.76	74.29	83.24	76.23	61.67	70.60	26 04	56.42	15.05	32.78
700	16.39	53.79	82 56	75.17	84.11	76.28	74.47	76.53	38.34	56 44	19.32	32.78

Appendix F: Spectral reflectance values for the selected sets S1, S2, S3 and combined set C1 generated in Chapter 6

Samp. No. (nm)	S1-1	S1-2	S1-3	S1-4	S1-5	S1-6	S1-7	S1-8	S1-9	S1-10
400	13.74	7.06	9.11	6.86	5.69	5.09	5.36	12.86	5.11	5.13
410	16.83	7.06	9.25	6.83	5.61	5.10	5.37	14.78	5.15	5.13
420	18.95	7.00	9.18	6.72	5.50	5.10	5.32	15.98	5.19	5.08
430	21.79	6.94	9.18	6.61	5.39	5.14	5.29	17.59	5.30	5.08
440	26.31	6.93	9.26	6.55	5.25	5.21	5.25	19.77	5.44	5.07
450	31.64	7.03	9.45	6.59	5.17	5.36	5.29	23.22	5.68	5.15
460	37.80	7.25	9.64	6.71	5.12	5.65	5.42	28.48	6.06	5.36
470	43.81	7.61	9.79	6.95	5.04	6.08	5.63	34.47	6.66	5.71
480	47.62	8.58	9.98	7.38	4.93	6.87	6.01	40.19	7.81	6.42
490	47.38	10.22	10.26	7.88	4.95	7.88	6.41	42.10	9.50	7.44
500	43.52	12.54	11.42	8.59	5.14	9.11	6.84	39.59	11.82	8.61
510	36.88	16.20	16.73	10.49	5.88	11.34	7.99	33.77	15.21	10.28
520	28.93	24.54	29.58	16.53	9.01	17.37	12.20	26.90	21.72	14.31
530	21.41	41.52	46.37	30.30	17.66	29.63	22.22	20.54	32.58	22.46
540	15.57	58.90	59.48	46.05	28.58	42.13	32.83	15.54	43.69	31.43
550	11.40	66.31	65.19	52.51	34.08	51.06	36.75	11.89	51.02	36.09
560	8.71	67.18	65.27	50.38	34.56	57.78	35.58	9.43	53.39	38.26
570	7.26	65.27	62.73	44.81	32.68	58.68	32.26	8.01	51.38	38.71
580	6.52	61.82	59.15	38.40	29.70	54.82	28.14	7.24	46.64	35.69
590	6.13	57.05	54.84	31.88	26.07	48.73	23.62	6.74	40.32	30.35
600	5.88	50.92	49.81	25.48	21.86	41.15	18.95	6.35	33.15	24.36
610	5.70	44.54	44.88	20.32	18.01	34.05	15.09	6.07	26.90	19.41
620	5.62	40.23	41.58	17.57	15.77	29.93	13.01	5.97	23.44	16.75
630	5.61	37.37	39.34	16.04	14.47	27.59	11.88	6.01	21.48	15.27
640	5.61	35.23	37.63	15.00	13.56	25.95	11.12	6.13	20.14	14.26
650	5.67	33.41	36.18	14.16	12.83	24.60	10.52	6.25	19.05	13.46
660	5.75	32.17	35.07	13.74	12.46	24.01	10.21	6.39	18.54	13.08
670	5.76	31.82	34.55	13.88	12.57	24.50	10.31	6.52	18.82	13.25
680	5.71	32.46	34.70	14.61	13.17	26.15	10.83	6.57	19.95	14.01
690	5.66	33.46	35.10	15.45	13.93	28.04	11.44	6.58	21.33	14.89
700	5.59	35.39	36.08	16.62	14.95	30.58	12.28	6.68	23.22	16.14

Samp. No. (nm)	S2-1	S2-2	S2-3	S2-4	S2-5	S2-6	S2-7	S2-8	S2-9	S2-10
400	7.47	11.63	10.52	15.29	12.16	11.23	20.94	16.72	33.23	29.86
410	7.88	11.41	10.66	16.43	11.82	11.00	22.18	13.64	29.08	25.52
420	8.31	11.07	10.68	17.74	11.33	11.28	23.03	10.47	24.83	20.99
430	9.01	10.71	10.59	19.37	10.93	12.12	23.58	8.87	22.18	18.29
440	10.03	9.96	9.91	21.50	10.22	12.03	23.19	7.23	19.48	15.50
450	11.72	8.97	8.68	24.12	9.31	10.96	21.94	8.10	20.77	16.72
460	14.04	7.99	7.38	27.16	8.39	9.54	20.28	9.16	22.29	18.36
470	16.31	7.11	6.30	30.06	7.59	8.33	18.70	16.09	30.64	27.93
480	17.88	6.67	5.79	32.36	7.20	7.67	17.92	23.05	39.02	37.54
490	18.03	6.56	5.65	33.13	7.25	7.56	17.88	22.90	37.03	36.40
500	16.07	6.44	5.61	31.61	7.26	7.52	17.98	22.66	34.94	35.07
510	13.57	6.81	6.14	29.05	7.96	8.16	19.24	20.01	31.81	31.90
520	12.01	8.85	8.82	27.45	11.20	11.27	24.53	17.31	28.63	28.69
530	10.56	12.11	14.25	25.62	17.60	17.10	34.44	15.82	26.56	26.73
540	8.53	14.29	19.87	22.46	23.75	22.10	45.17	14.29	24.46	24.76
550	7.32	15.55	22.66	20.23	26.06	23.25	52.38	13.72	23.51	23.96
560	7.53	17.42	23.10	20.33	25.45	21.59	56.45	13.12	22.53	23.16
570	8.05	19.04	22.32	20.89	22.86	18.66	58.19	12.94	22.09	22.86
580	7.58	17.97	21.07	19.52	18.77	15.41	57.36	12.77	21.65	22.57
590	7.00	15.31	20.16	17.97	15.00	12.96	55.45	13.46	22.32	23.37
600	7.83	13.06	19.98	19.48	12.45	11.36	54.75	14.17	23.01	24.18
610	10.11	11.58	20.25	24.15	10.92	10.10	55.04	18.09	27.07	28.56
620	12.73	9.84	20.46	29.66	9.27	8.39	54.10	22.06	31.17	32.95
630	14.48	7.69	20.51	33.63	7.23	6.72	51.03	25.18	33.75	35.73
640	15.82	6.14	21.15	36.57	5.77	6.07	47.96	28.29	36.33	38.50
650	17.89	5.97	23.24	40.16	5.64	7.02	47.71	33.42	41.37	43.55
660	21.88	7.57	27.67	45.96	7.23	10.22	52.22	38.53	46.40	48.58
670	28.13	11.23	34.71	53.85	10.85	16.18	60.42	48.63	55.74	57.66
680	36.85	17.27	44.47	62.98	16.85	24.94	69.73	58.73	65.06	66.75
690	47.78	26.41	56.02	71.63	26.04	36.85	77.73	66.94	71.70	72.94
700	59.43	38.57	67.12	78.43	38.34	51.16	83.59	75.15	78.33	79.14

Samp. No. (nm)	S3-1	S3-2	S3-3	S3-4	S3-5	S3-6	S3-7	S3-8	S3-9	S3-10
400	10.86	22.44	15.74	13.38	21.96	12.24	9.50	11.40	24.20	16.02
410	9.66	18.81	14.92	13.41	18.60	10.73	8.69	9.85	21.90	15.31
420	8.45	15.18	14.10	13.44	15.24	9.21	7.87	8.30	19.60	14.60
430	8.06	13.07	12.22	13.56	13.18	8.23	7.52	7.55	16.58	14.24
440	7.67	10.96	10.34	13.68	11.12	7.25	7.17	6.80	13.56	13.88
450	8.12	10.09	8.79	14.27	10.22	6.72	7.61	6.56	11.50	14.55
460	8.57	9.21	7.23	14.86	9.32	6.19	8.04	6.32	9.44	15.22
470	10.01	9.20	6.04	15.76	9.24	5.58	9.95	5.98	8.02	17.45
480	11.44	9.19	4.85	16.66	9.15	4.97	11.86	5.63	6.59	19.68
490	11.38	9.90	4.44	15.55	9.69	4.59	12.25	5.25	6.06	19.76
500	11.32	10.60	4.03	14.44	10.22	4.20	12.64	4.87	5.52	19.84
510	9.64	13.06	3.67	12.15	11.93	3.77	10.83	4.39	5.22	17.23
520	7.95	15.52	3.30	9.86	13.64	3.33	9.01	3.90	4.91	14.62
530	6.80	19.12	3.51	8.36	15.60	3.55	7.64	4.15	5.36	12.59
540	5.65	22.72	3.72	6.85	17.56	3.77	6.27	4.39	5.81	10.56
550	4.80	25.44	3.97	5.90	18.68	4.04	5.39	4.68	6.93	9.05
560	3.94	28.16	4.22	4.94	19.80	4.30	4.51	4.96	8.05	7.53
570	3.55	28.88	7.60	4.33	20.02	7.87	3.96	8.80	12.73	6.51
580	3.16	29.60	10.98	3.71	20.24	11.44	3.40	12.64	17.40	5.48
590	3.04	29.68	22.51	3.54	20.18	23.32	3.24	25.00	28.44	5.02
600	2.91	29.76	34.04	3.37	20.12	35.20	3.07	37.36	39.48	4.56
610	2.91	29.76	46.24	3.33	20.10	47.70	3.01	49.94	48.60	4.33
620	2.90	29.76	58.44	3.29	20.08	60.20	2.95	62.52	57.72	4.10
630	3.23	30.66	63.64	3.21	20.82	65.16	2.88	67.44	61.80	3.90
640	3.56	31.56	68.84	3.13	21.56	70.12	2.80	72.36	65.88	3.70
650	5.21	34.98	69.72	4.02	24.60	70.60	3.27	72.84	67.88	4.10
660	6.85	38.40	70.60	4.90	27.64	71.08	3.73	73.32	69.88	4.49
670	12.11	45.30	71.56	9.62	34.20	71.64	5.34	73.84	72.36	5.50
680	17.36	52.20	72.52	14.34	40.76	72.20	6.95	74.36	74.84	6.50
690	25.76	59 68	72.76	22.53	48.92	72.20	8.72	74.36	76.36	8.04
700	34.16	67.16	73.00	30.72	57.08	72.20	10.48	74.36	77.88	9.58

Samp. No. (nm)	C1-1	C1-2	C1-3	C1-4	C1-5	C1-6	C1-7	C1-8	C1-9	C1-10
400	31.33	55.08	32.35	5.28	12.60	7.55	6.86	11.63	10.52	12.16
410	31.88	55.83	45.55	5.10	11.63	6.53	6.83	11.41	10.66	11.82
420	32.60	56.00	48.75	4.98	10.83	7.70	6.72	11.07	10.68	11.33
430	33.43	55.53	48.13	4.80	10.43	12.48	6.61	10.71	10.59	10.93
440	34.58	54.35	46.18	4.58	10.50	20.75	6.55	9.96	9.91	10.22
450	36.03	52.13	43.85	4.23	11.03	29.68	6.59	8.97	8.68	9.31
460	38.13	48.78	41.23	3.80	12.38	34.25	6.71	7.99	7.38	8.39
470	40.25	44.85	38.18	3.30	14.93	33.93	6.95	7.11	6.30	7.59
480	41.45	40.75	35.18	3.00	19.25	30.60	7.38	6.67	5.79	7.20
490	41.83	36.30	32.43	2.83	25.35	25.65	7.88	6.56	5.65	7.25
500	41.30	32.50	29.93	2.83	32.20	20.40	8.59	6.44	5.61	7.26
510	40.28	30.10	28.28	2.98	35.30	15.38	10.49	6.81	6.14	7.96
520	38.88	28.25	26.95	3.08	34.45	10.93	16.53	8.85	8.82	11.20
530	37.20	26.58	25.63	3.18	31.38	7.55	30.30	12.11	14.25	17.60
540	35.28	25.78	25.05	3.30	27.10	5.13	46.05	14.29	19.87	23.75
550	33.10	25.88	25.43	3.53	22.70	3.50	52.51	15.55	22.66	26.06
560	30.80	25.95	26.38	4.08	18.80	2.53	50.38	17.42	23.10	25.45
570	28.38	25.60	27.18	4.80	15.35	1.93	44.81	19.04	22.32	22.86
580	25.95	25.53	27.85	6.20	12.55	1.70	38.40	17.97	21.07	18.77
590	23.28	27.08	29.75	10.40	10.65	1.63	31.88	15.31	20.16	15.00
600	21.00	30.30	34.90	19.30	9.60	1.60	25.48	13.06	19.98	12.45
610	19.43	34.35	43.35	33.65	8.98	1.60	20.32	11.58	20.25	10.92
620	18.55	37.63	52.65	50.23	8.48	1.60	17.57	9.84	20.46	9.27
630	18.00	39.98	60.13	63.63	8.03	1.75	16.04	7.69	20.51	7.23
640	17.60	41.98	64.70	71.40	7.83	1.80	15.00	6.14	21.15	5.77
650	17.50	43.75	67.50	75.65	7.80	1.90	14.16	5.97	23.24	5.64
660	17.55	45.15	69.28	78.05	8.08	2.25	13.74	7.57	27.67	7.23
670	18.00	46.18	70.48	79.68	8.80	2.65	13.88	11.23	34.71	10.85
680	18.60	46.80	71.20	80.88	10.23	3.58	14.61	17.27	44.47	16.85
690	19.20	47.33	71.70	81.90	12.58	5.73	15.45	26.41	56.02	26.04
700	19.83	48.30	72.03	82.75	16.13	9.90	16.62	38.57	67.12	38.34

Appendix G: A guideline for viewing cabinet design

A Guideline for Viewing Cabinet Design

SECTION 1 GENERAL

1.1 Scope

The drafted guidelines set out the colorimetric, photometric and physical requirements for viewing cabinet design.

1.2 Normative References

1.2.1 ISO 3664, 2000, Viewing conditions for graphic technology and photography.

1.2.2 ISO 3668, 2001, Paints and varnishes – Visual comparison of the colour of paints

1.2.3 CIE Publication No. 51.2, 1999, A method for assessing the quality of daylight simulators for colorimetry.

1.2.4 CIE Publication No. 116, Industrial Colour-Difference Evaluation.

1.2.5 CIE Publication No. 13.3, 1995, Method of measuring and specifying the colour rendering properties of light sources, 2nd edition.

1.2.6 CIE Publication No. 17.4, 1987, International lighting vocabulary.

1.2.7 CIE Publication No. 15.2, 1986, Colorimetry.

1.2.8 ASTM D1729-96, Standard Practice for Visual Evaluation of Color and Color Difference of Diffusely Illuminated Opaque Materials.

1.2.9 AATCC EP9, 1999, Visual Assessment of Color Difference of Textiles.

1.2.10 Australian Standard AS 4004, 1992, Lighting booths for visual assessment of colour and colour matching.

1.3 Terms and Definitions

1.3.1 Chromaticity: property of a colour stimulus defined by its chromaticity co-ordinates, or by its dominant or complementary wavelength and purity taken together [1.2.6].

1.3.2 Colour rendering index: measure of the degree to which the psychophysical colour of an object illuminated by a test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation [1.2.6].

1.3.3 Correlated colour temperature: temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions [1.2.6].

1.3.4 Illuminance (at a point of a surface): quotient of the luminous flux incident on an element of the surface containing the point by the area of that element [1.2.6].

1.3.5 Illuminant: radiation with a relative spectral power distribution defined over the wavelength range that influences object-colour perception [1.2.6].

1.3.6 Lux (lx): metric unit of quantity of light on 1 m^2 of surface area 1 m away from light source of 1 cd [1.2.6].

1.3.7 Relative spectral power distribution: ratio of the spectral power distribution of a source or illuminant to a fixed reference value which can be an average value, a maximum value, or an arbitrarily chosen value of this distribution [1.2.1].

SECTION 2 DESIGN AND CONSTRUCTION

2.1 Viewing Dimension

The manufacturer of the viewing cabinet shall specify the viewing area in the cabinet. This shall be expressed as an area in the horizontal plane, specified with reference to the walls of the cabinet or other convenient landmarks, and in the vertical plane, expressed as the distance below the diffuser of the luminaire or other convenient landmark. The dimensions of the viewing area in the horizontal plane shall be not less than 300(W) x 200(D) mm [1.2.10].

2.2 Light Sources

2.2.1 Daylight Simulator

General

The relative spectral power distribution of the daylight simulator shall approximate that of one phase of CIE daylight illuminants (i.e. CIE D75, D65 or D50), as defined in CIE

Publication 15.2 (1986). There is no single source that exactly matches the CIE daylight illuminants. It may be simulated using a variety of sources, such as filtered tungsten, fluorescent or xenon lamps. The choice of which CIE daylight illuminant to be used depends on the applications of the cabinet. For instance, D65 simulators are generally required for surface colour industries such as textile, paint, plastics, etc., while D50 simulators are specifically used for the graphic arts industry.

Quality of illumination

The quality of daylight simulator should be assessed according to the requirements of CIE Publication 51.2 (1999). It shall have u'_{10}, v'_{10} chromaticity coordinates within the radius of 0.015 from the corresponding CIE daylight illuminant [1.2.3]. The metamerism index of the daylight simulator shall be in category BC (CIELAB) or better [1.2.2]. The CIE general colour rendering index (CRI) of daylight simulator should be measured as specified in CIE Publication 13.3 (1995) and shall have a value of 90 or higher. In addition, the separate special colour rendering indices for samples 1 to 8 shall each have a value of 80 or higher [1.2.1]. (A set of new test colours has been generated in this study and it is hoped this set of test colours will be adopted by the CIE in the future for industrial applications.)

Note: The effects of all wavelength selective modulators, such as lenses, mirrors, filters and cabinet walls, are included in the measurement of the spectral quality of the simulator.

Level of illuminance

The illuminance level within the viewing area should be between 1,000 lx and 4,000 lx [1.2.2]. The preferable illumination level for general use is 1,500 lx to 2,500 lx [1.2.10]. Darker colours require illumination level at the upper end of the range.

Note: The illuminance level decreases over a period of time. For this reason, periodic checks on light intensity are required to confirm compliance with the above requirements. Attention should be paid to the maximum running hours of a particular lamp, which is normally disclosed by the lamp manufacturer (see Section 3).

Uniformity of illuminance

When measured at 50 mm intervals over the viewing area identified by the manufacturer, using a cosine-corrected detector of area not great than 1000 mm^2, the ratio of the highest to lowest illuminance over the viewing area shall not be great than 1.25 [1.2.10].

2.2.2 Incandescent Light Source

General

An incandescent light source should be fitted for the purposes of the assessment of metamerism.

Quality of illumination

The incandescent light source shall have correlated colour temperature of not less than 2200 K and not more than 2900 K [1.2.10].

Level of illuminance

The mean illuminance over the viewing area shall be not less than 0.7 times and not more than 1.3 times the mean illuminance provided by the daylight simulator [1.2.10].

Note: The illuminance level decreases over a period of time. For this reason, periodic checks on light intensity are required to confirm compliance with the above requirements. Attention should be paid to the maximum running hours of a particular lamp, which is normally disclosed by the lamp manufacturer.

Uniformity of illuminance

When measured at 50 mm intervals over the viewing area identified by the manufacturer, using a cosine-corrected detector of area not great than 1000 mm^2, the ratio of the highest to lowest illuminance over the viewing area shall not be great than 1.25 [1.2.10].

2.3 Additional Light Sources

A viewing cabinet is recommended to configure with at least two basic light sources, including a simulated daylight source (see Section 2.2.1) and an incandescent light source (see Section 2.2.2). To examine the colour constancy of a specimen or metamerism of a pair of specimen, additional sources such as customer fluorescent (TL84), cool white fluorescent (CWF). The illuminance level for these sources should be as specified for the incandescent light source (see Section 2.2.2). An ultraviolet (UV) source may be included as requested. The UV source is normally used in conjunction with other light sources to alter the UV content of that particular source.

2.4 Interior Colour

The interior of the viewing cabinet for general use shall be painted a matt neutral grey with a lightness L* of 50±5 [1.2.2] and C^*_{ab} not great than 4.0 [1.2.10]. The inside canopy where the lamps are should be painted as glossy white. For cabinets specifically made for viewing light or dark colours, higher or lower lightness may be considered for the interior colour [1.2.2].

2.5 Electrical Safety

The electrical components of the viewing cabinet shall comply with the requirements of the relevant British or international standards.

2.6 Recommended Life of Sources

The viewing cabinet manufacturer shall specify the recommended life of each light source for which the quality of designed illumination is maintained.

2.7 Heat Generation and Dissipation

2.7.1 Cooling air discharge

Where a flow of air is used to assist in cooling, the hot air shall be discharged from the viewing cabinet away from both the users and the surface on which the viewing cabinet is mounted.

2.7.2 Temperature of booth surfaces

The temperatures shall not exceed 50°C for metal surfaces of the cabinet and 60°C for wood and plastics surfaces of the cabinet [1.2.10].

SECTION 3 MAINTENANCE

The viewing cabinet shall be inspected after each 100 hour of operation to ensure that the reflectors, bulbs, filters and diffusing glass are kept clean, and the electric lamp is replaced at intervals nominated by the cabinet manufacturer, or when the illuminance falls below a specified level. Only the samples being assessed should be present in the cabinet during visual assessment. All other samples and materials should be removed. Cabinets having large scratches on the interior wall should be re-painted by the manufacturer. A record shall be kept of all checks of illumination, cleaning procedures and lamp replacements.

Note: It may be desirable to provide the equipment with a hour meter, determining the operating time of the viewing cabinet, to assist in the monitoring of inspection periods.