The New Colour Scales based on Saturation, Vividness, Blackness and Whiteness

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The candidate confirms that the works submitted are her own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

The works in Chapters 4, 5 and 6 of the thesis has appeared in publications as follows:

1. Cho Y. J., Ou L. C. and Luo M. R. (2011), Alternatives to the third dimension of colour appearance, Proceedings of the IS&T/SID Color Imaging Conference (CIC19), San Jose, USA, 88-93.
2. Cho Y. J., Ou L. C. and Luo M. R (2012), Individual Differences in the Assessment of Colour Saturation, Proceedings of the IS&T/SID Color Imaging Conference (CIC20), Los Angeles, USA, 221-225.
3. Luo M. R., Cui G. and Cho Y. J. (2013), The NCS-like Colour scales Based on CIECAM02, Proceedings of the IS&T/SID Color Imaging Conference (CIC21), New Mexico, USA, 177-179.

The works of Publications 1 and 2 were carried out almost entirely by the candidate. The candidate conducted and carried out the psychophysical experiments. The candidate collected the data, analyzed the results and wrote the manuscript. Prof. Luo and Dr Ou contributed.

The candidate also assisted Luo and Cui in Publication 3 to model the NCS data using the elliptical model and the modified Adam model. This was described in Section 6.4. The candidate worked on the elliptical model and then applied both methods to develop the Cho elliptical and the modified Adam models in terms of STRESS.

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Abstract

This research project has two goals. One is to understand the third dimension of colour scales describing the extent of chromatic contents such as saturation, vividness, chromaticness and colourfulness, which are less widely used than the other dimensions, e.g. lightness and hue. With that in mind, the first aim of this work is to derive new models that may serve as an alternative to the third-dimension scale of colour appearance on the basis of colorimetric values. The second goal is to develop important scales, blackness and whiteness. They are widely used because of the popularity of the NCS system.

To achieve the first goal, a psychophysical experiment for scaling 15 attributes (Korean corresponding words of “bright”, “light-heavy”, “active-passive”, “fresh-stale”, “clean-dirty”, “clear”, “boring”, “natural-not natural”, “warm-cool”, “intense-weak”, “saturated”, “vivid-dull”, “distinct-indistinct”, “full-thin” and “striking”) using the NCS colour samples was carried out with Korean observers. Each sample was presented in a viewing cabinet in a darkened room. Naive observers were asked to scale each sample using a categorical judgement method.

From the results, two scales widely used to represent the third dimension were identified: saturation and vividness. The same samples were assessed by British observers using these two scales. There was a great similarity between the results of the British and Korean observers. Subsequently, more samples were included to scale not only the new third dimension scales (saturation and vividness) but also whiteness and blackness scales. In total, 120 samples were scaled for saturation, vividness and whiteness experiments, and 110 samples were scaled for a blackness experiment.

Four sets of models were developed for each of the three colour spaces (CIELAB, CIECAM02 and CAM02-UCS). Type one was based on the ellipsoid equation. Type two was based on the hue-dependent model proposed by Adams (called “the hue-based model”). Each of the above two

types was used to fit the present experimental (Cho) data and the NCS data, which were measured using a spectrophotometer. In total, 39 models were developed.

The newly developed models were tested using the Cho and NCS datasets. The models that were based on the present visual data were tested using the NCS data. Similarly, the models developed from the NCS data were tested using the present visual data. The results showed that both types of models predicted visual data well. This means that the two sets of data showed good agreement. It is also proposed that the four scales (saturation, vividness, blackness and whiteness) based on CIECAM02 developed here are highly reliable.

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Chapter 1 Introduction

1.1 Motivation

There have been many colour appearance models developed over the years. In the current colour appearance models, important scales such as vividness, whiteness and blackness are missing. A saturation scale has already been developed in CIECAM02. Recently, Fairchild and Heckaman (2012) proposed simple colour appearance scales for saturation and brightness. However, more reliable experimental data are needed. Thus, the saturation scale is investigated in this study. Vividness is also an important scale for image quality and image enhancement. Whiteness is strongly related to the quality of cosmetic products, some white materials and image contrast. Blackness is related to the set up of black point in colour management systems for displays, colour printers etc. It is important to set up the black point because, if it is set incorrectly, part of the image level will be missing. A high-quality black and a high contrast ratio, can affect overall image quality. In 2008, Nayatani (2008) developed an equivalent whiteness-blackness, whiteness, blackness and greyness attribute.

The CIE system defines colour appearance in a three-dimensional space in terms of hue, lightness and colourfulness (or chroma, chromaticness). In a study of colour appearance, Luo *et al*. (1991) applied lightness, hue and colourfulness to describe a colour using the magnitude estimation technique, in which observers showed less confidence to assess colourfulness than the other two attributes, that is, the colourfulness scale always had a higher intra-observer variability than the others. Observers were normally well-trained to sufficiently understand the attributes of colour appearance. Even with well-trained observers, the visual results for colourfulness can still show poor data consistency as compared with the other two dimensions. This was also confirmed by the study by Zhang and Montag (2006). Hence, this study is intended to understand whether other terms can be used to replace colourfulness that better reflect novice observers' views of colour appearance. Therefore, the alternative scales were selected: saturation and vividness.

The natural colour system (NCS) is widely used as a practical aid by architects, designers and other professionals who are working in environmental colour design or by manufacturers of coloured products involving various types of materials. In 2008, Adams (2008 and 2010) developed NCS-like colour attributes in the CIELAB space, such as whiteness, blackness and chromaticness scales using alternative lightness and chroma. However, these attributes are not based on psychophysical experiments. Hence, there is a need to develop a model that reflects NCS and psychophysical experiments.

The main objectives of this study were to develop new colour appearance scales, such as saturation, vividness, blackness and whiteness using visual data obtained from naive observers without any knowledge of colour science. The novice observers were the target to investigate whether these terms can be better understood than those CIE-defined attributes by ordinary people (naive observers) that represent the real world situation. They were not even trained to understand the meaning of each term to represent the true understanding of these terms by two participants from two cultural backgrounds, Korean and British. The scales developed could be a one-dimensional scale or based on a well-established colour space or model.

1.2 Contribution to Colour and Imaging Science

The contributions of this thesis to colour science are the following:

1) To reveal the meanings of various scales to describe the third dimension. The two scales standing out are saturation and vividness. They are more widely used and better understood by Korean and British observers.

2) To investigate the valuable scales of whiteness and blackness. The present experimental data agree well with NCS data.

3) To develop a new one-dimensional scale to be integrated into a colour appearance like CIECAM02 for these new colour appearance attributes.

They can be used for various applications, such as image enhancement, colour quality assessment etc.

1.3 Thesis Aims

One of the goals of this study was to develop a new model that may serve as an alternative to the third dimension of colour appearance on the basis of colorimetric values. The other goals were to develop new blackness and whiteness models also based on colorimetric values. The following tasks were carried out to achieve this overall goal:

(1) To understand and clarify the meaning of each chromatic attribute based on data obtained from Korean and British observer groups,

(2) To investigate the cultural differences between Korean and British groups in relation to visual results obtained from observers for four scales (saturation, vividness, blackness and whiteness),

(3) To investigate the relationships between the colour appearance scales of CIELAB, CIECAM02 and CAM02-UCS colour spaces and the observer responses for four scales studied,

(4) To develop new colour models by fitting the present saturation, vividness, blackness and whiteness visual results. The new models are based on CIELAB, CIECAM02 and CAM02-UCS metrics.

(5) To test the models using an independent data set, NCS.

1.4 Thesis Structure

There are eight chapters in this thesis. Chapters 2 to 8 are described below.

Chapter 2: Literature Survey

In this chapter, literature which is relevant to this research is reviewed. It is divided into three subject areas: the human visual system, colorimetry and colour appearance.

Chapter 3: Experimental Preparation

The experimental setups for the psychophysical experiments (Experiments 1 to 3) were explained. This includes a survey for Korean translation, scale selection, colour sample selections, the number of observers, measurement of colour samples, experimental conditions, and the statistical method that was used for the data analysis.

Chapter 4: Comparing Results Obtained from British and Korean Observers

This chapter described the analysed results from Experiment 1. It investigates the relationship between the visual data of the 15 scales and CIELAB chroma, lightness and hue angle. Principal component analysis was applied to 15 scales. The intra- and inter-observer variabilities of 15 scales were investigated. Finally, the relationship between 15 scales of the Korean group and saturation and vividness scales of the British group are investigated.

Chapter 5: New Cho Ellipsoid Models Based on the Cho Data

The intra- and inter-observer variabilities of four scales were investigated. The visual data of the British and South Korean groups were compared. The relationship between the visual data of four scales and the colour appearance attributes in three colour spaces were investigated. The variability in assessing saturation is analysed.

The first new model (called “the Cho ellipsoid models”) was developed based on the visual data obtained from the psychophysical experiments (called the “Cho data”) to predict saturation, vividness, blackness and whiteness attributes. The second new model (called “the NCS ellipsoid model”) was developed based on the Cho ellipsoid model by fitting it to the NCS data.

Chapter 6: New Models Based on Cho or NCS Data

The third new model was developed based on the Cho data (called “the Cho hue-based model”) to predict whiteness, blackness and chromaticness scales. Finally, the fourth new model (called “the NCS hue-based model”) was developed based on the Cho hue-based model by fitting it to the NCS data.

Chapter 7: Testing Models Using Other Data Sets

The models developed in Chapters 6 and 7 were tested using an independent data set to investigate the performance of each model.

Chapter 8: Conclusions

This chapter summarises the major findings of Chapters 4 to 7 and suggests directions for future work.

1.5 Publications Based on this Work

The following publications were produced in the course of the present study:

1. Cho Y. J., Ou L. C. and Luo M. R (2011), A New Saturation Model, Proceedings of the 19th Congress of the International Colour Association (AIC Color 2011), Zurich, Switzerland, 334-337.

2. Cho Y. J., Ou L. C. and Luo M. R. (2011), Alternatives to the third dimension of colour appearance, Proceedings of the IS&T/SID Color Imaging Conference (CIC19), San Jose, USA, 88-93.

3. Cho Y. J., Ou L. C., Westland S. and Luo M. R (2012), Methods for Assessing Blackness, Proceedings of the 20th Congress of the International

Colour Association (AIC Color 2012), Taipei, 606-609.

4. Cho Y. J., Ou L. C. and Luo M. R (2012), Individual Differences in the Assessment of Colour Saturation, Proceedings of the IS&T/SID Color Imaging Conference (CIC20), Los Angeles, USA, 221-225.

5. Luo M. R., Cui G. and Cho Y. J. (2013), The NCS-like Colour scales Based on CIECAM02, Proceedings of the IS&T/SID Color Imaging Conference (CIC21), New Mexico, USA, 177-179.

Chapter 2 Literature Survey

2.1 Overview

In this chapter, the background information related to the present study is reviewed. The basic elements of colour perception are the human eye, light and object, and these elements are reviewed in this chapter. The structure of the human eye and the function of rods and cones are introduced. Also, the mechanism of colour vision is briefly explained. The CIE system of colorimetry to quantify colour appearance is presented in detail. This includes the light source, illuminant, viewing geometries, CIE standard colorimetric observers, tristimulus values, chromaticity coordinates and uniform colour space. Colour measurement instruments are briefly explained and colour order systems are reviewed in detail to understand the basic attributes. Colour appearance terminology is reviewed to understand the meaning of the basic attributes. The colour matching technique is reviewed to understand the method of matching colours. The CIECAM02 and CAM02-UCS models are reviewed to understand the structure and the equations of the models.

2.2 Human Colour Vision

The key elements of colour perception are the light, object and human eye. Understanding the human eye is a very important factor in the study of colour and colour appearance. Thus, the structure of the eye and how colour is perceived through the eye are reviewed in this section (p1-6, Fairchild, 2005).

2.2.1 Eye Structure

Figure 2.1 shows a schematic diagram of the optical structure of the human eye (one of the organs of the sensory system). It detects the light which enters the cornea, a transparent outer surface at the front of the eye. The cornea and the lens act together and focus an image on to the retina. The lens is a layered, flexible structure which varies in index of refraction. The retina comprises a thin layer of cells (neurons) located at the back of the eye. It includes photosensitive cells of the visual system and a circuit structure for initial signal processing and transmission. The photosensitive cells, which consist of rods and cones in the retina, convert incident light energy into electrochemical signals that are carried to the brain by the optic nerve.

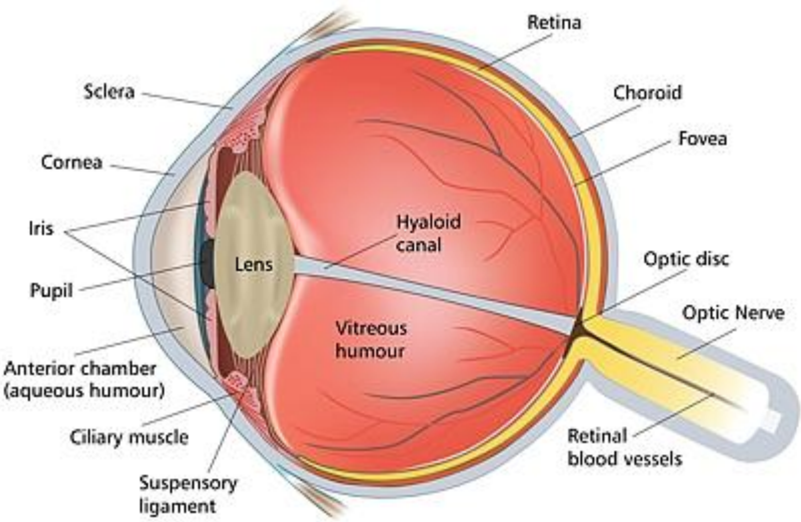


Figure 2.1 Schematic diagram of the human eye (Human eye, 2013)

2.2.2 Rods and Cones

There are two types of retinal photoreceptors, rods and cones (p8, Fairchild, 2005). Rods can only function under extremely dim light. They are quite light-sensitive and are responsible for dark vision. In scotopic vision, only rods are active. In mesopic vision, rods and cones are both active, and it occurs at slightly higher illuminance levels. Rod cells' peak spectral responsivity is approximately at 510 nm.

Cones function at higher luminance levels. Photopic vision is when only cones are active. There are three types of cones, referred to as L (long-wavelength sensitive cones), M (middle-wavelength sensitive cones) and S (short-wavelength sensitive cones) cones. As seen in Figure 2.2, the peak sensitivities of these three types of cones are at about 580 nm, 545 nm and, 440 nm, respectively (Estevez, 1979). For example, both L and M cones are strongly stimulated in yellowish-green light, but M cones are more weakly stimulated. Each type of cone information is combined in the brain to give rise to different perceptions corresponding to different wavelengths of light.

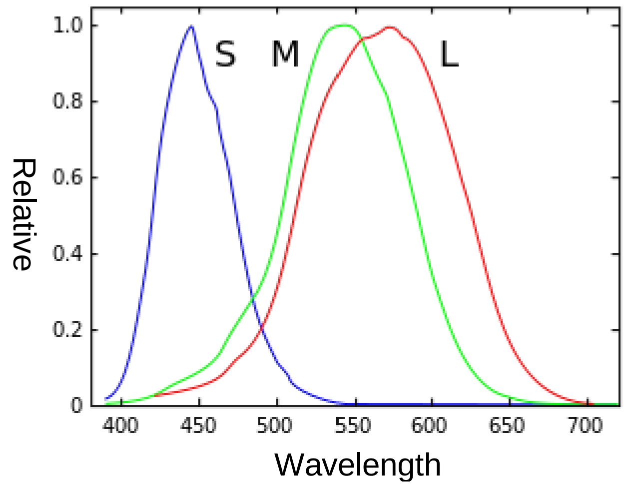


Figure 2.2 Spectral sensitivities of cone cells (Spectral sensitivity, 2013)

2.2.3 Mechanism of Colour Vision

In the last section, a simplified version was given to describe the function of rods and cones. In fact, visual information is quite complex within the retina and becomes even more complicated at the later transmission stages. The optical image on the retina is processed by the retinal neurons. The retinal neurons consist of horizontal, bipolar, amacrine, and ganglion cells. The input from the ganglion cells is collected. Then, the lateral geniculate nucleus (LGN) cells project to visual area one (V1) in the cortex.

The trichromatic theory of colour vision was developed from the work of Maxwell, Young and Helmholtz. They stated that there are three types of receptors, each sensitive to a different part of the spectrum such as red, green and blue regions. *"The trichromatic theory assumed that three images of the world were formed by these three sets of receptors and then transmitted to the brain where the ratios of the signals in each of the images was compared in order to sort out colour appearance"* (p17, Fairchild, 2005).

Hering (1920) proposed an opponent-colours theory at the same time as the trichromatic theory was proposed. It is based on subjective observations of colour appearance, including phenomena such as hues, simultaneous contrast, after-images and colour deficiencies. Hering noticed that certain hues never occur together. For example, there is no colour that is described as reddish-green or yellowish-blue.

Jameson and Hurvich (1955 and 1957) conducted a hue-cancellation experiment. Observers were asked whether the stimulus is reddish or greenish. Then, another colour was added to cancel the existing reddish or greenish. The amount of cancellation colour used was assumed as an indicator of the strength of the cancelled hue. These data were transformed to produce the opponent processing curve.

The (L+M+S) signal produces an achromatic response by summing the three cone types. The (L-M+S) signal produces a red-green response and (L+M-S) produces a yellow-blue response.

2.3 CIE Colorimetry

The purpose of colorimetry is to numerically specify the colour of a visual stimulus (p117, Wyszecki and Stiles, 1982; CIE, 2004a). Fairchild defined *colorimetry* as *"the measurement of colour* (p53, Fairchild, 2005)". The CIE system of colorimetry established the first international standard to allow the specification of colour matches for an average observer in 1931 and formed the basis of modern colorimetry. Colorimetry provides the basic measurement techniques requiring three components for a colour stimulus: the light source, the observed objects and the human visual system. This section describes how these three components are specified and how they are combined to define the human colour stimulus.

2.3.1 Light Source and Illuminant

A light source produces energy of electromagnetic radiation, and examples include daylight, incandescent lamps and fluorescent tubes. A light source can be quantified in terms of spectral power distribution (SPD), which is the level of energy at each wavelength across the visible spectrum. The spectral power distribution may be normalised by having an arbitrary value of 100 at 550nm and this is then referred to as relative spectral power distribution.

The light source can also be quantified by using colour temperature. William Kelvin Thomson investigated colour temperature by heating a lump of carbon. Carbon is black under cold conditions, but when it is heated it becomes dark red like a metal; with increasing temperature it turns yellow and then blue. Finally, it turns white at a high temperature. The colour changes according to the change of temperature and that of the temperature of the black body is the colour temperature. In other words, the colour temperature is the temperature of the black body which is the lump of carbon. The unit of the colour temperature is K. The correlated colour temperature (CCT) is the temperature of a black body that has nearly the same colour as the given stimulus (p319, Hunt, 1998).

Illuminants are defined as "*simply standardised tables of values that represent a spectral power distribution typical of some particular light source* (p56, Fairchild, 2005)". The CIE has standardised several illuminants by defining their relative SPD. For example, CIE standard Illuminant D65, which represents average daylight, has a correlated colour temperature of approximately 6500 K, and CIE standard illuminant A, which represents typical domestic tungsten-filament lights, has a correlated colour temperature of approximately 2856 K.

2.3.2 Object and Standard Measurement Geometry

The second component for defining the perception of colour stimulus is the object. A colour measurement instrument can be used to determine the spectral reflectance of the object at each wavelength across the visible spectrum. The measured results often depend on the geometric relationships between the measuring instrument and the sample, which is called the "geometric conditions" or "geometry". Similarly, visual assessments of coloured samples are affected by illumination and viewing geometry. The CIE specified standard methods to ensure consistent measurement results. The CIE introduced four types of illumination and viewing geometries for reflectance measurements (p6-8, CIE, 2004a): diffuse/8 degree specular component included (di:8° or 8°:di), diffuse/diffuse (d:d), diffuse/normal (d:0°), 45 annular/normal (45°a:0° or 0°:45°a) and 45 degree directional/normal (45°x:0° or 0°:45°x). The 'a' and 'x' mean the light is detected or illuminated using an 'annular' or 'single direction', respectively.

Figure 2.3 shows four CIE standard illumination and viewing geometries for reflectance measurement. A sample is irradiated from all directions by diffused light in the di:8° geometry. It is viewed at 8° from the normal direction to the surface shown in Figure 2.3-(a). The 8°:di geometry is the reverse geometry of di:8° as shown in Figure 2.3-(b). It provides identical results as di:8. In this geometry, the sample is irradiated at 8° from the normal direction. The reflected light is accumulated from every angle by an integrating sphere. The subscript 'i' represents specular included and another one 'e' for specular excluded.

In the 45°x:0° geometry, the sample is irradiated at 45°±5° from the normal direction to the sample. It is measured at the normal direction as shown in Figure 2.3-(c). The 0°: 45°x geometry is the reverse geometry of 45°x:0°. It also provides identical results as 45°x:0° as shown in Figure 2.3-(d). In the 45°x:0° and 0°:45°x geometries, the specular component of a sample is excluded.

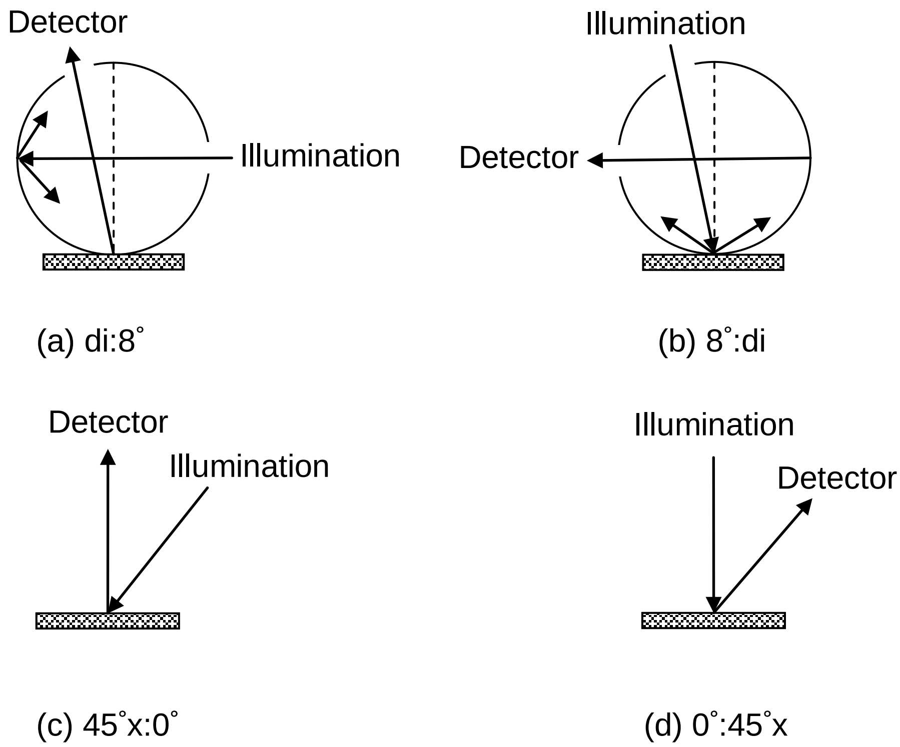


Figure 2.3 Four CIE standard illumination and viewing geometries for reflectance measurement

2.3.3 CIE Standard Colorimetric Observer

2.3.3.1 CIE 1931 Standard Colorimetric Observer

In 1931, the CIE introduced a 1931 Standard Colorimetric Observer which is a set of colour matching functions based on colour-matching experiments (CIE, 2004). The colour-matching functions were obtained by matching a target stimulus by adjusting red, green and blue primaries. This function was completed by combining two separate experimental results with 10 and 7 observers carried out by Wright (1929) and Guild (1931) respectively. It is often referred to as the 2° observer, and it correlates with visual colour-matching of fields subtending between about 1° and 4° at the eye of observers. The colour-matching functions are designated by $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$, which are expressed in terms of the primary colour stimuli of 700, 546.1 and 435.8 nm wavelengths. Figure 2.4 shows the $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$ functions of the CIE 1931 observer.

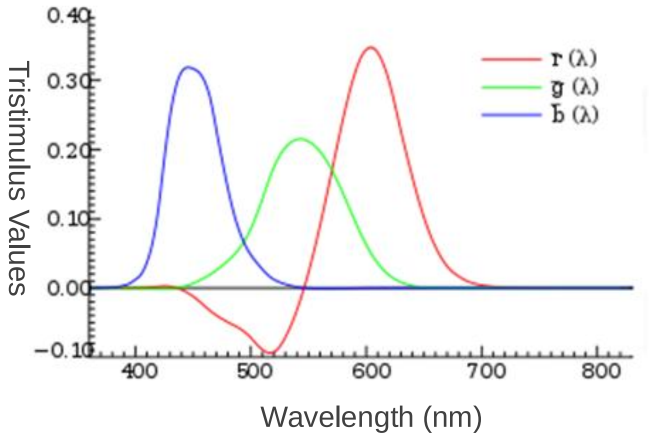


Figure 2.4 RGB colour-matching functions for the CIE 1931 standard colorimetric observer (RGB colour-matching function, 2013)

The $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$ functions were later linearly transformed to $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ to avoid negative values, which were deemed to be inconvenient. The $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ functions were introduced because they are convenient to apply to practical chromaticity and are shown in Figure 2.5.

2.3.3.2 CIE 1964 Standard Colorimetric Observer

In 1964, the CIE recommended the CIE 1964 Standard Supplementary Colorimetric Observer based on the colour matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ (p21-22, CIE, 1986). This is often referred to as the 10° observer which correlates with visual colour matching of fields subtending greater than 4° at the eye of an observer. This function was obtained from experimental data supplied by Stiles and Burch, and by Speranskaya (1959) as shown in Figure 2.5.

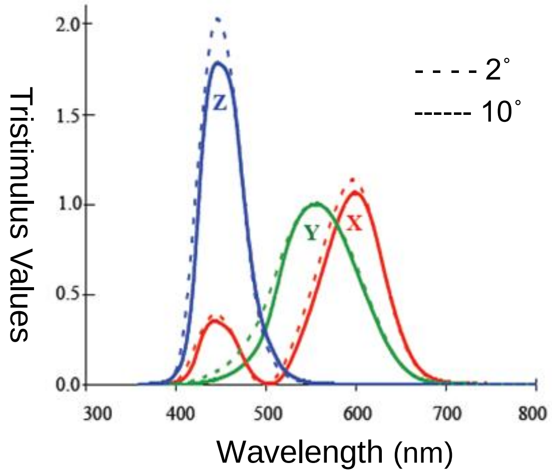


Figure 2.5 The CIE colour matching functions for the 1931 Standard Colorimetric Observer (2˚) and for the 1964 Supplementary Colorimetric Observer (10˚)

2.3.4 Tristimulus Values

According to the CIE system, colour stimuli can be represented by X, Y, and Z values, called tristimulus values. The CIE XYZ tristimulus values define the amount of three primaries that an observer would use, on average, to match the colour stimulus. XYZ values are calculated by integrating the product of the SPD of the light source (S(λ)), the spectral reflectance (R(λ)) and the CIE colour matching functions ($\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$), as defined in the following equations (p22-23, CIE, 1986):

$$X = k \int S(\lambda)R(\lambda)\bar{x}\,(\lambda)d\lambda,$$

$$Y = k \int S(\lambda)R(\lambda)\bar{y}\,(\lambda)d\lambda, \qquad (2\text{-}1)$$

$$Z = k \int S(\lambda)R(\lambda)\bar{z}\,(\lambda)d\lambda,$$

where X, Y and Z are tristimulus values, and λ is the wavelength in units of nm. Here, *k* is a constant which is used to normalise the tristimulus values based on a reference white. Normally *k* is chosen so that *Y*=100 for the perfect reflecting diffuser as defined in the following equation:

$$k = 100/\int S(\lambda)\bar{y}\,(\lambda)d\lambda. \tag{2-2}$$

In the CIE 1964 system, the colour matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, are replaced by $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, and $\bar{z}_{10}(\lambda)$, respectively.

When measuring self-luminous colours, such as those in a cathode ray tube (CRT) display, a television or a light source, $S(\lambda)R(\lambda)$, is replaced by the spectral radiance of the colour stimulus ($P(\lambda)$). The tristimulus values of self-luminous colours are then defined as

$$X = k\int P(\lambda)\bar{x}\,(\lambda)d\lambda,$$

$$Y = k\int P(\lambda)\bar{y}\,(\lambda)d\lambda, \tag{2-3}$$

$$Z = k\int P(\lambda)\bar{z}\,(\lambda)d\lambda.$$

2.3.5 Chromaticity Coordinates

A convenient way of visually representing tristimulus values is by chromaticity coordinates. The chromaticity coordinates (*x, y* and *z*) are proportional amounts of the tristimulus values (*X, Y* and *Z*) as follows (p15, CIE, 2004a):

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

$$y = \frac{\mathrm{Y}}{\mathrm{X}+\mathrm{Y}+\mathrm{Z}} \tag{2 - 4}$$

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

It suffices to quote only x, y due to the relation $x + y + z = 1$. Plotting y vs. x results in the CIE 1931 chromaticity diagram or the CIE x, y chromaticity diagram as shown in Figure 2.6.

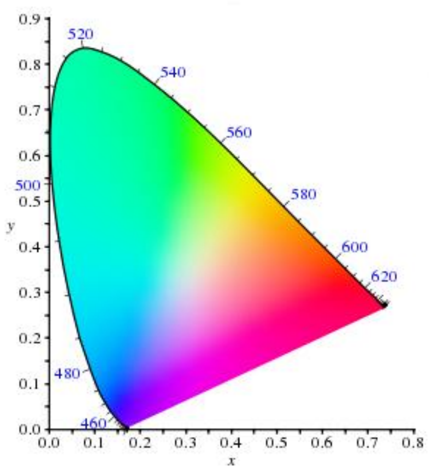


Figure 2.6 CIE 1931 x, y chromaticity diagram (chromaticity diagram, 2013a)

All colours are mapped into a two-dimensional space. It provides a colour map on which the chromaticities of all colours are plotted, including the spectrum locus and purple boundary. The spectrum locus is the curved line where the colours of the spectrum are positioned. The purple boundary is the straight line which is connected to the extreme red and blue colours. The area enclosed by the spectrum locus and the purple boundary covers the domain of all visible colours.

To sufficiently specify a coloured stimulus, the Y tristimulus value which contains the luminance information must be reported alongside the chromaticity coordinates (p77-78, Fairchild, 2005). Although the diagram has been widely used, there are some weaknesses. There is no information of the colour appearance of stimuli. There is no luminance (or lightness) information. It does not deal with chromatic adaptation. Also, the chromaticity diagram is a visually non-uniform space. Therefore, there has been effort to develop a diagram that is more perceptually uniform, which resulted in the CIE1976 Uniform Chromaticity Scales (UCS) diagram, defined by the following transform:

$$u' = \frac{4X}{X + 15Y + 3Z}, \qquad (2-5)$$

$$v' = \frac{X}{X + 15Y + 3Z}.$$

The chromaticity diagram defined by *u′* and *v′* coordinates in 1976, the CIE1976 UCS diagram, is shown in Figure 2.7.

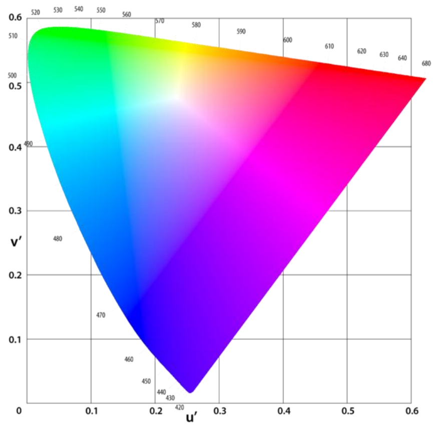


Figure 2.7 CIE 1976 *u′*, *v′* chromaticity diagram (chromaticity diagram, 2013b)

2.3.6 The CIE Uniform Colour Spaces

The CIE recommended two alternative uniform colour spaces, CIELUV and CIELAB, and associated colour difference formulae. The recommendations are in terms of the CIE 1931 Standard Colorimetric Observer and Coordinate System, but also apply to the CIE 1964 Standard Colorimetric Observer and Coordinate system. In this section, CIELAB and CIELUV uniform colour spaces are introduced (p164-169, Wyszecki and Stiles, 1982).

2.3.6.1 CIELAB Uniform Colour Space and Colour Difference Formula

In 1976, the CIE recommended a uniform colour space referred to as CIE

(1976) L*a*b* or CIELAB colour space. The uniform space is used in the field of colorant, graphic arts industries and subtractive mixing. The L*-axis, known as lightness, is normally in the range from 0 (black) to 100 (white), the a* coordinate represents redness-greeness and the b* coordinate represents yellowness-blueness as shown in Figure 2.8.

A three-dimensional, approximately uniform colour space is produced by plotting in *L**, *a** and *b** coordinates. The coordinates are defined by the following equations (p17-18, CIE, 2004a):

$$L^* = 116f(Y/Y_n) - 16,$$

$$a^* = 500[f(X/X_n) + f(Y/Y_n)], \qquad (2\text{-}6)$$

$$b^* = 200[f(Y/Y_n) + f(Z/Z_n)],$$

where

$$f(X/X_n) = (X/X_n)^{1/3} \qquad \text{if}(X/X_n) > (24/116)^3,$$

$$f(X/X_n) = (841/108)(X/X_n) + 16/116 \qquad \text{if}(X/X_n) \le (24/116)^3,$$

and

$$f(Y/Y_n) = (Y/Y_n)^{1/3} \qquad \text{if}(Y/Y_n) > (24/116)^3,$$

$$f(Y/Y_n) = (841/108)(Y/Y_n) + 16/116 \qquad \text{if}(Y/Y_n) \le (24/116)^3,$$

and

$$f(Z/Z_n) = (Z/Z_n)^{1/3} \qquad \text{if}(Z/Z_n) > (24/116)^3,$$

$$f(Z/Z_n) = (841/108)(Z/Z_n) + 16/116 \qquad \text{if}(Z/Z_n) \le (24/116)^3,$$

where X, Y and Z are considered as the tristimulus values of the test colour, and X_n, Y_n and Z_n are considered as the tristimulus values of a specified reference white.

Approximate correlates of the perceived attributes of lightness, chroma and hue angle are the following:

CIE 1976 (CIELAB) lightness: L^* as defined in the previous equation.

CIE 1976 (CIELAB) chroma: $C^*_{ab} = (a^{*2} + b^{*2})^{1/2}$ (2-7)

CIE 1976 (CIELAB) hue angle: $h_{ab} = \arctan(b^*/a^*)$

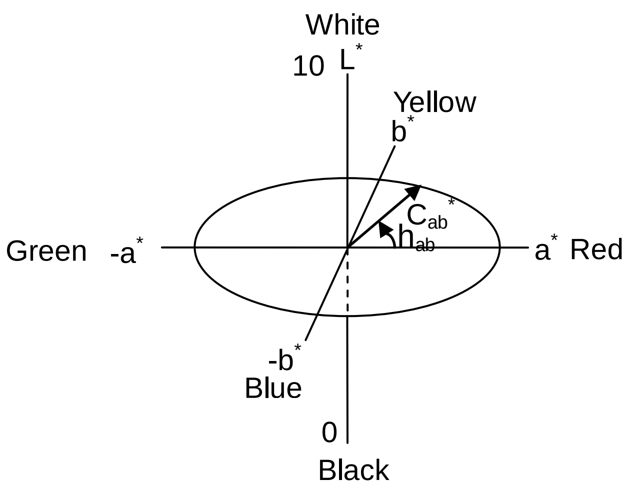


Figure 2.8 CIELAB colour space

Differences between two samples (denoted by subscripts 0 and 1) are calculated in the following equations:

CIELAB lightness difference:

$\Delta L^* = L^*_1 - L^*_0$

$\Delta a^* = a^*_1 - a^*_0$

$\Delta b^* = b^*_1 - b^*_0$

CIELAB chroma difference: (2-8)

$\Delta C^*_{ab} = C^*_{ab,1} - C^*_{ab,0}$

CIELAB hue angle difference:

$\Delta h_{ab} = h_{ab,1} - h_{ab,0}$

If the imaginary line joining two colours crosses the positive a^* axis, the equation Δh_{ab} will give a value outside the range ±180°. In this case, the value of Δh_{ab} must be corrected by adding or subtracting 360° to bring it within this range.

CIELAB hue difference:

$$\Delta H^*_{ab} = 2(C^*_{ab,1} \cdot C^*_{ab,0})^{1/2} \cdot \sin(\Delta h_{ab}/2) \qquad (2\text{-}9)$$

For small colour differences away from the achromatic axis,

$$\Delta H^*_{ab} = (C^*_{ab,1} \cdot C^*_{ab,0})^{1/2} \cdot \Delta h_{ab}\,, \qquad (2\text{-}10)$$

where the value of Δh_{ab} is in radians.

The CIE 1976 (L*a*b*) CIELAB colour difference, ΔE^*_{ab} between two colour stimuli is calculated as the Euclidean distance between the two points representing them in colour space by:

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

or (2-11)

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

2.3.6.2 CIELUV Uniform Colour Space and Colour Difference Formula

The CIE 1976 (*L*u*v**) or CIELUV colour space is based on the CIE 1976 uniform chromaticity scale diagram. It is mainly used in the field of lighting, CRT, television industries and additive mixing. Human perceptual attributes of lightness (L*), saturation ($S_{u,v}$), chroma (C_{uv}^*) and hue angle (h_{uv}) are predicted in the following equations.

A three-dimensional, approximately uniform colour space is produced by plotting in regular coordinates. The *L**, *u** and *v** quantities are defined by the following equations (p18- 20, CIE, 2004a):

$$L^* = 116f(Y/Y_n) - 16, \quad (2\text{-}12)$$

where

$$f(Y/Y_n) = (Y/Y_n)^{1/3} \qquad \text{if}(Y/Y_n) > \left(\frac{24}{116}\right)^3,$$

$$f(Y/Y_n) = (841/108)(Y/Y_n) + 16/116 \qquad \text{if}(Y/Y_n) \le \left(\frac{24}{116}\right)^3,$$

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

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

where Y, u', v' and Y_n, u'_n, v'_n are the CIELUV coordinates for test colour and a specified reference white, respectively.

Approximate correlates of the perceived attributes of lightness, saturation, chroma and hue are:

CIE 1976 lightness: L^* as defined in the previous equation

CIE 1976 (CIELUV) saturation: $s = 13[(u' - u'_n)^2 + (v' - v'_n)^2]^{1/2}$

CIE 1976 (CIELUV) chroma: $C_{uv}^* = (u^{*2} + v^{*2})^{1/2} = L^* s_{uv}$

CIE 1976 (CIELUV) hue angle: (2-13)

$$h_{uv} = \text{artan}[(v' - v'_n)/(u' - u'_n)] = \text{artan}(v^*/u^*)$$

CIE 1976 u, v (CIELUV) hue-difference: $\Delta H_{uv}^* = 2\left(C_{uv,1}^* C_{uv,0}^*\right)^{1/2} \sin(\Delta h_{uv}/2)$

where 1 and 0 refer to the two samples between which the colour difference is to be calculated, and $\Delta h_{uv} = h_{uv,1} - h_{uv,0}$.

The CIELUV space is illustrated with the vertical dimension L* axis and the u* and v* axes lying in a horizontal axis shown in Figure 2.9. The u* and v* axes represent the redness-greenness and yellowness-blueness perception of colours.

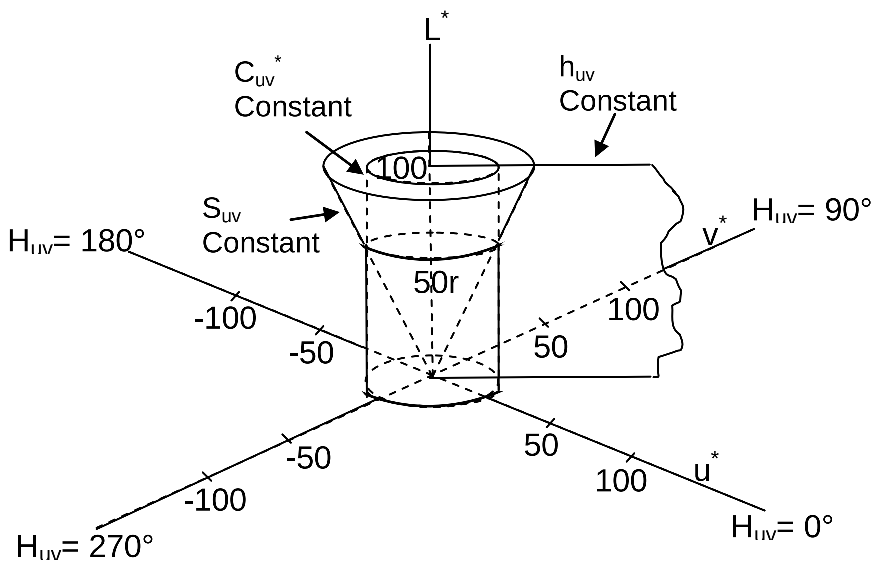


Figure 2.9 CIELUV colour space (Hunt, 1998)

The CIE 1976 (L*u*v*) CIELUV colour difference ΔE^{*}_{uv} between two colour stimuli is calculated as the Euclidean distance between representing them in the space by the following equation:

$$\Delta E^{*}_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2} \quad (2\text{-}14)$$

2.3.7 Colour Measurement Instrument

Colour measurement devices are used to measure colour in terms of reflectance, radiance or tristimulus values. In the following sections, two types of colour measurement instruments are introduced (p229-235, Chapter

3, Wyszecki and Stiles, 1982): the spectroradiometer and spectrophotometer. These instruments were used to measure the colour samples in this study.

2.3.7.1 Spectroradiometer

A spectroradiometer (Sangwine and Horne, 1998) is a colour measuring instrument that measures radiometric quantities, that is, irradiance (in W/m^2 units) or radiance (in $W/m^2.Sr$). Figure 2.10 shows the key elements of a tele-spectroradiometer. The key components are a telescope, a monochromator and a detector. The radiant power emitted by the test source enters the monochromator. The monochromator scatter the radiant power and sends the radiant power by way of a narrow band of wavelengths. "*The detector's photo-electric response is analyzed by the computer* (p229, Chapter 3, Wyszecki and Stiles, 1982)". A tele-spectroradiometer is frequently used in spectroradiometry. The specifications of the tele-spectroradiometer instrument will be given in Section 3.5.

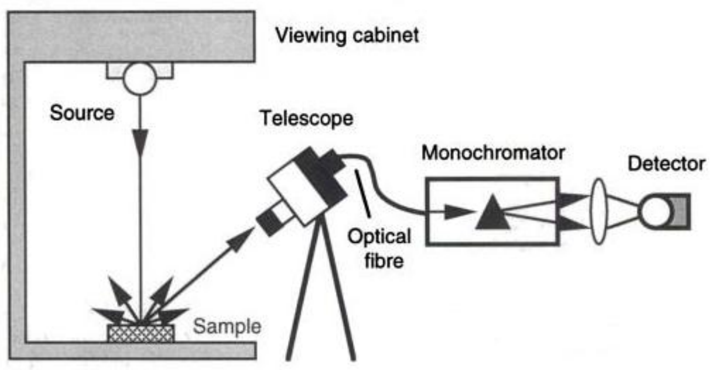


Figure 2.10 Key elements of Tele-spectroradiometer (Sangwine and Horne, 1998)

2.3.7.2 Spectrophotometer

A spectrophotometer (Sangwine and Horne, 1998) is used to measure the spectral transmittance and spectral reflectance of objects. Figure 2.11 shows the key elements of a spectrophotometer. The key optical elements of a spectrophotometer are a light source, a monochromator and a detector.

Radiant power emitted by the light source passes through the monochromator and is dispersed. The monochromator sends the radiant power by way of a narrow band of wavelengths. The detector system gets the spectral radiant power which is reflected from the object. The ratio of the power of the light reflected by the object at each wavelength to the power reflected by a perfect reflecting diffuser is calculated and is known as the spectral reflectance factor. The specifications of this instrument will be explained in Section 3.5.

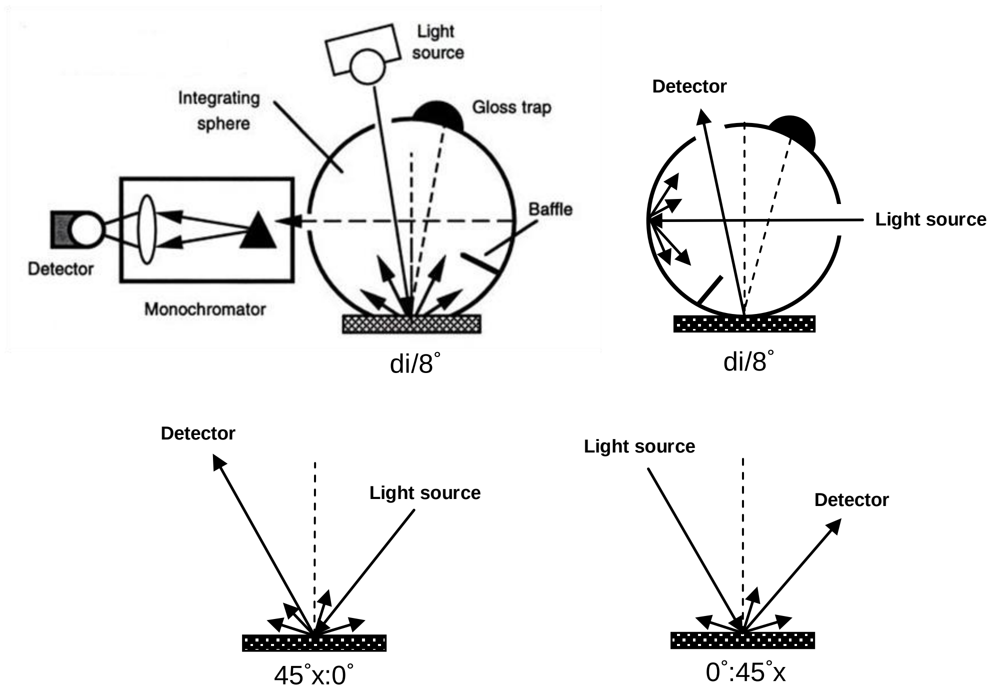


Figure 2.11 The key elements of a spectrophotometer (Sangwine and Horne, 1998)

2.3.8 Colour Order System

A colour order system is a rational method, or plan, of ordering and specifying all object colours (p506-512, Chapter 6, Wyszecki and Stiles, 1982). There are three types of colour order systems. The first type is based on the principles of additive mixtures of colour stimuli, and an example is the Ostwald Colour System. The second type is based on the principles of colorant mixtures. Finally, the third type is based on the principles of colour perception; examples of this type include the Munsell, NCS and DIN colour systems.

Since the main aim of this study is to find alternatives to the third dimension of colour appearance, it is necessary to investigate existing colour appearance models and colour spaces. Colour order systems, such as Munsell, NCS and DIN are highly relevant to this study. The Munsell colour system consists of the "chroma" scale, which is a widely used colour appearance attribute; NCS has "blackness", "whiteness" and "chromaticness" attributes, while and DIN has a "saturation" attribute. These scales are related to the "third dimension" of colour appearance. Although the newly developed blackness and whiteness scales in this study were based on the NCS system, the present and other studies also extensively investigate the basic scales in the Munsell and DIN systems. So, these three colour systems will be reviewed in the next sections. The NCS system was used as the basis of the new blackness and whiteness models because it has blackness and whiteness attributes. It is important and very popular in the field of colour design and colour communication. Also, this system is data based. Whiteness and blackness are widely used attributes. In addition, as mentioned in section 1.1, whiteness is useful for the quality of cosmetic products, white materials and image contrast. Blackness is important for black point for displays, colour printers and contrast ratio. However, there are no blackness and whiteness equations. Very few models have been developed that are not well known. Also, very few black and white datasets are available. The largest dataset available is that of the NCS system.

2.3.8.1 Munsell Colour Order System

The Munsell colour order system is one of the most widely used colour-order systems and was developed by Albert H. Munsell (1905 and 1969) in 1898. It is a natural and logical method of colour sensation ordering based on three attributes: hue (H), value (V) and chroma (C), denoted as HV/C. The three Munsell attributes are arranged in a cylindrical coordinate system in three dimensions. Munsell defined the three attributes as shown in Table

2.1 (Robertson, 1984).

Table 2.1 Definition of Munsell attributes

Colour Attribute	Definition
Hue (H)	*"An attribute according to which a sample appears to be one similar to one, or to proportions of two, of the perceived colours red, orange, yellow, green, blue, etc."*
Value (V)	*"A visual perception according to which a sample appears to reflect a greater or small fraction of the incident light"*
Chroma (C)	*"The degree to which a chromatic sample differs from an achromatic sample of the same value. It ranges from 0 (neutral) to maximum (20 for some hues)."*

Figure 2.12 shows the Munsell hue circle. There are five principal hues (5R, 5Y, 5G, 5B and 5P), and it is further divided into 100 steps. Figure 2.13 shows an example of a 10YR hue. The sample in a red box has the value of 8 and chroma of 2. This is defined as 10YR8/2.

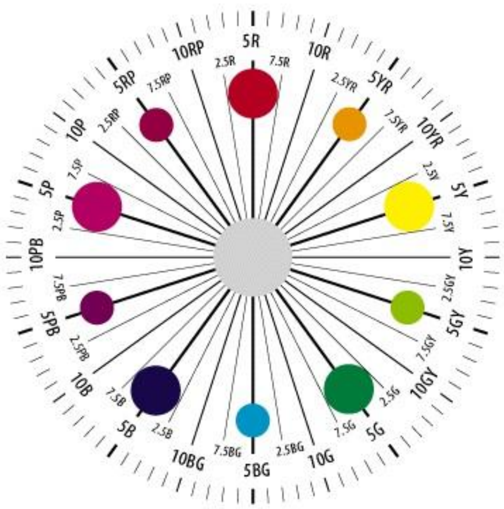


Figure 2.12 Munsell hue circle (2013)

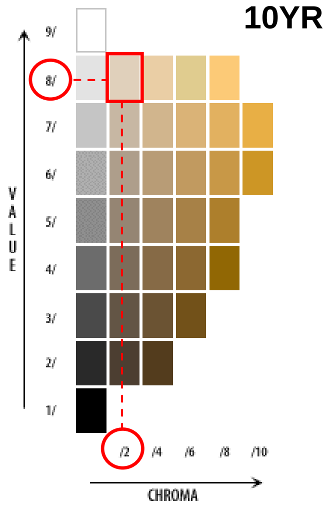


Figure 2.13 10YR hue (Munsell hue, 2013)

As mentioned earlier, the Munsell system is the earliest developed colour order system and has also been widely used to teach colour spacing for designers. However, it is not quite easy to learn. For example, chroma is not a concept or word used in the real world. Also, the concept of hue is difficult to grasp. i.e. 5 principle hues (5R, 5Y, 5G, 5B and 5P) and intermediate hues between, e.g. 7.5 PB.

2.3.8.2 Natural Colour System (NCS)

The Natural Colour System was developed in Sweden by Johansson and Hesselgren, and more recently, by Hård and his co-workers (Hård and Sivik, 1981). Approximately 16,000 NCS color samples were produced in the Colour Atlas based on four unique hues: red (R), yellow (Y), green (G) and blue (B) together with black (S) and white (W). Figure 2.14 shows the colours in a three dimension model called "the NCS colour solid". Figure 2.15 shows a vertical cut through the centre of the colour solid called "the NCS colour triangle". The notation of a colour is assessed by using the values of hue, whiteness (W), blackness (S), and chromaticness (C). Figure 2.16 shows the NCS colour circle which includes 40 hues in the NCS colour atlas. Hård and Sivik (1981) defined hue, whiteness, blackness and chromaticness as shown in Table 2.2.

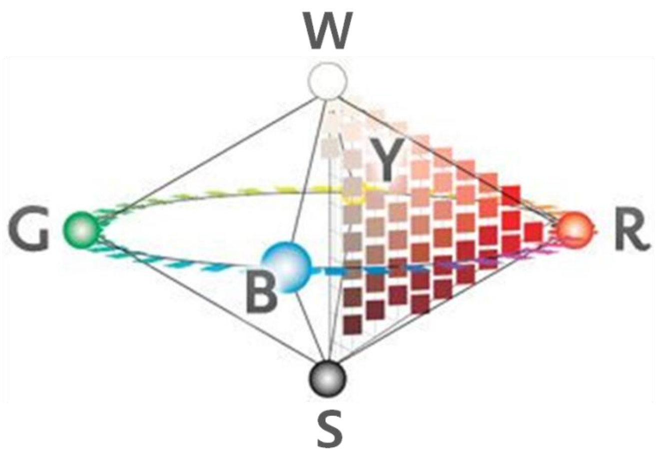


Figure 2.14 NCS colour solid (W: white, R: red, B: blue, G: green, Y: yellow, and S: black) (2013)

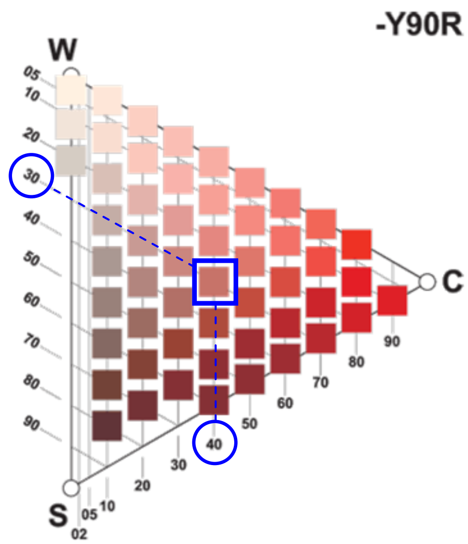


Figure 2.15 NCS colour triangle (W: whiteness, S: blackness and C: chromaticness) (2013)

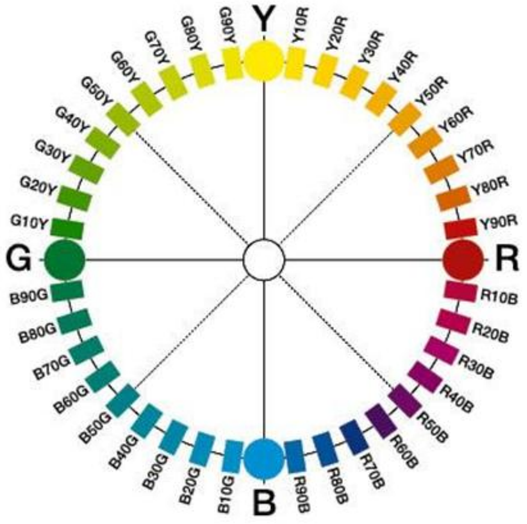


Figure 2.16 NCS colour circle (2013)

Table 2.2 Definition of NCS attributes

Colour Attribute	Definition
Hue	*"A resemblance of the two nearest hues (yellow, red, blue and green) and it is expressed in terms of percentage, for example, 90% of red and 10% of yellow (Y90R)"*
Whiteness (W)	*"A degree of resemblance to white"*
Blackness (S)	*"A degree of resemblance to black"*
Chromaticness (C)	*"A degree of resemblance to a maximum, or completely, chromatic colour"*

Mathematically, the visual composition of a colour is expressed as

$$W + S + C = 100 \tag{2-15}$$

where W, S and C are whiteness blackness and chromaticness, respectively.

For example, the colour in the blue box in Figure 2.15 is expressed as 3040 Y90R. 30 represents blackness (S) and 40 represents chromaticness (C). Therefore, whiteness (W) is 30 which is calculated as 100 - 30 - 40. For a Y90R colour, the 40 will be split into 36Y and 4R so that the total score of 100 will equal 30 (S) + 30 (W) + 36 (Y) + 4 (R).

The NCS colour samples were designed according to a series of psychophysical experiments. In the present study, NCS is focused upon among the colour systems to understand how it was produced. As mentioned earlier, the newly developed colour appearance attributes in the author's study are based on the NCS colour samples. Thus, it will be easier to understand this system by understanding the original experimental conditions such as viewing conditions, scaling method and procedure of the experiment. The experimental conditions, experimental stages and the methods for this experiment (Hård *et al*. 1996) are explained in the following section.

Experimental conditions

Observers assessed colour samples in a light-booth. In the light-booth simulated daylight was produced by six 20-W Luma Colorette fluorescent tubes. The correlated colour temperature was approximately 5400K. The background of the booth was light grey with a luminance reflectance factor of Y_{CIE} = 54%. The colour samples were 6 × 9 cm and were placed on a panel tilted about 45°. Hence, the 45°:0° illumination/viewing geometry was used. The panel constituted the immediate surround of the samples. It was white (with a reflectance of 78%) and was 40 cm by 15 cm. White was used in the panel because most of the users in practical colour design could easily have access to white cardboard. The colour samples were made from acrylic paint with a matte surface using the most fade-resistant pigments available.

About 50 observers took part in the NCS experiment at different periods between 1964 and 1972. Most of the subjects were unfamiliar with colour assessment and did not know the aims of the experiment. More than 60,000 observations were carried out during the experiment.

Colour samples

Fourteen achromatic samples were used for judging whiteness and blackness. The samples were chosen between the available highest whiteness and the blacknesss samples within the atlas, i.e. (0500-N and 9000-N). Also, the intention was to cover a large colour gamut. Three hundred and sixty samples were used for the assessment of chromaticness, blackness and whiteness. These samples comprised 6 to 8 samples within each of 24 hues.

Seventy-two samples were used for the assessment of hue. These samples were formed by 24 colour samples of a hue circle in three positions ('s-c' coordinates of $\approx$1010, $\approx$7010 and $\approx$3050).

Colour assessments

Samples were assessed one at a time in the experiment. There are no other colour stimuli or reference samples to be compared in the viewing field. Each of the observers assessed the samples in random sequence. Each observer was asked to assess the resemblance (or closeness) to the six primaries, i.e. white, black, red, yellow, green and blue.

For the whiteness and blackness experiment, observers were asked to assess the colour by considering the relationship between blackness (S) and whiteness (W) in numeric values between 0 and 100. The sum of the two should be 100 (= S + W).

For the chromaticness, blackness and whiteness experiment, observers were asked to assess the colour by considering relationship between blackness (S), whiteness (W) and chromaticness (C) in terms of numeric values as a percentage value between 0 and 100. The sum of the three should be 100 (= S + W + C).

For the hue experiment, observers were asked to assess the colour by considering the relationship between yellowness (Y), redness (R), blueness

(B) and greenness (G) in numeric values having the total sum of y, r, b and g as 100. The samples were not judged simultaneously yellowish and bluish or reddish and greenish. Thus, the judgement was Y + R = 100, R + B = 100, B + G = 100, or G + Y = 100.

The above results were used to develop the final version of NCS colour system. It becomes the most widely used colour system in the field of art and design. This is mainly due to the easy understanding of its attributes, hue, blackness and whiteness. However, it is not based on the concept of uniform colour scale. The obvious example is its hue spacing. For example, there is much larger colour spacing between blue and red, and between red and yellow.

In the author’s study, the NCS experiment described here plays an important part. One reason is that the observers in their experiment were naive for assessing colours. The present observers were trained with no provision of reference colours (such as pure white, black, red, yellow, green and blue for scaling hue). This can truly reflect how different the unitary colours are between observers and whether observers understand the tasks involved. Note that the actual NCS samples were used in the experiment, because these samples were available and they were easily chosen corresponding to the NCS attributes (whiteness and blackness) investigated.

2.3.8.3 DIN System

The DIN colour system undertaken by the German Standardization Institute (Deusches Institut für Normung (German Institute for Standardisation), DIN). The colour system was developed by M. Richter and his associates (Richter and Witt, 1986). In 1980, it became the German standard (DIN 6164 (1980)). The system defined three attributes (darkness degree, hue and saturation) as follows.

“Darkness degree is an attribute of lightness relative to the lightness of the optimal colour having the same CIE chromaticity as the sample being considered.”, where optimal colour is a theoretical construct. It has a

maximum luminance value of any physical realisable surface of the same chromaticity.

"DIN hue has the usual meaning except that a compromise is made in favour of simplicity by defining lines of constant hue to be straight in the CIE chromaticity diagram and invariant with lightness."

"Saturation is the DIN chromatic-amount attribute which measures the distance from an achromatic sample of the same luminance factor (not the same darkness degree) in psychologically uniform steps."

Figure 2.17 shows the sphere sector colour solid of this system.

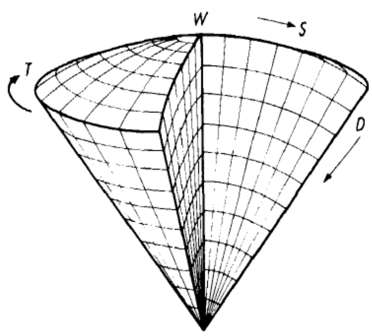


Figure 2.17 Sphere sector colour solid of the DIN Colour System (W = white, T = hue number, S = saturation degree and D = darkness degree) (Richter and Witt, 1986)

2.4 Colour Appearance Attribute

The CIE defined the colour appearance attributes using the International Lighting Vocabulary (CIE, 2012) ILV. These terms are listed in Table 2.3 (CIE, 2012).

Table 2.3 Definition of perceptual colour appearance attributes

Colour Attribute	Definition
Brightness	*"An attribute of a visual perception according to which an area appears to emit, or reflect, more or less light "*
Lightness	*"The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting"*
Colourfulness	*"An attribute of a visual sensation according to which the perceived colour of an area appears to be more or less chromatic"*
Chroma	*"Colourfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting"*
Saturation	*"Colourfulness of an area judged in proportion to its brightness"*
Hue	*"An attribute of a visual perception according to which an area appears to be similar to one of the colours: red, yellow, green, and blue, or to a combination of adjacent pairs of these colours considered in a closed ring"*

In this study, chroma, colourfulness and saturation were reviewed among the above colour appearance attributes. Also, the existing colour appearance attributes of vividness, blackness and whiteness were surveyed in the following sections.

Recently, Berns (2014) also introduced some new attributes based on CIELAB, namely, vividness (V_{ab}*), depth (D_{ab}*) and clarity (T_{ab}*) (see equation (2-16)). He gave them the definitions shown in Table 2.4. He then developed scales based on CIELAB chroma (see equation (2-16)). They are basically defined as the visual percept departure from white, black and the background, respectively. A bright yellow colour would have high vividness, low depth and high clarity against a mid-grey background. A dark red would have low vividness, high depth and high clarity against the same background.

Table 2.4 Definition of perceptual colour appearance attributes introduced by Berns

Terms	Definition
Vividness (V_{ab}*)	*"An attribute of colour used to indicate the degree of departure of the colour from a neutral black color"*
Depth (D_{ab}*)	*"An attribute of colour used to indicate the degree of departure of the colour from a neutral white colour"*
Clarity (T_{ab}*)	*"An attribute of colour used to indicate the degree of departure of the colour from its background colour"*

Berns also explained the effective word pairs in industry, such as cleaner-dirtier, brightness-duller, weaker-stronger, paler (whiter)-deeper shown in Figure 2.18. They are basically axes rotated in the lightness vs. chroma plane and are more frequently used by ordinary people than defined by CIE, such as chroma and colourfulness.

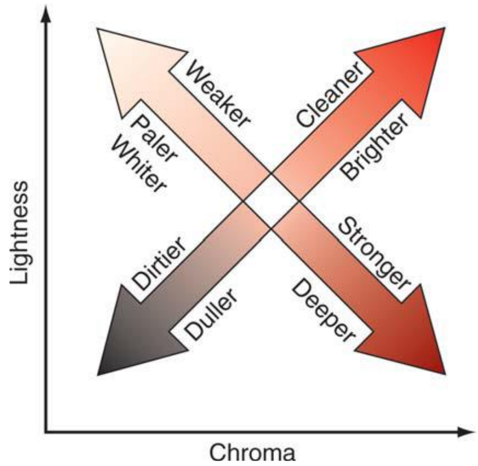


Figure 2.18 Opponent terms in lightness and chroma coordinates (Berns, 2014)

In addition to the vividness attribute developed by Berns, he also proposed Depth (D_{ab}*), Clarity (T_{ab}*) and vividness (V_{ab}*), which are calculated by equation (2-16). All of them were based on the CIELAB C^*_{ab} attribute. Vividness (V_{ab}*) will be introduced later in Section 2.4.1.2.

$$\mathrm{D}^*_{\mathrm{ab}} = \sqrt{(100 - \mathrm{L}^*)^2 + \left(\mathrm{C}^*_{\mathrm{ab}}\right)^2},$$

$$\mathrm{T}^*_{\mathrm{ab}} = \sqrt{\left(\mathrm{L}^*_{\mathrm{background}} - \mathrm{L}^*\right)^2 + \left(\mathrm{a}^*_{\mathrm{background}} - \mathrm{a}^*\right)^2 + \left(\mathrm{b}^*_{\mathrm{background}} - \mathrm{b}^*\right)^2}, \quad (2\text{-}16)$$

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

In addition to the colour attributes given by the CIE and Berns, those included in the NCS colour order systems are also important for applications such as whiteness, blackness (from the NCS system), as well as saturation (in the DIN system). The following sections will introduce most of the available saturation, vividness, blackness and whiteness attributes. Note that these four attributes were later identified as important attributes and have been extensively studied. The reasons will be given later.

2.4.1 Third-dimensional Attributes

A three-dimensional colour space when regarded as a cylindrical coordinate system typically includes three dimensions, (a) hue, (b) lightness or brightness, and (c) chroma, saturation or colourfulness, each of which has been defined by the CIE, as shown in Table 2.3. The latter ones (i.e. the (c) attributes such as chroma, saturation and colourfulness) are called the "third -dimension" attributes in this thesis.

Table 2.5 shows the structures of several popular colour systems. The CIELAB colour space can be seen as a Euclidean space determined by three orthogonal dimensions, L*, a* and b*, among which there is no chroma. However, CIELAB can also be seen as cylindrical coordinate system consisting of hue angle as the angular coordinate, lightness as the longitudinal axis and chroma as the radial distance. It is also similar to the CIELUV colour space. CIELUV can be regarded as having L*, u* and v* in a Euclidean space but can also be regarded as having hue angle, lightness and chroma in a cylindrical coordinate system. The NCS system has three dimensions, hue, blackness and whiteness. If seen as cylindrical coordinates, there is also a chromaticness scale in this system as the radial distance. In the Munsell system, there are hue, value and chroma. The DIN system has hue, darkness and saturation.

Although the colour systems and colour spaces have different dimensions, in general, they have very similar frameworks which are typically three dimensional. For consistency, this thesis regards lightness as the first dimension, hue as the second dimension, and attributes such as chroma, chromaticness or saturation as the third dimension.

Table 2.5 The structure of colour systems

Colour system	The 1st dimension	The 2nd dimension	The 3rd dimension	Note
CIELAB	Lightness	Hue	Chroma	The Cartesian system contains L*, a* and b* dimensions
CIELUV	Lightness	Hue	Chroma	The Cartesian system contains L*, u* and v* dimensions
NCS	Whiteness Blackness	Hue	Chromaticness	The Cartesian system defined to have blackness and whiteness scales
Munsell	Value	Hue	Chroma	
DIN	Darkness	Hue	Saturation	

The CIE has introduced chroma for CIELAB and CIELUV as mentioned earlier in equation (2-7) and equation (2-13), respectively. Both equations are also given as

$$C_{ab}^* = (a^{*2} + b^{*2})^{1/2}, \qquad (2\text{-}17)$$
$$C_{uv}^* = (u^{*2} + v^{*2})^{1/2}.$$

In the CIECAM02 colour appearance model, the CIE introduced a colourfulness (M) attribute shown in Appendix A in equation (9-21).

$$M = CF_L^{0.25} \tag{2-18}$$

where C is chroma, and F_L is the luminance level adaptation factor.

Luo *et al*. (1991) carried out a large-scale study to assess lightness, colourfulness and hue composition using the magnitude estimation method (see Section 2.6.3). Ten observers participated in this experiment. The observers had a five-hour training programme to learn how to apply the magnitude estimation scaling technique and to understand the concepts of lightness, colourfulness and hue. There was a reference colour with a value assigned 30. They were instructed to regard neutral colours as having a colourfulness of zero. For each test colour, observers were asked to assign a number considering its relationship with the reference colour. They also found that observers can estimate lightness and hue more precisely than colourfulness.

Zhang and Montag (2006) investigated how well people can use different colour attributes. Observers were asked to perform colour matching and discrimination using two sets of scales (lightness/chroma/hue and lightness/yellowness-blueness/redness-greenness). They found that hue and lightness were significantly more identifiable than chroma, yellowness-blueness and redness-greenness scales. They concluded that a higher level psychological processing involving cognition and language may be necessary for even apparently simple tasks involving colour matching and the description of colour differences. Hence, the third-dimensional attributes are less accurate, more difficult and less familiar than those associated with lightness and hue. Thus, new attributes need to be investigated - whether these terms can be better understood than those CIE defined scales by ordinary people (naive observers).

There are many terms that could possibly be a third dimension. Nevertheless, saturation and vividness were chosen to be studied here for the following reasons. First, saturation has been defined by the CIE as shown in its International Lighting Vocabulary (CIE, 2012). CIELUV (CIE,

2004) includes a saturation attribute as determined by C^*_{uv}/L^*. Fairchild and Rodney (2012) recently proposed deriving independent colour attributes, which when combined together can form a three-dimensional system according to particular applications. From their proposal, the sequences to build these scales are hue, saturation, lightness, brightness, chroma and colourfulness. The latter two attributes, chroma and colourfulness, are derived from 'saturation'. Thus, it is important for saturation to be derived first.

For vividness, as mentioned in Section 2.4, Berns believed that this attribute is a popular term used in imaging applications; therefore, he derived a model based on the CIELAB system, i.e. given earlier (section 2.4). The model was defined as an attribute of colour used to indicate the degree of departure of a colour from a neutral black colour. There are more reasons for choosing saturation and vividness, as mentioned in Sections 1.1 and 4.1. Therefore, the following subsections focus on saturation and vividness.

2.4.1.1 Saturation

Saturation has been developed by existing colour appearance models and colour spaces such as CIELUV (CIE, 2004a), Nayatani (1986, 1987, 1995), Hunt (1952, 1982, 1985, 1987, 1994, 1995, 1998), CIECAM97s (Luo and Hunt, 1998) and CIECAM02 (p9, CIE, 2004b). Some of the saturation models are introduced here.

CIELUV (s_{uv})

The saturation model was developed in the CIELUV space, which was mentioned in Section 2.3.6.2. The equation is written as follows:

$$s_{uv} = 13[(u' - u'_n)^2 + (v' - v'_n)^2]^{1/2}$$
$$\text{or } s_{uv} = C_{uv}^*/L^*, \qquad (2\text{-}19)$$

where L^* is lightness and C_{uv}^* is CIELUV Chroma.

The CIELUV model is formed by a subtractive shift in chromaticity coordinates ($u' - u'_n$, $v' - v'_n$). However, this subtractive shift will lead to a shift right out of the gamut of realizable colours in predicting corresponding colours (p194-195, Fairchild, 2005).

Similarly, the following equation can be used to calculate saturation based on CIELAB. However, this term is not defined by CIE:

$$s_{ab} = C_{ab}^{*}/L^{*} \qquad (2\text{-}20)$$

However, comparing with colour appearance models such as CIECAM02, CIELAB has some limitations in predicting hue composition (p193-194, Fairchild, 2005). It is incapable of predicting luminance-dependent effects such as the Hunt effect and the Stevens effect. Also, it does not correlate with brightness and colourfulness.

Lübbe's saturation model

Lübbe (2011) also introduced a general concept to scale saturation. However, the model is theoretical and has not been verified by other researchers. The model is similar to the CIELUV formulae, as given below:

$$\mathrm{S}^{+} = 100\,\frac{\mathrm{C}_{\mathrm{ab}}^{*}}{\sqrt{\mathrm{L}^{*2} + \mathrm{C}_{\mathrm{ab}}^{*}{}^{2}}}\,. \qquad (2-21)$$

Nayatani et al.'s saturation model

Nayatani *et al*. developed saturation models expressed in terms of a red-green component (SRG) derived from the r response and a yellow-blue component (SYB) derived from the p response in equation (2-22) (Nayatani *et al*., 1986, 1987, 1995). The model was developed and tested for simple patches (p213-223, Fairchild, 2013). In addition, this model is not for imaging applications. The model is more complex than Hunt model, and its prediction performance is not as good as that of the Hunt model.

Here, S_{RG} and S_{YB} are saturation expressed in terms of a red-green component and yellow-blue component:

$$S_{RG} = \frac{488.93}{\beta_1(L_{or})} E_S(\theta) t, \qquad (2\text{-}22)$$
$$S_{YB} = \frac{488.93}{\beta_1(L_{or})} E_S(\theta) p,$$

where

$$\beta_1(L_{or}) = \frac{6.469 + 6.362 R_o^{0.4495}}{6.469 + R_o^{0.4495}}.$$

Note that $\beta_1(L_{or})$ is an additional exponential factor that depends on the normalizing luminance:

$$\begin{vmatrix} R_o \\ G_o \\ B_o \end{vmatrix} = \frac{Y_o E_o}{100\pi} \begin{vmatrix} \xi \\ \eta \\ \zeta \end{vmatrix}$$

R_o, G_o and B_o are the cone response for the adapting field, Y_o is the luminance factor of the adapting background and E_o is the illuminance level.

$\xi = (0.48105 x_o + 0.78841 y_o - 0.08081)/y_o$
$\eta = (-0.27200 x_o + 1.11962 y_o + 0.04570)/y_o$
$\zeta = 0.91822\,(1 - x_o - y_o)/y_o$

ξ, η and ζ are the intermediate values.

$$\begin{aligned} E_S(\theta) = {} & 0.9394 - 0.2478 \sin\theta - 0.0743 \sin 2\theta + 0.0666 \sin 3\theta - 0.0186 \sin 4\theta \\ & - 0.0055 \cos\theta - 0.0521 \cos 2\theta - 0.0573 \cos 3\theta - 0.0061 \cos 4\theta \end{aligned}$$

$E_S(\theta)$ is the chromatic strength function to correct the saturation scale as a function of hue angle.

The preliminary chromatic channel responses t (red-green) and p (yellow-blue) are given as:

$$t = \beta_1(R_o) \log\frac{R+n}{20\xi+n} - \frac{12}{11}\beta_1(G_o) \log\frac{G+n}{20\eta+n} + \frac{1}{11}\beta_2(B_o) \log\frac{B+n}{20\xi+n},$$

$$p = \frac{1}{9}\beta_1(R_o)\log\frac{R+n}{20\xi+n} - \frac{1}{9}\beta_1(G_o)\log\frac{G+n}{20\eta+n} + \frac{1}{9}\beta_2(B_o)\log\frac{B+n}{20\xi+n}.$$

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix} = \begin{vmatrix} 0.40024 & 0.70760 & -0.08081 \\ -0.22630 & 1.16532 & 0.04570 \\ 0.0 & 0.0 & 0.91822 \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$

R, G and B are the cone responses for the test stimulus

Hunt's saturation attribute

Hunt (1952, 1982, 1985, 1987, 1994, 1995 and 1998) developed a saturation model with the following equation:

$$s = 50M/(\rho_a + \gamma_a + \beta_a), \tag{2-23}$$

where

$M = (M_{YB}^2 + M_{RG}^2)^{1/2}$

$M_{YB} = 100[(1/2)(C_2 - C_3)/4.5][e_S(10/13)N_cN_{cb}F_t]$

$M_{RG} = 100[C_1 - (C_2/11)][e_S(10/13)N_cN_{cb}]$

M is the chromatic response calculated as the quadrature sum of yellowness-blueness and redness-greenness responses, M_{YB} is the yellowness-blueness response; M_{RG} is the redness-greenness response and e_S is the eccentricity factor. The e_s factor is calculated for the test stimulus. This factor is accomplished through linear interpolation using the hue angle h_S of the test stimulus and the data in Table 2.6.

Table 2.6 Hue angles h_S and eccentricity factors e_S for the unique hues

Hue	h_S	e_S
Red	20.14	0.8
Yellow	90.00	0.7
Green	164.25	1.0
Blue	237.53	1.2

N_c is the chromatic background induction factor. The nominal values of this factor are listed in Table 2.7.

Table 2.7 Values of the chromatic induction factor

Situation	N_c
Small areas in uniform backgrounds and surrounds	1.0
Normal scenes	1.0
Television and CRT displays in dim surrounds	1.0
Large transparencies on light surrounds	0.7
Projected transparencies in dark surrounds	0.7

$N_{cb} = 0.725(Y_W/Y_b)^{0.2}$,

N_{cb} is a chromatic background induction factor.

$C_1 = \rho_a - \gamma_a$,

$C_2 = \gamma_a - \beta_a$,

$C_3 = \beta_a - \rho_a$,

C_1, C_2 and C_3 are three colour difference signals which represent all of the possible chromatic opponent signals that could be produced in the retina.

$\rho_a = B_\rho[f_n(F_L F_\rho \rho/\rho_W) + \rho_D] + 1$,

$\gamma_a = B_\gamma[f_n(F_L F_\gamma \gamma/\gamma_W) + \gamma_D] + 1$,

$\beta_a = B_\beta[f_n(F_L F_\beta \beta/\beta_W) + \beta_D] + 1$,

ρ_a, γ_a and β_a are the adapted cone signals determined from the cone responses for the stimulus $\rho\gamma\beta$ and those for the reference white $\rho_W\gamma_W\beta_W$.

$B_\rho = 10^7/[10^7 + 5L_A(\rho_W/100)]$,

$B_\gamma = 10^7/[10^7 + 5L_A(\gamma_W/100)]$,

$B_\beta = 10^7/[10^7 + 5L_A(\beta_W/100)]$,

B_ρ, B_γ and B_β are the cone bleaching factors.

$f_n[I] = 40[I^{0.73}/(I^{0.73} + 2)]$,

$f_n()$ is a general hyperbolic function.

$F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3}$,

F_L is a luminance-level adaptation factor incorporated into the adaptation model to predict the general behaviour of light adaptation over a wide range of luminance levels.

$k = 1/(5L_A + 1)$,

$F_\rho = (1 + L_A^{1/3} + h_\rho)/(1 + L_A^{1/3} + 1/h_\rho)$,

$F_\gamma = (1 + L_A^{1/3} + h_\gamma)/(1 + L_A^{1/3} + 1/h_\gamma)$,

$F_\beta = (1 + L_A^{1/3} + h_\beta)/(1 + L_A^{1/3} + 1/h_\beta)$,

F_ρ, F_γ and F_β are the chromatic adaptation factors to model the fact that chromatic adaptation is often incomplete.

$h_\rho = 3\rho_W/(\rho_W + \gamma_W + \beta_W)$,

$h_\gamma = 3\gamma_W/(\rho_W + \gamma_W + \beta_W)$,

$h_\beta = 3\beta_W/(\rho_W + \gamma_W + \beta_W)$,

h_ρ, h_γ and h_β are the chromaticity coordinates scaled relative to illuminant E (since ργβ themselves are normalized to illuminant E).

$\rho_D = fn[(Y_b/Y_W)F_LF_\gamma] - fn[(Y_b/Y_W)F_LF_\rho]$,

$\gamma_D = 0.0$,

$\beta_D = fn[(Y_b/Y_W)F_LF_\gamma] - fn[(Y_b/Y_W)F_LF_\beta]$,

ρ_D, γ_D and β_D are the parameters to allow prediction of the Helson-Judd effect, Y_b is the luminance of the background and Y_W is the reference white.

The main reason why the Hunt model is not adopted as a single standard colour appearance model for all application is its complexity (p224, Fairchild, 2005). It cannot be easily inverted, is computationally expensive, is difficult to implement and requires significant user knowledge to be used correctly. It is generally capable of making accurate predictions for a wide range of visual experiments when the model is flexible enough to be adjusted to the required situation.

CIECAM97s saturation

The CIE recommended the CIECAM97s colour appearance model in 1997. The CIECAM97s saturation model is given by

$$s = \frac{50(a^2+b^2)^{\frac{1}{2}}100e(10/13)N_cN_{cb}}{R'_a+G'_a+(21/20)B'_a}, \qquad (2-24)$$

where

$$R'_a = \frac{40(F_LR'/100)^{0.73}}{[(F_LR'/100)^{0.73}+2]},$$

$$G'_a = \frac{40(F_LG'/100)^{0.73}}{[(F_LG'/100)^{0.73}+2]},$$

$$B'_a = \frac{40(F_LB'/100)^{0.73}}{[(F_LB'/100)^{0.73}+2]},$$

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_H M_B^{-1} \begin{bmatrix} R_cY \\ G_cY \\ B_cY \end{bmatrix}, \ F_L=0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3},$$

$$M_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0 & 0 & 1 \end{bmatrix},$$

$$M_B = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix},$$

$R_c = [D(1.0/R_W)+1-D]R,$

$G_c = [D(1.0/G_W)+1-D]G,$

$B_c = [D(1.0/B_W^P) + 1 - D]|B|^P,$

$p = (B_W/1.0)^{0.834}$, $D = F - F/[1+2(L_A^{1/4})+(L_A^2/300)]$.

Here, D is for specifying the degree of adaptation; D=1.0 for complete adaptation or discounting the illuminant, and D=0 for no adaptation.

Here, L_A is the luminance of the adapting field, XYZ denotes the tristimulus values of the sample, $X_WY_WZ_W$ denotes the tristimulus values of the source white and Yb denotes the relative luminance of the source background in the source conditions.

Table 2.8 shows the input parameters for the CIECAM97s models. In the table, c denotes the constants for the impact of surround, Nc denotes the chromatic induction factor, F_{LL} denotes the lightness contrast factor and F denotes the factor for the degree of adaptation.

Table 2.8 Input parameters for the CIECAM97s

Viewing condition	c	N_c	F_{LL}	F
Average surround, samples subtending>4°	0.69	1.0	0.0	1.0
Average surround	0.69	1.0	1.0	1.0
Dim surround	0.59	1.1	1.0	0.9
Dark surround	0.525	0.8	1.0	0.9
Cut-sheet transparencies	0.41	0.8	1.0	0.9

Tristimulus values of the sample (X, Y and Z) and white (X_W, Y_W and X_W) are normalized and transformed by the following transformation as

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_B \begin{bmatrix} X/Y \\ Y/Y \\ Z/Y \end{bmatrix},$$

$k=1/(5L_A + 1)$,

$N_{cb} = 0.725(1/n)^{0.2}$, $n=Y_b/Y_W$,

n is a background induction factor and N_{cb} is a chromatic brightness induction factor.

The CIECAM97s model has limitations in its formulation and performance and the creation of additional data for improvement (p264, Fairchild, 2005).

CIECAM02 saturation

CIECAM02 (p1-13, CIE, 2004b) is a revised version of CIECAM97s. The CIECAM02 saturation model was developed as will be explained in detail in Section 2.5 and Appendix A. The model is still complicated as seen in the following equations:

$$s = 100\sqrt{\mathrm{M}/\mathrm{Q}}, \tag{2-25}$$

where

M (colourfulness) = $CF_L^{0.25}$, Q (brightness) $= (4/\mathrm{c})\sqrt{J/100}(A_w + 4)F_L^{0.25}$

c is the surround parameter, A is the achromatic response of the stimulus and A_w is the achromatic response for white (see Appendix A).

Here, $\mathrm{C}\ (\text{chroma}) = t^{0.9}\sqrt{J/100}(1.64 - 0.29^n)^{0.73}$,

t is a temporary quantity, F_L is the Luminance-level adaptation factor (see Appendix A), and

$J\ (\text{lightness}) = 100(A/A_w)^{cz}$.

The CIECAM02 saturation model was based on the Juan and Luo data (2002). They carried out psychophysical experiments for scaling colour appearance attributes under 12 different viewing conditions. Among the phases, 6 phases were related to saturation. The experiments were carried out using the magnitude estimation method (Stevens, 1958) in a VeriVide viewing cabinet under a D65 simulator against three different backgrounds (white, grey or black). A total of 132 coloured cube samples were used only for scaling saturation. Each sample was covered by a single colour. Seven to nine observers took part in the experiment. Observers had training sessions and were instructed that the colour appearance on each side of the cube has the same saturation, but different lightness and colourfulness. The neutral colours were considered to have a saturation of zero according to the CIE definition (CIE, 1987). Before the real experiment, scaling saturation for neutral colours, half of the observers considered black as the most saturated colour rather than zero. Dark colours were found to be the most difficult colours to scale for saturation when neutral colours have a saturation of zero. Therefore, neutral colours were excluded from the experiment due to the definition of the CIE.

It was found that saturation is a difficult attribute to estimate using magnitude estimation. It is especially difficult to scale saturation for dark stimuli. It was found that observers gave more accurate estimations in scaling saturation than colourfulness. It was found that the saturation results were not affected when samples were viewed against different background colours. It was concluded that observers can scale saturation with great accuracy with training. This means that it is hard to scale without training. Juan and Luo's saturation was found to be closely associated with lightness and colourfulness attributes, especially with high chromaticness samples.

Juan and Luo also developed a new saturation attribute, denoted by S_D, based on CAM97s2. It is given in following equation (Juan and Luo, 2002):

$$S_D = M_D/Q_D, \tag{2-26}$$

where

M_D (colourfulness) = $C_D F_L^{0.15}$ and

Q_D (brightness) = $(1.24/c)(J_D/100)0.67(A_W+3)^{0.9}$.

C_D (chroma) = $2.44s^{0.69}(J_D/100)^{0.67n}(1.64-0.29^n)$ and

J_D (lightness) = 100 $(A/A_W)^{cz'}$, with $z' = 0.85 + \sqrt{Y_b/Y_w}$.

n is a background induction factor, A is the achromatic response of the stimulus, Aw is the achromatic response for white, c is the surround parameter, Y_b is the relative luminance of the source background in the source conditions and Y_w is the tristimulus value of the source white.

Fairchild & Heckaman's saturation model

In 2012, Fairchild and Heckaman (2012) introduced a saturation model that is computed as the ratio of the distance from the white point (D65) to the stimulus in question to the distance from the white point to the spectrum locus. The saturation model is given as (Fairchild, 2012)

$$s = \sqrt{(u' - u'_n)^2 + (v' - v'_n)^2} \Big/ \sqrt{\left(u'_L - u'_n\right)^2 + \left(v'_L - v'_n\right)^2}\,, \qquad (2-27)$$

where u'v' are the chromaticities of the stimulus, $u_n'v_n'$ are the D65 diffuse white, and $u_L'v_L'$ are the spectrum locus for the same hue angle from the lookup table (LUT) of the chromaticities of pure colour in IPT hue (Ebner and Fairchild, 1998).

2.4.1.2 Vividness

Trémeau and Charrier (2000) have demonstrated that vividness could be a valuable attribute for assessing image quality. However, no vividness attribute has been developed in the existing colour appearance models. In 2005, Nayatani and Komatsubara (2005) proposed a simple model for estimating degree of vividness (DV), given in equation (2-28). Nayatani defined the degree of vividness as the "*degree of chromatic intensity perceived in object colour under study* (Nayatani and Komatsubara, 2005)." They suggest that this concept is similar to the term "chroma" defined in the CIE term list (CIE, 2012).

$$DV = C\{1 + 0.10[W\text{-}Bk]\}, \qquad (2\text{-}28)$$

where C is Munsell chroma and [W-Bk] is the whiteness-blackness. [W-Bk] = V - Vg - q(θ)C, where V is the Munsell value; Vg is the Munsell value of reference grey in the space. Here, Vg = 5.5 is used as a constant; the q(θ) function is used to transform the axis consisting of grey Gr and pure color in NCS system to Munsell space at each of various hues.

Kim *et al*. (2008) developed a model of vividness perception for colour laser printers in 2008, as given in equation (2-29). A categorical judgement method was used to generalise the vividness perception model. Six expert observers were asked to rate printed test images using a five-point scale by defining as '5: Highly Vivid', '4: Quite Vivid', '3: Vivid', '2: Quite Unvivid' and '1: Highly Unvivid'.

$$\psi = \frac{1}{n}\left(\omega_C \sum_{i}^{n} C^*_{ab_i} + \omega_L \sum_{i}^{n} L^*_i\right), \qquad (2-29)$$

where n is the number of primary colours to be used, (e.g. n=6 for CMYRGB), and ω_C and ω_L are weighting factors of C^*_{ab} and L^*, respectively. The weighting factors of C^*_{ab} and L^* were optimized as 0.91 and 0.09, respectively.

At a later stage, Kim *et al*. (2008) developed a preferred-vividness metric in the same optimised process as equation (2-29). The weighting factors, ω_C and ω_L, were determined to be 0.57 and 0.43, respectively. Six observers who took part in the previous vividness perception experiment also participated in the preferred-vividness experiment using five categories defined as '5: Favourably Vivid', '4: Acceptably Vivid', '3: Just Acceptably Vivid', '2: Unacceptably Vivid' and '1: Poor'.

Vividness perception and preferred-vividness were quantified as a function of mean C^*_{ab} and L^* in the CIELAB colour space in Kim *et al*.'s (2008) study. For a higher preferred vividness, a higher lightness level is required as well as a higher chroma level. On the other hand, for vividness perception, only the contribution of chroma is higher and lower in the lightness level. The limitation of Kim *et al*.'s model is that the model can only be applied for printing. It is not a generic model.

Fedorovskaya *et al*. (1997) defined vividness as colourfulness. Trémeau and Charrier also defined vividness as “*the degree of colourfulness of each image element and to the degree of contrast that distinguished the colour of one image element from the colour of its surrounding elements*” (Trémeau and Charrier, 2000).

Recently, Berns (see Section 2.4) defined new vividness (V^*_{ab}) coordinates based on CIELAB. The purpose was to extend the utility of CIELAB. He defined it as "*an attribute of colour used to indicate the degree of departure of the colour from a neutral black colour*” (see Table 2.4). The formula of vividness (Berns, 2014) is given in equation (2-16).

Figure 2.19 show the dimensions of vividness for colours 1 and 2. The two vividness coordinates define the line length from either $L^* = 0$ and $C_{ab}^* = 0$ to a point on the $L^*C_{ab}^*$ plane.

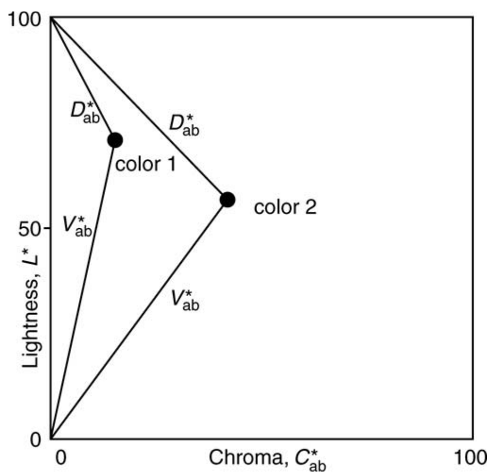


Figure 2.19 Dimensions of vividness for colours 1 and 2 (Berns, 2014)

2.4.2 Blackness

There has been little attention paid to the assessment of blackness throughout the years. However, it has been considered recently. Westland *et al*. (2006) carried out a psychophysical experiment to develop an instrumental method to assess perceptual blackness. Observers were asked to rank 100 black printed samples in order of their perceptual blackness. New blackness models were developed and tested for their performance. Among the models, the best performing model was suggested in the following equation (Westland *et al*., 2006):

$$B3 = 8.6542 - 0.2583L^* - 0.0052\, a^{*2} - 0.0045\, b^{*2}. \qquad (2\text{-}30)$$

Adams's blackness and whiteness models

Adams (2008) developed NCS-like blackness (b^+), whiteness (w^+) and chromaticness (c^+) models in 2008. In 2010, a CIELAB version of $w^+c^+s^+$ (Adams, 2010) was defined. These attributes offer an alternative to lightness and chroma for describing colour. The symmetries of $w^+c^+s^+$ are based on the symmetries and scaling laws of lightness and chroma for Lab interpolation. The chromaticness model is simply normalised chroma. However, the definition of $w^+c^+s^+$ is theoretical and it is not based on colour matching experiments.

$$\begin{aligned} w^+ &= L^* - (C^*_{ab}/C^*_{ab,Pure})\cdot L^*_{Pure} \\ c^+ &= 100\cdot(C^*_{ab}/C^*_{ab,Pure}) \qquad (2\text{-}31) \\ s^+ &= (100 - L^*) - (C^*_{ab}/C^*_{ab,Pure})\cdot(100 - L^*_{Pure}) \end{aligned}$$

where L^*_{Pure} and $C^*_{ab,Pure}$ are lightness and chroma for the lightest colour with the least amount of white for the hue, that is, the colour with the greatest chroma. The sum of wcs colour attributes is $w^+ + c^+ + s^+ = 100$.

Nayatani et al.'s Model

Nayatani developed a new type of colour appearance model named In-

CAM (CIELUV) (Nayatani, 2008) which means an integrated colour appearance model using the CIELUV space. The attributes of equivalent whiteness-blackness $[W\_Bk]_{eq}$, whiteness (w), blackness (bk) and greyness (gr) were developed. These attributes are calculated as (Nayatani, 2008)

$$[W\_Bk]_{eq} = L^{*} - L^{*}_{Gr} - q(\theta)\cdot C^{*}_{uv} + 0.0872\cdot K_{Br}\cdot C^{*}_{uv}\,, \qquad (2\text{-}32)$$

where L^{*}_{Gr} is the metric lightness of the reference grey; $L^{*}_{Gr} = 55.0$, which roughly corresponds to s = w = 50 (grey colour) in the NCS system. Here, $q(\theta)\cdot C^{*}_{uv}$ is approximated by 1 for simplicity (strictly, it should be 0.8660).

$$w = [W\_Bk]_{eq}/\{(100 - L^{*}_{Gr})/10\},$$
$$bk = 0, \text{ for } [W\_Bk]_{eq} \geq 0,$$
$$\text{and} \qquad (2\text{-}33)$$
$$w = 0,$$
$$bk = [W\_Bk]_{eq}/\{(L^{*}_{Gr}/10\}, \text{ for } [W\_Bk]_{eq} < 0.$$

where the value ranges from 0 to 10, and bk from 0 to 10.

$$gr = 10 - (w + bk + <C>), \text{ for } (w + bk + <C>) \leq 10,$$
$$\text{and} \qquad (2\text{-}34)$$
$$gr = 0, \text{ for } (w + bk + <C>) > 10.$$

According to the above equations, the model does not appear simple as it has a certain condition for white (w) and black (bk).

In Clonts *et al*.'s study (2010), they carried out blackness experiments by preparing a range of samples (i.e. 20 glossy Munsell (L* of approximately 20.5 and C* between 4 and 6), 27 over-dyed woollen (L* range of 14-16 and C* of 0.5-3.5) and 30 dyed acrylic samples (L* range of 10.5-12 and C* ranges of 0.12-0.20, 0.42-0.57, 0.89-0.97, 1.58-1.86 and 3.34-3.46)). They determined that the perception of blackness is affected by hue and chroma.

For the Munsell and over-dyed woollen samples, 30 and 25 observers ranked the samples in order from most black to least black, respectively. For the dyed acrylic samples, there were two tasks for 100 observers. The observers categorised the samples as black or not black in the first task. In the second task, the observers rated the samples according to a reference black. A full hue circle could not be acquired from the Munsell and over-dyed woollen samples. The potential role of hue cannot be generalized from the over-dyed woollen samples. However, it was found that the samples in the cyan to blue region were considered the most black, and those in the purple region were considered as the least black. In the experiment using the dyed acrylic samples, it was found that higher chroma samples were considered to be less black. Cyan to bluish blacks was again perceived as the most black. Reddish blacks were perceived as the least black.

Tao *et al*. (2011) carried out a psychophysical experiment on colour perception and colour preference on blackness with Chinese and British observers using a pair-wise comparison (see Section 2.6.2) procedure. Thirteen colour samples (10 chromatic and 3 achromatic colours) from the Munsell system were used in this experiment. The darkest colour in each hue (R, YR, Y, GY, G, BG, B, PB, P and RP) was selected according to a value 1 and chroma 2. The samples were displayed by a LCD monitor in pairs on a grey background. Observers were asked to choose which colour they preferred (referred to as blackness preference) and then they were asked to select which colour was the closest to a pure black (referred to as blackness perception). The disadvantage of Tao *et al.*'s experiment (2011) is that the monitor was not characterised. This could lead to a significant difference between the real sample and its corresponding screen colour. In Tao *et al.*'s study (2011), neither nationality nor gender difference had a significant impact on blackness perception. On the other hand, it was found that blackness preference was influenced by culture and that nationality has a greater effect on blackness preference than did gender. Observers had a strong preference for bluish blacks and a weaker preference for yellowish blacks.

Recently, Tao *et al.* (2012) carried out another psychophysical experiment with Chinese and British observers using the ranking method to extend and validate the previous findings. Observers were asked to arrange all colour samples in order from like to dislike (referred to as blackness preference) and then they were asked to put them in order from the purest to the least pure black (referred to as blackness perception) by a using mouse on the GUI. The results were consistent with those of the previous study. No culture or gender effect was found in blackness perception.

In Haslup *et al*.'s study (2013), they carried out a blackness experiment to determine the effect of hue on the perception of blackness using 20 glossy low chroma Munsell samples. The samples had a value and chroma of two and one, respectively. Observers were asked to force-rank two sets of 10 samples from "most like black" to "least like black". Six samples, three samples from each set of 10 samples, were chosen from "most like black". These selected samples were ranked again to select the "most like black". This was to ensure that they chose the one that was considered to be the most like black. It was found that observers perceived bluish to greenish black as blacker than yellowish and reddish blacks. The limitation of Haslup *et al*.'s study is that it used a small number of samples with a value and chroma of two and one, respectively.

2.4.3 Whiteness

Many whiteness formulae have been proposed to evaluate the whiteness of white materials throughout the years. However, these whiteness formulae are usually only valid for a limited white area. In 1986, the CIE recommended a whiteness formula as an assessment method of white materials. The equations are given as follows (CIE, 1986):

$$W = Y + 800\,(x_n - x) + 1700\,(y_n - y) \tag{2-35}$$

for the CIE 1931 standard observer,

where x and y are the chromaticity coordinates of the sample, and x_n and y_n

are those of the illuminant.

$W_{10} = Y_{10} + 800\ (x_{n,10} - x_{10}) + 1700\ (y_{n,10} - y_{10})$ (2-36)

for the CIE 1964 standard observer,

where x_{10} and y_{10} are the chromaticity coordinates of the sample, and $x_{n,10}$ and $y_{n,10}$ are those of the illuminant. For a perfect diffuser, W and W_0 are 100. The region of W and W_0 are $40<W<5Y\text{-}280$ and $40<W_0<5Y_{10}\text{-}280$.

However, it has been found that the formula is not correlated to visual estimation for many white samples (Uchida, 1990). In 1988, Uchida (1998) proposed a new whiteness formula that considers tint and excitation purity to accommodate the variety of visual estimations. The formula was divided into two types: one serves as an in-base point sample and the other serves as an out-base point sample in equations (2-37) and (2-38). In a chromaticity diagram, the CIE whiteness equation does not identify white in colour for samples over the maximum white point (in the direction of bluish white) defined by $5Y_{10}$ - 280. *The base point (below base point) is a chromaticity point in which the maximum whiteness index of each sample is calculated by the limit of application for the sample over the limit of application (5Y_{10} – 275)* (Uchida, 1998). On the other hand, *the base point is the chromaticity point on the baseline that is obtained by 5Y_{10} – 275 for the luminance factor of each sample* (Uchida, 1998). The in-base point is when the CIE whiteness index ($W_{CIE,10}$) of a sample is $40 < W_{CIE,10} < 5Y_{10} - 275$. The out-base point is when the whiteness index ($P_{W,10}$) of the sample is far from the base point in the direction of high purity.

$W_{10} = W_{CIE,10} - 2\ (T_{w,10})^2$, (2-37)

where the CIE whiteness index ($W_{CIE,\,10}$) of a sample is $40 < W_{CIE,\,10} < 5Y_{10} - 275$. Here, $T_{w,10}$ is a tint for the CIE 1964 supplementary standard colorimetric observer. $T_{w,10} = 900\ (x_{n,10} - x_{10}) - 650\ (y_{n,10} - y_{10})$,

$P_{w,10} = (5Y_{10} - 275) - \{800(0.2742 - x_{10}) + 1700(0.2762 - y_{10})\}$, (2-38)

where x_{10} and y_{10} are the chromaticity coordinates of a sample.

This formula enlarges the region of white evaluation in the colour space. However, the white index is non-uniform in vision.

In 2002, the whiteness formula in the CIELUV uniform space was developed by He and Zhang (2002). This whiteness equation improves visual correlativity, visual uniformity and applicability. It is given as (He and Zhang, 2002)

$W_{uv} = W_H - 2(T_{uv})^2$, $40 < W_H < 3.37L^*_{10} - 185.35$, (2-39)
$W_{uv} = P_{uv} - 2(T_{uv})^2$, $WH < 3.37L^*_{10} - 185.35$,

where $W_H = L^*_{10} + 260(u'_{n,10} - u'_{10}) + 1294\,(v'_{n,10} - v'_{10})$, $P_{uv} = 5.74L^*_{10} + 260(u'_{10} - u'_{n,10}) + 1294\,(v'_{10} - v'_{n,10}) - 382.73$ and $T_{uv} = 1294\,(u'_{n,10} - u'_{10}) + 260\,(v'_{n,10} - v'_{10})$. Here, u'_{10} and v'_{10} are the chromaticity coordinates in the CIELUV uniform colour space of the sample, $u'_{n,10}$ and $v'_{n,10}$ are the chromaticity coordinates of the perfect diffuse and L^*_{10} is the lightness of the sample for CIE 10° standard observer and the CIE standard illuminant D65.

A whiteness formula in the CIELAB uniform colour space that correlates well with observers' evaluations was also developed in 2007 (He and Xhou, 2007).

$W_{LAB} = W_{ab} - 2(T_{ab})^2$, $40 < W_{ab} < 3.37L^*_{10} - 191$, (2-40)
$W_{LAB} = P_{ab} - 2(T_{ab})^2$, $W_{ab} < 3.37L^*_{10} - 191$,

where $W_{ab} = L^*_{10} - 0.1131a^*_{10} - 1.6772b^*_{10}$, $P_{ab} = 5.74L^*_{10} + 0.1131a^*_{10} - 1.6772b^*_{10} - 382.73$ and $T_{ab} = - 1.4965a^*_{10} - 0.4224b^*_{10}$. When W_{LAB} is less than 40, the sample is not considered white.

The W_{LAB} model is a kind of a regression model. There are two equations for $W_{LAB.}$ There is an option to choose W_{LAB} for a certain condition. This means that it is a complex model. The W_{uv} model is shown in equation (2-39). Equations (2-39) and (2-40) have similar structures. Thus, the W_{uv} model is also a complex model.

Note that all whiteness models given in this subsection have been developed just for a small region of white.

Adams's whiteness Model

In 2010, Adams proposed a whiteness formula based on NCS in the CIELAB version which was earlier described also in section 2.4.2. The existing whiteness models are limited to certain colour samples. In the NCS system, there are whiteness and blackness attributes. However, there are no simple equations that can transform NCS whiteness and blackness into XYZ or CIELAB values. Thus, a new whiteness attribute needs to be developed based on the CIE colour spaces and to cover the NCS colour order system. There are also the reasons mentioned earlier in Section 1.1 why new whiteness and blackness models are needed. Note that there are models to perform transformation via a large look-up table, which consists of NCS samples in terms of both NCS coordinates and XYZ values (Rhodes and Luo, 1996).

In general, some of the existing models of saturation, vividness, blackness and whiteness are complex in structure, or some are limited to certain viewing or application conditions. Thus, simple and easily understandable models based on the psychophysical experiment and the NCS colour order system for saturation, vividness, blackness and whiteness are highly desired by industry.

2.5 CIECAM02 Colour Appearance Model

CIECAM02, a revised version of CIECAM97s, was proposed by CIE TC

(Technical Committee) 8-01 in 2002 (p1-13, CIE, 2004b). This new latest model is based on the CIECAM97s model (Luo and Hunt, 1998), but a number of revisions were considered to improve the performance and to simplify the model. The CIE simplified a linear chromatic adaptation transform and modified a non-linear response compression function considering its impact on the chroma attribute. They improved the saturation attribute for different values of the luminance of the adapting field (L_A). They revised lightness attribute and the surround parameter. The full forward and inverse CIECAM02 are given in Appendices A and B respectively.

2.5.1 Input and Output Parameters

The input and output parameters are described in Tables 2.9 to 2.11 (p4-6, CIE, 2004b).

Table 2.9 Input parameters for the CIECAM02

Input parameters	Description
X Y Z	Relative tristimulus values of the test stimulus
X_W Y_W Z_W	Relative tristimulus values of the reference white
X_{wr} Y_{wr} Z_{wr}	Reference white in reference conditions
Y_b	Y of achromatic background
L_W	Luminance of reference white in cd/m^2
L_A	Luminance of achromatic background in $\mathrm{cd/m^2} (= \mathrm{L_W Y_b}/100)$
C F N_C	Surround parameters (shown in Table 2.10)

Table 2.10 Surround parameters for the CIECAM02

Viewing condition	*c*	*F*	N_c
Average surround	0.69	1.0	1.0
Dim surround	0.59	0.9	0.9
Dark surround	0.525	0.8	0.8

Table 2.11 Output parameter for the CIECAM02

Output parameters	Description
J	Lightness
Q	Brightness
C	Chroma
M	Colourfulness
s	Saturation
h	Hue angle
H	Hue quadrature
H_C	Hue composition

2.5.2 The Appearance Phenomena Predicted

The appearance phenomena predicted by CIECAM02 are as follows:

Hunt effect

In the Hunt effect, the chromatic contrast (colourfulness) increases as the luminance increases. The haploscopic matching method was used in the experiment. Observers were to view two identical stimuli with different luminance levels. They were asked to match two stimuli viewed separately by each eye with varying the chromaticities of the two stimuli. They adjusted a test colour seen in one eye by controlling the red, green and blue light from the other eye side. The result of the matched stimuli had a high colourfulness under a high luminance level.

Stevens effect

In the Stevens effect, the brightness (or lightness) contrast increases as the luminance increases (Stevens and Stevens, 1963). In this study, observers were asked to perform magnitude estimation to investigate how the level of adaptation affects the power function relating brightness to luminance.

Dark colours appear darker and light colours appear lighter when the luminance level increases. The effect can be seen in an image at high and low luminance levels (Bartlson and Breneman, 1967). At a low luminance level, low contrast will be seen in an image. At a higher level of illumination, the contrast will be increased. This means that white areas appear substantially brighter and dark areas appear darker.

Chromatic adaptation

Chromatic adaptation is the ability to adapt to the varying colours of illumination to maintain the appearance of object colours (p148, Fairchild, 2005). For example, when a piece of white paper is illuminated by daylight, it will still appear white when it is in a room with an incandescent light.

2.5.3 CAM02-UCS

More recently, Luo *et al.* (2006) carried out research to further extend CIECAM02 to be a uniform colour space, i.e. to be able to accurately predict perceived colour difference. Two distinct types of colour difference data sets were accumulated by Zhu *et al*. (2002). There are large colour difference data (LCD) and small colour difference data (SCD). Three uniform colour spaces based upon CIECAM02, simply modified versions to fit the LCD, SCD, and the combined LCD and SCD data sets, were developed (Luo *et al*., 2006). These colour spaces have simple structures with the least modification to the original CIECAM02. They are CAM02-LCD, CAM02-SCD, and CAM02-UCS (uniform colour space), respectively given in the following equation (Luo *et al*., 2006):

$$\Delta E' = \sqrt{(\Delta J'/K_L)^2 + \Delta a'^2 + \Delta b'^2}, \quad (2\text{-}41)$$

where

$$J' = \frac{(1 + 100c_1)J}{1 + c_1 J},$$

$$M' = \left(\frac{1}{c_2}\right) In(1 + c_2 M),$$

$$a' = M' \, cos(h), \; b' = M' \, sin(h),$$

where *J*, *M* and *h* are the CIECAM02 lightness, colourfulness, and hue angle values, respectively. The $\Delta J'$, $\Delta a'$ and $\Delta b'$ are the J', a' and b' differences between the "standard" and "sample" in a pair. The K_L, c_1 and c_2 are coefficients for the CAM02-LCD, CAM02-SCD and CAM02-UCS, respectively, listed in Table 2.12.

Table 2.12 Three coefficients for each version of UCS based upon CIECAM02 (Luo *et al*., 2006)

Versions	CAM02-LCD	CAM02-SCD	CAM02-UCS
K_L	0.77	1.24	1.00
c_1	0.007	0.007	0.007
c_2	0.0053	0.0363	0.0228

2.6 Methods for Assessing Colour Appearance

Three colour assessment techniques developed to describe colour appearance are introduced in the following section. Only a categorical judgement method was used for this study. The other two techniques were used by others which were referred to this study.

2.6.1 Categorical Judgement

The categorical judgement method requires observers to separate a large number of stimuli into a given numbers of categories. The results are analysed by following the law of categorical judgements (Torgerson, 1958). In the experiment, the category selected for each stimulus is recorded. The data obtained from this method can be analysed by transferral into an interval scale using the law of categorical judgement. Equal intervals were used in the experiment.

The law of categorical judgement method is to judge the perception of stimulus by assigning them into predefined categories. It is particularly useful when the number of stimuli is large. The law of categorical judgement is expressed as

$$B_k - R_j = z_{jk}\sqrt{\sigma_j^2 + \sigma_k^2 - 2r_{jk}\sigma_j\sigma_k}\ , \tag{2-42}$$

where B_k is the mean location of the k^{th} category boundary, R_j is the mean response to stimulus *j*, $B_k - R_j$ is the probability density function which forms a normal distribution, σ_k is the discriminal dispersion of the k^{th} category boundary, σ_j is the discriminal dispersion of stimulus *j*, r_{jk} is the coefficient of correlation between momentary position of stimulus *j* and category boundary *k* on the attribute, and z_{jk} is the normal deviate corresponding to the proportion of times stimulus *j* is placed below boundary *k*.

The observations of all the stimuli are supposed to use the same standard deviation in Condition D, i.e. $\sigma_i = \sigma_j = \sigma$. The scale values of the stimulus are independent of category boundaries, i.e. $\rho_{ij} = 0$. Equation (2-43) is simplified as

$$B_i - x_j = z_{ij}\sigma\sqrt{2}\ , \tag{2-43}$$

where σ is the standard deviation for each stimulus and categorical boundary.

A frequency matrix is calculated for each category and stimulus. The frequency of a stimulus is classified into a category. A cumulative frequency matrix is calculated by accumulating the value of the frequency matrix in each category. A cumulative probability matrix and a z-score matrix are generated from the cumulative frequency matrix. The cumulative probability matrix is calculated by dividing the cumulative frequency matrix by the number of observers. The z-scores can be estimated as probability values of 0 or 1 by using the Maxwell function as

$$\mathrm{LG} = \ln\left(\frac{f_{ij} + k}{N - f_{ij} + k}\right), \qquad (2-44)$$

where f_{ij} is the frequency for stimulus i judged greater than stimulus j, k is a constant having a value of 0.5, and N is the number of observations.

Then, the difference matrix is calculated as shown in equation (2-45). The range of the category is the mean value of B_{i+1}-B_i.

$$Z_{(i+1)j} - Z_{ij} = (B_{i+1} - x_i) - \left(B_i - y_j\right) = B_{i+1} - B_i\ . \qquad (2-45)$$

Finally, each scale value is calculated by averaging the difference between the z-score and the corresponding category boundary values for each category.

In this study, the categorical judgement method was applied to every experiment. Observers gave responses using a six-point categorical judgement method, such as 'very dull', 'dull', 'a little dull', 'a little vivid', 'vivid' and 'very vivid'. The data collected by this method was then analysed using the categorical judgement method.

An example is shown in the following for scaling vividness using six pairs. Each sample can be assessed by observers using a 6-point scale. Observers are to select one of the six categories of each stimulus. These categories are defined as follows:

1. Very vivid
2. Vivid
3. Little vivid
4. Little dull
5. Dull
6. Very dull

2.6.2 Pair Comparison

A pair comparison method is a colour assessment technique in which observers are asked to compare a pair of stimuli or images with a separate standard image. It is then judged which sample is more similar to the standard. This method has been used in Tao *et al.*'s blackness study (2011) which was described in Section 2.4.2. In Tao *et al.*'s experiment, observers were asked to select one of a pair over the other in terms of blackness preference and blackness perception.

2.6.3 Magnitude Estimation

Stevens (1958) derived a magnitude estimation method. It requires observers to estimate the scale values of various colour appearance attributes, such as hue, lightness, brightness, colourfulness, chroma and saturation. Observers are asked to assign numbers to the test stimuli according to the magnitude of the perception.

The advantage of magnitude estimation is that observers can directly scale colour appearance attributes based on reference stimuli under normal viewing conditions with both eyes. The training period is shorter than that of other matching methods. The experiment is setup with a simple adapting field.

The disadvantage is that the uncertainty is typically much larger than that of other matching techniques. Well-trained observers are necessary due to the difficulty of obtaining consistent scaling by naive observers.

This method was used in Juan and Luo's saturation study (2002) (see Section 2.4.1.1). Observers were trained to describe the colour appearance using samples and asked to scale saturation considering the relationship to the reference saturation.

2.7 Colour Naming and Colour Terminology Translation

Berlin and Kay (1969) conducted a comprehensive study of colour naming for several major human languages. They found a universal set of 11 basic colour names: white, black, red, green, yellow, blue, brown, purple, pink, orange and gray.

Lin *et al.* (2001a) carried out a colour naming experiment with British and Chinese observers to investigate the difference in usage between the two languages. The results were found to agree well with Berlin and Kay's (1969) 11 basic colour names. However, it was found that the Chinese language appears to have five more additional basic colour terms: *ju* red, *chen* orange, *ching* green, diann blue, and *hur* brown. Among them, *ju* red *and ching* green are ancient words from the Chinese 5-primary colour theory which relates to the five basic elements of wood, fire, metal, water and earth. For secondary names, culture difference was found between the British and Chinese groups. "*Chinese participants rarely used British secondary words, such as mauve, lilac, turquoise, violet, beige, lime, salmon and maroon. British subjects rarely used Chinese secondary words, such as iron, water, pig-liver and lipstick*" (Lin *et al*., 2001a). Small proportion of secondary terms was found to be common for both cultures. The result also suggests that cultural background influenced the gender difference. "*British females used certain secondary words more often than male, such as magenta and maroon. Chinese males used certain secondary words more often than females such as rice, earth and milk*" (Lin *et al*., 2001a).

Lin *et al.* (2001b) defined boundaries for the 11 basic colour names in terms of CIELAB values (e.g. L* and C_{ab}*). For example, the boundary of white was defined as $90 < L^* \leq 100$ and $0 < C_{ab}^* \leq 5$. For black, the boundary was defined as $0 < L^* \leq 40$ and $0 < C_{ab}^* \leq 5$.

In 2010, Tominaga *et al.* (2010) found 15 colour terms in Japanese which include gold, silver, turquoise and yellow-green and in addition to Berlin and Kay's 11 basic colour terms (1969).

Gorji Kandi *et al*. (2014) carried out an experiment to investigate colour naming in the Persian language in six major cities: Tehran, Isfahan, Mashhad, Yazd, Rasht, and Shiraz. Observers were asked to name a singular displayed colour chips. The general result agreed well with Berlin and Kay's 11 basic colour terms. However, there was not perfect agreement between all the six cities. All cities except Mashhad, Shiraz and Isfahan did not agree well with Berlin and Kay's finding. Mashhad had a lack of the terms blue and yellow. Berlin had a lack of the terms white and grey. Isfahan had a lack of term grey. This implies that the basic colour terms vary by the city of residence.

Korean industrial standards (KS) (p2-4, KS, 2005) regulated the colour names of non-luminous object colours in Korean. Twelve basic colour names of chromatic colours were provided: red, orange, yellow, yellow green, green, blue green, blue, bluish violet, purple, reddish purple, pink and brown. The basic colour names of achromatic colours, white, grey and black, were also provided. The adjective of chromatic colours were defined such as, vivid, soft, dull, light, dark, deep and pale.

Ekici *et al*. (2006) conducted a colour naming experiment in Turkish language to investigate the range of colour samples for basic and non-basic colour name. Three-hundred and twenty-two observers were asked to choose the Munsll colour samples that match most with 8 basic and 24 non-basic colour names. It was found that the participants chose the best representatives for each basic colour names as the most saturated colour samples. Ekici *et al*. investigated that colour naming and perception for non-basic colour names are affected by city of residence, age, gender and occupation.

Ou *et al.* (2012) investigated colour terms for two-colour combinations, such as warm/cool, heavy/light and active/passive, which were also used in this study (see Section 3.3). The terms were translated into the languages of observers from seven countries (British, Taiwanese, French, German, Spanish, Swedish, Argentinean and Iranian). The warm/cool responses were compared for the eight observer groups, having an average correlation coefficient of 0.85. The heavy/light and active/passive responses of the eight groups were also compared, having an average correlation coefficient of 0.90 and 0.87, respectively. The translated terms showed good agreement between the eight observer groups. Ou *et al*.'s study implies that, in terms of the correlation coefficient, the effects of culture have a low influence on the three terms which were translated into eight languages.

According to the previous studies, colours and colour names do not all correspond to each other within a language. One colour may correspond to several names. Or one colour may cover many colour samples. Variations of colour naming can occur by cultures, residence, age, gender and occupation

In this section, a brief review of earlier studies on colour naming is given here. They are related to the present study on the descriptors used between cultures. Also, whether the same name used in both cultures is also investigated. Some of Ou *et al*.'s emotion words relating to the third dimension perception are also investigated here.

2.8 Summary

This chapter covered human colour vision, CIE colorimetry, colour order systems, colour appearance attributes, uniform colour spaces and the CIECAM02 colour appearance model. Existing findings in these areas laid a foundation for the present study and gave a fundamental direction to design a psychophysical experiment and to develop a new model based on uniform colour spaces. The aims of this study were to develop a new third dimensional attribute (such as colourfulness, chroma and saturation or vividness), new blackness attributes and a new whiteness model.

The present chapter described the findings in the literature relevant to the author’s study, which are summarised as follows:

1) Regarding existing scales of the third-dimensional attribute, colourfulness and chroma have been arguably the most widely used in the area of colour science. Luo *et al.* (1991) pointed out, however, in the visual assessment of colour appearance that colourfulness was the hardest attribute to scale among the other attributes (e.g. lightness and hue). In Montag *et al.*'s (2006) study, chroma was found to be the most difficult attribute to scale among the other attributes.

2) Regarding saturation, the CIELUV saturation was developed based on a subtractive shift in the chromaticity coordinates. However, the disadvantage is that it could lead to out of gamut in the prediction of corresponding colours. A colour gamut is a range of colours that are capable of being reproduced by an imaging device such as, display and printer. If a colour is out of gamut, this means that the colour is not able to be reproduced by the device. Nayatani *et al.*'s saturation is more complex than that of the Hunt model. It is not for complex stimuli and imaging application. Hunt's saturation is also complex, computationally expensive, difficult to implement and needs significant knowledge for it to be used consistently. The CIECAM02 saturation was based on psychophysical data obtained by Juan and Luo (2002), who showed that saturation was very hard to scale without the proper training of the observers. This was the case especially for colours in dark regions and for neutral colours.

3) Regarding vividness, although vividness has been found to be a valuable attribute for assessing image quality, this scale has yet to be recognised by the CIE as a colour appearance. There have been a number of studies looking into the modelling of vividness, such as Nayatani and Komatsubara (2005), Kim *et al.* (2008) and Berns (2013). In general, vividness has been found to be correlated closely

with chroma.

4) Regarding blackness, there have been a number of studies looking into the modelling of blackness, such as Westland *et al*. (2006), Nayatani (2008), Adam (2010) and Tao *et al*. (2011, 2012). According to Tao *et al.*'s (2011, 2012) blackness studies, no cultural difference was found between British and Chinese observers in assessing blackness perception. However, the largest data set should be from NCS.

5) Regarding whiteness, there have been many whiteness formulae, including one recommended by the CIE (1986). The CIE (1986) formula has been found to perform poorly in predicting perceived whiteness in visual assessments (Uchida, 1990). Uchida's own whiteness model (1998) seems to perform better than the CIE model, but its white index was non-uniform in vision. To address the uniformity issue, He and Zhang (2002) proposed a uniform model based on CIELUV in 2007. He and Xhou (2007) proposed a uniform model based on CIELAB. Finally, Adams (2010) proposed an NCS-like whiteness model based on CIELAB.

According to these findings, it is necessary to develop new psychophysical models that can become good alternatives to the third dimension of colour appearance. Such models should be easier to scale than colourfulness and chroma in the visual assessment of colour appearance and thus will be more accurate in the prediction of visual perception. It is also necessary to compare psychophysical data between different cultures to clarify whether it is feasible to develop a universal model. In addition to develop models as alternatives to the third dimension of colour appearance, whiteness and blackness would also need to be investigated to develop psychophysical models that can better meet the industrial demand in various application areas.

Chapter 3 Experimental Preparation

3.1 Overview

This chapter describes the general experimental settings, including the colour sample selections, the specifications of the colour sample measurement, and the statistics applied for the data analysis. Three sets of psychophysical experiments, experiments 1 to 3, were conducted.

The remainder of this chapter is organized as follows.

- Many attributes in English terms were surveyed for Korean translation and were used in an experiment with Korean subjects. This is explained in Sections 3.2 and 3.3.
- Section 3.4 explains how the samples were selected. The colour sample measurement results are presented in Section 3.5.
- The number of participants in the experiments are explained in Section 3.6.
- Section 3.7 describes the specific settings for the colour appearance experiment in detail.
- In Section 3.8, the overall procedures and instructions of each experiment for two groups of observers are briefly explained.
- The data analysis methods for this experiment are explained in the final section.

3.2 Survey for Word Translation

As stated in Chapter 1, the third-dimension attributes in relation to chromatic content (chroma and colourfulness) are more difficult for ordinary people to understand than those of the first and the second dimensions (Luo *et al*., 1991; Zhang and Montag, 2006). Hence, the strategy in this study is to identify other attributes (see Table 3.19). It is also of a great interest to compare these attributes between cultures, i.e. British and Korean.

Firstly, efforts were made to identify English terms, or adjectives, to describe colours. Twenty-three English terms were obtained including “active”, “passive”, “fresh”, “stale”, “clean” and “dirty”. There are also other emotional expressions used such as, “intense”, “weak”, “striking”, “boring”, “vivid”, “dull”, “brilliant”, “bright”, “clear”, “opaque”, “distinct”, “indistinct”, “full”, “thin” and “flat”. These expressions come from three main sources: 1) the Oxford dictionary, 2) Berns' concept (2014) and 3) emotion terms of Wright and Rainwater (1962), Hogg (1969), Kobayashi (1981), Sato *et al*. (2000a), Ou *et al.* (2004 and 2012), and Gao *et al*. (2007).

The Oxford dictionary (2014) is typically used to define the meaning of words. For example, the meaning of “vivid” is “intensity deep or bright”. “Deep” is “dark and intense” and “bright” is “vivid and bold appearance”.

Berns' concept (2014) to describe the attributes along the lightness and chroma axes (see Figure 2.18) reveals terms used by colourists, such as clean-dirty, bright-dull, intense-weak, weaker-stronger, whiter-deeper, and finally vividness, depth and clarity.

A trend was found that the colour emotion responses can be correlated closely with hue, lightness and chroma (Wright and Rainwater, 1962; Hogg, 1969; Kobayashi, 1981; Sato *et al*., 2000a; Gao *et al*., 2007; Lee *et al*., 2009; Ou *et al*., 2004 and 2012). Wright and Rainwater (1962) revealed that “warmth” and “activity” was associated with hue. Hogg (1969) found that one of the factors, “warmth”, correlated with chroma and hue. In Kobayashi’s study (1981), “clear-grayish” response was highly correlated with chroma. Sato *et al*. (2000a) found that warm–cool, potency, and activity correlated with hue, lightness and chroma, respectively. Gao *et al*.’s (2007) colour emotion responses were classified into three factors. Factor 1, which includes “passive-dynamic”, “vague-distinct”, “vivid-sombre”, and “subdued-striking”, was highly correlated with chroma. Factor 2, which includes “heavy-light”, and “strong-weak”, was highly correlated with lightness. The other factor was “warm-cool”. In Ou *et al*.’s colour emotion study (2004) for single colour, “warm-cool” was found to correlate with hue angle and chroma, “heavy-light” with lightness and “active-passive” with chroma. Ou *et al*.'s colour emotion study (2012) for two-colour combination was on emotion scales. In their three dimensions (“light-heavy”, “warm-cool” and “active-passive”), the latter one is closely associated with chromatic content.

The 23 terms selected here (see Table 3.13) should include some that are potentially easier to understand than the previously developed ones (chroma and colourfulness). The 23 terms were then translated into the Korean language. Psychophysical experiments for these scales were carried out with a Korean group, and the visual data obtained from this experiment were analysed to investigate whether the scales have a relation to the third-dimensional scale. The scales were used in Korean.

The participants were to fill in the term in Korean for each scale in the questionnaire shown in Table 3.13. They could write down more than one term using the non-constraint method used by Lin *et al*. (2001). Twenty one Koreans took part in the survey. Among them, five participants had doctor’s degrees in colour science; two participants had doctor’s degrees in design, five were professors, twelve were researchers, and two were postgraduate students in the fields of colour image and colour design. Among them, 19 participants were members of the Korea Society of Colour Studies.

Table 3.13 Questionnaire for translating 23 attributes

영어용어 (English term)	한글용어 (Korean term)		영어용어 (English term)	한글용어 (Korean term)
1. Colourful			**13. Stale**	
2. Vivid			**14. Intense**	
3. Dull			**15. Weak**	
4. Brilliant			**16. Striking**	
5. Bright			**17. Boring**	
6. Clear			**18. Full**	
7. Opaque			**19. Thin**	
8. Distinct			**20. Flat**	
9. Indistinct			**21. Clean**	
10. Active			**22. Dirty**	
11. Passive			**23. Saturated**	
12. Fresh				

Tables 3.14 to 3.18 show the result that was answered most frequently for each attribute. Note that “colourful”, “brilliant”, “opaque”, and “flat” were excluded from the experiment for the following reasons. Generally, the meaning of “colourful” in Korea is full of bright colours or having a lot of different colours. This is expressed when there are many bright colours. However, the colours were assessed one at a time in the experiment. Thus, this attribute was not appropriate for the experiment to describe just one colour. “Brilliant” has the same meaning as “bright”. “Opaque” and “flat” were not used because all the colour patches were opaque and flat. Thus, the remaining attributes, “vivid”, “dull”, “bright”, “distinct”, “fresh”, “intense”, “weak”, “striking”, “boring”, “full”, “clean” and “saturated”, were translated

considering the results that were most frequently answered in the questionnaire and according to the dictionary for the accuracy. It was found that “vivid” (“선명한”) was also translated the same as Korean industrial standards (2005) (see Section 2.7).

• In Table 3.15, the words that were most frequently selected for “clear” were “맑은” (24%) and “선명한” (24%). “선명한” has the same meaning as vivid. However, “맑은” is commonly used in the South Korea translation of “clear”, meaning “without a cloud or mist” to describe the sky in daily life. Thus, “맑은” was selected as a translation of “clear”.

• “Indistinct”, “passive”, “stale” and “thin” were translated as having the opposite meanings of “distinct”, “active”, “fresh” and “full”, respectively. For example, “distinct” is “뚜렷한” and “indistinct” is translated as “not distinct” which “not” is meant as “않은” in Korea. Thus, “indistinct” is translated as “뚜렷하지 않은”.

• In Table 3.16, the words that were most frequently selected for “passive” were “수동적인” (24%) and “활기 없는” (14%). The meaning of “수동적인” is “doesn't move by oneself but moves from other effect”. “활기 없는” means “not active and lively”. Thus, “활기 없는” was selected as translation for “passive” in describing colour.

• In Table 3.18, the words that were most frequently selected for “dirty” were “탁한 (43%)” and “더러운 (24%)”. “탁한” means “water or air is murky". “더러운” is commonly used in Korea as translation of “dirty” meaning "covered or marked with an unclean substance". Thus, "더러운" was selected for translating "dirty".

- "Saturated" followed the result "포화된" (52%) from Table 3.18 including "채도 (10%)" and "색의 순수한 정도 (5%)". "포화된" was hard for observers to understand which means "the greatest possible amount of the substance that has been dissolved in it" in the field of chemistry. Therefore, for the lack of understanding "채도" and "색의 순수한 정도" were included. In an English-Korean dictionary, "saturated" is also translated as "채도" which means "it is close to a pure colour without no mixture and it is pure and clean". If you translate "채도" from Korean into English, it is "the degree of colour purity" which also means "색의 순수한 정도" in Korean. Thus, "채도" and "색의 순수한 정도" were also included.

Table 3.14 The attributes surveyed for translation: colourful, vivid, dull and brilliant

Participant	Colourful	Vivid	Dull	Brilliant
1	색이 진한	선명한	불명확한, 흐릿한	화려한
2	다채로운	강렬한, 선명한, 생생한	흐릿한, 칙칙한	선명한, 또렷한
3	다채로운	생생한	탁한	밝은
4	다채로운	선명한	탁한	빛나는
5	다채로운	선명한	분명치 않은	선명한
6	화려한	명료한	탁한	밝은
7	색채가 풍부한	선명한	흐릿한	눈부신
8	다채로움 (서로 다른 색상들이 많다는 의미)	선명한	흐릿한	아주 밝은
9		선명한	색깔이 빠진듯한	빛나는
10	화려한	생생한	흐릿한	눈부신
11	다채로움	선명한	흐릿한	밝은
12	색감이 풍부한	생생한	흐린	밝은
13	다채로움	선명한	불분명한	색상이 밝은
14	다채로운, 채도가 높은 색들이 많이 분포된	진하고, 선명한	흐린, 탁한	밝으면서도 채도가 높은
15	다채로운	선명한	칙칙한	눈부신
16	채도가 높은, 색이 강한	생생한, 선명한	흐릿한	눈부신
17	다채로운	선명한	희미한	밝은
18	선명한	선명한	탁한	선명한
19	색이 풍부한	생생한	칙칙한	빛나는
20	화려한, 다채로운	강렬한	희미한, 강하지 않은	선명한
21	다채로운	선명한	둔한, 둔탁한	눈부신, 아주 밝은
Result	**다채로운**(=색(or 색채, 색감)이 풍부한) 71%, 화려한 14%	**선명한** 71%, 생생한 29%	**흐릿한** 48%, 탁한 24%	**밝은** 38%, 눈부신 24%, 빛나는 14%

Table 3.15 The attributes surveyed for translation: bright, clear, opaque, distinct and indistinct

Participant	Bright	Clear	Opaque	Distinct	Indistinct
1	밝은	분명한, 맑은	불투명한	뚜렷한, 확실하게 구분이 되는	흐릿한, 구분이 안 되는
2	밝은	선명한, 깨끗한	불투명한	분명한, 또렷한	흐릿한
3	밝기	선명한	흐릿한	분명한	불분명한
4	밝은	분명한	불투명한	뚜렷한	희미한
5	밝은	맑은	분명치 않은	뚜렷한	흐릿한
6	밝기	투명한	불투명한	명료한	흐릿한
7	밝은	명확한	불투명한	뚜렷한	희미한
8	밝은	투명한	불 투명한	분명한	흐릿한
9	밝은	깨끗한, 분명한	불투명한, 뿌연	뚜렷한	불분명한
10	밝은	선명한	불투명한	뚜렷한	희미한
11	선명한	맑은	불투명한	뚜렷한	흐릿한
12	밝은	선명한	불투명한	뚜렷한	흐릿한
13	밝기가 밝은	뚜렷한	탁한	색상차가 뚜렷한	색상차가 희미한
14	밝은	약간 밝으면서도 (명도가 높으면서) 선명한	불투명한, 탁한	또렷한, 선명한	흐린, 탁한
15	밝은	투명한	불투명한	뚜렷한	희미한
16	밝은	맑은	불투명한	뚜렷한	뚜렷하지 않은
17	밝은	또렷한	불투명한	뚜렷한	흐릿한
18	밝은	투명한	불투명한	확실한	모호한
19	밝은	투명한	불투명한	뚜렷한	흐릿한
20	밝은, 산뜻한	맑은, 뚜렷한	불투명한	뚜렷한, 명료한	뚜렷하지 않은, 흐릿한
21	밝은	깔끔한	불투명해보이는	또렷한	희미해보이는, 흐릿한
Result	**밝은** 95%	**맑은** 24%, **선명한** 24%, 투명한 10%, 깨끗한 10%, 분명한 10%	**불투명한** 86%	**뚜렷한** 81%, 분명한 10%	**흐릿한** 52%, 희미한 29%

Table 3.16 The attributes surveyed for translation: active, passive, fresh and stale

Participant	Active	Passive	Fresh	Stale
1	생동감 있는, 활동적인	생동감 없는, 소극적인	새로운, 신선한	새롭지 않은
2	채도가 높은, 따뜻한	채도가 낮은, 차가운	산뜻한, 선명한	칙칙한
3	생동감있는	침울한	쾌적한	바랜
4	활동적인	활동적이아닌	신선한	신선하지 않은
5	화려한	단순한	밝은	안정적인
6	생생한	생생하지 않은	선명한	탁한
7	적극적인	수동적인	신선한	오래된
8	활발한	활기가 없는	생생한	생생하지 않은
9	생동감있는	소극적인	신선한	오래된듯한
10	생기있는	침울한	쾌적한	바랜
11	생기있는	침울한	쾌적한	바랜
12	활동적인	수동적인	새로운, 깨끗한	오래된
13	두드러진	드러나지 않은	밝은	칙칙한
14	활동적인	수동적인	신선한	썩은, 쾌적하지 못한, 신선하지 못한
15			신선한	진부한
16	능동적인	수동적인	신선한	칙칙한
17	활동적인	수동적인	산뜻한	칙칙한
18	활성화	비활성화	신선한	변질된
19	능동적	수동적	신선한	신선하지 않은
20	활기찬	활기없는	생기 넘치는, 신선한	신선미 없는, 진부한
21	활동적인, 역동적인	수동적인, 활기 없는	신선한, 상쾌한	케케묵은, 진부한, 흔한
Result	**활동적인** 29%, 생기있는 10%, 생동감있는 10%, 능동적인 10%, 활기찬 5%	**수동적인** 24%, 활기없는 14%, 소극적인 10%	**신선한** 52%, 산뜻한 10%, 쾌적한 10%	**신선하지않은** 19%, 칙칙한 19%, 오래된 14%, 바랜 14%

Table 3.17 The attributes surveyed for translation: intense, weak, striking, boring, full and thin

Participant	Intense	Weak	Striking	Boring	full	Thin
1	강렬한	약한	두드러진, 눈에 띄는	지루한	(색이) 짙은	(색이) 옅은
2	강렬한	약한, 희미한	눈에 띄는	색이 없는?	강렬한, 짙은	흐릿한, 연한, 묽은
3	짙은	희미한	현저한	지루한	짙은	연한
4	진한	약한	인상적인	지루한	가득한	엷은
5	짙은	옅은	두드러진	분명치 않은	짙은	연한
6	강도	약한	대조	따분한	강렬한	옅은
7	강렬한	약한	현저한	지루한	가득한	얇은
8	강렬한	연한	눈에띄는	지루한	짙은	엷은
9	강하고 분명한	약한	강한 효과를 주는	지루한, 똑같은	가득찬, 꽉찬	얇은, 가느다란
10	강렬한	희미한	강렬한	지루한	풍부한	옅은
11	매우 짙은	희미한	현저한	지루한	짙은	연한
12	강한	약한	직접적인	지루한	가득 찬	얇은
13	밝고 어두운 정도가 강한	밝고 어두운 정도가 약한	주위 색보다 두드러진	회색빛을 띈	짙은 색상	옅은 색상
14	강렬한	약한, 흐린 명도가 높으면서도 흐린	매우 채도가 높은, 형광색의	지루한	순색, 알찬, 꽉찬	명도가 높고 가벼운
15	강렬한	묽은	매력적인	지루한	완전한	흐릿한, 묽은
16	강렬한	약한	눈에 띄는	지루한	색이 풍부한	색이 연한
17	강렬한	희미한	뚜렷한	싫증나는	선명한	옅은
18	강한(채도)	약한(채도)	분명한	분명치 않은	진한	연한
19	강한	약한	눈에 띄는	눈에띄지 않은	가득한	얇은
20	강렬한	약한	인상적인, 두드러진	지루한	강렬해지는	엷어지는
21	강렬한	약한, 희미한	현저한, 두드러진, 인상적인	지루한, 따분한	풍부한	엷은, 옅은
Result	**강렬한** 52%, 강한 24% 짙은 14%	**약한** 67%, 희미한 29% 옅은 5%	**두드러진** 24%, **눈에 띄는** 24%, 인상적인 14%	**지루한** 67%	**짙은** 33%, 강렬한 14%, 가득한 14%, 가득찬 10%	**옅은** 29%, 연한 29%, 엷은 19%, 얇은 19%

Table 3.18 The attributes surveyed for translation: flat, clean, dirty and saturated

Participant	Flat	Clean	Dirty	Saturated
1	균일한	깨끗한	지저분한	색이 포화된
2	단조로운, 평범한	흠이 없는, 명료한	탁한	채도가 높은
3	단조로운	선명한	탁한	포화된
4	광택이 없는	깨끗한	더러운	포화도에 이른
5	단조로운	순수한	탁한	포화된
6	단조로운	깨끗한	탁한	포화된
7	평평한	깨끗한	탁한	포화된
8	어두운	깨끗한	칙칙한	채도가 높은
9	평편한	깨끗한, 분명한	더러운, 지저분한	순수한, 미혼합된
10	보통의	깨끗한	칙칙한	진한
11	단조로운	순수한	탁한	포화된
12	평평한	깨끗한	더러운	포화된
13	밝기차와 색상착가 없는	순수한	탁한	포화된
14	톤 다운 된, 흐린	깨끗한	지저분한, 명도가 많이 낮은	진한, 선명한
15	무난한, 고른	깨끗한	칙칙한	포화된
16	단조로운	깨끗한	지저분한	색이 짙은
17	무난한	산뜻한	칙칙한	강렬한
18	밋밋한	차이나는	탁한	선명한
19	납작한	깨끗한	지저분한	강렬한
20	단조로운	깨끗한	더러운, 탁한	짙은, 진한
21	무난한, 고른	깨끗한, 맑은	더러운, 지저분한, 칙칙한	포화상태의, 가득한, 충만한, 강렬한
Result	**단조로운** 38%, 평평한 14%, 무난한 14%	**깨끗한** 67%	**탁한** 43%, 지저분한 29%, 더러운 24%	**포화된** 52%, 진한14% 채도가 높은 10%, 순수한 5%

"Light-heavy", "natural-not natural" and "warm-cool" were added at the very late stage after the translation survey was completed and they were translated according to the dictionary. These attributes were added because they are also generally used as emotion attributes mentioned earlier in relation to previous studies in this section.

"Light" and "heavy" were translated as "가벼운" and "무거운" meaning "not heavy" and "heavy", respectively. "Natural" was translated as "자연적인" which mean "existing in nature" according to the dictionary. "Not" was translated as "않은". Thus, "not natural" is "자연적이지 않은" in Korean. "Warm-cool" was translated as "따뜻한-차가운" which is commonly used according to the English-Korean dictionary.

3.3 The Words Selected

In total, 25 words were selected and some of them were grouped into pairs. The words were grouped into pairs because some words are binary and opposite. Finally, there are 15 words to be used which are shown in Table 3.19. A single Korean word with the highest frequency for Korean observers was used to correspond to its English term. The selected words were used to scale a number of colours by a group of Korean observers. Among the words, only "saturated" and "vivid-dull" were used by British observers. The reason for selecting these two colours will be given later in Section 4.1. Hence, saturation and vividness were assessed by both Korean and British observers. Additionally, blackness and whiteness attributes were assessed by both groups of observers.

Table 3.19 The words used for visual assessments

The words in English	Korean translated
Bright	밝은
Light - heavy	가벼운 - 무거운
Active - passive	활기 있는 - 활기 없는
Fresh - stale	신선한 - 신선하지 않은
Clean - dirty	깨끗한 - 더러운
Clear	맑은
Boring	지루한
Natural - Not natural	자연적인 - 자연적이지 않은
Warm - cool	따뜻한 - 차가운
Intense - weak	강렬한 - 약한
Saturated	포화된, 채도, 색의 순수한 정도
Vivid - dull	선명한 - 흐릿한
Distinct - indistinct	뚜렷한 - 뚜렷하지 않은
Full - thin	짙은 - 옅은
Striking	두드러진, 인상적인

3.4 Colour Samples

The NCS system was introduced in Section 2.3.8.2. This section describes the sample selection. Figure 3.1 shows the hues divided into eight to cover the entire hue range in the NCS colour circle. The hues were not equally divided due to the lack of colour patches in each hue except Y50R. Thus, the nearest hues which included many colour patches were selected. The selected hue samples were Y10R, Y50R, Y90R, R30B, R90B, B30G, G10Y and G70Y.

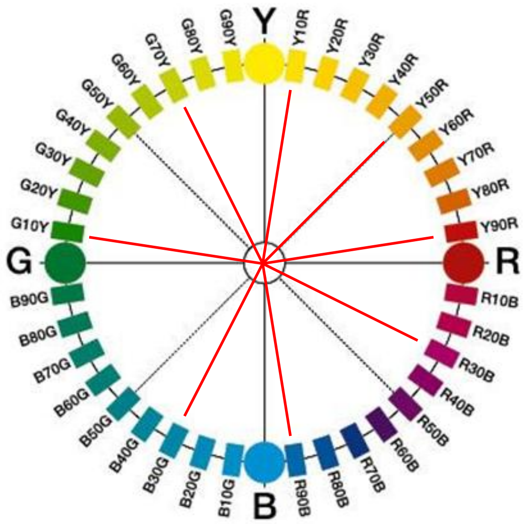


Figure 3.1 Hues selected from NCS colour circle (NCS colour circle, 2013)

Figure 3.2 shows the NCS colour triangle of a hue. It shows how colours are selected in the NCS colour triangle of a hue. W, S and C refer to whiteness, blackness and chromaticness, respectively. Each hue consists of about 15 colours at 4 levels of chromaticness (c = 10, 30, 60 and 80) and 6 levels of blackness (s = 0, 10, 20, 40, 60 and 80) and are demonstrated by the solid and dotted line, respectively in Figure 3.2. One of the colours in the Y10R, Y90R, and G10Y hue was replaced to cover the highest chromaticness.

Figure 3.3 shows some examples of the colour patches used in the experiment. They were 3×3 inches framed by a grey coloured board. All the samples were selected from Version 1 of the NCS system. They all had a quite a matte surface with little gloss. (Note that NCS are now selling their Version 2 with a different formulation for each sample to use more environmentally friendly chemicals. The colour coordinates of the two versions are also different.)

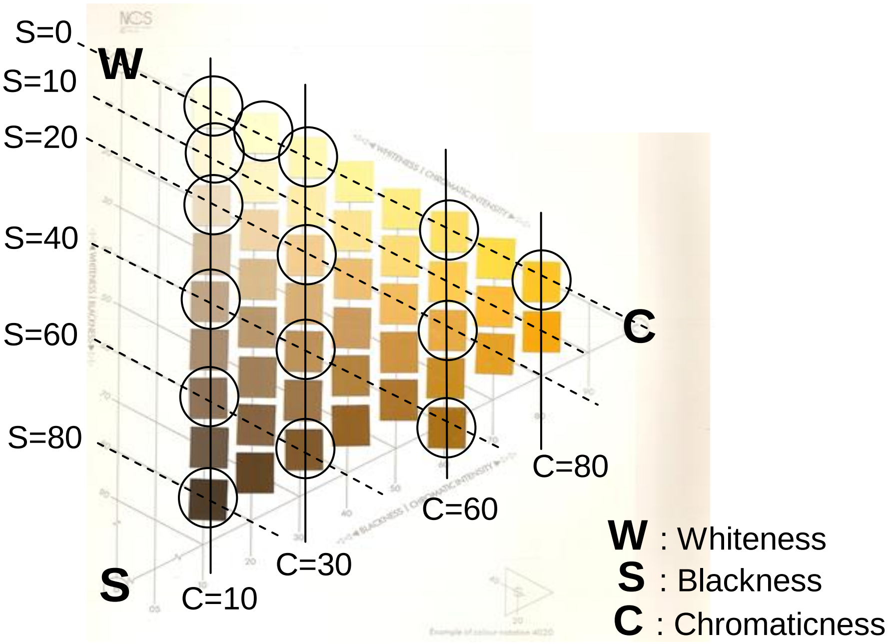


Figure 3.2 Selected colours in the NCS Colour Triangle of a hue

Figure 3.3 Colour samples

The experimental arrangement used in this study is summarised in Table 3.20. Colour samples for the saturation and vividness experiment were divided into three parts (Experiment 1, 2 and 3) because they were studied in the period of 2010 to 2012 to cover high chromaticness, blackness and whiteness samples in a hue, respectively. The experiment for saturation and vividness was carried out in 2010. In 2011 and 2012, the experiment was extended to scale blackness and whiteness, respectively. Hence, new samples were added for each experiment. In Experiment 1, 48 samples were selected for the saturation and vividness experiments. In Experiment 2, 45 samples including 6 samples which that had already been used for Experiment 1 were selected. In Experiment 3, 33 samples were selected for the saturation and vividness experiment.

The samples for the blackness experiment were also divided into two parts (Experiments 2 and 3). In Experiment 2, 77 samples were selected for the blackness experiment, and 33 samples were selected in Experiment 3. The samples that were used in Experiments 1 to 3 were used for the whiteness experiment in Experiment 3.

Table 3.21 shows the total number of samples used for each of the 4 attributes (saturation, vividness, blackness and whiteness). One-hundred and twenty colour samples were selected for each attribute except blackness. Unfortunately, 10 colour samples were lost for the blackness experiment. Thus, a total of 110 samples were used in the blackness experiment.

Table 3.20 Summary of experiments

	Attributes Scaled	Year	Number of Selected Samples	Number of Observers		
				Korean	British	Total
Experiment 1	13 attributes	2010	48	24		53
	Saturation Vividness				29	
Experiment 2	Saturation Vividness	2011	45	20	19	39
	Blackness		77			
Experiment 3	Saturation Vividness Blackness	2012	33	20	20	40
	Whiteness		120			
			Total	64	68	132

Table 3.21 Total number of samples used for each attribute

Attribute	Number of Samples
Saturation	120
Vividness	120
Blackness	110
Whiteness	120

Figure 3.4 shows how the samples were divided in the NCS colour triangle of a selected hue for the scaling of saturation and vividness. In Experiment 1, the colours that have high chromaticness in the right corner of the NCS colour triangle were selected. The colours that have high blackness in the bottom left corner of the NCS colour triangle were selected in Experiment 2. In Experiment 3, the colours that have high whiteness in the top left corner of the NCS colour triangle were selected. Figure 3.5 shows the colour distribution of the samples selected for the saturation and vividness experiments plotted by a*-b* and L*-C_{ab}* coordinates in CIELAB space.

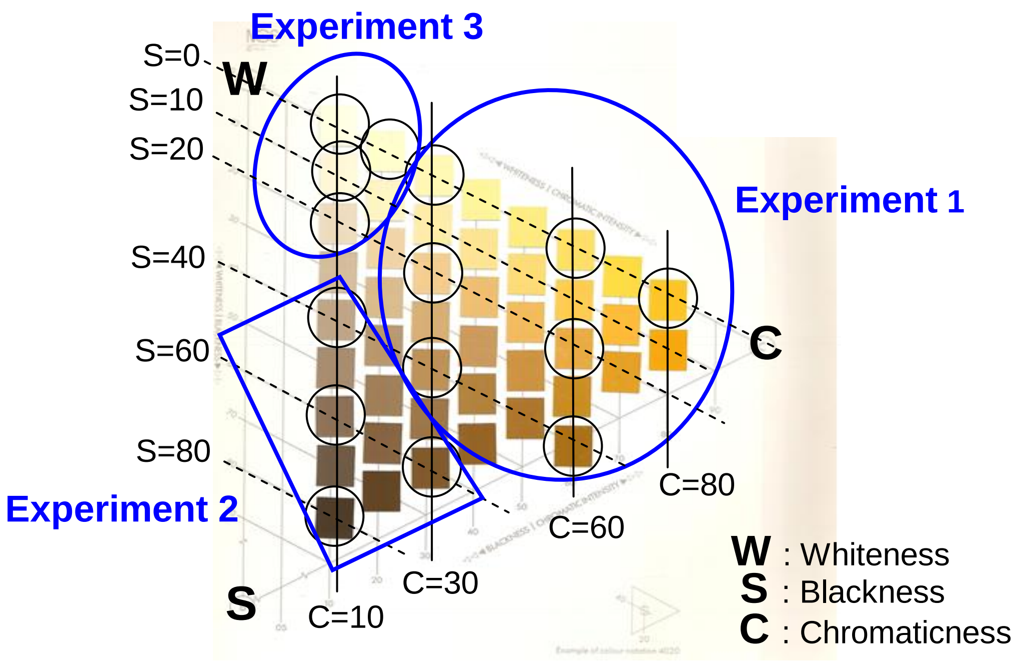


Figure 3.4 Colour selections of a hue for saturation and vividness experiment

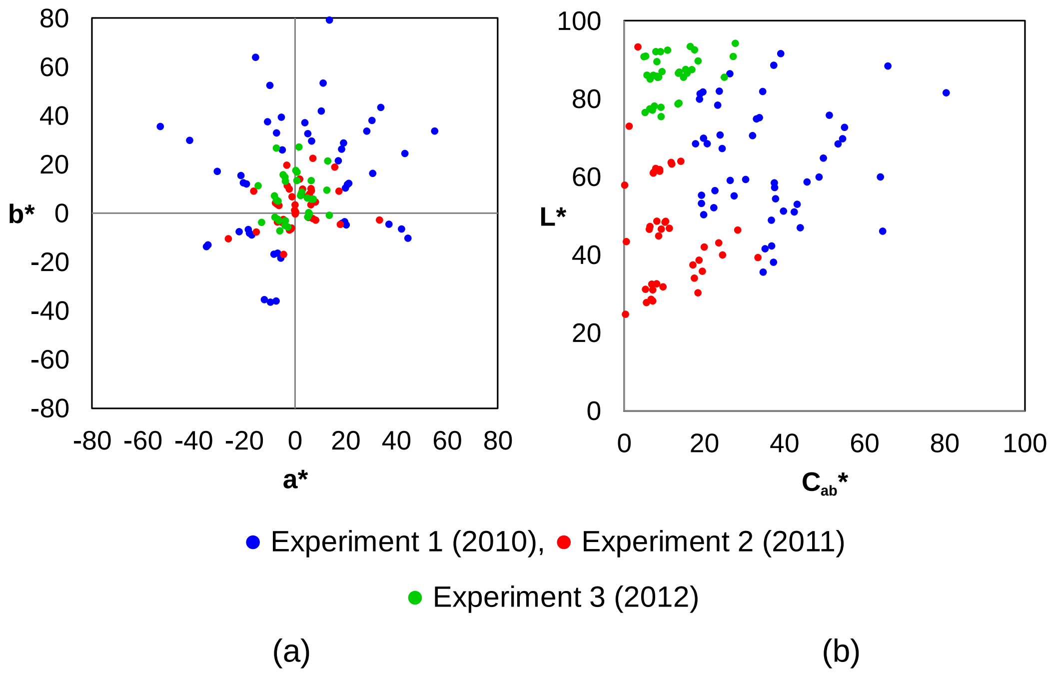


Figure 3.5 Distribution of colour samples used in saturation and vividness experiments according to their (a) a*-b* coordinates of CIELAB colour space and (b) L*-C* coordinates

Figure 3.6 show the samples divided in the NCS colour triangle of a hue for scaling blackness. In Experiment 2, the colours that have high chromaticness in the right corner and high blackness in the bottom left corner of the NCS colour triangle were selected. The colours that have high whiteness in the top left corner of the NCS colour triangle were selected in Experiment 3. Figures 3.7 and 3.8 show the colour distribution of samples selected in the blackness and whiteness experiments plotted according to their a*-b* and L*-C_{ab}* coordinates in CIELAB space, respectively.

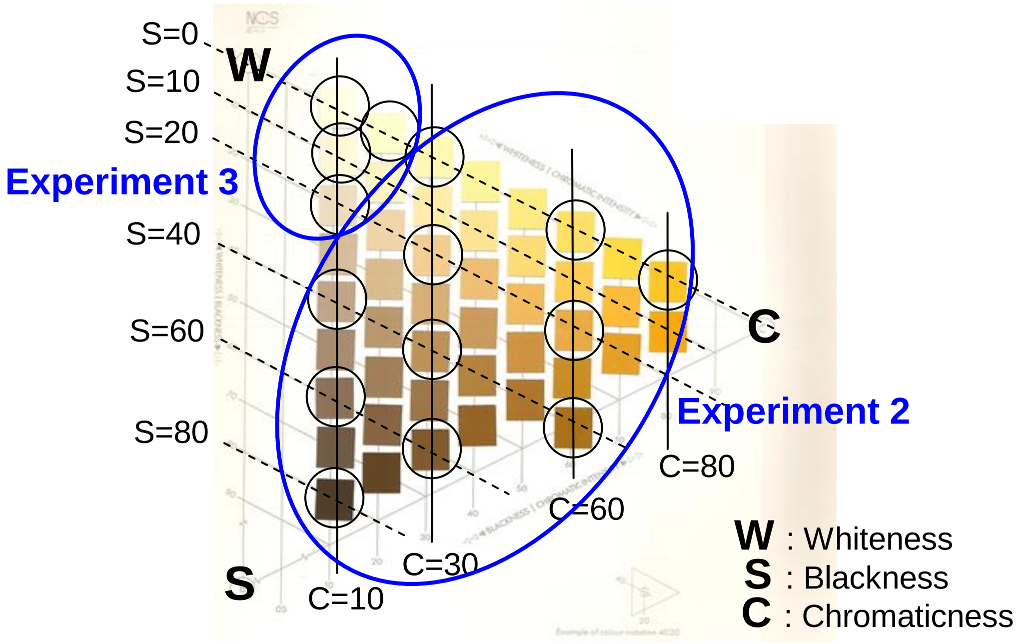


Figure 3.6 Colour selections of a hue for blackness experiment

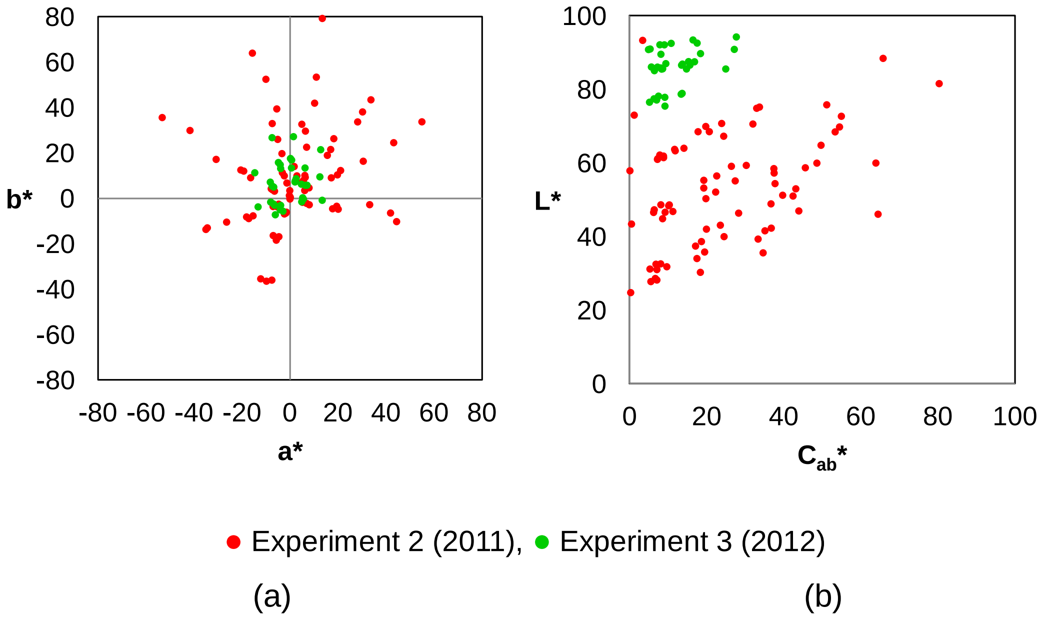


Figure 3.7 Distribution of colour samples used in blackness experiment according to their (a) a*-b* coordinates of CIELAB colour space and (b) L*-C* coordinates

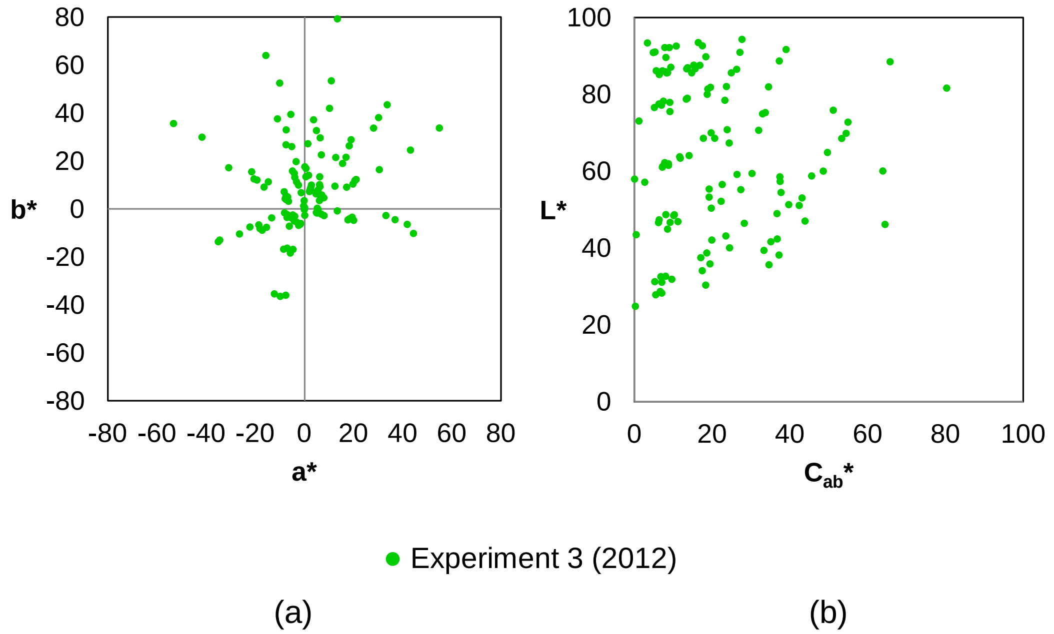


Figure 3.8 Distribution of colour samples in whiteness experiment in (a) a*-b* coordinates of CIELAB colour space and (b) L*-C* coordinates

Table 3.22 shows the number of colour samples used in each experiment with Korean and British observers. In each experiment, observers randomly repeated (randomly selected from the colour samples) assessment of the colours to investigate the repeatability. The colour sample sequence was randomised. In Experiment 1 with Korean observers, half of the 48 samples were repeated. Thus, 72 samples were used to assess the 15 attributes including saturation and vividness. In Experiment 1 with British observers, 12 of the 48 colour samples were repeated. A total of 60 samples were observed in saturation and vividness assessment.

In Experiment 2 with both Korean and British observers, 20 colours from the selected samples were repeated for each attribute. Forty-five samples were selected for the saturation and vividness experiments and 77 samples for blackness. Thus, 65 samples were observed in saturation and vividness assessment and 97 samples were assessed for blackness.

In Experiment 3 with both Korean and British observers, 10 colours from the selected samples were repeated for saturation, vividness and blackness, and 20 samples were repeated for the whiteness experiment. Thirty-three samples for saturation, vividness and blackness were selected and 120 samples for whiteness. Thus, 43 samples were used for saturation, vividness and blackness and 140 samples for whiteness.

Table 3.22 Number of samples used in each experiment

		13 attributes	Saturation	Vividness	Blackness	Whiteness
Exp.1	Korean	72 (=48+24R)	72 (=48+24R)	72 (=48+24R)		
	British		60 (=48+12R)	60 (=48+12R)		
Exp.2	Korean		65 (=45+20R)	65 (=45+20R)	97 (=77+20R)	
	British		65 (=45+20R)	65 (=45+20R)	97 (=77+20R)	
Exp.3	Korean		43 (=33+10R)	43 (=33+10R)	43 (=33+10R)	43 (=33+10R)
						97 (=87+10R)
	British		43 (=33+10R)	43 (=33+10R)	43 (=33+10R)	43 (=33+10R)
						97 (=87+10R)
Total		72	348	348	280	280

Note: R means repeated colours.

3.5 Measuring Colours

A Minolta CS1000 tele-spectroradiometer (TSR) was used to measure a white tile used as the reference white in the experiment. The white tile was measured using an XRite CE7000a spectrophotometer (see section 2.3.7.2). These are introduced below.

Minolta CS1000 Tele-spectroradiometer

A Minolta CS1000 Tele-spectroradiometer was used to measure the white tile (reference white) as shown in Figure 3.9. It measures the spectral power distribution (SPD) of a colour in terms of radiance (in W/m2.Sr). It is measured at the range of from 380 to 780 nm with a 1 nm interval. Note that the instrument had a bandwidth of 5nm and then the data were subsequently interpolated into 1 nm interval by the manufacturer.

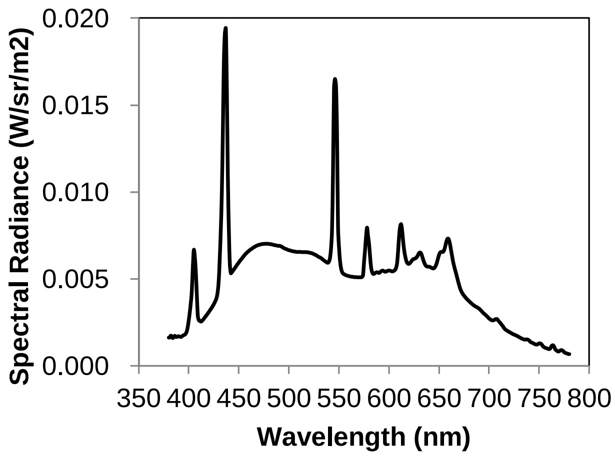
Figure 3.9 Minolta CS1000 Tele-spectroradiometer (Tele-spectroradiometer, 2013)

The instrument can directly report tristimulus values to represent a colour that is observed under a given set of viewing conditions. It has an advantage that the measurement conditions correspond to those used for viewing. It measures the colour of a distant object from its usual observing position and using common viewing conditions. This measurement device also reports the correlated colour temperature (CCT), and CIE chromaticity coordinates of self-luminous colours. The TSR was positioned in front of the viewing cabinet, the same position as the observer’s experimental position shown in Figure 3.10. Figure 3.11-(a) shows the spectral power distribution of the reference white, a white tile, from one particular measurement during the experiment.

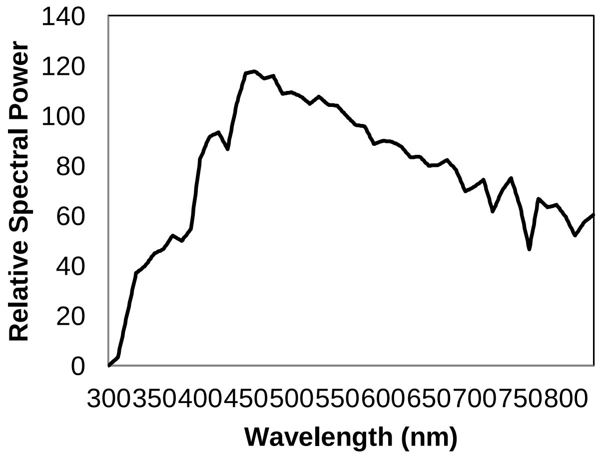
The experimental uncertainty may have come from observer variation, samples fading or contamination, instrument varying over time and unstableness of the viewing cabinet. The light source in the viewing cabinet was measured in a routine basis for a period of 3 years to examine its stability. The average x and y are 0.3168 and 0.3286, respectively. The standard deviations are 0.0026 and 0.0015 and correlation coefficients are 0.8% and 0.5%, respectively. Also, for the luminance values measured against reference tile is 490 cd/m^2 with a standard deviation of 25. The correlation coefficient was 5%. The above performance is considered to be highly satisfactory. The uncertainty is very small. This indicates the fluorescent D65 simulator used was highly stable and the TSR used was highly repeatable during the whole experimental period.

The CIE D65 illuminant is also plotted in Figure 3.11 (b). As it can be seen that the two agree reasonably well. The x and y for the CIE D65/10 are 0.3182 and 0.3310 respectively. There is only 1.30 CIELAB units between the light source used and CIE illuminant. This indicate that the light source used is highly agreed with the CIE specification.

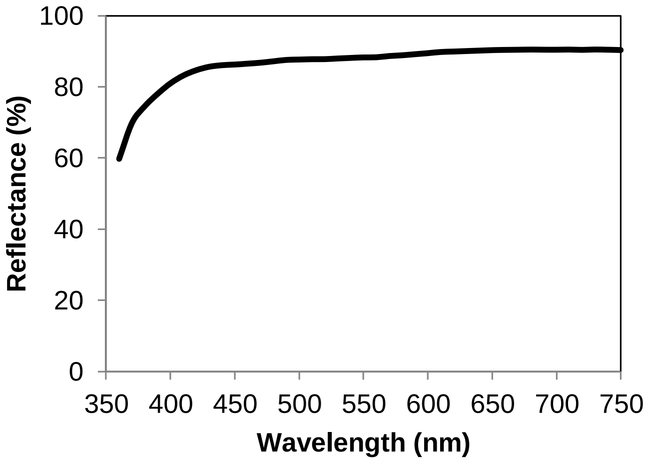
Figure 3.10 Setup of a white tile and TSR



(a)



(b)



(c)

Figure 3.11 (a) Spectral power distribution of white tile, (b) CIE D65 illuminant and (c) reflectance of white tile

CE7000a Spectrophotometer

A GretagMacbeth CE 7000A spectrophotometer was used in this study to measure the spectral reflectance of the surface colours (see Figure 3.12) and the grey background board. The instrument provides spectral measurement between 360 to 750 nm at a 10 nm interval. It is a sphere-based system that has a viewing geometry of d:8^{o}. It is a true double-beam system that includes two monochrometers to provide accurate readings for measuring the sample and white surface in the integrating sphere simultaneously. The instrumental parameters include specular included/excluded, UV included/excluded, three sizes of apertures. There are three aperture sizes: large, medium and small. The large aperture is 25.4 mm (1"), the medium aperture is 15 mm (0.591") and the small aperture is 10 mm (0.394") by 7.5 mm (0.295"). During the sample measurement, the large aperture was used. The specular included condition was used to correspond to the characteristics of the samples measured. Also, UV included was used.

After the instrumental parameters were setup, the measurement device was calibrated with a black tile, white ceramic calibration tile and green tile to verify calibration. After the calibration, each sample was measured.

Figure 3.12 GretagMacbeth CE 7000A spectrophotometer

Note that the white tile referred to here is not the same tile as that used to calibrate the CE7000a. Instead, this second white tile was used to measure the actual lighting using CS1000.

Ten samples were measured twice over the time period of single seconds by the CE7000A to assess the short-term repeatability. The colour difference (ΔE_{ab}^{*}) between these two XYZ measured results was calculated. The difference between the results was very small with a mean of 0.04 ranging from 0.03 to 0.07. This indicates that the samples were stable during the experiment. The samples were mounted on grey cardboard and were kept in the dark except during the experimental period.

The colour differences between the measured samples and the same samples measured by Juan (2000) in 2000 were calculated to evaluate the long-term repeatability. Long-term repeatability is used to see the stability of the sample over a long period. The difference could represent colour changes over more than 10 years. The average colour difference result was 0.75. This indicates that the same samples are stable in a long period of time.

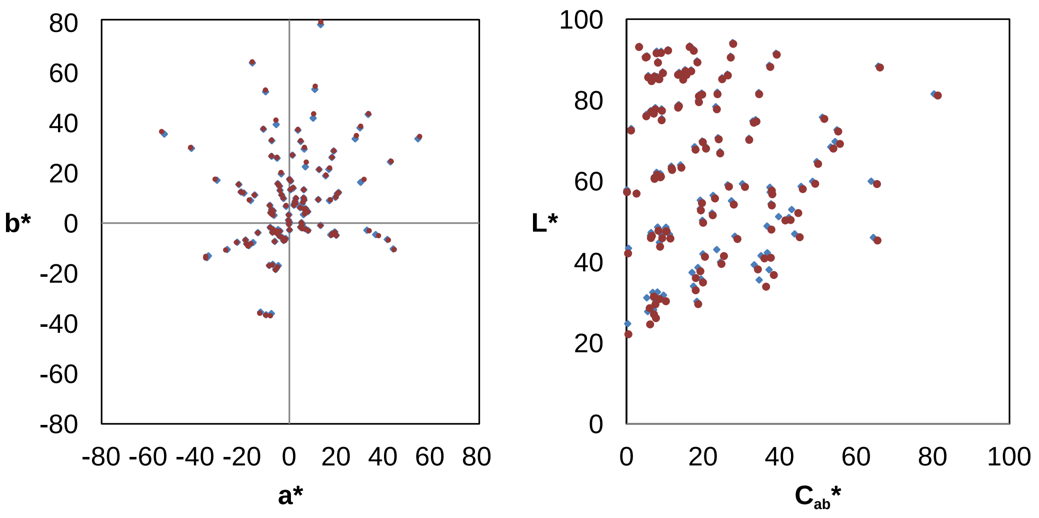


Figure 3.13 a^{*}-b^{*} and C_{ab}^{*}-L^{*} coordinates of colour samples under specular included (◆) and excluded (●) conditions

Calculation of XYZ values

Each sample's tristimulus values were calculated based on the spectral reflectance from CE7000a (10 nm interval) multiplying the ASTM table of D65/10 conditions (ASTM International, 2008). The reason is the x and y values calculated by the TSR and the present method are very close, i.e. differ by x of 0.0014 and by y of 0.0024 for the reference white sample. This corresponds to a CIELAB colour difference of 1.30. The reflectance of each sample needs to be calculated in 1 nm interval. The interpolation method which is the ATSM (ASTM International, 2008) will be used to abridge from 10 to 1 nm interval data. This could further reduce the precision because different interpolation methods could produce quite different results.

3.6 Observers

The numbers of Korean and British observers who took part in each experiment are summarised in Table 3.23. Males and females were almost equal in number for each experiment. Observers had normal colour vision and had passed the Ishihara test (Ishihara, 1985) before the experiment. Observers were students of the University of Leeds aged from 20 and 36. They had no knowledge of colour science and were naive to colour-appearance scaling.

In Experiment 1, 24 Korean observers participated in assessing 15 attributes including saturation and vividness. Twenty-nine British observers assessed saturation and vividness. In Experiment 2, 20 Korean and 19 British observers took part in assessing saturation, vividness and blackness. Finally, 20 Korean and 20 British observers participated in assessing saturation, vividness, blackness and whiteness in Experiment 3. Overall, 132 observers took part in this study.

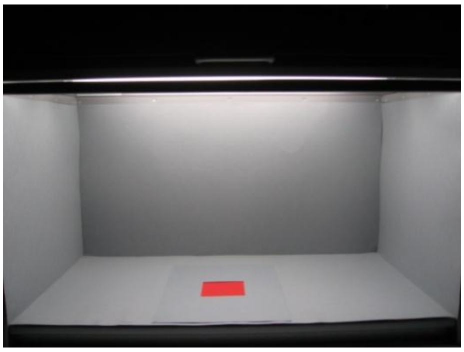
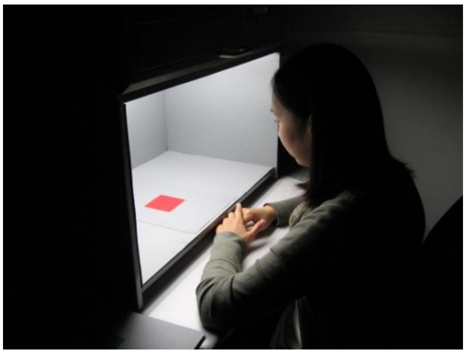
Table 3.23 Number of observers

		13 attributes	Saturation	Vividness	Blackness	Whiteness
Exp .1	Korean	24 =10M+14F	24 =10M+14F	24 =10M+14F		
	British		29 =14M+15F	29 =14M+15F		
Exp .2	Korean		20 =10M+10F	20 =10M+10F	20 =10M+10F	
	British		19 =10M+9F	19 =10M+9F	19 =10M+9F	
Exp .3	Korean		20 =10M+10F	20 =10M+10F	20 =10M+10F	20 =10M+10F
	British		20 =10M+10F	20 =10M+10F	20 =10M+10F	20 =10M+10F
Total		24	132	132	79	40

Note: M (Male) and F (Female).

3.7 Experimental Viewing Conditions

Figure 3.14 shows the viewing conditions of the experiment. Each colour sample was placed inside the viewing cabinet covered with a mid-grey background shown in Figure 3.14-(a). The L*a*b* values of the mid-grey background were 57.06, 0.24 and -2.71, respectively. Observers sat in front of the viewing cabinet with a D65 simulator, situated in the darkened room shown in Figure 3.14-(b). They were asked to adapt to the viewing condition for about one minute before starting the experiment. The viewing distance between the observer and the stimuli was about 60 cm. The field of view was about 10 degrees. During the experiment, the viewing cabinet was used only for this particular project. It was well protected and in good working condition.

(a) (b)

Figure 3.14 (a) and (b): viewing conditions

3.8 Instructions

Only Korean observers participated in Experiment 1. Observers were seated and instructed to view the colour patches. They were asked to rate each colour based on the 6-point categorical scale according to the 25 attributes (see section 3.3): “vivid-dull”, “distinct-indistinct”, “striking”, “intense-weak”, “full-thin”, “saturated”, “warm-cool”, “clean-dirty”, “clear”, “light-heavy”, “active-passive”, “fresh-stale”, “natural-not natural”, “boring” and “bright”. An example of “vivid-dull” would be categorized as “6: very vivid”, “5: vivid”, “4: a little vivid”, “3: a little dull”, “2: dull” and “1: very dull”. A single attribute, such as “clear” would be categorized as “6: very high”, “5: high”, “4: a little high”, “3: a little low”, “2: low” and “1: very low”.

The twenty-five attributes had quite different meanings. The arrangement of these attributes could affect the results, so it was decided to divide them into two groups with similar and dissimilar meanings. Furthermore, fifteen scales were divided into 5 sessions according to the similarity of the colour attributes. Observers were divided into two groups: For groups 1 and 2, the colour attributes were arranged as shown in Tables 3.24 and 3.25, respectively. The attributes in the former group had similar meaning in each session, whereas those in the latter group had no similarity.

Table 3.24 Five sessions of Group 1 for Experiment 1

Session 1	Session 2	Session 3	Session 4	Session 5
1 Vivid-dull	1 Intense-weak	1 Clean-dirty	1 Light-heavy	1 Natural-not natural
2 Distinct-indistinct	2 Full-thin	2 Clear	2 Active-passive	2 Boring
3 Striking	3 Saturated	3 Warm-cool	3 Fresh-stale	3 Bright

Table 3.25 Five sessions of Group 2 for Experiment 1

Session 1	Session 2	Session 3	Session 4	Session 5
1 Natural-not natural	1 Light-heavy	1 Warm-cool	1 Clear	1 Active-passive
2 Full-thin	2 Vivid-dull	2 Clean-dirty	2 Saturated	2 Distinct-indistinct
3 Bright	3 Fresh-stale	3 Intense-weak	3 Striking	3 Boring

Among the attributes, British observers assessed saturation and vividness for Experiment 1. In Experiment 2, both Korean and British observers scaled saturation, vividness and blackness based on the 6 point-scale. In Experiment 3, both Korean and British observers scaled saturation, vividness, blackness and whiteness also based on the 6 point-scale.

Each attribute was assessed for one colour at a time. This means that one attribute was the focus for each colour sample. The experimental setup and conditions of Experiments 2 and 3 were the same as those of Experiment 1.

The blackness experiment of the present study differed from Tao *et al*.'s (2011 and 2012) blackness experiment (see Section 2.4.2) in that it did not focus on choosing one sample based on perception and preference of blackness. The blackness experiment of the present study basically focused on estimating the blackness level of each colour sample and developing a blackness model.

Definitions were not in the instructions, but definitions were provided to every observer. Observers were asked if they exactly understood the meaning of the words. Thus, definitions were provided for all British and Korean observers in all experiments when it is needed. Definitions according to the Oxford dictionary were given to the British observers (see Appendix F); for Korean observers, definitions based on the Korean dictionary were provided (see Appendix F). The definition of saturated was “the greatest possible amount of the substance that has been dissolved in it”. As mentioned in section 3.2, this word in Korean is translated to “포화된”. However, “포화된” was hard for Korean observers to understand. The second meaning of saturation was “채도” which means “it is close to a pure colour without any mixture, and it is pure and clean”. The word “채도” itself was hard for Korean observers to understand. Thus, the meaning “채도” was provided for Korean observers as “색의 순수한 정도” which means “the degree of colour purity” according to the Korean dictionary. For British observers, the meaning of each word was provided (see Appendix F). Vivid was defined as “(of light, colours, etc) very bright”. This was translated to “선명한” which was also defined in Korean industrial standards (KS). This word itself has a clear meaning in Korean. Thus, Korean observer found it easy to understand. Black is defined as “of the very darkest colour owing to the absence of or complete absorption of light; the opposite of white”. White is defined as “of the colour of milk or fresh snow, due to the reflection of all visible rays of light; the opposite of black”. Although great care was taken in the experiment, it was found that the whole experiment, the dictionary definition was never used by the British observers, and only two Korean observers requested for the definition for the word ‘saturated’. This implies that observers did not have problem to understand the words collected. So, it can be concluded that the results obtained in the present study representing the true understanding of the observers.

The instructions for the experiments are given below:

Experiment 1 for Korean experiment

You will be presented with 72 colour samples shown individually in the viewing cabinet. There are 5 sessions. In each session, there will be 3 attributes to describe what each sample looks like.

For example,

Vivid-Dull	*Bright*
6 Very vivid	*6 (Very high)*
5 Vivid	*5 (High)*
4 A little vivid	*4 (A little high)*
3 A little dull	*3 (A little low)*
2 Dull	*2 (Low)*
1 Very dull	*1 (Very low)*

Experiment 1 for British experiment

You will be presented with 60 colour samples shown individually in the viewing cabinet. There will be 2 attributes to describe what each sample looks like.

Vivid – Dull	*Saturated*
1 Very vivid	*6 Very saturated*
2 Vivid	*5 Saturated*
3 A little vivid	*4 A little saturated*
4 A little dull	*3 A little not saturated*
5 Dull	*2 Not saturated*
6 Very dull	*1 Very not saturated*

Experiment 2

You will be presented with 65 colour samples (for vividness and saturation) and 97 colour samples (for blackness) shown individually in the viewing cabinet. All the colours will be assessed for one word attribute at a time.

Three attributes will be used to describe what each sample looks like according to the following:

Vivid – Dull	***Saturated***	***Blackness***
1 Very vivid	*6 (Very saturated)*	*6 (high)*
2 Vivid	*5*	*5*
3 A little vivid	*4*	*4*
4 A little dull	*3*	*3*
5 Dull	*2*	*2*
6 Very dull	*1 (Very not saturated)*	*1 (Low)*

Experiment 3

You will be presented with 87 colour samples (for whiteness) and 33 colour samples (for saturation, blackness, vividness and whiteness) shown individually in the viewing cabinet. Ten colour samples will be repeated for each attribute. All the colours will be assessed for one attribute at a time.

The attributes above will be used to describe what each sample looks like according to the following:

Saturated	***Blackness***	***Vivid – Dull***	***Whiteness***
6 (Very saturated)	*6 (High)*	*1 Very vivid*	*6 (High)*
5	*5*	*2 Vivid*	*5*
4	*4*	*3 A little vivid*	*4*
3	*3*	*4 A little dull*	*3*
2	*2*	*5 Dull*	*2*
1 (Very not saturated)	*1 (Low)*	*6 Very dull*	*1 (Low)*

There may be different perceptions found between two cultural groups due to the lack of training and the use of different languages (or culture) for saturation and vividness. On the other hand, as blackness and whiteness are more universally understood, both cultural groups will have similar understanding and perception to the colour samples.

3.9 Data Analysis

3.9.1 Correlation Coefficient

The Pearson product-moment correlation coefficient (or Pearson correlation coefficient) indicates the strength of the linear relationship between two data sets (Lewis, 1998). It is defined in the following equation:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{[\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2]^{1/2}} \qquad (3-1)$$

where x_i and y_i are individual values of two data sets for stimulus i, and $\bar{x}$ and $\bar{y}$ are the mean value of the two data sets.

The range of the correlation coefficient is -1.0 to 1.0. If the correlation between the two data sets is positive and close to 1, the two data sets have a strong linear correlation. If the correlation between the two data sets is negative and close to -1, the two data sets have a strong negative linear relationship.

In the present study, the correlation coefficient was used to investigate the relationship between British and Korean observer responses for saturation, vividness, blackness and whiteness.

3.9.2 R Squared

The coefficient of determination (R^2) is a statistical measure to investigate how well the regression line approximates the real data points (Steel and Torrie, 1960). It indicates how well data points fit a line or curve. It is simply the square of the Pearson correlation coefficient. If the R^2 is 1, the regression line perfectly fits the data. The coefficient of determination ranges from 0 to 1. In the present study, the R^2 is calculated to investigate whether the independent data set fit into the new model.

3.9.3 Principal Component Analysis

Principal component analysis (PCA) is a method to reduce a large amount of data from a group of interrelated variables into a small set of independent ones (Jolliffe, 2002). The principal components are extracted by determining the eigenvectors and eigenvalues of a covariance matrix. Eigenvectors and eigenvalues are defined as the solution to the following equation:

$$Av_k = \lambda_k v_k \ (k = 1 \ldots n), \tag{3-2}$$

where A is a real and symmetric matrix with n×n size, v_k denotes the eigenvectors of matrix A and λ_k denotes the associated eigenvalues.

In this study, A is the covariance matrix of experimental data for a set of attributes. The principal component analysis method was used to analyse the visual data obtained from the Korean experiment for 15 attributes which will be explained in Section 4.4. The output from the principal component analysis is the classified results of 15 attributes from the Korean experiment in terms of component loadings, that is, the correlation coefficients between 15 attributes and the principal components derived.

3.9.4 Root Mean Square

Root mean square (RMS) is the extent to which two data set agree with each other, as shown in the following equation (Lewis, 1998):

$$RMS = \sqrt{\frac{\sum(x_i - y_i)^2}{N}} \tag{3-3}$$

where x_i and y_i are values of two sets of data for specific sample i, and *N* is the number of colour samples.

The minimum value of RMS is 0, which indicates perfect agreement between the two sets of data. In the present study, the RMS was used for the repeatability of repeated samples for saturation, vividness, blackness and whiteness. Also, the RMS values were calculated between observer responses and the predicted values from saturation, vividness, blackness and whiteness models.

3.9.5 STRESS

Standard residual sum of squares (STRESS) (García *et al*., 2007) is a standard statistical measurement to estimate the relationship between two sets of data. Dissimilarities between pairs of objects are estimated by the distance between corresponding pairs of entities in a visual representation. The quality of the approximation is denoted as loss function. The loss function generates the optimal arrangement at its minimum. In this study, the STRESS value was calculated to evaluate how well the model fit the NCS data. The STRESS (García *et al*., 2007) is defined as follows:

$$\mathrm{STRESS} = \left(\frac{\sum(\Delta \mathrm{E_i} - \mathrm{F_1}\Delta \mathrm{V_i})^2}{\sum \mathrm{F_1^2}\Delta \mathrm{V_i^2}}\right)^{1/2}, \qquad (3\text{-}4)$$

with $\mathrm{F_1} = \frac{\sum \Delta \mathrm{E_i^2}}{\sum \Delta \mathrm{E_i}\Delta \mathrm{V_i}}$

where colour pairs with ΔV_i and ΔE_i are visual and computed differences. F_1 is not arbitrary scaling factors, but factor minimizing the STRESS. The STRESS value is in the range of 0 to 100. If the STRESS value is zero, the agreement will be perfect. For example, a STRESS value of 40 means a disagreement of about 40%.

3.10 Summary

In the present study, three sets of psychophysical experiments were conducted. Specific setups for each experiment were described including attributes selection, colour samples selection, observers, procedures and viewing conditions.

The general settings for the psychophysical experiments were also described, such as the specification of the colour samples measured by TSR and spectrophotometer. The categorical judgement method was used for the experimental method.

Finally, the statistical methods to analyse the visual results were explained, such as correlation coefficient (r), principal component analysis (PCA), root mean square (RMS), R squared (R^2), and the standard residual sum of squares (STRESS).

The unique features in this experiment include the following:

1) It is a cross-cultural study on the descriptors used to describe the chromatic content of colours.

2) Only the naive observers participated in this study. They represent the true understanding of each descriptor and hence the real meaning of each word in each culture. For two cultural groups, there could have differences in colour perception for saturation and vividness due to the lack of training and different languages (culture) used. However, there should be little difference in perception for blackness and whiteness because these words are more widely used in both languages.

3) The colour attributes were arranged according to similar and dissimilar meanings to elucidate the effect on observer uncertainty.

Chapter 4 Identifying the Third Dimension of Colour Appearance

4.1 Overview

One of the aims of this study was to find an alternative to the third-dimension. In this chapter, fifteen semantic scales (“bright”, “light-heavy”, “active-passive”, “fresh-stale”, “clean-dirty”, “clear”, “boring”, “natural-not natural”, “warm-cool”, “intense-weak”, “saturated”, “vivid-dull”, “distinct-indistinct”, “full-thin” and “striking”) were assessed by 24 Korean observers to find an alternative to the third dimension of colour appearance. Among the fifteen scales, saturation and vividness were selected to be the representative scales. Saturation has been studied and defined by CIE (2012). It was also developed in CIELUV (CIE, 2004a) colour space, CIECAM02 (p1-13, CIE, 2004b), Nayatani *et al*. and Hunt models. In 2012, Fairchild and Heckaman (2012) proposed a saturation scale which was derived from two attributes: chroma and colourfulness. Thus, there is a need to develop a more reliable model based on the experimental data (see Section 1.1). On the other hand, vividness is important for image quality and image enhancement. Nayatani (2005) defined the degree of vividness in 2005. In 2013, Berns (2013) derived a vividness model based on the CIELAB system. There is a need to develop a vividness model based on psychophysical experiments. The two scales, saturation and vividness, were thus selected to be assessed in the present PhD studies using 29 British observers. The visual results obtained from Korean and British observers were then compared to investigate whether there was any cultural difference in the observer response and to determine whether it would be feasible to develop a universal model from these visual data.

The structure of this chapter is described below.

- The intra- and inter-observer variability of 15 scales is discussed in Section 4.2. The results are used to understand which scales are more consistent or inconsistent.

- In Section 4.3, the 15 scales are plotted against the CIELAB C_{ab}^*, L^* and h_{ab} to reveal whether there is any relationship between them and the 15 scales studied.

- The principal component analysis (PCA) results of the 15 scales are discussed in detail in Section 4.4. Two components are found in relation to lightness and chroma.

- In Section 4.5, the relationships are investigated between the visual data of each scale of Korean group and the saturation data of British group; similarly the relationships are investigated between the visual data of each scale and the vividness data of British group.

4.2 Intra- and Inter-observer Variability

Intra- and inter-observer variability were used to represent the consistency of observers' response. The intra-observer variability can represent the repeatability of each observer's judgement. It was determined by averaging the root mean square (RMS) between each observer's result and the repeated result (see equation (3-4).

Inter-observer variability represents how well the observers agreed with each other. This was also determined by using the averaged RMS between each observer's result and the overall mean. It was calculated by replacing y_i with $\bar{x_i}$ and $n = 24$ with $n = 48$ in Eq. (3-4), in which $\bar{x_i}$ represents the overall mean result and *n* represents the total number of stimuli. The smaller the variations, the more the observer responses agree with each other.

Table 4.26 summarises the result of intra- and inter-observer variability of the 15 scales for the Korean observers. Among the scales, the best repeatability (intra-observer variability) was found for "bright" with an RMS value of 1.00, and the poorest repeatability was "natural-not natural" with an RMS value of 1.37. The best accuracy (inter-observer variability) was also "bright" with an RMS value of 0.99 and the poorest accuracy was also "natural-not natural" with an RMS value of 1.51.

Table 4.26 shows that overall inter-observer variability is higher than intra-observer variability. Overall, "bright" seems to give better repeatability and accuracy than other scales. “Natural-not natural” seems to give the poorer repeatability and accuracy than the other scales.

The fifteen scales were divided into 5 sessions. The Korean observer group was divided into two groups (Groups 1 and 2). Group 1 observers assessed scales that have similar meanings in each session. Group 2 assessed scales that have different meanings. For example, there were “vivid-dull”, “distinct-indistinct” and “striking” in session 1 for Group 1. These three scales have similar, although slightly different, meanings in the Korean language. There were “natural-not natural”, “full-thin” and “bright” in Session 1 for Group 2. In the Korean language the three scales are quite different in literal meanings. As mentioned in Section 3.8, Group 1 (similar scales in the same session) and Group 2 (dissimilar scales in the same session) observers were compared to investigate which group performed better in terms of intra- and inter-observer variability. Table 4.27 summarised the intra- and inter-observer variability results of Groups 1 and 2. In Group 1, “bright” showed the best repeatability with an RMS value of 0.93 and “distinct-indistinct” showed the poorest repeatability with an RMS value of 1.31. In Group 2, “clean-dirty” showed the best repeatability with an RMS value of 1.00 and “natural-not natural” showed the poorest repeatability with an RMS value of 1.45.

'Bright' showed the best accuracy with an RMS value of 0.91, and 'natural-not natural' showed the poorest accuracy with the RMS value of 1.61 in Group 1. In Group 2, “light-heavy” showed the best accuracy with an RMS value of 1.04, and “natural-not natural” showed the poorest accuracy with an RMS value of 1.42.

Overall, Group 1 seemed to give better repeatability than Group 2. Also, Group 1 seemed to give more accurate results than Group 2. This indicates that the group who assessed scales that are related to each other (Group 1) found it much easier to scale the colours than the group who assessed scales that have no relation to each other (Group 2).

Table 4.28 shows that the observer data of the 15 scales were found to agree well between Groups 1 and 2. This implies that the presentation sequence of the scales had little effect on the results during the experiment.

Table 4.26 Intra- and inter-observer variability of the attributes for Korean

The scale	Intra	Inter
Vivid-dull	1.29	1.18
Distinct-indistinct	1.23	1.22
Striking	1.17	1.19
Intense-weak	1.23	1.22
Full-thin	1.24	1.24
Saturated	1.02	1.20
Clean-dirty	1.06	1.07
Clear	1.13	1.17
Warm-cool	1.13	1.25
Light-heavy	1.08	1.00
Active-passive	1.15	1.12
Fresh-stale	1.22	1.15
Natural-not natural	**1.37**	**1.51**
Boring	1.24	1.28
Bright	**1.00**	**0.99**
Mean	1.17	1.19

Table 4.27 Intra- and inter-observer variability of Groups 1 and 2

	Group 1		Group 2	
The scale	Intra	Inter	Intra	Inter
Vivid-dull	1.28	1.16	1.30	1.19
Distinct-indistinct	**1.31**	1.23	1.15	1.22
Striking	1.13	1.00	1.20	1.35
Intense-weak	1.17	1.08	1.28	1.33
Full-thin	1.30	1.17	1.19	1.30
Saturated	0.96	1.05	1.07	1.33
Clean-dirty	1.13	1.03	**1.00**	1.10
Clear	0.95	1.00	1.29	1.32
Warm-cool	1.19	1.21	1.09	1.28
Light-heavy	1.03	0.96	1.12	**1.04**
Active-passive	1.12	1.00	1.17	1.23
Fresh-stale	1.08	1.09	1.34	1.20
Natural-not natural	1.28	**1.61**	**1.45**	**1.42**
Boring	1.14	1.27	1.33	1.30
Bright	**0.93**	**0.91**	1.05	1.07
Mean	**1.13**	**1.12**	1.20	1.24

Table 4.28 Correlation coefficient (r) between the scales of Groups 1 and 2

The scale	r
Vivid-dull	0.84
Distinct-indistinct	0.93
Striking	0.93
Intense-weak	0.93
Full-thin	0.82
Saturated	0.91
Clean-dirty	0.91
Clear	0.91
Warm-cool	0.91
Light-heavy	0.97
Active-passive	0.92
Fresh-stale	0.90
Natural-not natural	0.80
Boring	0.86
Bright	0.93

4.3 Relationships Between Observer Response and CIELAB Values (Chroma, Lightness and Hue Angle)

To understand the relationship between each scale and CIELAB values and accordingly to identify the scales that can represent the third dimension, the correlation coefficients (r) were calculated for each scale compared with the CIELAB lightness (L^*), chroma (C_{ab}^*) and hue angle (h_{ab}). The results are given in Table 4.29. It can be seen that the 15 scales can be roughly divided into 2 categories. One category includes those having high r values on the CIELAB C_{ab}^*, such as “vivid-dull”, “distinct-indistinct”, “striking”, ‘intense-weak” and “saturated”. This suggests that the more colourful the colour, the more vivid, distinct, striking, intense and saturated it tends to appear. The other category includes those having high r values on the CIELAB L^* such as “full-thin”, “light-heavy” and “bright”. This suggests that the three scales are connected closely to the CIELAB L^*.

Among the 15 scales, “saturation” showed the highest r value with the CIELAB C_{ab}^*, with a correlation coefficient of 0.73. “Light-heavy” showed the highest r value with the CIELAB L^*, with a correlation coefficient of 0.92. This means that “saturation” is highly correlated with CIELAB chroma and “light-heavy” is highly correlated with CIELAB lightness. “Warm-cool” showed the highest r value with the CIELAB h_{ab}, with a correlation coefficient of -0.51. Figure 4.1-(a) shows the visual data plotted against the hue angle. Though the r value is low there are trends to be seen. It can be seen that the warmest colours are in red and yellow regions, followed by green until it reaches blue (the coolest colour), and there is a sharp change from about 270° to 360°. If you connect the x coordinates of 360° and 0° in Figure 4.1-(a), the result will be a diagonal line which suggests linear correlation. Although “natural-not natural” is not associated with the CIELAB hue angle, a trend can also be found. (Note that the pure red is about 20˚ in hue angle.

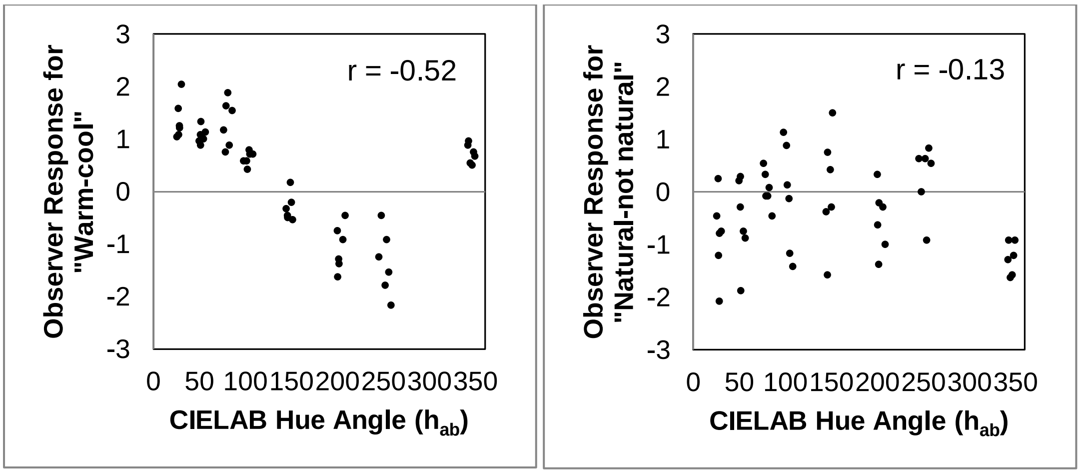
Figure 4.1-(b) shows the attribute of “natural-not natural” plotted against the hue angle. The most natural colour is seen in the green region about 150°. If you also connect the x coordinates of 360° and 0° in Figure 4.1-(b), though it

is scattered a lot; the observer response of “natural-not natural” seems to be linearly associated with the CIELAB hue angle.

In Ou *et al*.’s (2004 and 2012) study, “light-heavy” was found to be highly correlated with lightness. This result agrees well with the observer response of “light-heavy” in the present study, which was found to correlate with lightness. Gao *et al*. (2007) classified the colour emotion responses into three factors. Among them, one of the factors, which include “passive-dynamic”, “vague-distinct”, “vivid-sombre’” and “subdued-striking” responses, was highly correlated with chroma. These results agree well with the current observer responses of “active-passive”, “distinct-indistinct”, “vivid-dull” and “striking”, which were found to correlate with chroma. In the studies of Wright and Rainwater (1962), Hogg (1969), Sato *et al*. (2000a) and Ou *et al*. (2004 and 2012) (see Section 3.2), “warm-cool” was found to correlate with the hue angle. These findings agree with the current study of “warm-cool”. These results imply that the colour emotion responses associate well with colour appearance attributes, i.e. lightness, chroma and hue angle, which was found as a trend by Wright and Rainwater (1962), Hogg (1969), Kobayashi (1981), Sato *et al*. (2000a), Gao *et al*. (2007), Lee *et al*. (2009) and Ou *et al*. (2012) (see Section 3.2). Thus, the more lightness is a colour, the lighter it connotes. The more chroma a colour, the more active, distinct, vivid and striking it appears to be.

Table 4.29 The correlation coefficient (r) of the scales with the existing colour appearance values in terms of chroma (C_{ab}^*), lightness (L^*) and hue angle (h_{ab}) in the CIELAB system

	C_{ab}^*	L^*	h_{ab}
Vivid-dull	0.72	0.02	-0.02
Distinct-indistinct	0.72	0.04	-0.03
Striking	0.64	0.20	0.02
Intense-weak	0.71	-0.42	-0.01
Full-thin	0.52	-0.79	-0.04
Saturated	0.73	-0.23	0.00
Clean-dirty	0.39	0.49	0.08
Clear	0.46	0.52	0.06
Warm-cool	0.35	0.12	-0.51
Light-heavy	0.07	0.92	-0.03
Active-passive	0.50	0.54	0.00
Fresh-stale	0.44	0.56	-0.01
Natural-not natural	0.02	-0.29	-0.13
Boring	-0.50	-0.50	-0.06
Bright	0.31	0.79	-0.04



(a) (b)

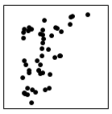
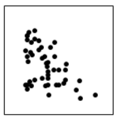
Figure 4.1 CIELAB h_{ab} plotted against the observer response for (a) “warm-cool” and (b) “natural-not natural”

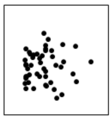
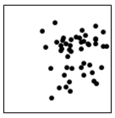
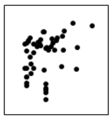
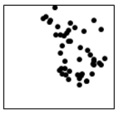
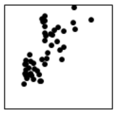
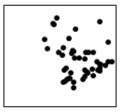
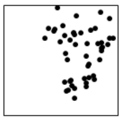
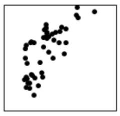
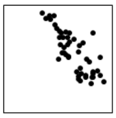
4.4 The Principal Component Analysis Results

The 15 scales were classified into two principal components as shown in Table 4.30. To understand the nature of each scale, the third and fifth column of Table 4.30 show scatter graphs of the visual results plotted against CIELAB lightness (L^*) and chroma (C_{ab}^*). The two principal components account for 65% and 24% of the total variance, i.e. they can explain almost 90% of the total variance in the data. In other words, the whole data can be well explained by two principal components. “Bright”, “light-heavy”, “active-passive”, “clean-dirty”, “clear”, and “boring” (as shown in the red box of Table 4.30) showed high component loadings for Component 1; “Intense-weak”, “saturated”, “vivid-dull”, “distinct-indistinct”, “full-thin”, and “striking” (see blue box in Table 4.30) showed high component loadings for Component 2. These two components are associated with “bright” and “intense-weak” which are the scales closest to the Component 1 and 2 axes, respectively (see Figure 4.2). Those in-between, such as “natural-not natural” and “warm-cool”, were not associated with CIELAB lightness or chroma.

Component 1 represents the lightness contents because the scales that had high component loadings in Component 1 were highly correlated with CIELAB lightness as shown in Table 4.30 (first table). The scatter graphs in the fifth column of Table 4.30 (first table) show wider spread in the low chroma region. It can be found that several scales that had high component loading in Component 2 were highly correlated with CIELAB chroma as shown in the fifth column of Table 4.30 (second table). In the third column of Table 4.30 (second table), a wider spread is found in the high lightness region. Thus, Component 2 represents the chromatic contents. “Light-heavy”, “active-passive”, “distinct-indistinct”, “vivid-dull” and “striking” in the two components also agree with the findings of Ou *et al*. (2004 and 2012) and Gao *et al*. (2007) (see Section 4.3).

Table 4.30 Component loading matrix of the scales for the Korean observers (Those within the red and blue correspond to Components 1 and 2 respectively)

	Component 1	Visual data vs. L*	Component 2	Visual data vs. C_{ab}*
% of variance	65.24		23.76	
Bright	0.98		0.09	
Light-heavy	0.96		-0.22	
Active-passive	0.90		0.43	
Fresh-stale	0.89		0.40	
Clean-dirty	0.88		0.44	
Clear	0.87		0.45	
Boring	-0.86		-0.47	

Natural-not natural	-0.34		0.11	
Warm-cool	-0.05		-0.02	
Intense-weak	0.02		0.99	
Saturated	0.22		0.92	
Vivid-dull	0.48		0.86	
Distinct-indistinct	0.49		0.86	
Full-thin	-0.49		0.85	
Striking	0.65		0.73	

※ Third column: The horizontal axis is CIELAB $C_{ab}*$, and the vertical axis is the corresponding observer responses. Fifth column: The horizontal axis is CIELAB L*, and the vertical axis is the corresponding observer responses.

Figure 4.2 shows the relationship between each set of observer responses by plotting them in a semantic space on the basis of the component loadings in Table 4.30. The fifteen scales are located in two-dimensional space having the two principal components as coordinates. It shows that “bright”, “light-heavy”, “active-passive”, “fresh-stale”, “clean-dirty”, “clear” and “boring” are closely located along the Component 1 axis. “Intense-weak”, “saturated”, “vivid-dull”, “distinct-indistinct”, “full-thin” and “striking” are closely located along the Component 2 axis. The data of “boring” can be transformed to the other side of the diagram to have the same distance and opposite direction. The descriptor can be “exciting” as opposed to “boring”

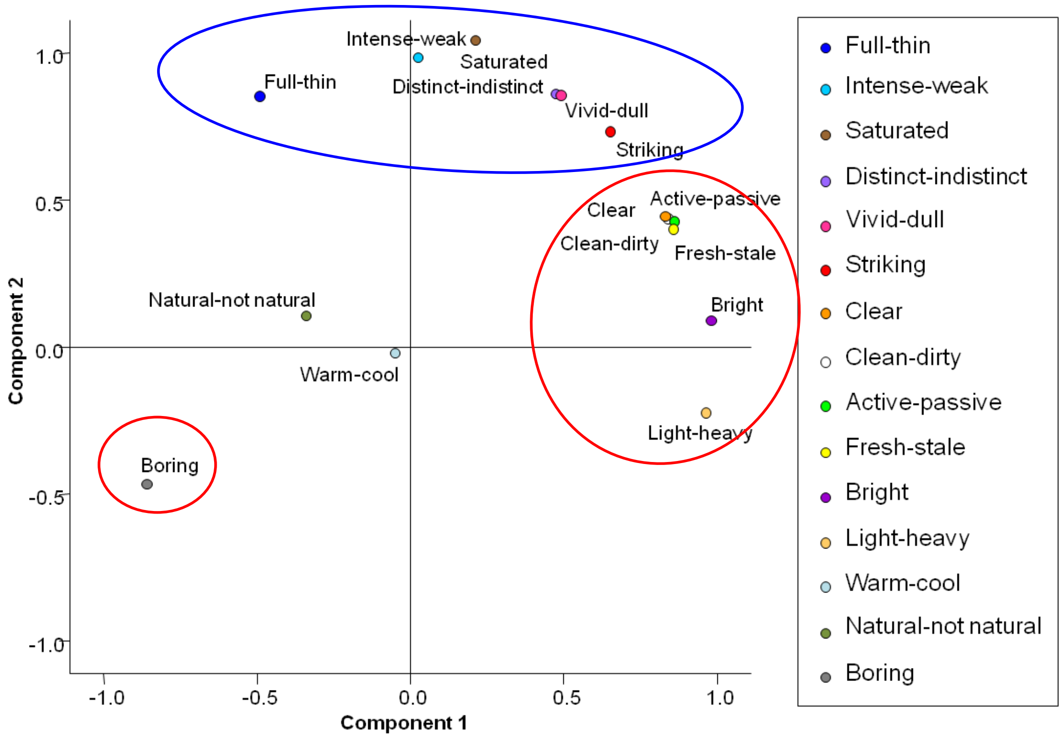


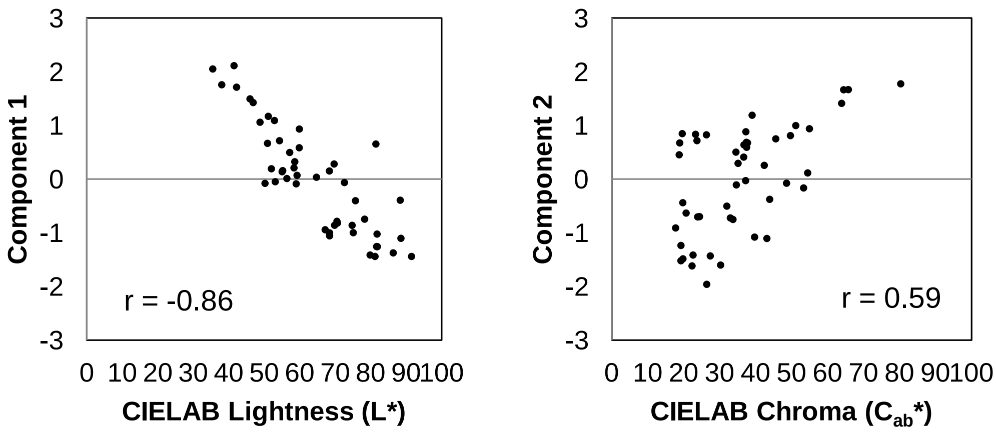
Figure 4.2 Component plots of the 15 scales for Korean observers

It can also be found that “full-thin”, “active-passive” and “boring” were affected by both CIELAB lightness and chroma attributes. “Clean-dirty”, “clear” and “bright” had great similarity to attributes mentioned by Berns (2013) in terms of the relationship with the CIELAB lightness and chroma. Although these scales are low in correlation with either CIELAB lightness or chroma, they show linear trends, as seen in Table 4.30. Berns’ proposed a concept that agrees well with the present results. He used scales such as cleaner-dirtier, brighter-duller, weaker-stronger, and whiter-deeper (see Section 2.4 and Figure 2.18). These attributes were compared with lightness and chroma. For example, the higher the lightness and chroma of a colour, the cleaner the colour. The lower the lightness and chroma of a colour, the dirtier the colour.

Table 4.31 shows the correlation coefficients calculated between each components and CIELAB C_{ab}^*, L^* and h_{ab}. The highest r value with Component 1 was CIELAB L^*, with the correlation coefficient of -0.86. The highest r value with Component 2 was CIELAB C_{ab}^*, with the correlation coefficient of 0.59. Figure 4.3 shows the components plotted against CIELAB C_{ab}^* and L^* to investigate the relationship between them. Figure 4.3 shows that as Component 1 increases, CIELAB lightness decreases. As Component 2 increases, CIELAB chroma increases. The comparison result indicates that the scales in Component 1 have a very high correlation with CIELAB lightness. The scales in Component 2 were found to be highly correlated with CIELAB chroma. Component 2 (chromatic content) is the main interest in this study; hence, “saturated” and “vivid-dull” were selected to represent the new third dimension of colour appearance. Thus, these two scales were also investigated for the British experiment.

Table 4.31 Correlation coefficients between components and CIELAB C_{ab}^*, L^* and h_{ab}

r	C_{ab}^*	L^*	h_{ab}
Component 1	0.44	**-0.86**	-0.03
Component 2	**0.59**	0.38	0.01



(a) (b)

Figure 4.3 (a) Component 1 plotted against L^* and (b) Component 2 plotted against C_{ab}^*

4.5 Cultural Difference Between British and Korean Observers

As mentioned in the previous section, the experiment with Korean observers was conducted using 15 scales, but only two scales were used in the British experiment. The two scales were selected for the new third-dimensional scale. The two observers groups were compared to see whether the two groups have a significant cultural effect and whether it is feasible to develop a universal model based on the visual results of the two observer groups. Hence, this section describes the comparison of the visual data of the 15 scales (“bright”, “light-heavy”, “active-passive”, “fresh-stale”, “clean-dirty”, “clear”, “boring”, “natural-not natural”, “warm-cool”, “intense-weak”, “saturated”, “vivid-dull”, “distinct-indistinct”, “full-thin” and “striking”) obtained from the Korean observers with the “saturated” and “vividness”' data obtained from the British observers. Figure 4.4 shows the component plot already presented in Figure 4.2, with correlation coefficients between each observer response and the saturation response by British observers. These r values were calculated between different Korean's scales and the British saturation data. Among the 15 scales, “full-thin’' of the Korean observers was highly correlated with “saturated” of the British observers, with correlation coefficient of 0.89. This correlation result is even higher than the correlation (r = 0.79) between “saturated” of the British observers and “saturated” of the Korean observers. This seems to imply that the English language 'saturated' was better represented in the Korean language by “full-thin” (“짙은-옅은”) than by “saturated” (“색의 순수한 정도”). Note that “full-thin” and “saturated” responses were highly correlated with CIELAB chroma and lightness as shown in Figures 4.5 (a) to (c).

Figure 4.6 shows the correlation coefficients between each observer response and the vividness response of the British observer group. Among the 15 scales, the British response for “vivid-dull” was highly correlated with Korean response of “striking”, with correlation coefficient of 0.90. This seems to imply that the British response for “vivid-dull” was better represented in Korean by “striking” (“두드러진”) than by “vivid-dull” (“선명한”).

Although the visual responses for “saturated” and “vivid-dull” of the Korean observer group did not show the highest correlation to the corresponding scales of the British observer group, they still correlated well with the correlation coefficients of 0.79 and 0.83, respectively. They showed linear correlation to each other as seen in Figure 4.7. This figure indicates that the visual responses of the two cultural groups seem to have little cultural difference.

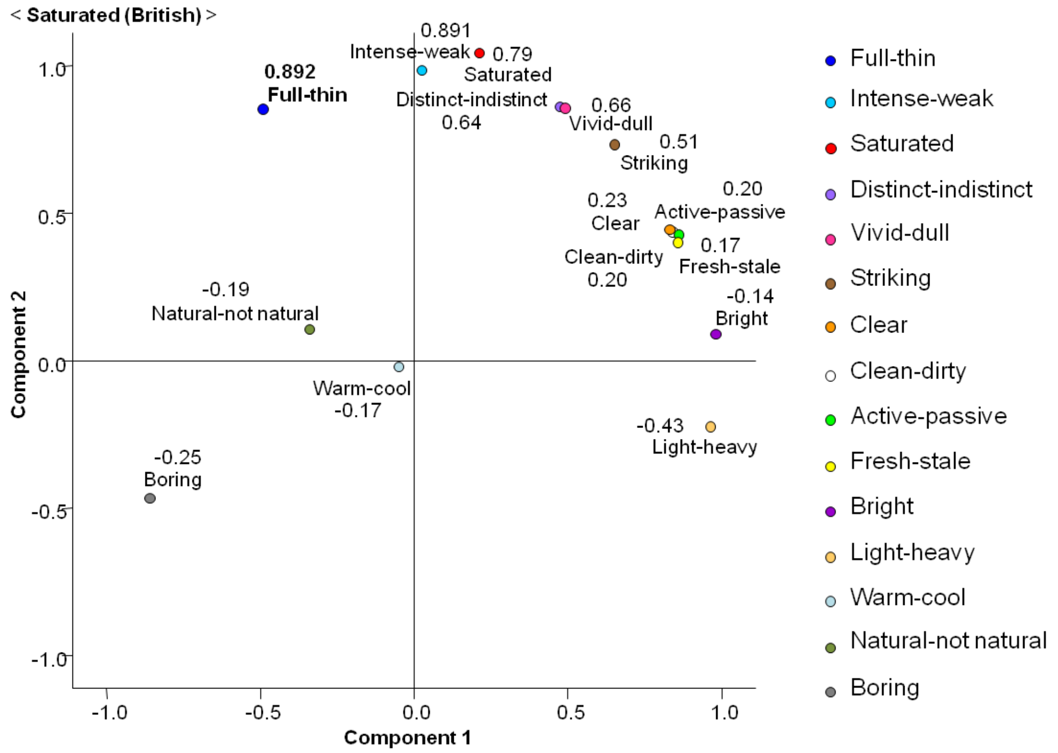


Figure 4.4 Comparison between “saturated” for the British observers and the 15 scales of the Korean observers as shown in component plot in Figure 4.2

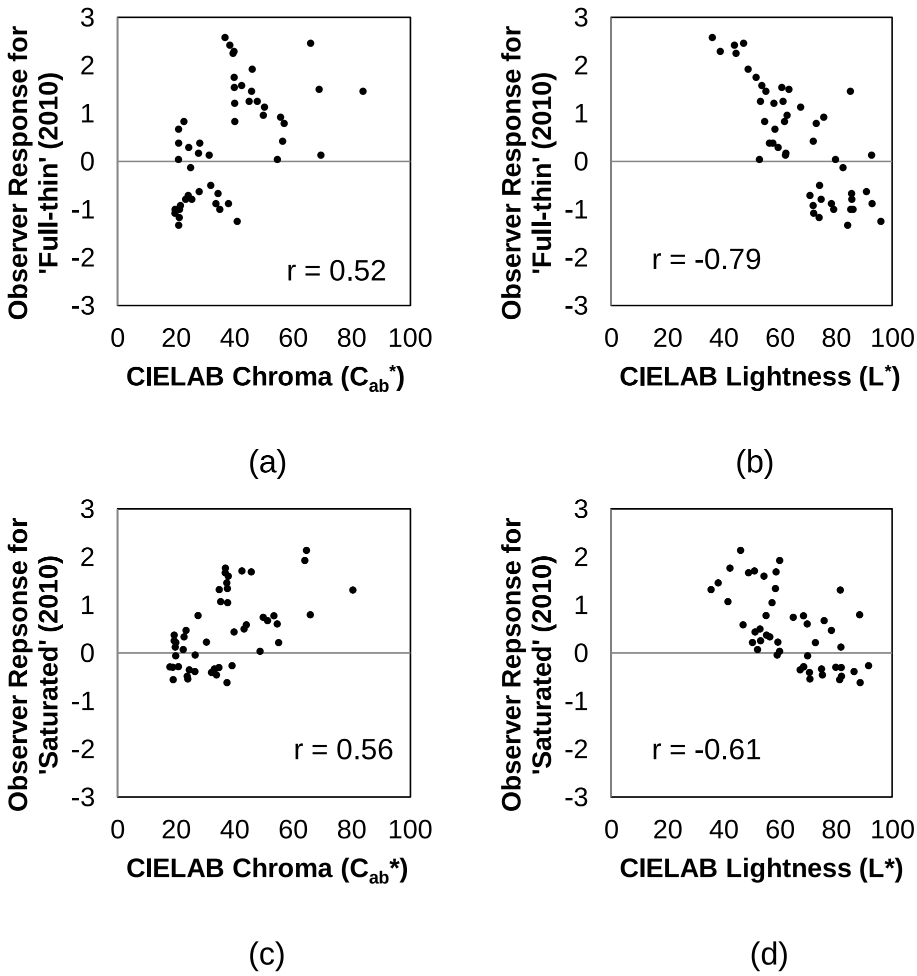


Figure 4.5 Observer “Full-thin” response from Korean observer group plotted against the CIELAB (a) C_{ab}^* and (b) L^*; observer 'saturated' response from British observer group plotted against the CIELAB (c) C_{ab}^* and (d) L^*

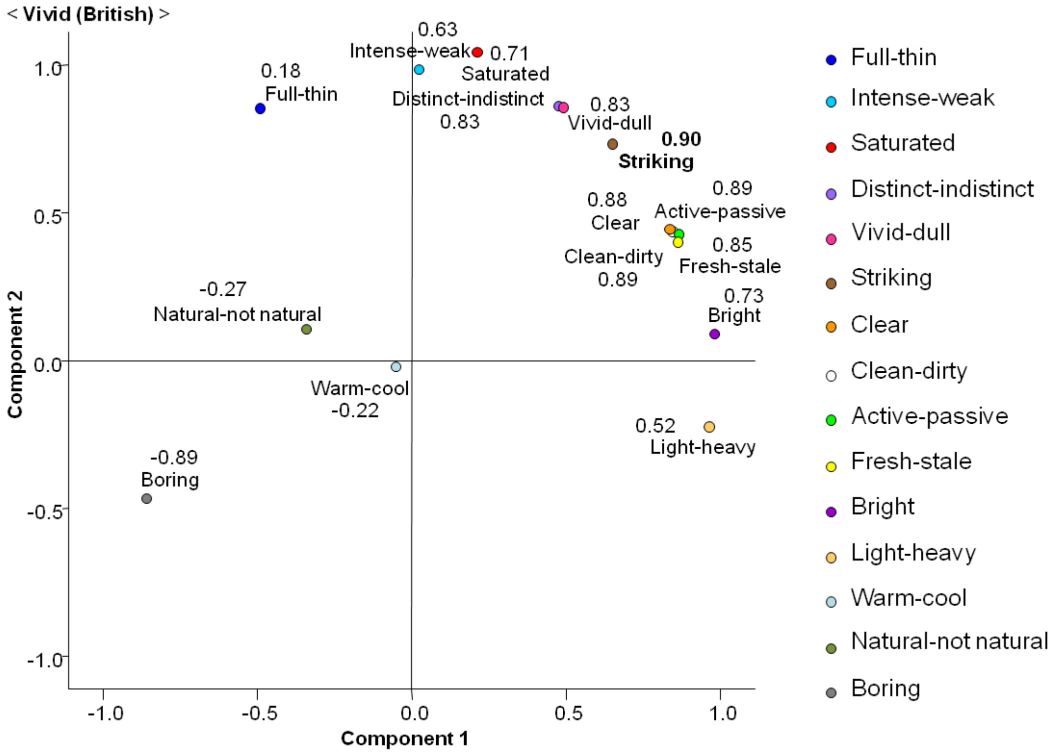
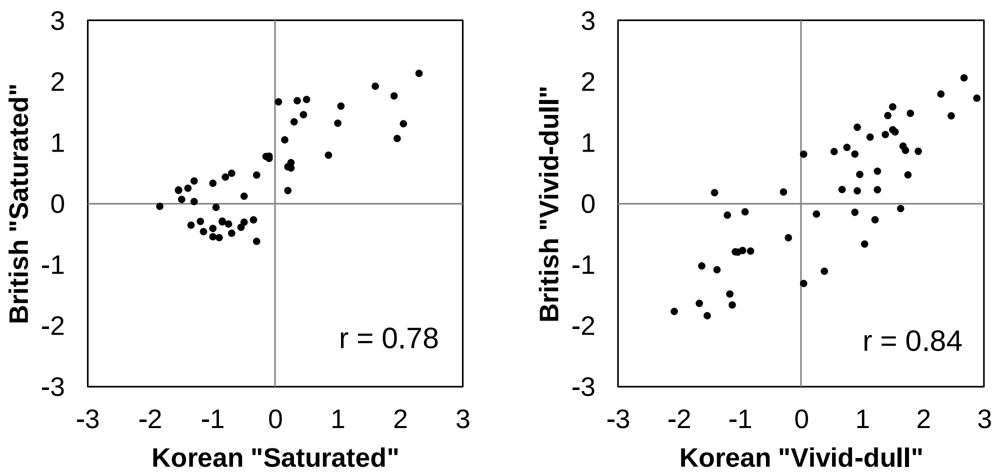


Figure 4.6 Comparison between "vivid-dull" for the British observers and the 15 scales of the Korean observers as shown in component plot in Figure 4.2



(a) (b)

Figure 4.7 (a) Saturation data for British observers plotted against saturation data for Korean observers and (b) vividness data for British observers plotted against vividness data for Korean observers

4.6 Summary

This chapter described the experimental results in terms of the 15 scales ("bright", "light-heavy", "active-passive", "fresh-stale", "clean-dirty", "clear", "boring", "natural-not natural", "warm-cool", "intense-weak", "saturated", "vivid-dull", "distinct-indistinct", "full-thin" and "striking") assessed by Korean observers. Principal component analysis was carried out for the 15 scales, followed by data analysis of intra- and inter-observer variability, and finally, an investigation of the cultural difference in the experimental results between Korean and British observers was carried out.

It was found that all the scales can be divided into two groups according to their correlation with CIELAB lightness or chroma. The observer responses for "intense-weak" and "saturated" showed the highest correlation with CIELAB chroma; the observer responses for "bright" and for "light-heavy" showed the highest correlation with CIELAB lightness. The two CIELAB attributes were also found to have the highest component loadings for the two underlying components (Components 1 and 2) extracted by the principal component analysis. Component 2, which includes "saturated" and "vivid-dull" was found to have high correlation with CIELAB chroma. Thus, both "saturated" and "vivid-dull" were selected to represent the third dimension of colour appearance. "Intense-weak" was not selected because it is not frequently used in related industries.

In the present study (see Section 4.3), the colour emotion attributes such as "warm-cool", "light-heavy", "active-passive", "distinct-indistinct", "vivid-dull" and "striking" from the Korean group agreed with the studies of Wright and Rainwater (1962), Hogg (1969), Kobayashi (1981), Sato *et al*. (2000a), Ou *et al*. (2004 and 2012), Gao *et al*. (2007) and Lee *et al*. (2009) that the emotion responses can correlate well with the CIELAB chroma, lightness or hue angle.

Berns (2013) compared "cleaner-dirtier", "brighter-duller", "weaker-stronger", and "whiter-deeper" with the CIELAB chroma and lightness. The result agreed well with the scales ("clean-dirty", "clear" and "bright") of the present study. The results indicate that the higher chroma and lightness, the cleaner and brighter the colour appeared.

The experimental results also show some cultural effects in this study. For example, the “saturated” response given by the British was correlated more closely with the Korean response for “full-thin”, than the Korean response for “saturated”. The British response for “vivid-dull” had the higher correlation with the Korean response for “striking” than the Korean response for “vivid-dull”. The meaning of “saturated” for British observers seems to be closer to the meaning of “full-thin” than to “saturated” for Korean observers. This implies that many meanings for Korean observers correspond to the terms “saturated” and “vivid-dull”. Although “saturated” and “vivid-dull” for Korean observers did not agree exactly with the corresponding scales for British observers, the two sets of data are still correlated reasonably well with each other, as shown in Figure 4.7. This seems to suggest a possibility of combining these visual data and of developing universal models of saturation and vividness.

Among the scales, “saturated” and “vivid-dull” were found to give high correlation with the third dimension of colour appearance according to the comparison with CIELAB chroma and the principal component analysis results in Section 4.4. The two scales were selected to represent the third dimension of colour. Fairchild and Heckaman (2012) stated that saturation is one of the fundamental attributes for deriving other colour appearance scales, such as colourfulness, brightness, etc. As shown in Sections 2.4 and 2.4.1.1, the saturation attribute was defined in the CIE Lighting Vocabulary and has been included in various colour systems, such as the CIELUV uniform colour space, the CIECAM02 model, the Nayatani *et al*. model and the Hunt model. Ordinary people are more familiar with the wording of saturation than colour science terms such as chroma and colourfulness. However, they could have different meanings in western and eastern cultures. It should be noted that only colour scientists are familiar with chroma, colourfulness and saturation. Vividness is another important attribute for imaging applications, and was regarded by Berns (2013) as an attribute of colour for indicating the degree of departure of the colour in question from black. It has been widely used in the imaging industry for image quality, enhancement and gamut mapping. Usually, more vivid contents in outdoor images are preferred over dull (i.e. less vivid) images.

Chapter 5 Development of the Ellipsoid Models

5.1 Overview

Experiment 1 was carried out in 2010 to scale saturation and vividness. Visual assessment of these two attributes was conducted again to cover darker and whiter colour samples by British and Korean observers in 2011 (Experiment 2) and 2012 (Experiment 3).

As mentioned in Section 1.1, blackness is an important attribute for setting up the black point of colour management systems for displays, colour printers and image quality. Whiteness is important for the quality of cosmetic products, materials and image contrast. Thus, there is a need to develop blackness and whiteness models based on psychophysical experiment results. Experiments for assessing blackness were carried out in 2011 and 2012. In 2012, an experiment for assessing whiteness was also conducted. In total, 132 British and Korean observers assessed NCS colour samples to scale four attributes: saturation, vividness, blackness and whiteness.

One of the aims of the project was to develop new models for saturation, vividness, blackness and whiteness using the CIELAB, CIECAM02 and CAM02-UCS metrics. The result will be described in this chapter.

The structure of the chapter is given below:

- In Section 5.2, the procedures for combining the visual data of three attributes (saturation, vividness and blackness) are described.
- The intra- and inter-observer variability of the 4 attributes for British and Korean groups are compared to investigate the consistency of visual response for each attribute in Section 5.3.
- The British and the Korean data of the 4 attributes are compared in Section 5.4.
- In Section 5.5, the relationships between the colour appearance attributes of the three metrics, CIELAB, CIECAM02 and CAM02-UCS, and the visual data from the British and Korean groups are investigated.

- The visual responses for each attribute are compared individually in Section 5.6.
- In Section 5.7, the observers’ individual differences in assessing the saturation are investigated.
- The newly developed models in this study are presented in Sections 5.8 and 5.9.

5.2 Data Combination

The saturation samples were divided into three parts, i.e. the first part comprises the samples used in the experiment undertaken in 2010 (which is called 'Experiment 1'), the second part comprises the samples used in the 2011 experiment (which is called 'Experiment 2') and the third part comprises the samples used in the 2012 experiment (which is called 'Experiment 3'). The reason for the division of samples is that the saturation experiment was carried out in three different periods of the whole PhD study. In 2010, the original experiment was planned to study only saturation and vividness. It was decided to extend the study to scale blackness in 2011 and whiteness in 2012, so new samples were added. Finally, 120 samples were obtained. Each sample was assessed regarding the full set of attributes: saturation, vividness, blackness and whiteness.

The saturation data obtained through psychophysical experiment in the years 2010, 2011 and 2012 were combined to form the total dataset. Before the data were combined, the data of 2011 and 2012 were modified to keep consistency with the data of 2010 as a standard.

All the experimental conditions were the same, i.e. the same viewing cabinet was used with the same illuminance level, and all colours were assessed against the same grey background in a darkened room. However, the colour samples used in each experiment covered a specific region in the colour space. For example, the samples in Experiment 2 were all located in the darker region and were less colourful than those in Experiment 1 (see

Figure 3.4). This was to cover darker colours for assessing blackness. The samples in Experiment 3 were mainly paler colours for assessing whiteness.

The three experiments were all conducted using the categorical judgement method. This means that the experimental data (i.e. observer response) were "interval scale" values. According to Stevens (1957), an interval scale has an arbitrarily-defined zero point and an arbitrarily-defined scale unit. Although the viewing conditions of the three experiments were identical, the colour stimuli used were different from one experiment to another. Thus, it is highly likely that the zero point and the scale unit for the "saturation" scale would also differ from one experiment to another.

The aim of this study was to model observer response (i.e. the scale values) for the entire colour space. Doing this requires combining all scale values obtained from the three experiments with a unified zero point and a unified scale unit. According to Stevens, any interval scale data can be transformed by a linear transformation in the form of $Y = C_1X + C_0$ (see Figure 5.1) without losing their characteristics, where C_0 and C_1 are constants. Thus, in the present study, experimental data obtained in 2010, 2011 and 2012 were combined using the linear transformation described above by modifying the data obtained in 2011 and the data obtained in 2012 to match the visual data obtained in 2010.

Let us consider the linear equation $Y = C_1X + C_0$, where Y is 'the saturation data obtained in 2010', C_1 is a coefficient representing the slope, X is the saturation data obtained in 2011 or 2012 and C_0 is a constant representing the intercept. This is illustrated in Figure 5.1.

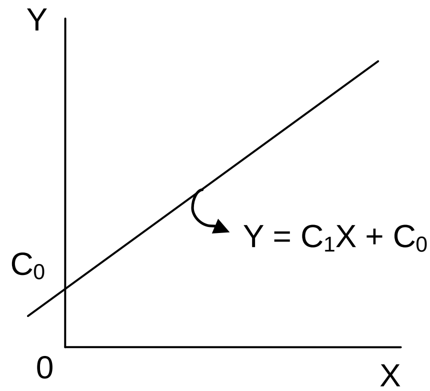


Figure 5.1 A simple linear equation method

Two equations were needed to combine the data, one for year 2011 data, the other for year 2012:

$$Y_{2011} = C_{2011\_1} \times X_{2011} + C_{2011\_0}, \tag{5-1}$$

$$Y_{2012} = C_{2012\_1} \times X_{2012} + C_{2012\_0}, \tag{5-2}$$

where Y_{2011} is the rescaled saturation data for the year 2011. Here, X_{2011} is the saturation data for the year 2011, Y_{2012} is the rescaled saturation data for the year 2012 and X_{2012} is the saturation data of the year 2012. C_{2011_0} and C_{2011_1} are the parameters for modifying the year 2011 data, while C_{2012_0} and C_{2012_1} are the parameters for modifying the year 2012 data.

C_{2011_0}, C_{2011_1}, C_{2012_0} and C_{2012_1} are calculated to correct the 2011 and 2012 data to keep consistency with the 2010 data using the solver tool in Excel by minimizing the RMS value between 'the combined predictions' and 'the combined visual data'. It is difficult to find these coefficients because the samples used in each year are different. So, a method was developed via ‘generic’ model.

Three ‘generic’ models, namely the saturation_2010, saturation_2011 and saturation_2012 models, were derived from the saturation data from the years 2010, 2011 and 2012, respectively. These models were derived to predict the data in each year. Each model was developed based on the formula mentioned in equation (5-7) described in Section 5.8. The predicted values from each model were combined. At a later stage, the visual data obtained in the years 2010, 2011 and 2012 were combined. Then, these data were used to calculate C_0 and C_1 coefficients as scaling factors. These coefficients were used to adjust the saturation data from 2011 and saturation data from 2012 to the saturation data from 2010.

The whole procedure of modifying the saturation data of 2011 and 2012 to be consistent with the saturation data of 2010 is the same as that of modifying the vividness data obtained in the psychophysical experiment of vividness from 2010, 2011 and 2012.

The samples used in the psychophysical experiment for blackness are divided into two parts, i.e. the first part comprises the samples used in the experiment of 2011 ('Experiment 2') and the second part comprises the samples used in the experiment of 2012 ('Experiment 3'). Thus, the visual result of blackness obtained in 2012 was modified to keep consistency with the blackness data obtained in 2011 as a standard before combining the data. The following equation is used to match the 2012 data to the 2011 data:

$$Y_{b2012} = C_1 \times X_{b2012} + C_0 \qquad (5\text{-}3)$$

where Y_{b2012} is the rescaled blackness visual result of 2012, and X_{b2012} is the blackness visual result of 2012, while C_0 and C_1 are the parameters to rescale the visual result of blackness in 2012 to match the visual result of 2011.

The adjustment factors are summarised in Table 5.32. Note that whiteness assessments were conducted to include all the 120 samples in one session, so it did not need to be rescaled.

Table 5.32 Slope (C_1) and intercept (C_0) of visual data

		2011		2012	
		Slope (C_1)	Intercept (C_0)	Slope (C_1)	Intercept (C_0)
Saturation	British	1.00	0.00	0.82	-0.13
	Korean	0.95	0.02	0.76	-0.22
Vividness	British	0.95	0.02	0.91	0.01
	Korean	0.88	-0.01	0.89	0.02
Blackness	British	n/a		1.00	0.00
	Korean	n/a		0.89	-0.15

It can be seen that, in general, the slope values ranged between 0.76 and 1.0. All visual results in these two years were judged somewhat higher than those in 2011. The largest is the adjustment of saturation results for 2012. This is mainly because when scaling saturation, vividness and blackness attributes all colours scaled had low chroma light and dark shades without medium lightness and high chroma colours to compare with. In this situation, all observers estimated too high values. In other words, no criteria or reference colour was provided to observers. Every observer has their own criteria to estimate colours for a certain scale. Note that each participant only took part in one experiment. Also, observers in Experiment 2 did not have a chance to assess brighter and whiter colours, which were used in Experiments 1 and 3. These samples could help to establish clear criteria. Therefore, this could lead to different criteria for observers. Observers may have estimated the colours of the four scales higher than observers in Experiment 1. This is also relevant to Experiment 3. Although observers assessed all the brighter, darker and whiter samples in Experiment 3, the criteria value could be different from Experiment 1. Based on Table 5.32, it may be supposed that observers scaled somewhat paler shades giving too high values for saturation, vividness and blackness attributes. This means that observers think lighter colours in 2012 are more saturated than darker colours in 2011. It was found that Korean observers judged higher than the British observers for the three scales in both years.

The systematic difference in the 2010 and 2011 data can be examined by the predictive performance of the tested model (see Tables 7.62 to 7.66 in Section 7.2) in terms of correlation coefficients. These tested models predict the NCS data and the experimental data (the Cho data) well, with an average correlation coefficient of 0.78. According to the tested results shown in Section 7.2, the "simple method" as described by equations (5-1) and (5-2) was found to work well for the experimental data sets.

5.3 Observer Variability

In this section, the observer variability for the four attributes (saturation, vividness, blackness and whiteness) was investigated to test the performance of observers who took part in these experiments in terms of repeatability (intra-observer variability) and accuracy (inter-observer variability).

5.3.1 Intra-observer Variability

Table 5.33 summarises the RMS values of intra-observer variability of four attributes for two cultural groups (British and Korean) and two gender groups in each year.

In 2010, an experiment was conducted for two attributes (saturation and vividness) using samples that had high chromaticness. For British and female groups, vividness showed better repeatability than saturation, whereas for Korean and male groups, saturation showed better repeatability than vividness. In terms of the mean value for each attribute in the 2010 results, saturation showed better repeatability than vividness.

In 2011, experiments for three attributes (saturation, vividness and blackness) were carried out using samples that had high blackness. For the two cultural groups, blackness showed the highest repeatability with RMS values of 0.92 and 0.97, respectively. The blackness attribute also showed the highest repeatability for the two gender groups with RMS values of 0.93 and 0.96, respectively. The vividness attribute showed the poorest repeatability for both cultural and gender groups. In terms of the mean value for each attribute in the 2011 results, blackness and vividness showed the highest and the lowest repeatability with the RMS values of 0.94 and 1.34, respectively.

An experiment for four attributes (saturation, vividness, blackness and whiteness) was conducted in 2012. For three of these attributes (saturation, vividness and blackness) samples that had high whiteness were used. For the whiteness attribute, all of the samples from 2010 to 2012 were used. For the two cultural and two gender groups, blackness showed the highest repeatability. Vividness showed the poorest repeatability for the two cultural and two gender groups. Whiteness also showed the poorest repeatability for the Korean group. In terms of the mean value for each attribute in the 2012 results, the results showed the same trend as the 2011 results.

Table 5.33 Intra-observer variability of four attributes

	Saturation	Vividness	Blackness	Whiteness	Mean
	Intra 2010				
British	1.29	1.16			1.22
Korean	1.02	1.29			1.16
Female	1.21	1.17			1.19
Male	1.12	1.29			1.20
Mean 2010	1.16	1.22			1.19
	Intra 2011				
British	1.17	1.36	0.92		1.15
Korean	1.01	1.32	0.97		1.10
Female	1.17	1.54	0.93		1.21
Male	1.00	1.14	0.96		1.03
Mean 2011	1.08	1.34	0.94		1.12
	Intra 2012				
British	1.05	1.22	0.85	1.05	1.04
Korean	1.08	1.19	0.79	1.19	1.06
Female	1.00	1.19	0.67	1.05	0.98
Male	1.13	1.21	0.96	1.18	1.12
Mean 2012	1.06	1.20	0.82	1.12	1.05
Mean	1.10	1.25	0.88	1.12	1.11

※ The yellow and orange boxes in Table 5.33 indicate the lowest and the highest variation values among the attributes, respectively.

5.3.2 Inter-observer Variability

Table 5.34 summarises inter-observer variability of the four attributes in each year. For the two cultural and gender groups in the 2010 results, vividness clearly shows better accuracy than saturation. This trend is also observed in terms of the mean value for each attribute in the 2010 results.

In the 2011 and 2012 results for the two cultural and gender groups, blackness and vividness show the highest accuracy and the poorest accuracy, respectively. This pattern is also observed in terms of the mean value for each attribute in the 2011 and 2012 results.

Table 5.34 Inter-observer variability of four attributes

	Saturation	Vividness	Blackness	Whiteness	Mean
	Inter 2010				
British	1.51	1.27			1.39
Korean	1.29	1.26			1.28
Female	1.56	1.28			1.42
Male	1.51	1.36			1.43
Mean 2010	1.55	1.35			1.45
	Inter 2011				
British	1.10	1.36	1.08		1.18
Korean	1.18	1.36	1.04		1.20
Female	1.19	1.51	0.96		1.22
Male	1.13	1.35	1.06		1.18
Mean 2011	1.19	1.46	1.08		1.24
	Inter 2012				
British	1.11	1.41	1.10	1.25	1.22
Korean	0.93	1.33	0.91	1.12	1.07
Female	1.06	1.35	0.93	1.25	1.15
Male	1.01	1.43	1.06	1.08	1.14
Mean 2012	1.06	1.43	1.02	1.22	1.18
Mean	1.26	1.41	1.05	1.22	1.26

※ The yellow and orange boxes in Table 5.34 indicate the lowest and the highest variation values among the attributes, respectively.

Table 5.35 shows the mean values of intra- and inter-observer variability for the two cultural and gender groups. Overall, it shows that inter- is higher than intra-observer variability. The male and female observers showed similar performance consistently. The Korean data seem to give more precise results (less observer variability) than the British data.

According to the mean results of intra- and inter-observer variability, the blackness attribute showed the best repeatability and accuracy among the attributes. Vividness showed the poorest repeatability and accuracy.

Table 5.35 Mean intra- and inter-observer variability

Mean	British	Korean	Female	Male	Mean
Intra	1.12	1.09	1.10	1.11	1.11
Inter	1.24	1.16	1.23	1.22	1.26

In the present study without any training, saturation was found be the second hardest attribute to scale accurately. This result agrees with Juan and Luo’s saturation study (see Section 2.4.1.1) that saturation is hard to scale without any training.

As discussed in this thesis, the terms, 'saturation', 'vividness', 'blackness’ and 'whiteness', were translated into Korean for the Korean experiments. According to Berlin and Kay (1969) the two colour terms 'black' and 'white' are widely used terms in all human languages. This implies that these two words have exactly the same meanings in most countries. These two formal words may have been easily scaled by observers with various cultural backgrounds. However, saturation and vividness may not be consistent across different human languages. These two attributes can be hard for observers to scale because they are complex to understand. This is shown in intra- and inter-observer variability in the scaling of saturation and vividness in two countries, the UK and Korea, as demonstrated in Tables 5.33 and 5.34.

5.4 British Observer Responses vs. Korean Observer Responses

Comparisons of visual responses for four attributes (saturation, vividness and blackness and whiteness) were made between the British and Korean observer groups to investigate the cultural difference by calculating the Pearson's correlation coefficient between them (see Section 3.9.1). The observer responses obtained in each experiment were compared between the two groups. Also, the combined observer responses were compared between the two groups. Tables 5.36 to 5.38 show the results of the correlation coefficients between the British and Korean observer responses for three attributes (saturation, vividness and blackness), respectively. Figures 5.2 to 5.5 show the plots of the British observer response against the Korean observer response for four attributes (saturation, vividness, blackness and whiteness). It can be seen that they agree reasonably well with each other, i.e. most of the data are close to 45 degree line which means that the two observer groups' responses show a highly linear relationship. They also had high correlation coefficients in the range of 0.76 to 0.95.

For saturation, there was no difference, even without neutral data. The results show very high correlation between the two groups, especially for blackness and whiteness, with the correlation coefficients in the range of 0.92 to 0.95.

In Tao *et al.*'s (2011) blackness perception (see Section 2.4.2), they found no cultural difference in terms of scale value and correlation coefficient. Ou *et al.* (2012) colour terms (see Section 2.7) were translated into seven languages. They were compared in terms of correlation coefficient, and it was found that there was little cultural effect.

In the present study, four English terms (i.e. saturation, vividness, blackness and whiteness) were translated into Korean. The observer responses for saturation, vividness, blackness and whiteness were compared for the two cultural groups (i.e. British and Korean) in terms of correlation coefficient to identify cultural effect. There were also no cultural differences found in blackness perception, with NCS samples showing a correlation coefficient value of 0.95. This was also relevant to whiteness results, with correlation coefficient of 0.92. The four (i.e. saturation, vividness, blackness and whiteness) responses all showed good agreement between the two observer groups. Thus, in general, there were no cultural differences found regarding the two attributes (i.e. blackness and whiteness). This implies that there is little cultural effect on the understanding of these two terms between Korean and British observers. These results support the statement of Berlin and Kay (1969) that black and white are universal words.

All four attributes showed good agreement between the two observer groups, and that may indicate that culture has little influence. However, for saturation and vividness there was little difference found between the two groups in Figures 5.2 and 5.3. Figures 5.2 (a), (c), (d) and (e) show that the visual data are more scattered in the upper part of the diagonal line. This means that when a Korean observer responds that a colour has a saturation of -1, a British observer responds one level higher than the Korean, or more than -1. British observers consider bright samples to be more saturated than Korean observers do. The same trend is seen in Figure 5.3-(b) for vividness. For darker samples, British observers tend to judge their vividness to be much higher than Korean observers do.

On the other hand, Figure 5.2-(b) shows that the data are more scattered in the lower part of the diagonal line. The visual response to darker colours shows that, when a Korean observer responds that a colour has a saturation of -1, a British observer responds one level lower than the Korean, or less than -1. This implies that Korean observers consider darker colours to be more saturated than British observers do. This trend also shows in Figures 5.3 (a) and (d) that Korean observers estimate vividness higher than British observers. For bright colours, Korean observers tend to estimate vividness higher than British observers. For the combined data of saturation, British observers tend to estimate saturation higher than Korean observers. On the other hand, for the combined data of vividness, Korean observers tend to estimate vividness higher than British observer. Although these two groups show little difference, they follow similar judgements and have reasonably high correlation.

Table 5.36 Correlation coefficients (r) calculated between the British saturation data and the Korean saturation data

r	Korean 2010	Korean 2011	Korean 2012	Korean Combined	Korean Combined (without Neutral Data)
British 2010	0.76				
British 2011		0.89			
British 2012			0.76		
British Combined				0.81	
British Combined (without Neutral Data)					0.81

Table 5.37 Correlation coefficients (r) calculated between the British data and the Korean vividness data

r	Korean 2010	Korean 2011	Korean 2012	Korean Combined
British 2010	0.84			
British 2011		0.85		
British 2012			0.79	
British Combined				0.79

Table 5.38 Correlation coefficient (r) calculated between the British and the Korean blackness data for the years 2011 and 2012 and the combined data

r	Korean 2011	Korean 2012	Korean Combined
British 2011	0.94		
British 2012		0.92	
British Combined			0.95

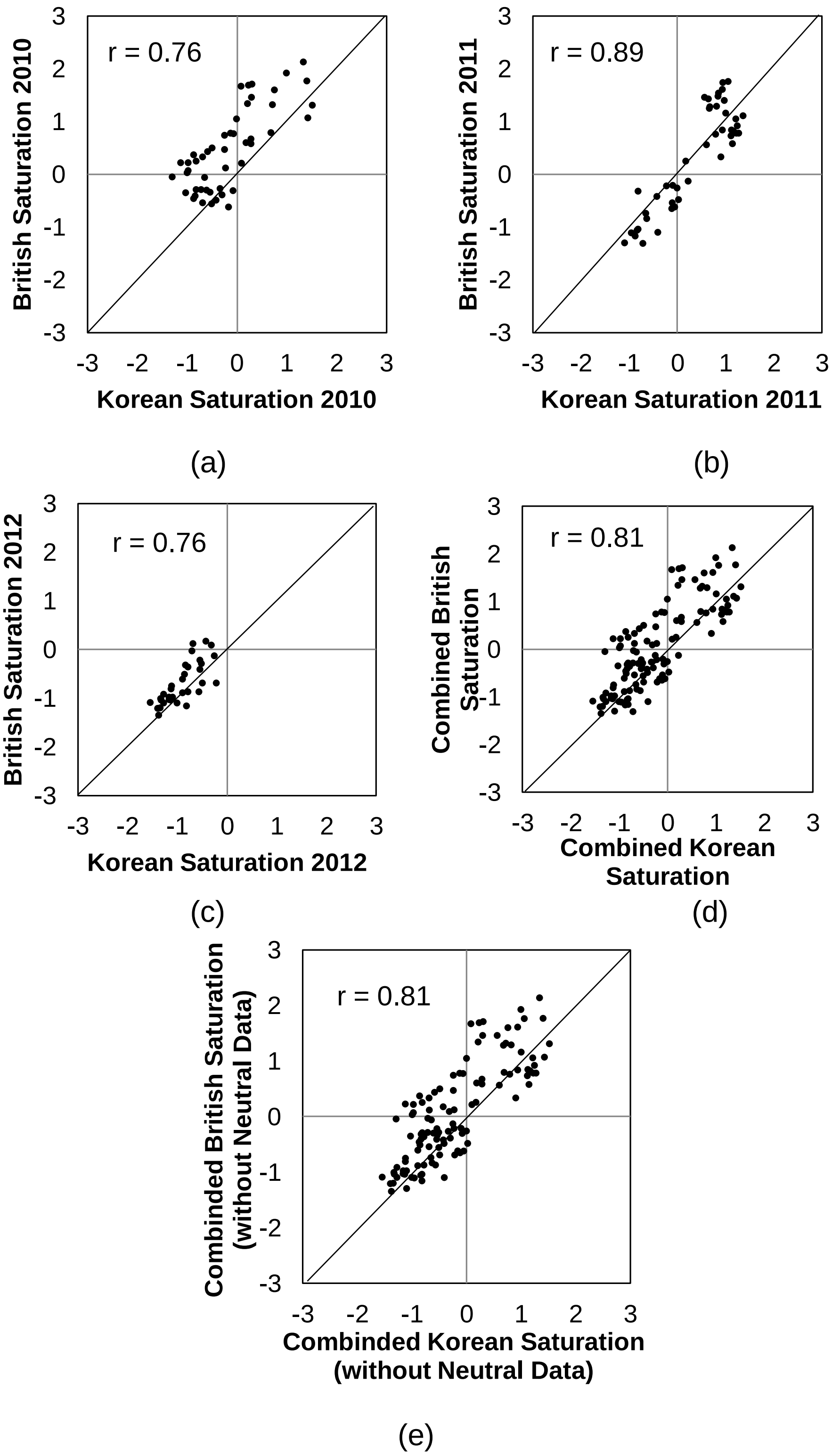


Figure 5.2 Plots of the Korean saturation data vs. the British saturation data for (a) 2010, (b) 2011 and (c) 2012, (d) the combined data and (e) the combined data without neutral data, respectively

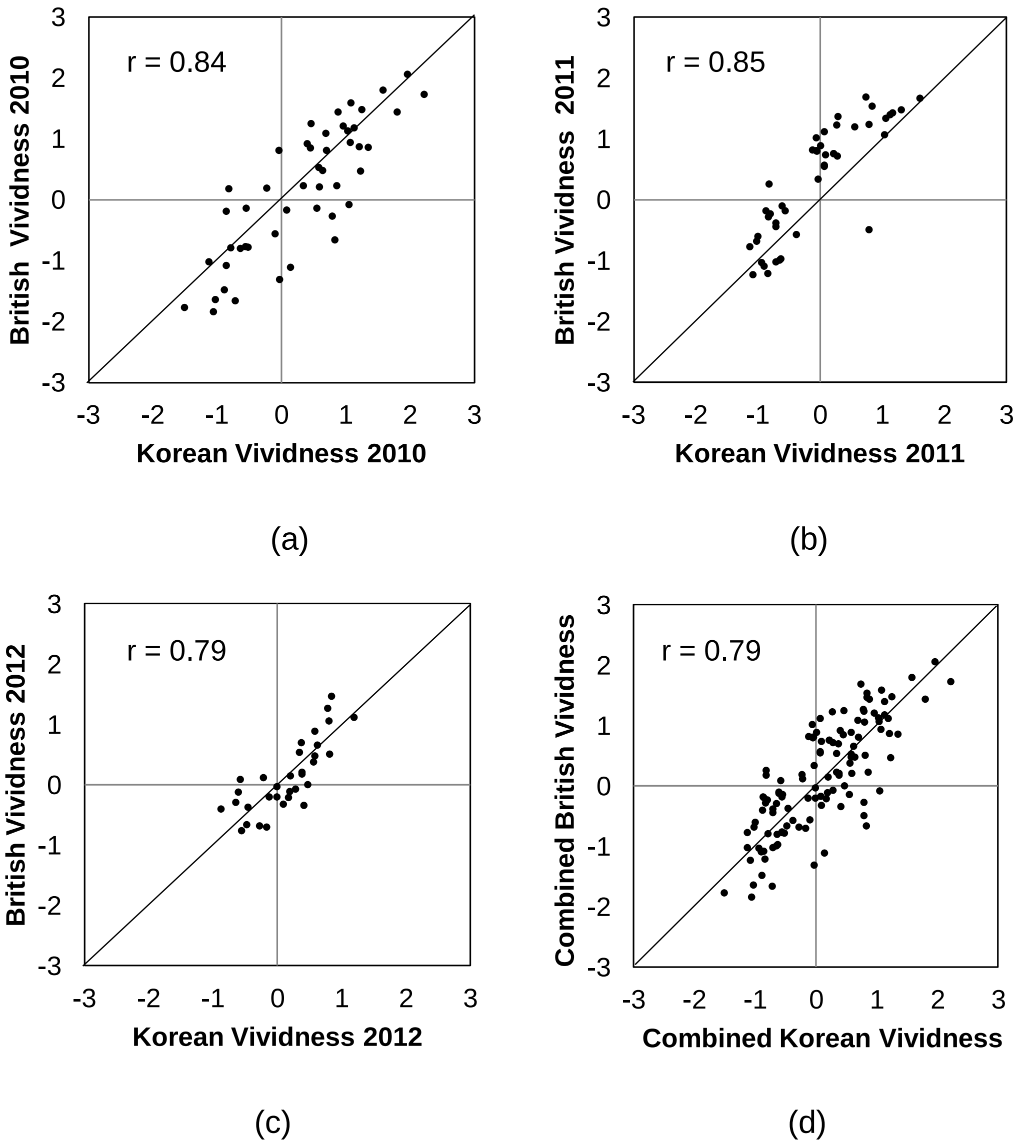


Figure 5.3 Plots of Korean vividness data vs. British vividness data for (a) 2010, (b) 2011 and (c) 2012 and (d) the combined data, respectively

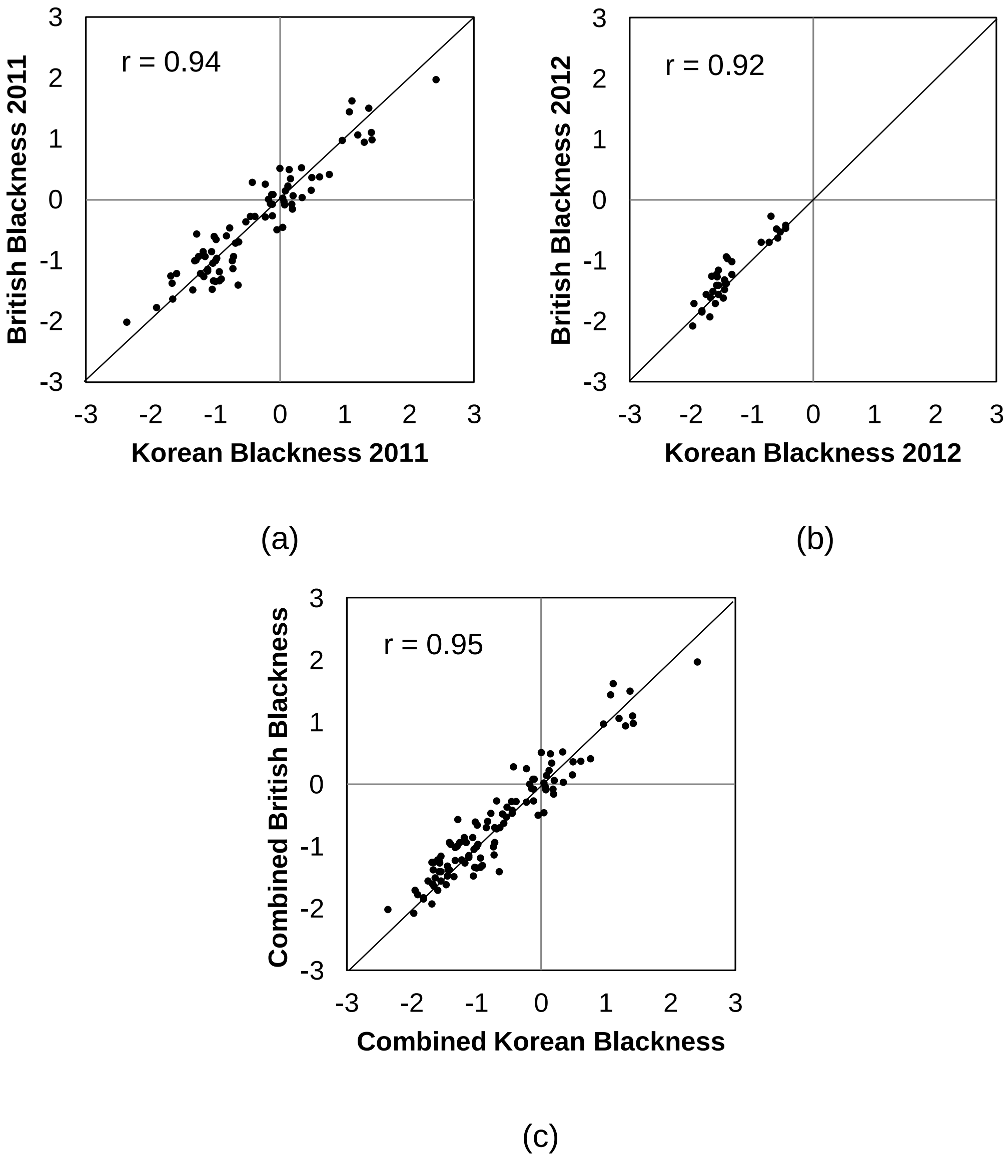


Figure 5.4 Plots of the Korean blackness data vs. the British blackness data for (a) 2011 and (b) 2012 and (c) the combined data, respectively

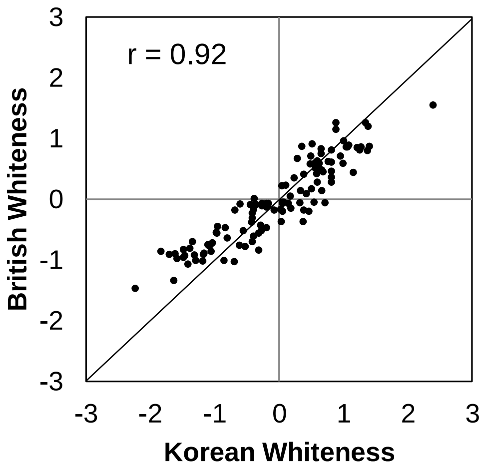


Figure 5.5 Plot of Korean whiteness data vs. British whiteness data

5.5 Colour Appearance Predictions vs. Observer Response

This section investigates the relationship between the observer response and colour appearance predictions from the models' third-dimensional scales, such as chroma, colourfulness and saturation. Thus, the observer responses of the four attributes (saturation, vividness, blackness and whiteness) were compared with different colorimetric predictions from the CIELAB, CIECAM02 and CAM02-UCS spaces. In addition, the visual results were also compared with other one-dimensional scales including CIELUV s_{uv}^*, CIELAB s_{ab}^*, Lübbe's S^+ and those proposed by Berns (depth (D_{ab}^*), vividness (V_{ab}^*) and clarity (T_{ab}^*) (see equation (2-16)) and black and white models (see equations (6-10) and (6-11)). The aim of this study was to see whether the visual result would fit those of other models. The models' predictions were also compared with the visual results of the two groups (British and Korean) to reveal any cultural differences. Tables 5.39 to 5.43 show the correlation coefficients calculated between each attribute's predictions and the visual results for the four attributes. Figures 5.6 to 5.10 plot the r results between the British and Korean observer groups for the results presented in Tables 5.39 to 5.43.

The observer responses (including the neutral data) for saturation were compared with various colorimetric predictions from the three metrics

(CIELAB, CIECAM02 and CAM02-UCS) and other models. Table 5.39 shows that all the attributes fitted the British data well except for Berns' vividness (V_{ab}^*) and clarity (T_{ab}*). It has been clarified that among the attributes, the Berns' depth (D_{ab}^*) fitted the observer responses best for all attributes for both British and Korean groups. The D_{ab}* is defined as a degree of departure of a colour from a white colour in a colour space. This agrees well with the present saturation data from both race groups as expected. Additionally, British observers judged colours with high chroma and colourfulness to be highly saturated, while Korean observers did not. Almost all the attributes did not fit the Korean data well except the lightness and Berns' depth attribute. It was also found that the British group had an understanding of saturation that agreed with the CIE definition more than the Korean group's understanding did. It can be seen that higher saturation colours will have higher chroma and lower lightness. The visual results were predicted well by the S_{uv}, S_{ab}^*, Lübbe's S^+ and CIECAM02 saturation scales for British observer groups. Generally, saturation was an unfamiliar word for the Korean group. During the saturation experiment, most of the Korean observers were not familiar with the word 'saturation'. According to the English-Korean dictionary (Doosan Dong-A., 2010) in Korea, the meaning of saturation has the same meaning as chroma. Therefore, there are some cultural differences for scaling saturation.

The observer responses for saturation without the neutral data were also compared with the colour appearance attributes from the three metrics. This was done to investigate whether the neutral data would affect the saturation results. It is meaningful comparison because it can be clearly seen that the results shown in Table 5.40 tend to show a pattern similar to that of the results shown in Table 5.39. This means that the small number of outlier data does not affect the prediction of other models. In other words, the visual data without the neutral data fitted better with the different colorimetric predictions from three metrics than the visual data with the neutral data. The results in Figures 5.13 and 5.14 clearly show that some observers in both cultural groups consider neutral colours to be saturated. Nevertheless, the

CIE definition of saturation, in which a neutral colour has a saturation of zero should be taken into account to model saturation. Hence, the new Cho ellipsoid saturation models excluding the neutral data are recommended to be developed in the next section.

The current study agrees with Juan and Luo's findings (see Section 2.4.1.1) that saturation correlate with lightness and colourfulness. Additionally, this study also agrees with the definition of saturation (s_{ab}) based on CIELAB (see Section 2.4.1.1) that the higher the saturation, the higher the chroma and the lower the lightness.

Table 5.39 Correlation coefficients calculated between the saturation data (including the neutral data) and the colour appearance attributes in terms of CIELAB, CIECAM02 and CAM02-UCS metrics and other models

r		British Saturation	Korean Saturation
CIELAB	C_{ab}^*	0.58	0.32
	L^*	-0.64	-0.71
	D_{ab}^*	0.82	0.81
	V_{ab}^*	-0.42	-0.56
	T_{ab}^*	0.41	0.25
	s_{uv}	0.66	0.42
	s_{ab}^*	0.77	0.51
	S^+	0.77	0.50
CIECAM02	M	0.68	0.36
	C	0.68	0.36
	J	-0.63	-0.68
	s	0.78	0.47
CAM02-UCS	M'	0.67	0.33
	J'	-0.64	-0.71

Table 5.40 Correlation coefficients calculated between the saturation data (excluding the neutral data) and the colour appearance attributes in terms of CIELAB, CIECAM02 and CAM02-UCS metrics and other models

r		British Saturation	Korean Saturation
CIELAB	C_{ab}^*	0.59	0.35
	L^*	-0.65	-0.71
	D_{ab}^*	0.83	0.82
	V_{ab}^*	-0.42	-0.55
	T_{ab}^*	0.39	0.25
	s_{uv}	0.67	0.45
	s_{ab}^*	0.79	0.55
	S^+	0.80	0.55
CIECAM02	M	0.70	0.40
	C	0.70	0.40
	J	-0.64	-0.69
	s	0.83	0.55
CAM02-UCS	M'	0.69	0.38
	J'	-0.65	-0.71

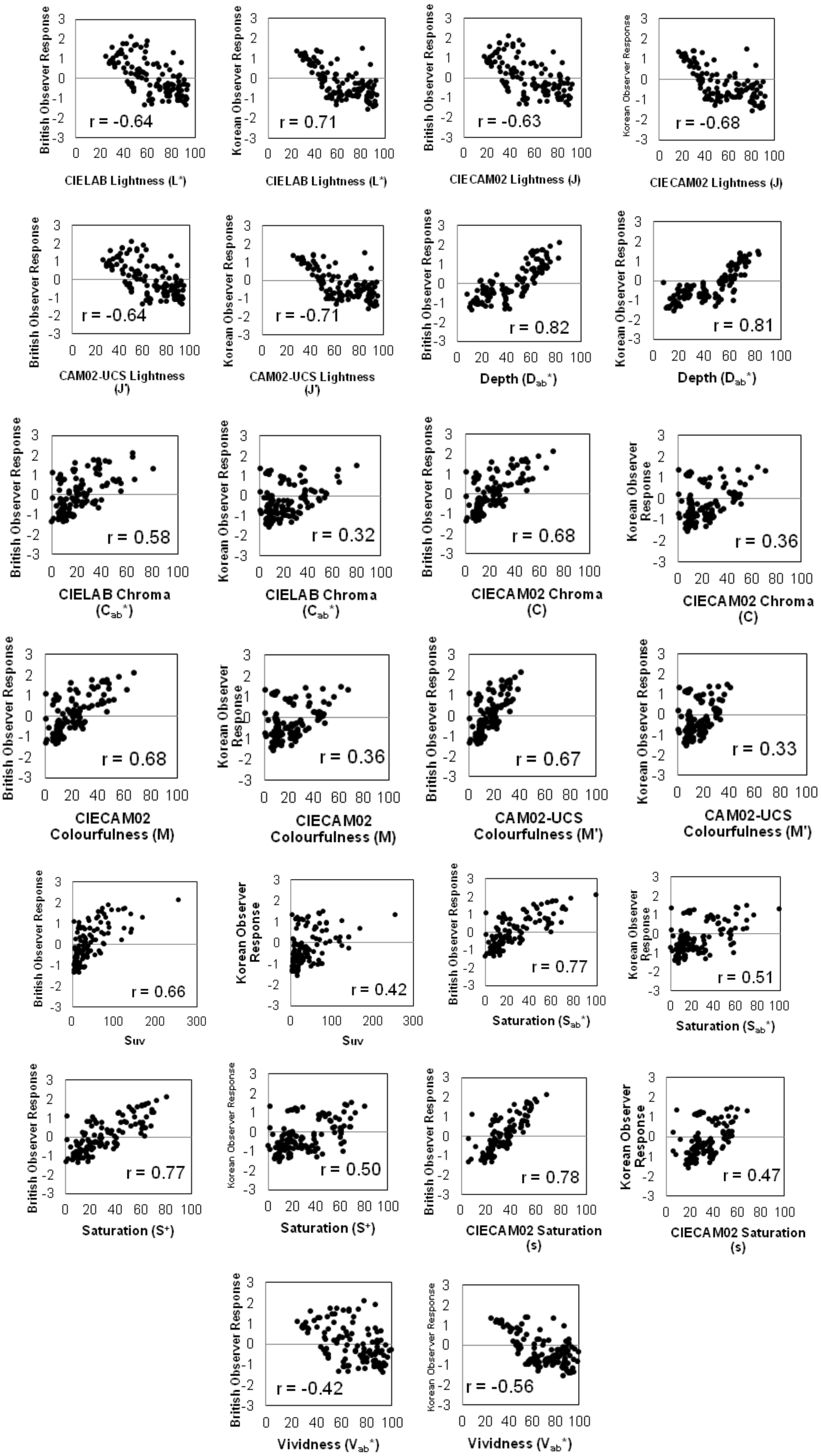


Figure 5.6 Saturation data (including the neutral data) plotted against CIELAB C_{ab}^*, L^*, D_{ab}^*, S_{ab}^*, S^+, V_{ab}^*; CIECAM02 s, M, C, J; and CAM02-UCS M'

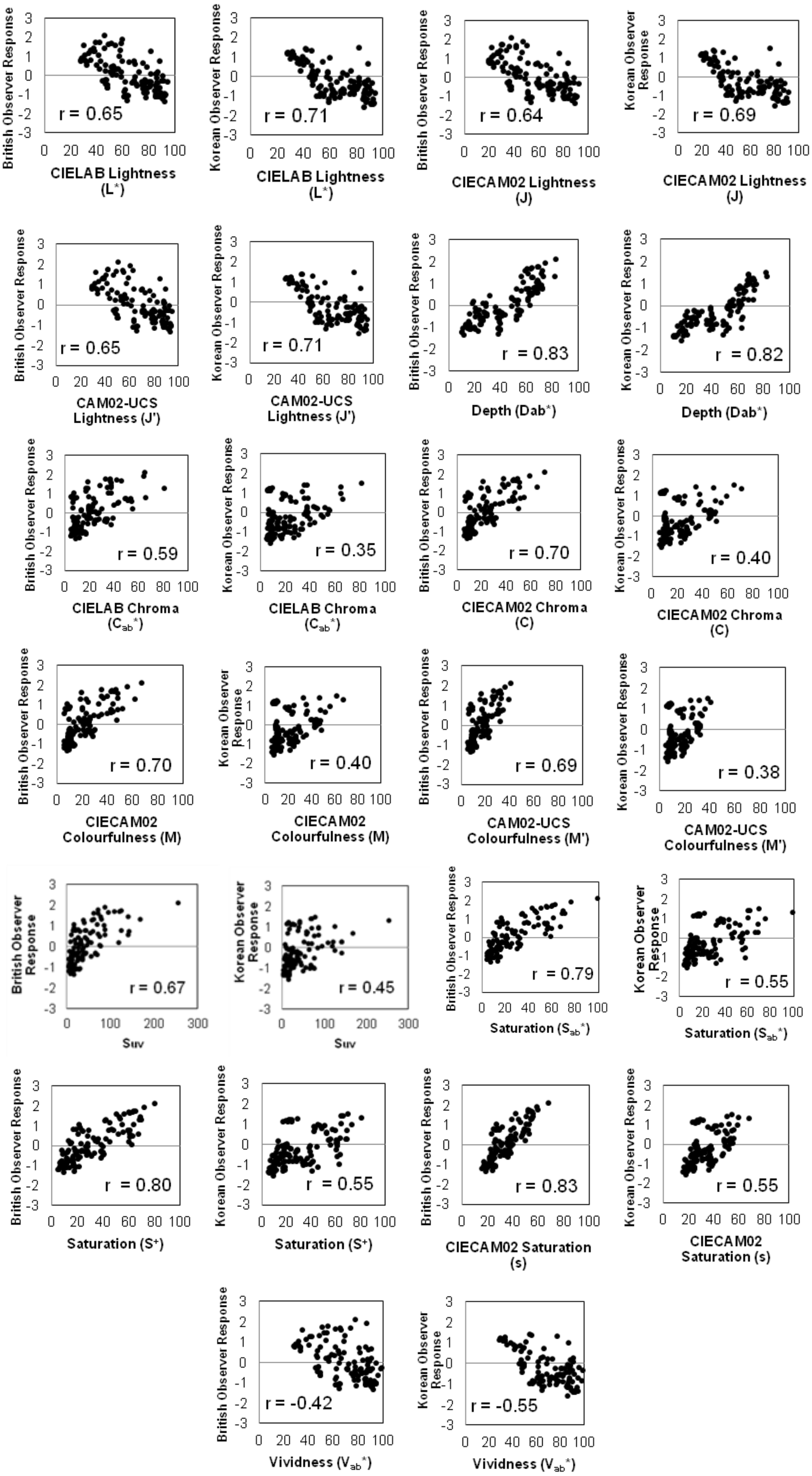


Figure 5.7 Saturation data (excluding the neutral data) plotted against CIELAB C_{ab}^*, L^*, D_{ab}^*, S_{ab}^*, S^+, V_{ab}^*, CIECAM02 M, C, J, s and CAM02-UCS M', J'.

Table 5.41 shows the correlation coefficients between the vividness observer response and the colour appearance attributes. The r values between the visual results and chroma or colourfulness predictions are particularly low for British observers. For Korean observers, the Bern's clarity, chroma and colourfulness attributes predicted vividness better than the other scales. Among the attributes, Bern's clarity was found to fit well with the Korean visual results. S_{ab}^* and Lübbe’s S^+ also fitted the Korean visual response. The results indicate that vividness is a new dimension, and a new colorimetric attribute is needed to represent this perception. Figure 5.8 plots the results that have high correlation coefficient values in Table 5.41. Also, there are some results that have low r values but show relationship as seen in Figure 5.8. Wider spread is found in the low chroma and colourfulness region. This implies that observers also think that a colour is vivid when the colour has low chroma and colourfulness.

Comparing Kim *et al*.'s (2008) preferred vividness metric (see Section 2.4.1.2) with vividness perception in this study, the contribution of chroma for Kim *et al*.'s vividness agrees well with the findings of the present study. This means that vividness makes a stronger contribution to chroma than lightness. However, regarding vividness preference in Kim *et al*.'s study, observers thought that both chroma and lightness make a strong contribution to vividness. Fedorovskaya *et al*. (1997), Trémeau and Charrier (2000) stated that vividness is similar to colourfulness (see Section 2.4.1.2). This statement illustrates in the relationship between vividness and colourfulness (see Table 5.41).

Table 5.41 Correlation coefficients calculated between the vividness data and the colour appearance attributes in terms of CIELAB, CIECAM02 and CAM02-UCS metrics and other models

r		British Vividness	Korean Vividness
CIELAB	C_{ab}^*	0.34	0.60
	L*	-0.07	0.10
	D_{ab}^*	0.27	0.23
	V_{ab}^*	0.04	0.30
	T_{ab}^*	0.48	0.77
	s_{uv}	0.29	0.50
	s_{ab}^*	0.31	0.55
	S^+	0.30	0.51
CIECAM02	M	0.41	0.61
	C	0.41	0.61
	J	-0.04	0.13
	s	0.38	0.52
CAM02-UCS	M'	0.39	0.58
	J'	-0.08	0.09

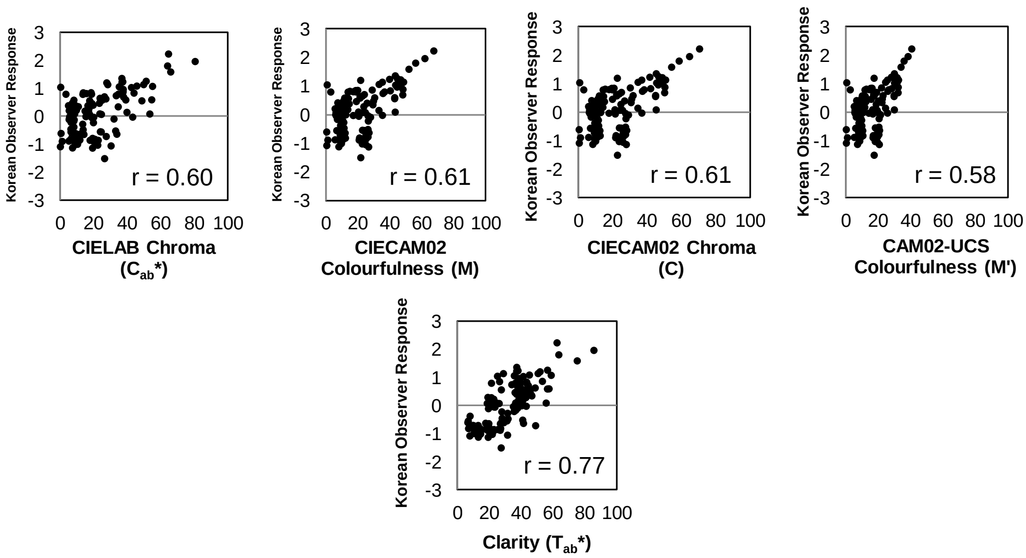


Figure 5.8 Vividness data plotted against CIELAB C_{ab}^*, T_{ab}^*, CIECAM02 M and C and CAM02-UCS M'

In the blackness and whiteness results, both cultural groups agree well with each other. Also, Berns' depth can fit very well to the visual blackness and whiteness data and has positive and negative relationships, respectively.

The Berns' depth (D_{ab}^*) and vividness (V_{ab}^*) scales well predict the reverse relationship with whiteness and blackness visual results, i.e. Berns' definition of these scales are departure from white and black points, respectively. The results also show that among the attributes, lightness fitted the visual data very well. Figures 5.9 and 5.10 plot the results that have high r values in the results shown in Tables 5.42 and 5.43. Figure 5.9 implies that observers think that colours with high blackness have low lightness and vividness and high depth. High depth means a colour departure far away from white colour in a colour space. On the other hand, according to the whiteness results in Figure 5.10, observers think that whiter colours have higher lightness and vividness and lower depth. Black and white equations (6-10) and (6-11) also fit very well with the visual blackness and whiteness, respectively. A higher black colour would have high blackness. For a whiter colour, the colour would have high whiteness.

Table 5.42 Correlation coefficients calculated between the blackness data and the colour appearance attributes in terms of CIELAB, CIECAM02 and CAM02-UCS metrics and other models

r		British Blackness	Korean Blackness
CIELAB	C_{ab}^*	-0.19	-0.27
	L^*	-0.84	-0.87
	D_{ab}^*	0.64	0.63
	V_{ab}^*	-0.86	-0.92
	T_{ab}^*	-0.26	-0.38
	s_{uv}	0.05	-0.004
	s_{ab}^*	0.06	-0.02
	S^+	0.09	0.02
CIECAM02	M	-0.17	-0.24
	C	-0.17	-0.24
	J	-0.82	-0.85
	s	0.04	-0.03
	s (Equation 6-10)	0.88	0.93
CAM02-UCS	M'	-0.16	-0.24
	J'	-0.84	-0.87
	s (Equation 6-11)	0.88	0.93

Table 5.43 Correlation coefficient calculated between the whiteness data and the colour appearance attributes in terms of CIELAB, CIECAM02 and CAM02-UCS system and other models

r		British Whiteness	Korean Whiteness
CIELAB	C_{ab}^{*}	-0.27	-0.07
	L^{*}	0.79	0.86
	D_{ab}^{*}	-0.82	-0.78
	V_{ab}^{*}	0.65	0.78
	T_{ab}^{*}	-0.13	0.05
	s_{uv}	-0.41	-0.33
	s_{ab}^{*}	-0.52	-0.38
	S^{+}	-0.52	-0.38
CIECAM02	M	-0.32	-0.13
	C	-0.32	-0.13
	J	0.78	0.85
	s	-0.47	-0.33
	w (Equation 6-10)	0.83	0.82
CAM02-UCS	M'	-0.31	-0.12
	J'	0.79	0.86
	w (Equation 6-11)	0.84	0.80

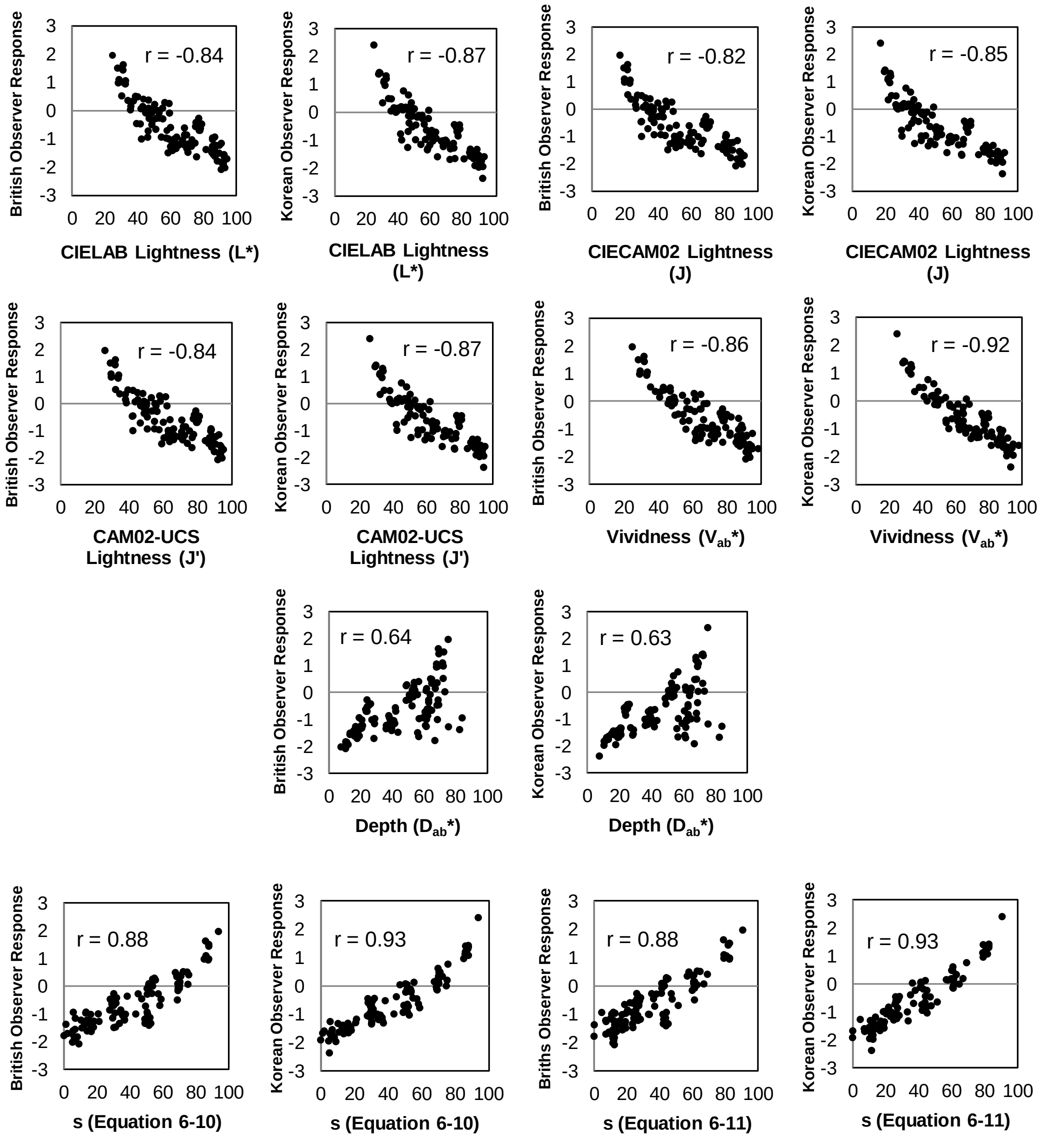


Figure 5.9 Blackness data plotted against L^*, D_{ab}*, V_{ab}*, s (equation 6-10), s (equation 6-11), J and J'.

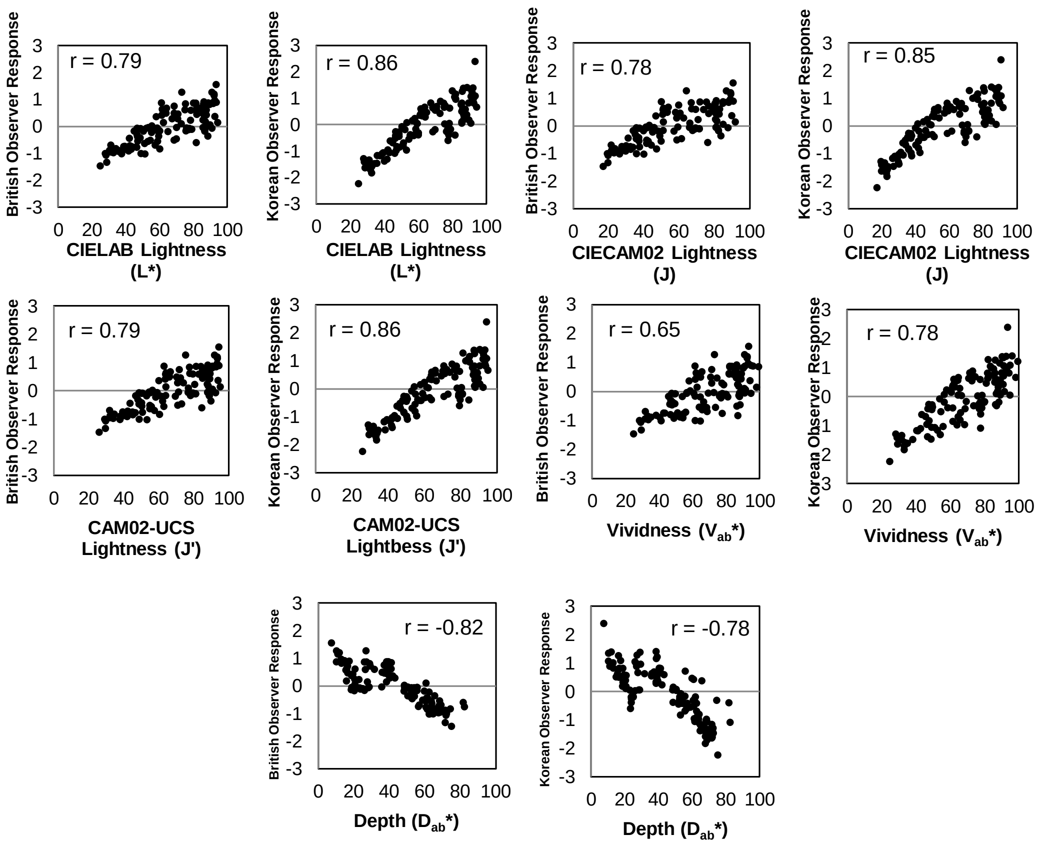


Figure 5.10 Whiteness data plotted against L^*, D_{ab}^*, V_{ab}^*, J and J'

5.6 Comparing the Visual Results Between the Four Attributes

This section is focused on understanding the relationships among the four attributes studied. Figure 5.11 shows 6 scatter plots for the four attributes. Note that the averaged data between the British and Korean results were used here. Although there could be some differences between the two cultures, as reported earlier, the correlations between the results from the two cultures are quite high, i.e. to have r values of -0.81, -0.82 and 0.61. This can also be verified in Figures 5.11 (a), (d) and (f).

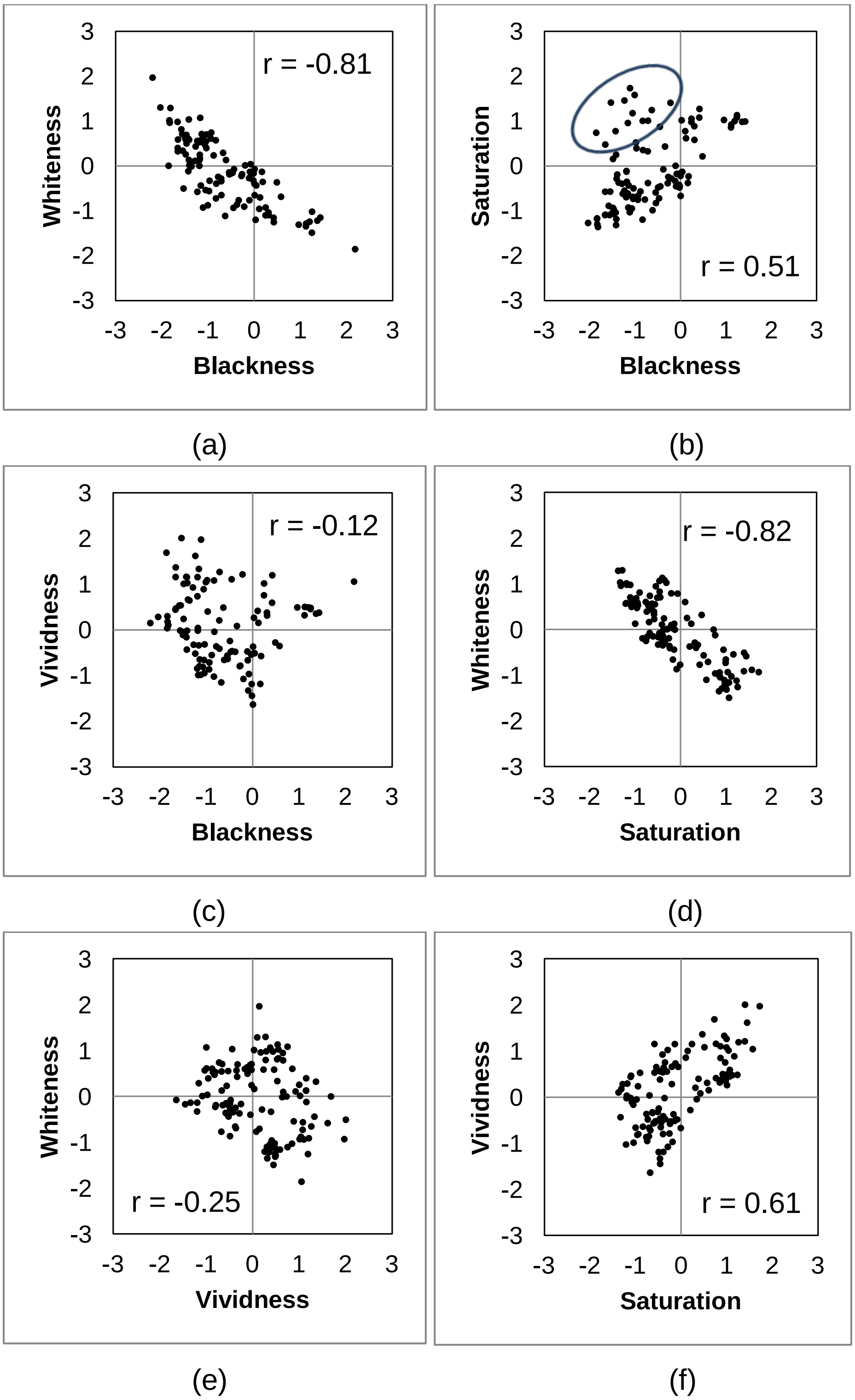


Figure 5.11 Plots of the visual data between whiteness, blackness, vividness and saturation (a) blackness vs. whiteness, (b) blackness vs. saturation, (blue circle: outlying data), (c) blackness vs. vividness, (d) saturation vs. whiteness, (e) vividness vs. whiteness, (f) saturation vs. vividness

The findings are summarised below:

1. Figure 5.11-(a) shows a high correlation between whiteness and blackness. It may be considered that whiteness adding blackness is a constant. They are the reverse of each other.

2. Figures 5.11 (a) and (b) show good agreement. Both blackness and saturation had a negative relationship with whiteness, i.e. a whiter colour would also appear to be less black and more saturated.

3. The plot between blackness and saturation (Figure 5.11-(b)) shows that they have a positive relationship, but there is wide scattering. Those deviation data are indicated by a circle, and it was found that they were very saturated colours with high lightness and chroma that did not predict well.

4. Figure 5.11-(f) also shows reasonable agreement between saturation and vividness.

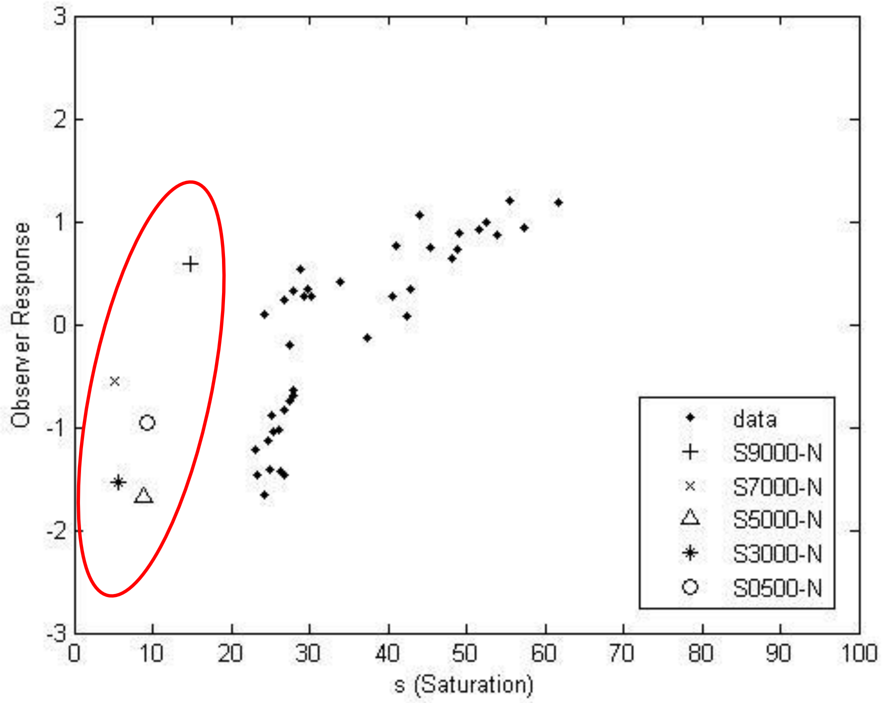
5. Figures 5.11 (c) and (e) show that there is little relationship between vividness and blackness and between whiteness and vividness.

5.7 Does A Neutral Colour Have Saturation?

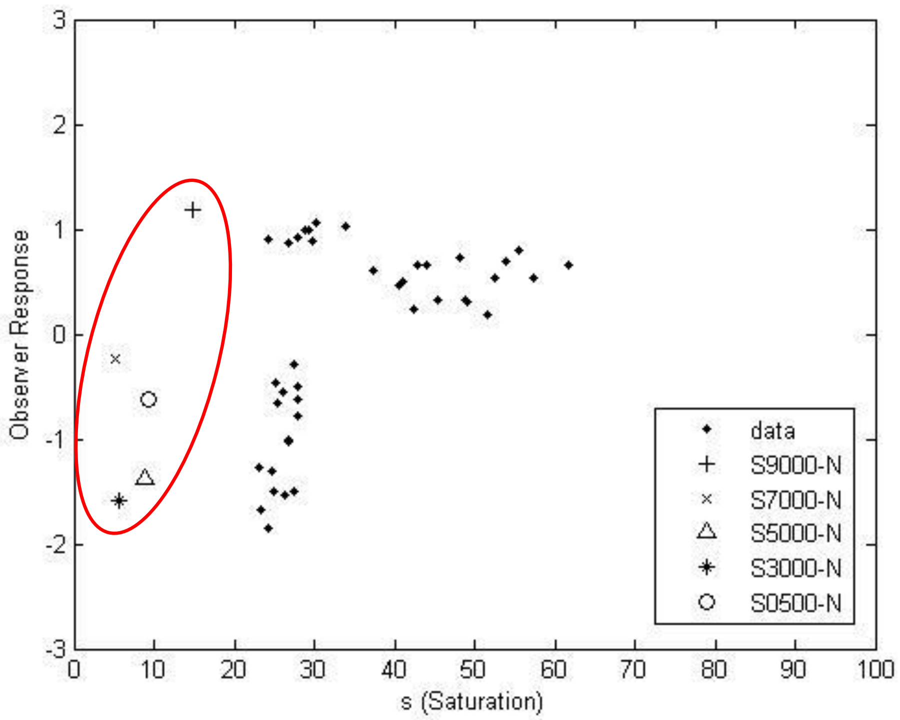
The individual observers' visual data were investigated using the saturation data for the year 2011 to understand the difficulties in the assessment of 'saturation'. It is assumed that the difficulties were caused by the diversity in observers' experience and "natural understanding" of saturation. The word saturation could not be exactly translated due to cultural differences.

Figures 5.12 (a) and (b) show the observer data plotted against CIECAM02 saturation for the British and Korean groups, respectively. Note that CIECAM02 is used here because it performed well in the prediction of the present saturation data.

In Figure 5.12, achromatic colours are represented by special symbols as shown in the red circle. A plus sign (+) represents a dark grey (or black) with an NCS specification of S9000-N. This specification means that the colour has a blackness of 90 and a chromaticness of 0. For the British group, light grey seems to have the lowest saturation among the achromatic colours. On the other hand, for the Korean group, medium grey seems to have the lowest saturation. For both the British and Korean groups, black (represented by the 'plus' sign) seems to be the most saturated among the achromatic colours. The trend of black followed by dark grey, white, medium grey and light grey seems to be shared by both the British and Korean groups. For chromatic colours (indicated by dots), the British group seems to have a better correlation with CIECAM02 saturation than the Korean group has.



(a)



(b)

Figure 5.12 (a) Saturation data for the British group for 2011 plotted against CIECAM02 saturation and (b) saturation data for the Korean group for 2011 plotted against CIECAM02 saturation

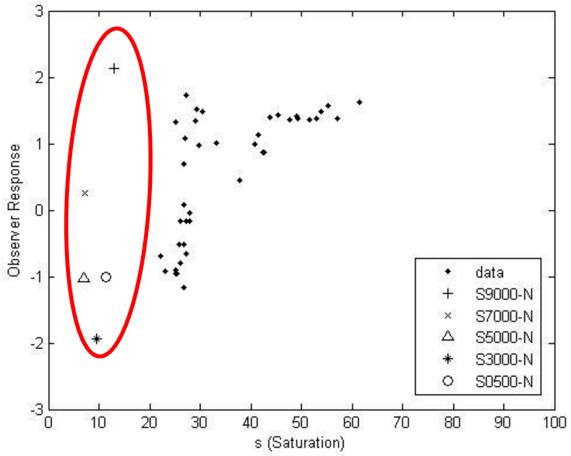
PCA analysis was again conducted. It can be seen that the British observers were further divided into three subgroups. Each subgroup was highly correlated with components 1, 2 and 3. Table 5.44 shows the highest component loadings for each observer which are highlighted in grey. Observers that were highly correlated with Component 1 (called Group A) include observers 6, 9, 13, 21, 22, 26, 29, 31, 33 and 35. Observers 16, 27, 28 and 37 were highly correlated with Component 2 (called Group B). Those highly correlated with Component 3 (called Group C) were observers 10, 25, 30 and 38. The eigenvalues of components 1, 2 and 3 are 12.31, 1.54 and 0.95, respectively.

Table 5.44 Component matrix for British group based on the saturation response

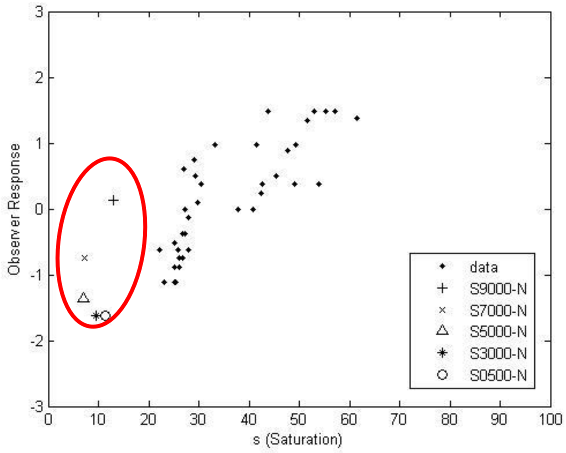
Observer	Component 1	Component 2	Component 3
6	0.81	0.23	0.18
9	0.67	0.46	0.45
13	0.80	0.40	0.17
21	0.68	0.25	0.47
22	0.68	0.55	0.29
26	0.89	0.14	0.06
29	0.77	0.50	0.21
31	0.77	0.27	0.41
33	0.65	0.53	0.27
35	0.65	0.31	0.41
16	0.30	0.74	0.34
27	0.30	0.81	0.26
28	0.54	0.66	0.35
37	0.47	0.53	0.45
10	0.12	0.41	0.70
25	0.29	0.08	0.83
30	0.36	0.30	0.70
38	0.08	0.21	0.67

Figures 5.13 (a) to (c) show the observer responses for each colour sample, calculated for each subgroup of the British observers plotted against CIECAM02 saturation. It shows that CIECAM02 correlates with most of the

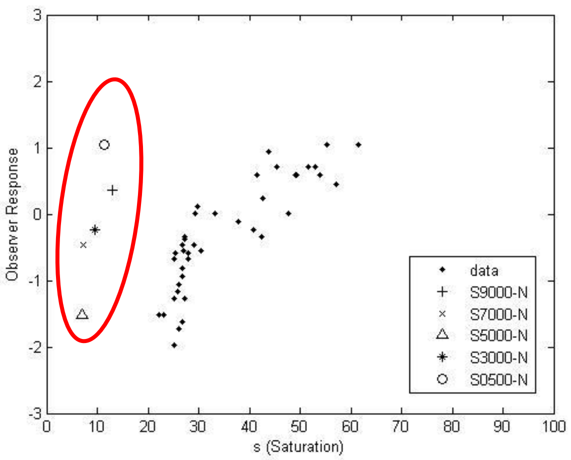
chromatic colours. However, there are some differences between the three observer groups in the achromatic colours. The least saturated colours seem to be different for the three groups of observers. The observers in Group A seemed to regard the least saturated colour as light grey. The least saturated colours for Group B were light grey and white. The observers in Group C seemed to regard the least saturated colour as medium grey. It is noted that only Group B showed a high correlation between observer response and the CIECAM02 saturation. It is suggested that there were at least three definitions of saturation during the experiment. The least saturated colour of each of them was located in the colour space somewhere between white and medium grey.



(a)



(b)



(c)

Figure 5.13 CIECAM02 Saturation plotted against observer responses of British (a) Group A, (b) Group B and (c) Group C

Three observer groups were compared using the predictive models developed in this study on the basis of the observer responses of each group. The models were based on CIECAM02 values. One of the typical model frameworks of colour emotion (Sato *et al*. 2000b, Ou 2004) was taken into account in the form of a modified colour difference formula mentioned in equation (5-6) of Section 5.8.

The new saturation models were defined using the CIECAM02 space in terms of J, $\mathrm{a_M}$ and $\mathrm{b_M}$ mentioned in equation (5-8) of Section 5.8. The following equations define the new saturation models based on Groups A to C of the British data, with the correlation coefficients of 0.96, 0.92 and 0.91, respectively:

$$
\begin{aligned}
\mathrm{S_{BA\_CIECAM02}} &= -2.93 + 0.07\sqrt{(\mathrm{J}-76)^2 + 0.83(\mathrm{a_M}-2)^2 + 1.09(\mathrm{b_M}+4)^2} \\
\mathrm{S_{BB\_CIECAM02}} &= -2.55 + 0.04\sqrt{(\mathrm{J}-83)^2 + 4(\mathrm{a_M}-1)^2 + 2.11(\mathrm{b_M}-1)^2} \qquad (5\text{-}4) \\
\mathrm{S_{BC\_CIECAM02}} &= -1.98 + 0.06\sqrt{(\mathrm{J}-50)^2 + 1.31(\mathrm{a_M}-5)^2 + 0.74(\mathrm{b_M}+3)^2}
\end{aligned}
$$

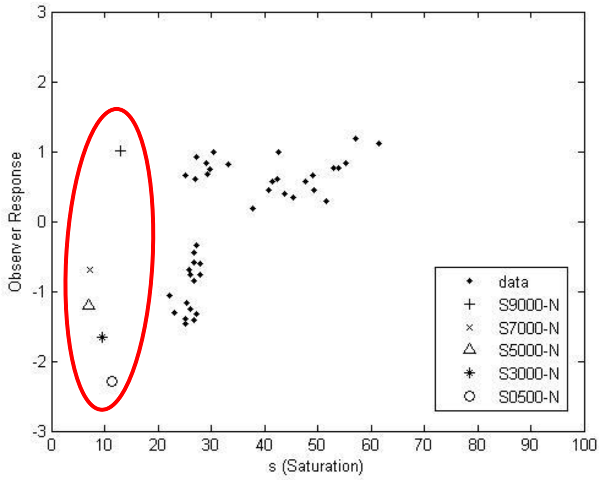
The high correlation coefficients imply that the predicted values represent the majority of the total variance of observer response. The reference colours of the three models suggest that the least saturated colours for the three subgroups of British observers are pinkish/purplish greys with a high or medium lightness. The colour tends to appear more saturated when it is further away from the reference colour.

The Korean observers were also classified into three subgroups. The observers that were highly correlated with Component 1 (called Group A) include observers 2, 4, 7, 8, 12, 15, 23 and 39. Observers 1, 5, 14, 17, 18, 19, 20, 32 and 34 were highly correlated with Component 2 (called Group B). Observers 3 and 11 were highly correlated with component 3 (called Group C). The eigenvalues of components 1, 2 and 3 were 11.20, 2.25 and 1.51, respectively.

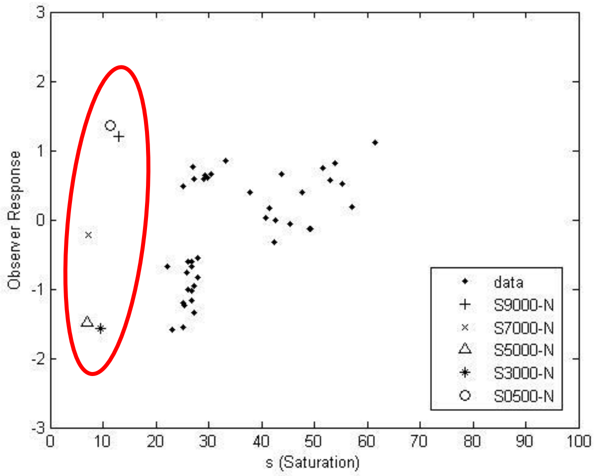
Table 5.45 Component matrix for Korean observers based on the saturation response

Observer	Component 1	Component 2	Component 3
2	0.83	0.42	0.03
4	0.80	0.31	0.26
7	0.64	0.23	0.40
8	0.90	0.28	0.10
12	0.74	0.35	0.18
15	0.84	0.47	0.00
23	0.80	0.43	0.07
39	0.66	0.22	0.34
1	0.05	0.60	-0.27
5	0.17	0.79	0.10
14	0.37	0.75	0.10
17	0.55	0.64	-0.02
18	0.33	0.67	0.08
19	0.56	0.75	0.04
20	0.37	0.72	0.08
32	0.22	0.73	0.22
34	0.47	0.80	-0.01
3	0.53	0.18	0.70
11	0.21	0.02	0.86

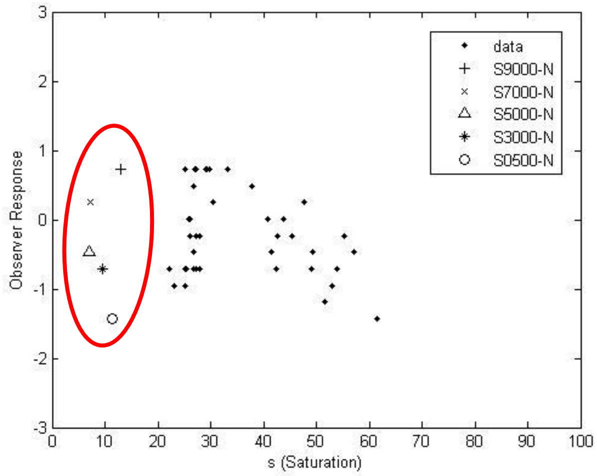
Figures 5.14 (a) to (c) show the observer response to each colour sample, calculated for each subgroup of the Korean observers plotted against the CIECAM02 saturation. It shows that the least saturated colours for the three subgroups are either light grey or medium grey. It is noted that Figure 5.14-(c) shows a distinct pattern for chromatic colours. It illustrates the trend for highly saturated colours. The observer response tends to decrease as the CIECAM02 saturation value gets higher. This trend appears to be different from both Figures 5.14 (a) and (b). The observer response tends to increase as the CIECAM02 saturation value gets higher in both Figures 5.14 (a) and (b).



(a)



(b)



(c)

Figure 5.14 CIECAM02 Saturation plotted against observer response of Korean (a) Group A, (b) Group B and (c) Group C

The following saturation models are based on Groups A to C of the Korean data, with the correlation coefficients of 0.97, 0.94 and 0.87, respectively:

$$
\begin{aligned}
S_{\mathrm{Ka\_CIECAM02}} &= -3.36 + 0.06\sqrt{(J-85)^2 + 0.98(a_M+1)^2 + 1.15(b_M+7)^2} \\
S_{\mathrm{Kb\_CIECAM02}} &= -1.87 + 0.07\sqrt{(J-56)^2 + 0.38(a_M-1)^2 + 0.48(b_M-2)^2} \quad (5\text{-}5) \\
S_{\mathrm{Kc\_CIECAM02}} &= 1.3 - 0.03\sqrt{(J)^2 + 2.18(a_M-3)^2 + 1.09(b_M)^2}
\end{aligned}
$$

The high correlation coefficients imply that the predicted values represent the majority of the total variance of observer response. Colour tends to appear more saturated when further away from the reference colour. The model for Group C shows that the most saturated colour is black. A colour tends to appear less saturated when it is further away from black.

From the above results, it can be concluded that naive observers can be divided into three types for scaling saturation according to whether white, grey or black are considered to be saturated colours. If there is no training session using CIE definition as zero saturation of the neutral colours, many people will think that black and grey neutral colours could be saturated colours. We cannot say that they are right or wrong. It is down to previous experience driving the concept. Note in the dictionary definition on ‘saturated’ for both languages, it was defined as the trace of colorant in the solution. So, by treating black as a colorant, it can produce a large range of neutral colours. However, as the present study is associated with colour science, it is better to follow the CIE definition, for which all neutral colours have a saturation of zero. Hence, the Cho ellipsoid saturation models developed by deleting the neutral data have been taken into account as shown in Table 5.47.

In Juan and Luo’s saturation study (see Section 2.4.1.1), before the actual experiment, they found that, without any training, half of the observers considered black as highly saturated. This finding agrees with the current results of British and Korean groups. Thus it can be concluded that, in the real world, naive observers may think that a neutral colour can be saturated. However, they can be trained to judge this as zero saturation.

5.8 New Cho Ellipsoid Models Based on the Cho Data

In this study, new models for each of the four attributes (i.e. saturation, vividness, blackness and whiteness) were developed for three colour systems, namely CIELAB, CIECAM02 and CAM02-UCS. For each model, three versions were developed using the British, Korean and combined data. Two sets of models were developed especially for saturation: one is a saturation model developed including the neutral data, and the other is a saturation model developed excluding the neutral data (called "the Cho ellipsoid saturation NN model"). The saturation model developed excluding the neutral data was recommended to follow the CIE definition for neutral colour, which was mentioned in Section 5.7. In the CIE definition, a neutral colour is considered as having a saturation of zero. For scaling saturation, some of the neutral data were found to be saturated (see Figures 5.13 and 5.14). Hence, considering the CIE definition, the saturation model was developed by removing the neutral data. A saturation model developed including the neutral data was also derived to compare the performance with the saturation model developed excluding the neutral data. Thus, a total of 39 models were developed.

In general, the model structure was based on a colour emotion modelling technique using a colour difference formula (Sato *et al.,* 2000b; Ou *et al.*, 2004). This modelling technique was used because it is easily approached by referring to the colour difference between a colour and the reference colour in the CIELAB, CIECAM02 and CAM02-UCS metrics. For example, if a colour is very saturated, it shows a big difference (high value) from the least saturated colour. This may be expressed as:

$$\Delta E = k_M + \sqrt{\{k_L(L^* - L_O^*)\}^2 + \{k_A(a^* - a_O^*)\}^2 + \{k_B(b^* - b_O^*)\}^2}, \qquad (5\text{-}6)$$

where L_O^*, a_O^* and b_O^* are the coordinates of the reference colour in the CIELAB space in terms of L*, a* and b* values. For example, a colour will appear saturated if it departs far away from the reference colour (i.e. the least saturated colour). This also applies to the vividness model. For blackness, the colour will appear less black if it departs far away from the reference colour (i.e. the colour with the highest blackness). This also applies to the whiteness model. The greater the distance is from the reference white, the less white the colour is. Here, k_L, k_A and k_B are constant values representing the contribution of the CIELAB space in terms of L*, a* and b*, while k_M is a constant value used as a scaling factor. Each model includes the best optimised parameters.

The following equation is the new Cho ellipsoid model of the CIELAB version:

$$\text{Cho Ellipsoid Model}_{\text{CIELAB}} = k_M + k_L\sqrt{(L^* - L_O^*)^2 + k_A(a^* - a_O^*)^2 + k_B(b^* - b_O^*)^2} \tag{5-7}$$

where the seven parameters, k_L, k_A, k_B, k_M, L_O^*, a_O^* and b_O^*, which are set to changing cells, were calculated using the Excel Solver tool by optimising the RMS value (target cell) between the observer response and the predicted value from the new Cho ellipsoid model.

This model was also defined as a CIECAM02 metric in terms of J, $\mathrm{a_M}$ and $\mathrm{b_M}$. It is expressed as:

$$\text{Cho Ellipsoid Model}_{\text{CIECAM02}} = k_M + k_L\sqrt{(J - J_0)^2 + k_A(a_M - a_0)^2 + k_B(b_M - b_0)^2}. \tag{5-8}$$

The following model was defined in the CAM02-UCS space in terms of $\mathrm{J'}$, $\mathrm{a'}$ and $\mathrm{b'}$:

$$\text{Cho Ellipsoid Model}_{\text{CAM02-UCS}} =$$

$$k_M + k_L\sqrt{(J' - J_0')^2 + k_A(a' - a_0')^2 + k_B(b' - b_0')^2}. \quad (5\text{-}9)$$

The new models were developed based on the British data (called the Cho ellipsoid British model), Korean data (called the Cho ellipsoid Korean model) and combined data (called the Cho ellipsoid model). Tables 5.46 to 5.53 show the summary of the parameters of the newly developed models. These tables also include the r and RMS values. The r (correlation coefficient) and RMS (root mean square) were calculated between the visual data and the predicted values from the model. These values were calculated for every developed model.

Comparing the models based on experimental data from the three observer groups (i.e. British, Korean and combined), it is expected that the reference colour of a model based on the combined data would fall somewhere in the middle between the reference colour for the model based on British data and that based on Korean data. For example, the reference colour for the vividness model using the CIELAB system based on the combined data is (L0*, a0*, b0*) = (61, 2, 16), the coordinates of which seem to be somewhere in the middle between the reference colour based on British data (L0*, a0*, b0*) = (62, 3, 21) and that based on Korean data (L0*, a0*, b0*) = (60, 1, 8).

There are also tendencies found in the reference colours for blackness and whiteness models. The reference colour for blackness models seems to be yellowish black for the three observer groups. This means that yellowish black is considered to be the least black. The most black could be the bluish black. This agrees with Clonts *et al*. (2010) blackness perception that cyan to bluish black are the most black. Also, Haslup *et al*.'s (2013) results agree with the present finding that bluish to greenish black is considered blacker than yellowish black. For the whiteness model, the reference colour seems to be bluish-white except for the whiteness combined model in the CIECAM02 version.

The plots of the visual data against the predicted values from the model given in Tables 5.46 to 5.53 are shown in Appendix C (Figures 8.1 to 8.8), respectively. According to the r results, the visual data fitted well to both the British and Korean models with high correlation coefficient values ranging from 0.78 to 0.95. It can be seen in Figures 8.1 to 8.8 that the models fitted the observer results. Overall, the British and Korean models fitted very well with the data. Thus, it is reasonable to develop a combined model. It demonstrates that the combined model fitted very well with the fitted data. Comparing the three models for each attribute, there were not great differences among the three models in terms of correlation coefficient values.

The RMS results in Tables 5.46 to 5.53 and the inter-observer variability (RMS) results given in Table 5.34 were compared to investigate whether the models performed well or not. All the RMS results from the models showed better results than the inter-observer variability results. This implies that the models did performed well with low RMS values. Note that, according to the r and RMS values, the British and Korean models performed well. Hence, the combined model is recommended as the universal model based on the combination of the British and Korean data.

Westland *et al.* (2008) introduced a blackness model (see equation (2-30). The difference between the Cho ellipsoid blackness models in this thesis and Westland *et al.*'s study is that their model was based on ink-jet printing. The newly suggested Westland *et al.*'s model is similar in using L*, a* and b* values.

Table 5.46 Parameters of the Cho ellipsoid saturation_British models and the Cho ellipsoid saturation_Korean models, together with r, RMS and STRESS values

	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_British_CIELAB}$	-1.63	0.05	1.46	0.88	77	2	12	0.91	0.36	40.3
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_British_CIECAM02}$	-1.64	0.05	1.79	1.18	71	1	4	0.92	0.35	39.2
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_British_CAM02\text{-}UCS}$	-1.83	0.05	3.03	2.11	78	0	2	0.94	0.31	35.3
	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_Korean_CIELAB}$	-1.64	0.05	0.45	0.46	76	3	11	0.86	0.42	49.8
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_Korean_CIECAM02}$	-1.61	0.05	0.55	0.63	72	2	-1	0.83	0.45	54.0
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_Korean_CAM02\text{-}UCS}$	-1.70	0.05	0.93	1.00	79	1	0	0.85	0.42	50.7

Table 5.47 Parameters of the Cho ellipsoid saturation models (developed including neutral data) and the Cho ellipsoid saturation NN models (developed excluding neutral data) all based on the combined data, together with r, RMS and STRESS values

	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_CIELAB}$	-1.62	0.05	0.87	0.64	77	2	12	0.86	0.44	50.5
Cho Ellipsoid SaturationNN$_{_CIELAB}$	-1.59	0.05	0.90	0.67	78	2	11	0.86	0.44	51.0
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_CIECAM02}$	-1.61	0.05	1.08	0.89	71	1	3	0.85	0.45	52.6
Cho Ellipsoid SaturationNN$_{_CIECAM02}$	-1.59	0.04	1.15	0.94	73	1	3	0.85	0.46	52.8
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Saturation$_{_CAM02\text{-}UCS}$	-1.75	0.05	1.83	1.50	79	0	2	0.86	0.43	50.0
Cho Ellipsoid SaturationNN$_{_CAM02\text{-}UCS}$	-1.78	0.05	1.89	1.55	79	0	2	0.86	0.43	50.0

Table 5.48 Parameters of the Cho ellipsoid vividness British models and the Cho ellipsoid vividness Korean models, together with r, RMS and STRESS values

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
Cho Ellipsoid Vividness$_{\text{British_CIELAB}}$	-2.03	0.08	0.63	0.38	62	3	21	0.82	0.51	57.1
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Vividness$_{\text{British_CIECAM02}}$	-1.78	0.07	0.76	0.42	54	3	14	0.78	0.55	61.6
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Vividness$_{\text{British_CAM02-UCS}}$	-1.94	0.08	1.29	0.63	64	2	8	0.80	0.54	59.6
	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Vividness$_{\text{Korean_CIELAB}}$	-1.70	0.07	0.93	0.42	60	1	8	0.89	0.35	45.2
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Vividness$_{\text{Korean_CIECAM02}}$	-1.87	0.06	1.04	0.43	52	2	-6	0.90	0.33	42.7
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Vividness$_{\text{Korean_CAM02-UCS}}$	-2.11	0.08	1.79	0.77	61	1	-4	0.89	0.35	45.6

Table 5.49 Parameters of the Cho ellipsoid vividness models, all based on the combined data, together with r, RMS and STRESS values

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
Cho Ellipsoid Vividness$_{\text{CIELAB}}$	-1.81	0.07	0.76	0.38	61	2	16	0.82	0.47	56.0
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Vividness$_{\text{CIECAM02}}$	-1.72	0.06	0.89	0.41	53	2	4	0.81	0.48	57.7
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Vividness$_{\text{CAM02-UCS}}$	-1.95	0.08	1.51	0.70	63	1	2	0.81	0.48	57.5

Table 5.50 Parameters of the Cho ellipsoid blackness British models and the Cho ellipsoid blackness Korean models, together with r, RMS and STRESS values

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
Cho Ellipsoid Blackness$_{\text{British_CIELAB}}$	2.28	-0.04	1.34	0.73	0	0	21	0.89	0.39	36.5
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Blackness$_{\text{British_CIECAM02}}$	1.63	-0.04	1.28	0.77	0	2	9	0.88	0.41	38.1
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Blackness$_{\text{British_CAM02-UCS}}$	2.36	-0.04	2.83	1.68	0	1	8	0.90	0.38	35.7
	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Blackness$_{\text{Korean_CIELAB}}$	2.14	-0.05	1.43	0.72	7	1	13	0.94	0.32	28.0
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Blackness$_{\text{Korean_CIECAM02}}$	1.84	-0.04	1.55	0.86	0	3	3	0.94	0.32	28.6
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Blackness$_{\text{Korean_CAM02-UCS}}$	2.04	-0.05	2.75	1.49	14	1	2	0.95	0.29	25.9

Table 5.51 Parameters of the Cho ellipsoid blackness models, all based on the combined data, together with r, RMS and STRESS values

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
Cho Ellipsoid Blackness_CIELAB	2.35	-0.04	1.47	0.76	0	0	17	0.91	0.36	32.7
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Blackness_CIECAM02	1.73	-0.04	1.42	0.81	0	2	5	0.91	0.37	33.9
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Blackness_CAM02-UCS	2.48	-0.04	3.17	1.79	0	1	5	0.92	0.35	31.5

Table 5.52 Parameters of the Cho ellipsoid whiteness British models and the Cho ellipsoid whiteness Korean models, together with r, RMS and STRESS values

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
Cho Ellipsoid Whiteness_British_CIELAB	1.14	-0.03	0.60	0.37	97	5	-5	0.84	0.36	53.8
	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Whiteness_British_CIECAM02	1.33	-0.03	0.76	0.73	100	0	-10	0.83	0.37	55.6
	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Whiteness_British_CAM02-UCS	1.44	-0.03	1.54	0.83	100	3	-14	0.85	0.35	53.1
	kM	**kL**	**kA**	**kB**	**L0***	**a0***	**b0***	**r**	**RMS**	**STRESS**
Cho Ellipsoid Whiteness_Korean_CIELAB	1.54	-0.04	-0.09	0.09	100	-2	-29	0.87	0.43	48.7
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Whiteness_Korean_CIECAM02	1.79	-0.04	0.00	0.17	100	11	-34	0.86	0.45	50.9
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Whiteness_Korean_CAM02-UCS	1.46	-0.04	0.06	0.32	100	0	-10	0.87	0.43	48.7

Table 5.53 Parameters of the Cho ellipsoid whiteness models, all based on the combined data, together with r, RMS and STRESS values

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
Cho Ellipsoid Whiteness_CIELAB	1.28	-0.03	0.18	0.22	100	4	-4	0.84	0.42	53.7
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Whiteness_CIECAM02	1.38	-0.03	0.20	0.60	100	0	0	0.83	0.44	56.0
	kM	**kL**	**kA**	**kB**	**J0'**	**a0'**	**b0'**	**r**	**RMS**	**STRESS**
Cho Ellipsoid Whiteness_CAM02-UCS	1.45	-0.04	0.60	0.28	93	3	-24	0.85	0.42	53.2

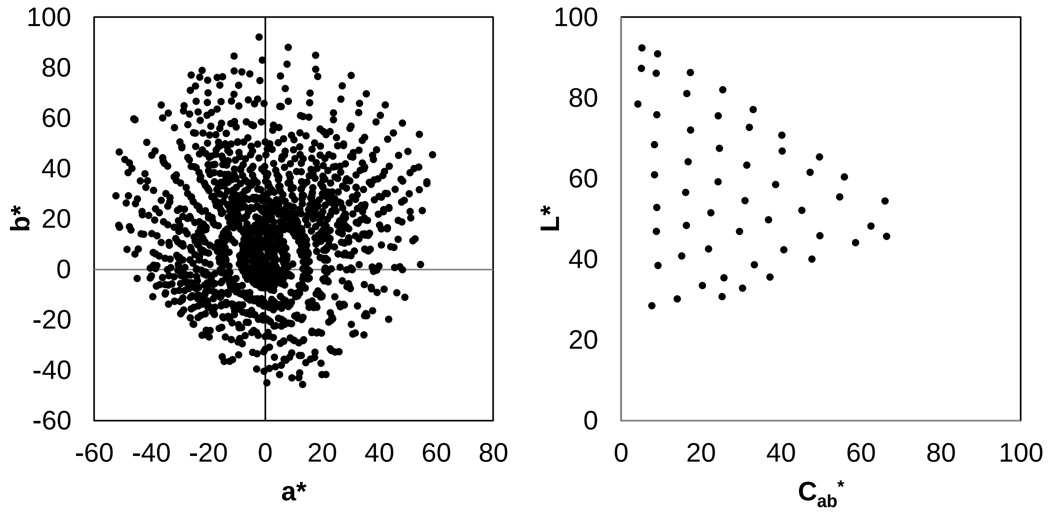
5.9 New NCS Ellipsoid Models Based on the NCS Data

New NCS ellipsoid models for blackness (called the "NCS ellipsoid blackness model"), whiteness (called the "NCS ellipsoid whiteness model") and chromaticness (called the "NCS ellipsoid chromaticness model") attributes were developed using the NCS data with CIELAB, CIECAM02 and

CAM02-UCS metrics. These models were based on the Cho ellipsoid models presented in equations (5-7) to (5-9) of Section 5.8. The models were developed using 1,749 NCS data samples.

The samples were obtained from the NCS Atlas and were measured by an X-Rite CE7000A spectrophotometer under the specular included, small aperture and UV included conditions. The NCS data were measured by Juan (2000) in 2000. The spectral reflectance of each sample was transformed to tristimulus XYZ values for the D65 and 1931 standard colorimetric (or 2-degree) observer. The viewing conditions used in CIECAM02 were L_a=20, Y_b=20 and average surround.

Figure 5.15-(a) shows the colour distribution of all the colours in a*-b* coordinates in CIELAB. The figure shows that the samples cover a large colour gamut. Figure 5.15-(b) shows the colour distribution of all the samples in the NCS Y90R hue page in the L^*-C_{ab}^* coordinates in CIELAB. The samples in the top side of the triangle are known as 'light' and the bottom side is 'dark'. The slopes are different in the light and dark series, which have positive and negative signs, respectively. The 'whiteness' value is the same in the samples of each line having similar slope of light series from top to bottom. Similarly, the 'blackness' value is the same in the samples from bottom to top. The 'full' colour is the cross point between the light and dark series. The definition of this colour is the colour having the maximum chromaticness in each hue. They do not physically exist. However, they are fundamentals for developing all 3 NCS attributes (whiteness, blackness and chromaticness).



(a) (b)

Figure 5.15 (a) Distribution of NCS colours in a*-b* coordinates of CIELAB and (b) distribution of NCS colours in the Y90R hue page in the L*-C_{ab}* coordinates of CIELAB

For modelling the blackness attribute, for example in the CIELAB version, seven parameters, k_L, k_A, k_B, k_M, L^*_0, a^*_0 and b^*_0 were calculated using the Excel Solver function by optimising the RMS value between the predicted value from the model and the NCS blackness data. The parameters of the two versions (CIECAM02 and CAM02-UCS) are also calculated in the same way as the CIELAB version.

For modelling the whiteness attribute, the parameters were calculated using the Solver function by optimising the RMS value between the predicted value from the model and the NCS whiteness data.

The parameters for the chromaticness attribute were calculated using the Solver function by optimising the RMS value between the model predictions and the NCS chromaticness data.

Tables 5.54 to 5.56 show the parameters of the NCS ellipsoid models of blackness, whiteness and chromaticness. The r result between the NCS data and the model predictions are also presented. It shows that the ellipsoid models were very highly correlated with the NCS data, with correlation coefficient values ranging from 0.97 to 0.99. Figures 5.16 to 5.18 show the plots of the NCS data and the NCS ellipsoid model predictions in three versions for blackness, whiteness and chromaticness attributes, respectively. Nine predicted attributes show a clear linear relationship with the NCS data.

Table 5.54 Parameters of the NCS ellipsoid blackness models

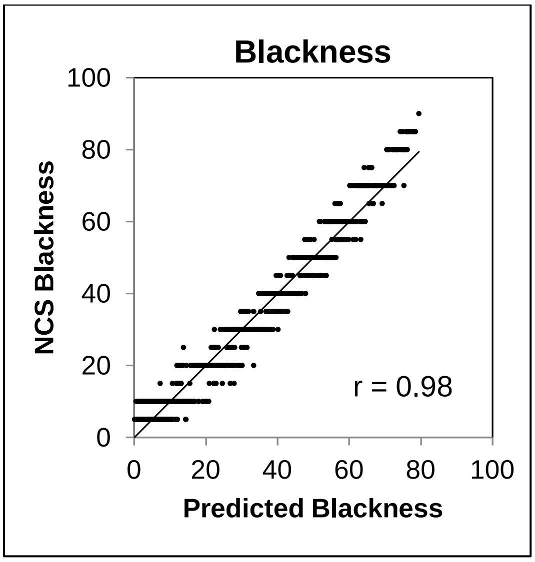
	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
NCS Ellipsoid Blackness_CIELAB	100.09	-1.22	1.49	0.56	13	-2	16	0.98	3.97	11.2
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
NCS Ellipsoid Blackness_CIECAM02	99.14	-1.10	1.58	0.88	0	-2	5	0.98	4.31	12.1
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
NCS Ellipsoid Blackness_CAM02-UCS	105.23	-1.27	3.69	2.23	15	-1	3	0.99	3.02	8.5

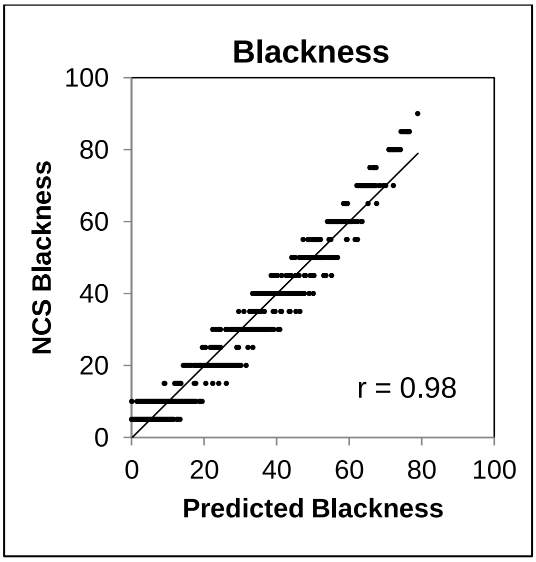
Table 5.55 Parameters of the NCS ellipsoid whiteness models

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
NCS Ellipsoid Whiteness_CIELAB	102.91	-1.40	0.70	0.61	100	4	0	0.98	4.77	10.2
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
NCS Ellipsoid Whiteness_CIECAM02	111.01	-1.30	0.76	1.00	100	3	-6	0.99	3.85	8.3
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
NCS Ellipsoid Whiteness_CAM02-UCS	105.84	-1.46	1.94	2.46	100	0	-2	0.98	4.40	9.4

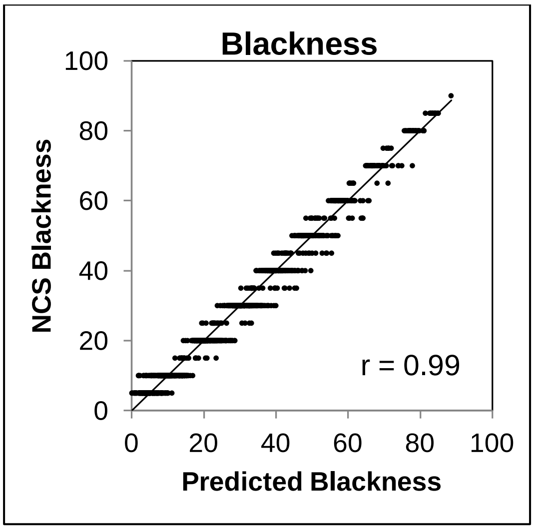
Table 5.56 Parameters of the NCS ellipsoid chromaticness models

	kM	kL	kA	kB	L0*	a0*	b0*	r	RMS	STRESS
NCS Ellipsoid Chromaticness_CIELAB	-0.89	0.14	99.37	60.52	89	0	5	0.97	4.78	12.5
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
NCS Ellipsoid Chromaticness_CIECAM02	-3.33	0.12	122.32	110.36	87	-1	-1	0.98	4.28	11.2
	kM	**kL**	**kA**	**kB**	**J0**	**a0**	**b0**	**r**	**RMS**	**STRESS**
NCS Ellipsoid Chromaticness_CAM02-UCS	-9.82	0.33	58.50	54.65	73	-1	0	0.98	4.39	11.5





(a) (b)



(c)

Figure 5.16 NCS blackness plotted against the predicted value from the NCS ellipsoid blackness model using (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics

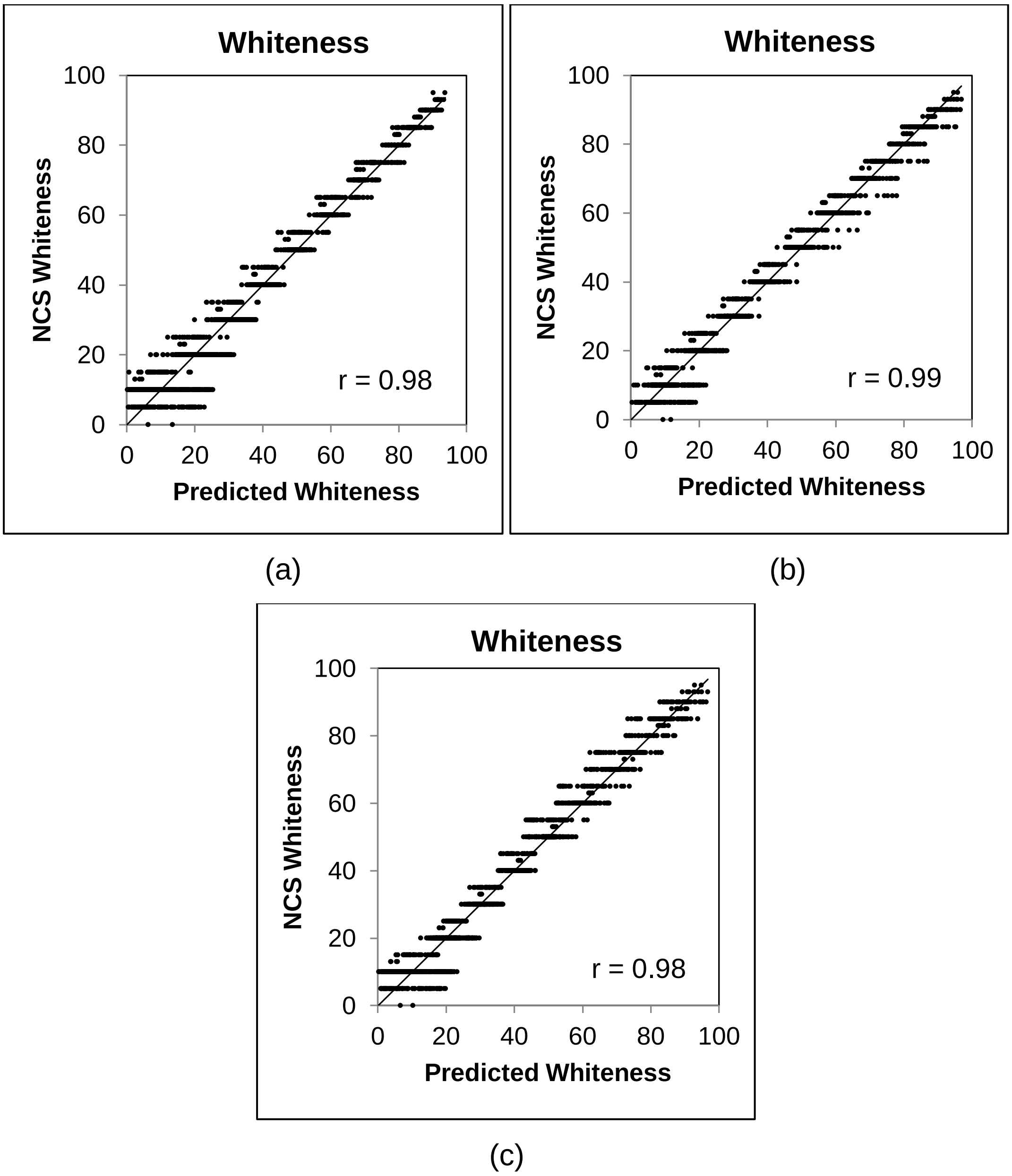


Figure 5.17 NCS whiteness plotted against the predicted value from the NCS ellipsoid whiteness model using (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics

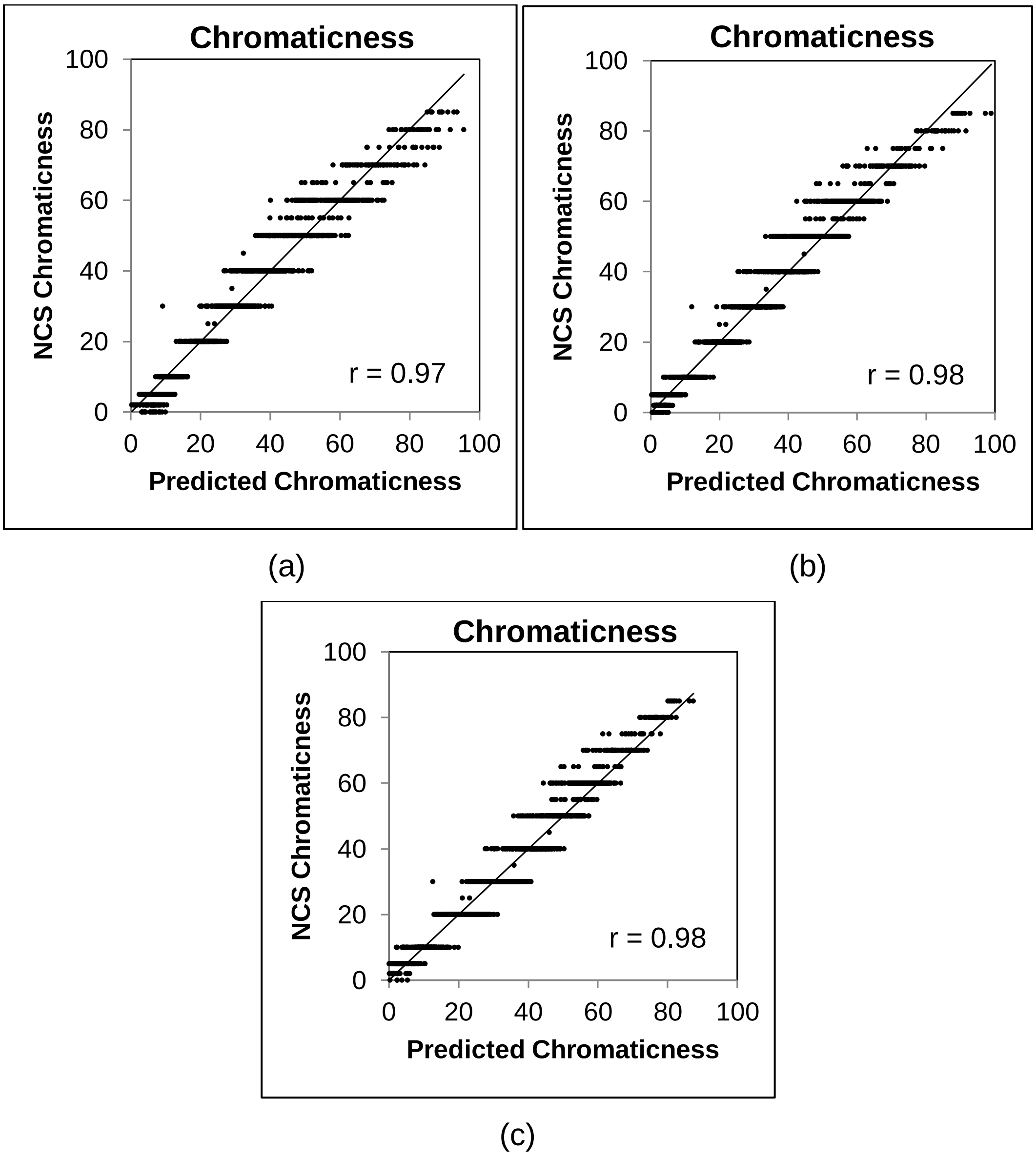


Figure 5.18 NCS chromaticness plotted against the predicted value from the NCS ellipsoid chromaticness model using (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics

5.10 Summary

This chapter described the testing of various available colorimetric models using the present psychophysical data of four attributes: saturation, vividness, blackness and whiteness. New models of the four attributes were developed based on the observer response, as shown in Tables 5.46 to 5.53.

The intra- and inter-observer variability values of the four attributes were compared between observer groups that differed in nationality and in gender. On the whole, the Korean group showed better repeatability and accuracy than the British group. Males and females showed similar repeatability and accuracy. Among the attributes, blackness showed the best repeatability and accuracy. Vividness showed the poorest repeatability and accuracy. This implies that there was uncertainty in scaling vividness, and this may have led to the variability of the visual response. This demonstrates that universal words such as blackness and whiteness (Berlin and Kay, 1969) were easily scaled by observers.

In the Tao *et al*. and Ou *et al.* studies, they compared the results of different cultural groups to check whether there were any cultural differences. In terms of a correlation coefficient, they found no cultural differences between cultural groups. In the present study, the visual results of two cultural groups (British and Korean) for each attribute were compared. There were little differences found by plotting saturation or vividness data between the two groups. This implies that, for the two groups, there may be some cultural effect. However, they agreed well with each other having correlation coefficient as high as 0.8. Hence, both sets of data (i.e. the British and Korean data) were combined to develop a universal model for saturation, vividness, blackness and whiteness as shown in Tables 5.47, 5.49, 5.51 and 5.53.

The relationship between the observer responses for the four attributes and the colour appearance attributes in three colour spaces (CIELAB, CIECAM02 and CAM02-UCS) were explored. Some existing models, such as Berns (see equation (2-16) and 2010) were tested using the present experimental data. It was found that, in general, all Berns' models, except the Berns' vividness (V_{ab}^{*}) attribute, fitted well with the visual results. Berns' depth (D_{ab}^{*}) agreed well with the visual result of saturation. The visual result for vividness agreed well with Berns' clarity (T_{ab}^{*}) rather than Bern' vividness (V_{ab}^{*}). Berns' depth (D_{ab}^{*}) and vividness (V_{ab}^{*}) fitted to the present reverse directions of blackness and whiteness results respectively. This verifies his definitions that depth and vividness are the degrees of departure from white and black, respectively. His vividness is different from the present results here. It seems that his clarity scale agrees better to the current vividness results. The present blackness and whiteness responses associated well with the lightness of the three metrics (CIELAB, CIECAM02 and CAM02-UCS). These results imply that the visual result obtained from observers that are naive to colour can fit other published models.

A cultural difference was found between the British and Korean groups. In the British group, almost all the attributes in terms of CIELAB, CIECAM02 and CAM02-UCS metrics fitted well with the present saturation response, whereas for the Korean group, only the CIELAB, CIECAM02 and CAM02-UCS lightness and the CIECAM02 saturation fitted well with the saturation response. This implies that the Korean group has less understanding of scaling saturation. This may be due to variable understanding of the concept colour saturation. Nevertheless, for both the British and Korean groups, $S_{ab}*$, Lübbe's S^+ and CIECAM02 saturation attributes were associated well with the visual response for saturation. Also, the visual result for saturation agrees with Juan and Luo's saturation findings that saturation associates well with lightness and colourfulness. This implies that these relationships enable the development of a new saturation model based on data from naive observers without any knowledge of saturation.

The visual results for saturation without the neutral data were better correlated with the attributes than the visual results including the neutral data. This implies that there may be uncertainty in the scaling of the neutral colours for saturation. In other words, neutral colours were difficult to scale in terms of saturation. This may have affected the correlation between the saturation model and the NCS data (see Tables 7.62 and 7.63).

According to the relationship between the visual data and the other attributes, the British observer group was unfamiliar with vividness which did not fit well with the other attributes. This implies that vividness was a new concept for the British observer group. On the other hand, the vividness response for the Korean observer group fitted well with chroma in terms of

CIELAB and CIECAM02 metrics, CIECAM02 coloufulness and Berns' clarity. The vividness response of the Korean group agreed with Kim *et al*.'s findings (2008) that vividness is more closely associated with chroma than lightness. Also, the result supports the statements of Fedorovskaya *et al*. (1997) and Trémeau and Charrier (2000) that vividness is the same concept as colourfulness (see Section 2.4.1.2). Thus, there is a need to develop a new vividness model to represent both observer groups.

The individual difference in assessing saturation was investigated. Among the six subgroups of observers, only one group of British observers agreed well with CIECAM02 saturation. The majority of observers showed different understandings of saturation. Some of them regarded the least saturated colour as white, a light grey or a medium grey. The result suggests that there is a wide diversity in the assessment of saturation, not only between cultural backgrounds, but also between subgroups of the same cultural background. These findings also support the results of Juan and Luo's saturation study. Before the real experiment, they tested observers without any training and found that black is a very saturated colour. Note that, in colour science (CIE, 2004), saturation has been defined as zero for all neutral colours. However, in the real world, people do believe that neutral colours have different degrees of saturation.

Three types of Cho ellipsoid models for the four attributes were developed in CIELAB, CIECAM02 and CAM02-UCS versions. These new models were based on the British, Korean and combined visual data, respectively. The predicted value from each model was highly correlated with the visual results. The RMS values of the models were found to be lower than the inter-observer variability (RMS). This implies that the Cho ellipsoid models performed well. The blackness ellipsoid model suggests that yellowish black should be the reference colour. This means that yellowish black appears less black than other colours. Thus, bluish black appears to be the most black. This finding agrees with the findings of Clonts *et al*.'s (2010) blackness perception study that cyan to bluish blacks are blacker than reddish black. This also agrees with the findings of Haslup *et al*.'s (2013) study that greenish to bluish blacks are perceived to be blacker than yellowish black.

Chapter 6 Development of Models Based on the Adams Equations

6.1 Overview

As described in the previous chapter, a set of models based on the frameworks of colour emotion models, called the ellipsoid models, were developed to reflect novice observer responses to colour appearance. The NCS system has been regarded as an important system in particular for its inclusion of colour appearance attributes, such as whiteness and blackness. One of the aims of this study was to develop colour appearance models that reflect the NCS data. Hence, two new sets of models based on the NCS framework in terms of the Adams equations, called the Cho hue-based and NCS hue-based models, were also developed, as described in this chapter. The new models were developed in a different way to investigate whether the new models based on the Adams equation would perform better than the ellipsoid models. The models were also compared with a new equation recently developed by Luo, Cui and the author (2013, also see Section 6.4) in terms of the STRESS measure (see Section 3.9.5).

6.2 New Cho Hue-based Models Based on the Cho Data

A new model, named the Cho hue-based model, was developed using the frameworks of the Adams equation (see Section 2.4.2) by fitting the predicted values to the experimental results obtained by the present study, in terms of blackness, whiteness and chromaticness attributes. The framework of Adams' equations was used because they were simple and accurate in fitting the NCS data in whiteness, blackness and chromaticness. Chromaticness can be calculated using the following equation:

Chromaticness (denoted by c^+) = 100 - Whiteness (w^+) - Blackness (s^+)

It can be seen that the model predicts the NCS data using CIELAB attributes, such as lightness and chroma.

The Adams equations mentioned in Section 2.4.2 are given in equation (6-1):

$$w^+ = L^* - (C^*_{ab}/C^*_{ab,\ Pure})\cdot L^*_{Pure},$$
$$c^+ = 100\cdot(C^*_{ab}/C^*_{ab,\ Pure}), \qquad (6\text{-}1)$$
$$s^+ = (100 - L^*) - (C^*_{ab}/C^*_{ab,\ Pure})\cdot(100 - L^*_{Pure}),$$

in which

$$w^+ + c^+ + s^+ = 100, \qquad (6\text{-}2)$$

where w^+, c^+ and s^+ are whiteness, chromaticness and blackness, respectively. Here, L^*_{Pure} is the lightness for a colour with the least amount of white for the hue, and $C^*_{ab,\ Pure}$ is the colour with the greatest chroma. The sum of the colour attribute is given in equation (6-2).

Based on the frameworks of Eq. (6-1) and (6-2), the Cho hue-based models were developed in terms of L_p and C_p, as shown in equation (6-3). Table 6.57 lists the parameters of the Cho hue-based models in three versions.

$$L_p = k_0 + k_1\cos(h - h_1) + k_2\cos(2h - h_2) + k_3\cos(3h + h_3) + k_4\cos(4h + h_4), \qquad (6\text{-}3)$$
$$C_p = k_0 + k_1\cos(h - h_1) + k_2\cos(2h - h_2) + k_3\cos(3h + h_3) + k_4\cos(4h + h_4),$$

where L_p and C_p are the predicted lightness and chroma, respectively. L_p and C_p in equation (6-3) were calculated as follows. L_p' and C_p' are the full (pure) colours. Firstly, 'full' colours in terms of L^* and C_{ab}^* values for each of the 40 hue pages were found by minimising the predicted *Cho hue-based Whiteness* $_{CIELAB}$ and *Cho hue-based Blackness* $_{CIELAB}$ to fit the Cho visual data. Then, a sine-wave curve function was optimised using the solver function to fit the full colours (L_p' and C_p') for the L_p and C_p functions, respectively. Figure 6.1 plots the 40 optimised 'full' colours in terms of CIELAB L^* and C_{ab}^* against its hue angle (h). This figure also shows the curves of equation (6-4) in CIELAB space.

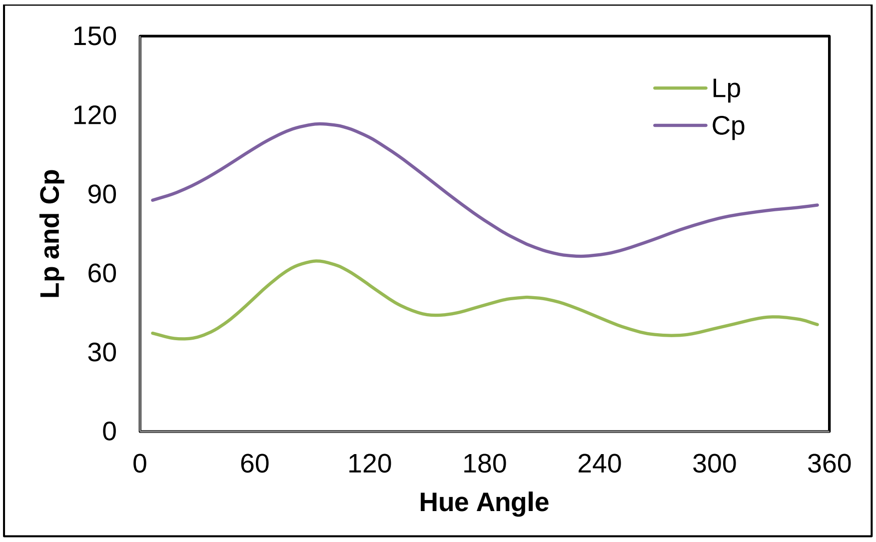


Figure 6.1 Plot of the predicted functions (L_p and C_p)

In the Cho hue-based model, the CIELAB attributes, such as lightness and chroma were used to predict the NCS attributes. There are problems in using this model to transform CIELAB to NCS coordinates. This is because the colour spaces for CIELAB and NCS are different. The CIELAB space is a uniform colour space designed to predict colour difference. However, the NCS space is an appearance colour space designed to describe appearance. The main difference is one uses hue angle and the other uses the hue composition (see Section 2.3.8.2) which is based on unitary hues (pure red, yellow, green and blue). In the latter, for example, an orange colour will have a proportion of yellow 40% and red 60% (denoted as Y60R). In CIELAB, lightness, chroma and hue are three independent attributes. For example, there are two pairs of samples having the same lightness and chroma (zero difference in lightness and chroma) say a blue pair and a red pair. If two pairs have the same hue angle difference the perceived difference will be the same. If they have the same hue composition difference, the perceived difference could be different.

The new models were developed in terms of CIELAB, CIECAM02 and CAM02-UCS metrics using the Cho data. The three colorimetric versions were developed because the attributes of these versions are the basic attributes of colour spaces and colour appearance models. The model performance of these three versions will be compared in Chapter 7. The Cho data are the observer response data from experiments 1 to 3, and they were averaged between the British and Korean data. The parameters were calculated by optimising the correlation coefficient (r) between the Cho data and the predicted value from the model. Table 6.57 shows the parameters of the Cho hue-based models in three versions. The r values between the observer response data fitted well to the models with correlation coefficients ranging from 0.83 to 0.94. The Cho hue-based blackness model fitted very well with the Cho data. Figures 6.2 and 6.3 plot the visual data against the model predictions for whiteness and blackness attributes, respectively. They show that both models were linearly correlated with the visual data.

Table 6.57 Parameters of Cho hue-based models

Version		k_0	k_1	k_2	k_3	k_4	h_1	h_2	h_3	h_4
CIELAB	***Lp***	45.86	8.35	-3.58	6.97	1.17	123	4	-90	-8
	Cp	88.94	21.02	-7.62	1.04	0.25	80	41	-118	8
CIECAM02	***Jp***	45.95	12.03	-5.15	4.59	1.87	106	-13	-123	-29
	Cp	76.27	-4.93	-7.64	0.38	0.95	-2	-74	-129	-24
CAM02-UCS	***Jp***	39.66	7.60	-4.14	6.60	1.23	105	-4	-124	-65
	Cp	86.09	3.26	-6.70	-1.52	0.16	19	-74	-113	8

The new Cho hue-based models in the CIELAB metric are given as:

$\textit{CHO hue-based Whiteness}_{CIELAB} = L^* - (C_{ab}^*/C_{p\_CIELAB})L_{p\_CIELAB}$,

$\textit{CHO hue-based Blackness}_{CIELAB} = (100 - L^*) - (C_{ab}^*/C_{p\_CIELAB})(100 - L_{p\_CIELAB})$,

$\textit{CHO hue-based Chromaticness}_{CIELAB} = 100(C_{ab}^*/C_{p\_CIELAB})$,

where (6-4)

$$L_{p\_CIELAB} = 45.86 + 8.35\cos(h_{ab} - 123) - 3.58\cos(2h_{ab} - 4) + 6.97\cos(3h_{ab} - 90) + 1.17\cos(4h_{ab} + 8),$$

$$C_{p\_CIELAB} = 88.94 + 21.02\cos(h_{ab} - 80) - 7.62\cos(2h_{ab} - 41) + 1.04\cos(3h_{ab} + 118) + 0.25\cos(4h_{ab} - 8).$$

The new Cho hue-based models in the CIECAM02 metric are given as:

$CHO\ hue\text{-}based\ Whiteness_{\ CIECAM02} = J - (C/C_{p\_CIECAM02})J_{p\_CIECAM02}$,
$CHO\ hue\text{-}based\ Blackness_{\ CIECAM02} = (100 - J) - (C/C_{p\_CIECAM02})(100 - J_{p\_CIECAM02})$,
$CHO\ hue\text{-}based\ Chromaticness_{\ CIECAM02} = 100(C/C_{p\_CIECAM02})$,

where (6-5)

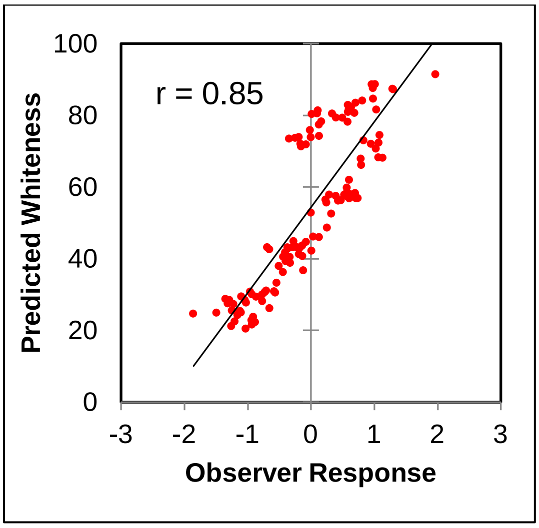
$J_{p\_CIECAM02} = 45.95 + 12.03\cos(h - 106) - 5.15\cos(2h + 13)$
$+ 4.59\cos(3h + 123) + 1.87\cos(4h + 29)$,
$C_{p\_CIECAM02} = 76.27 - 4.93\cos(h + 2) - 7.64\cos(2h + 74)$
$+ 0.38\cos(3h + 129) + 0.95\cos(4h + 24)$.

The new Cho *hue-based* models in the CAM02-UCS metric are given as:

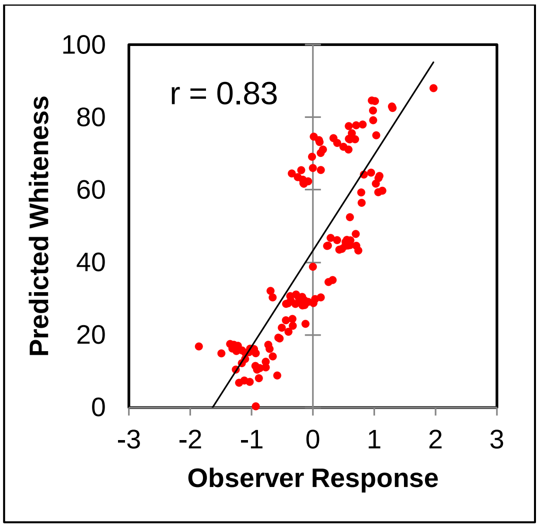
$CHO\ hue\text{-}based\ Whiteness_{CAM02\text{-}UCS} = J' - (C/C_{p\_CAM02\text{-}UCS})J_{p\_CAM02\text{-}UCS}$,
$CHO\ hue\text{-}based\ Blackness_{\ CAM02\text{-}UCS} = (100 - J') - (C/C_{p\_CAM02\text{-}UCS})(100 - J_{p\_CAM02\text{-}UCS})$,
$CHO\ hue\text{-}based\ Chromaticness_{\ CAM02\text{-}UCS} = 100(C/C_{p\_CAM02\text{-}UCS})$,

where (6-6)

$J_{p\_CAM02\text{-}UCS} = 39.66 + 7.6\cos(h - 105) - 4.14\cos(2h + 4)$
$+ 6.6\cos(3h + 124) + 1.23\cos(4h + 65)$,
$C_{p\_CAM02\text{-}UCS} = 86.09 + 3.26\cos(h - 19) - 6.7\cos(2h + 74)$
$- 1.52\cos(3h + 113) + 0.16\cos(4h - 8)$.



(a)



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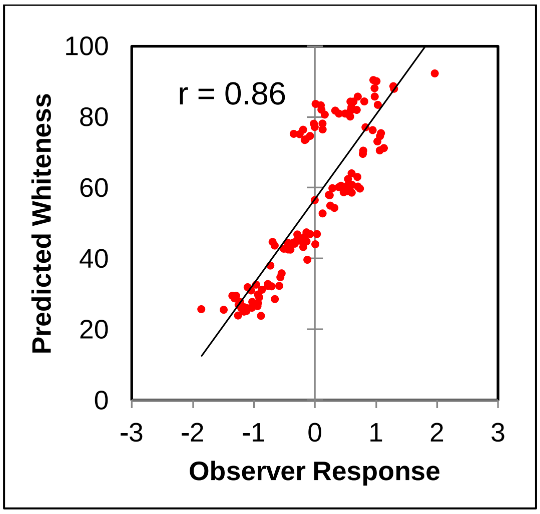
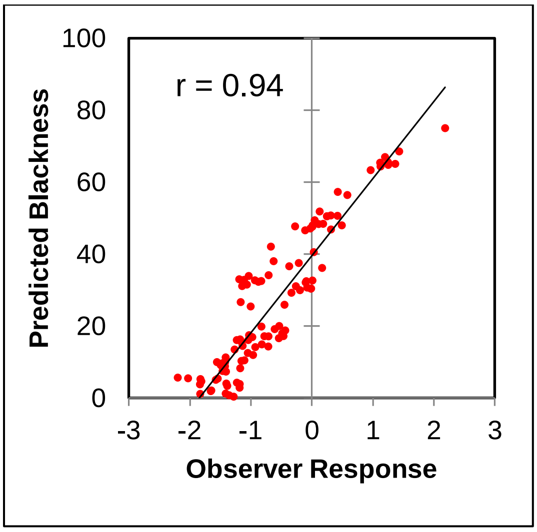
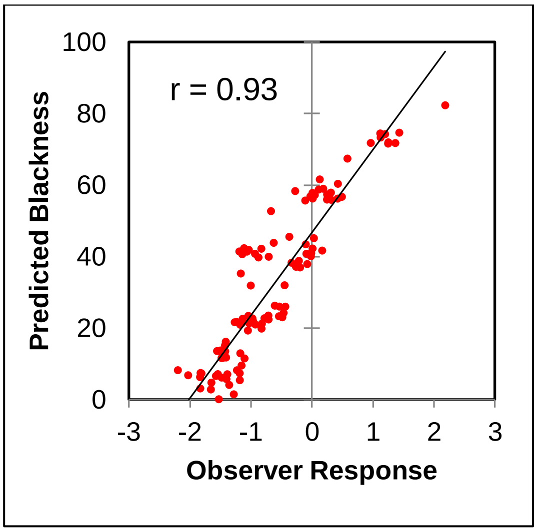


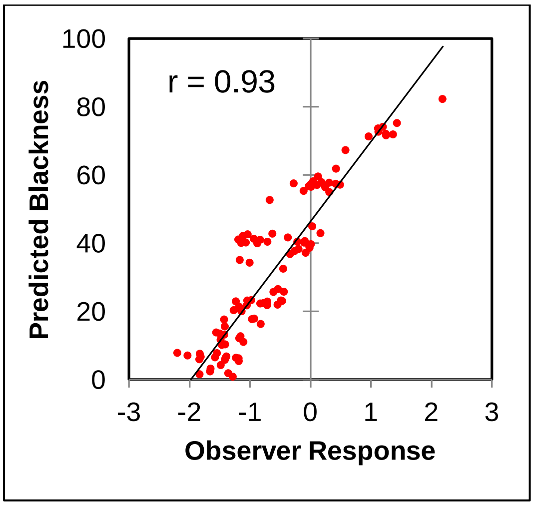
(c)

Figure 6.2 Observer responses plotted against the predicted value from the Cho hue-based whiteness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions





(a) (b)



(c)

Figure 6.3 Observer responses plotted against the predicted value from the Cho hue-based blackness model in the (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions

6.3 New NCS Hue-based Models Based on the NCS Data

Another set of models (called "the NCS hue-based model") were developed based on NCS data consisting of 1,749 samples (see Section 5.8). Three colour appearance attributes were developed based on the NCS whiteness, blackness and chromaticness attributes. New NCS whiteness (*W*), blackness (*B*) and chromaticness (*Ch*) attributes were developed on the basis of the Cho hue-based models as described in equations (6-4) to (6-6) in Section 6.2. Table 6.58 shows the parameters of NCS hue-based models in three versions.

Table 6.58 Parameters of NCS hue-based models

Version		k_0	k_1	k_2	k_3	k_4	h_1	h_2	h_3	h_4
CIELAB	***Lp***	60.25	12.62	-5.79	4.14	1.36	123	4	-90	-9
	Cp	72.93	15.26	-8.63	3.02	1.54	80	42	-118	8
CIECAM02	***Jp***	47.09	13.00	-6.01	4.69	1.49	106	-13	-123	-29
	Cp	74.43	-4.60	-7.54	0.85	0.99	-2	-74	-129	-24
CAM02-UCS	***Jp***	65.22	9.97	-4.75	4.65	1.08	107	-4	-123	-65
	Cp	43.57	-2.69	-3.39	1.00	0.52	19	-74	-113	8

The new NCS hue-based models in the CIELAB metric are given as:

$$\textit{NCS hue-based Whiteness}_{CIELAB} = L^* - (C_{ab}^*/C_{p\_CIELAB})L_{p\_CIELAB},$$
$$\textit{NCS hue-based Blackness}_{CIELAB} = (100 - L^*) - (C_{ab}^*/C_{p\_CIELAB})(100 - L_{p\_CIELAB}),$$
$$\textit{NCS hue-based Chromaticness}_{CIELAB} = 100(C_{ab}^*/C_{p\_CIELAB}),$$

where (6-7)

$$L_{p\_CIELAB} = 60.25 + 12.62\cos(h_{ab} - 123) - 5.79\cos(2h_{ab} - 4) + 4.14\cos(3h_{ab} + 90) + 1.36\cos(4h_{ab} + 9),$$
$$C_{p\_CIELAB} = 72.93 + 15.26\cos(h_{ab} - 80) - 8.63\cos(2h_{ab} - 42) + 3.02\cos(3h_{ab} + 118) + 1.54\cos(4h_{ab} - 8).$$

NCS hue-based Whiteness$_{CIELAB}$, *NCS hue-based Blackness*$_{CIELAB}$ and *NCS hue-based Chromaticness*$_{CIELAB}$ are the whiteness, blackness and chromaticness attributes, respectively. L^* and C_{ab}^* are the CIELAB lightness and chroma of the test colour. L_p' and C_p' are the lightness and chroma of the 'full colour' (see Figure 6.4), which are the functions of CIELAB hue angles (h).

L_p and C_p in equation (6-7) were calculated in the same way as the predicted L_p and C_p in the Cho hue-based model mentioned in Section 6.2. L_p and C_p are the predicted lightness and chroma, respectively. Figure 6.4 plots the 40 optimised 'full' colours (L_p and C_p) in CIELAB space against its hue angle (h) and the full (pure) colours (Lp' and Cp'). It shows that both curves fit the data well, and the maximum L_p value of the 'full' colour is located in the yellow region.

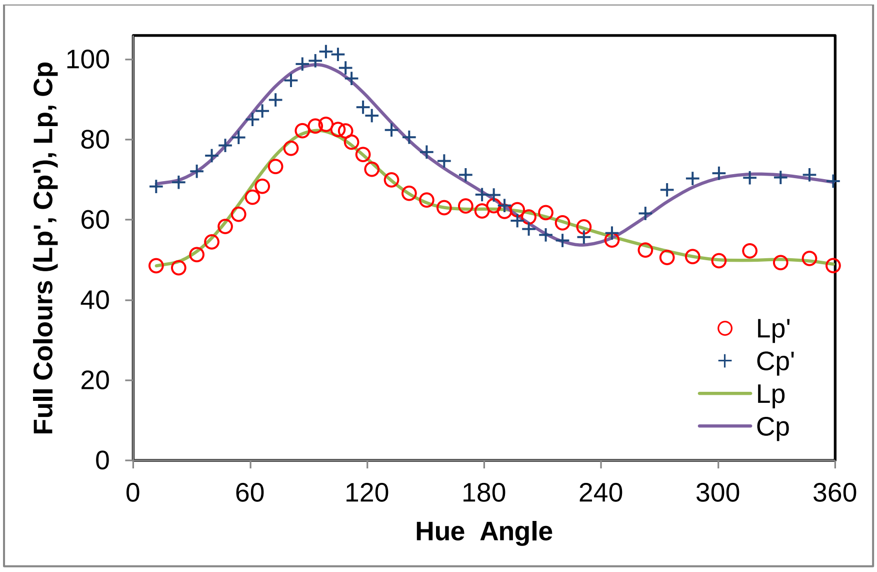


Figure 6.4 Plot of full colours (L_p' and C_p'), and L_p and C_p functions, respectively

The new NCS hue-based models in the CIECAM02 metric are given as:

NCS hue-based Whiteness $_{CIECAM02}$ = J - ($C/C_{p\_CIECAM02}$)$J_{p\_CIECAM02}$,
NCS hue-based Blackness $_{CIECAM02}$ = (100 - J) - ($C/C_{p\_CIECAM02}$)(100 - $J_{p\_CIECAM02}$),
NCS hue-based Chromaticness $_{CIECAM02}$ = 100($C/C_{p\_CIECAM02}$),

where (6-8)

$J_{p\_CIECAM02}$ = 47.09 + 13.00cos(h-106) - 6.01cos(2h+13)
+4.69cos(3h+123)+1.49cos(4h+29),

$C_{p\_CIECAM02}$ = 74.43 - 4.60cos(h+1.56) - 7.54cos(2h+74)
+0.85cos(3h+128)+0.99cos(4h+24).

NCS hue-based Whiteness $_{CIECAM02}$, *NCS hue-based Blackness* $_{CIECAM02}$ and *NCS hue-based Chromaticness* $_{CIECAM02}$ are the whiteness, blackness and chromaticness attributes, respectively. J and C are the CIECAM02 lightness and chroma of the test colour. J_p and C_p are the lightness and chroma of the 'full colour', which are the functions of CIECAM02 hue angles (h).

The new NCS hue-based models in the CAM02-UCS metric are given as:

$NCS\ hue\text{-}based\ Whiteness_{\ CAM02\text{-}UCS} = J' - (C/C_{p\_CAM02\text{-}UCS})J_{p\_CAM02\text{-}UCS}$,
$NCS\ hue\text{-}based\ Blackness_{\ CAM02\text{-}UCS} = (100 - J') - (C/C_{p\_CAM02\text{-}UCS})(100 - J_{p\_CAM02\text{-}UCS})$,
$NCS\ hue\text{-}based\ Chromaticness_{\ CAM02\text{-}UCS} = 100(C/C_{p\_CAM02\text{-}UCS})$,

where (6-9)

$$J_{p\_CAM02\text{-}UCS} = 65.22 + 9.97\cos(h - 107) - 4.75\cos(2h + 4) + 4.69\cos(3h + 123) + 1.08\cos(4h + 65),$$

$$C_{p\_CAM02\text{-}UCS} = 43.57 - 2.69\cos(h - 19) - 3.39\cos(2h + 74) + 1.00\cos(3h + 113) + 0.52\cos(4h - 8).$$

NCS hue-based Whiteness $_{CAM02\text{-}UCS}$, *NCS hue-based Blackness* $_{CAM02\text{-}UCS}$ and *NCS hue-based Chromaticness* $_{CAM02\text{-}UCS}$ are the whiteness, blackness and chromaticness attributes, respectively. J' and C are the CAM02-UCS lightness and chroma of the test colour. J_p' and C_p' are the lightness and chroma of the 'full colour', which are the functions of CAM02-UCS hue angles (h).

Figures 6.5 to 6.7 show the plots of the NCS data against the predicted value from the model. It shows that the predicted value from all the models fitted the NCS data very well with the high r values of 0.98 to 0.99.

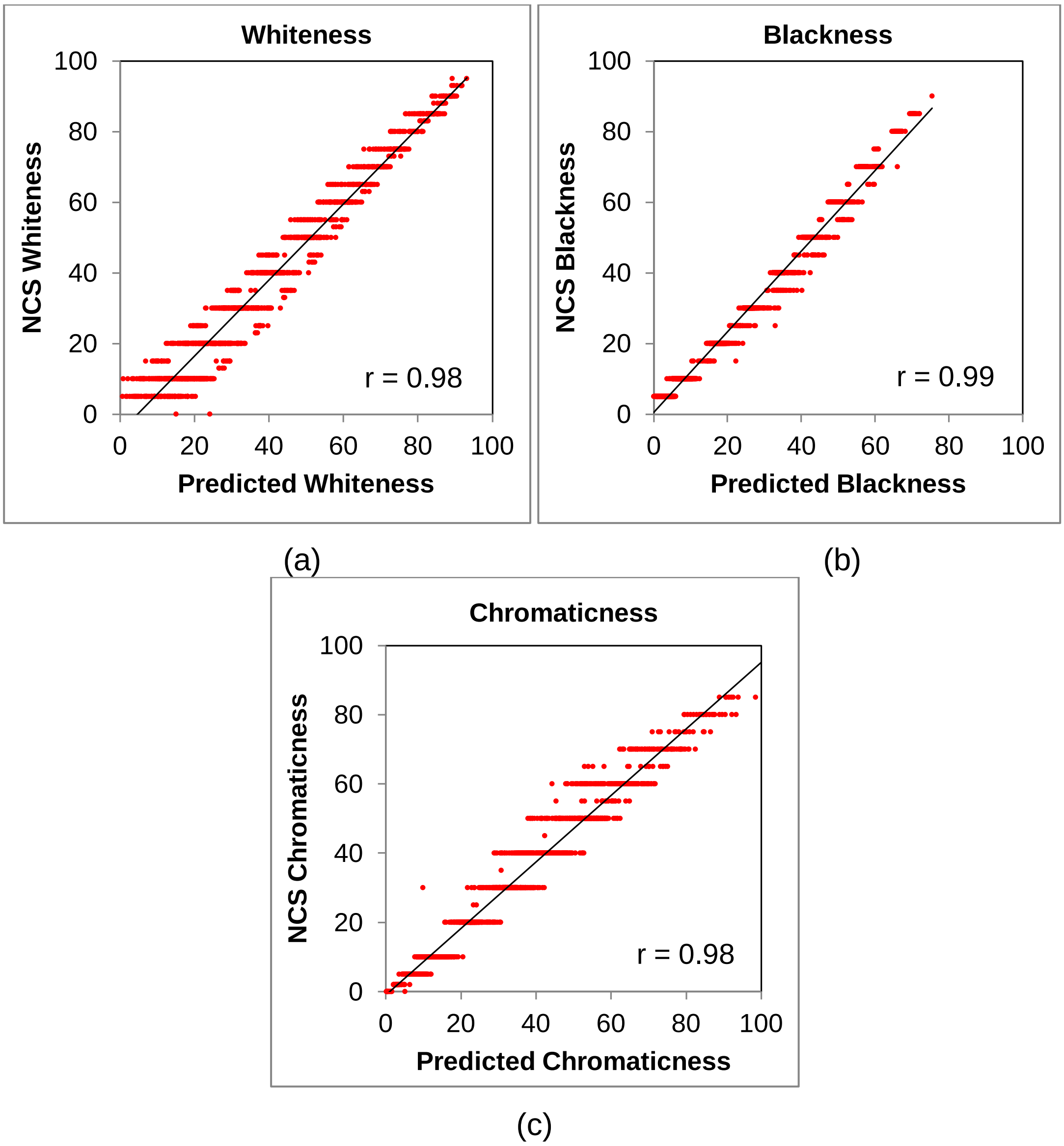
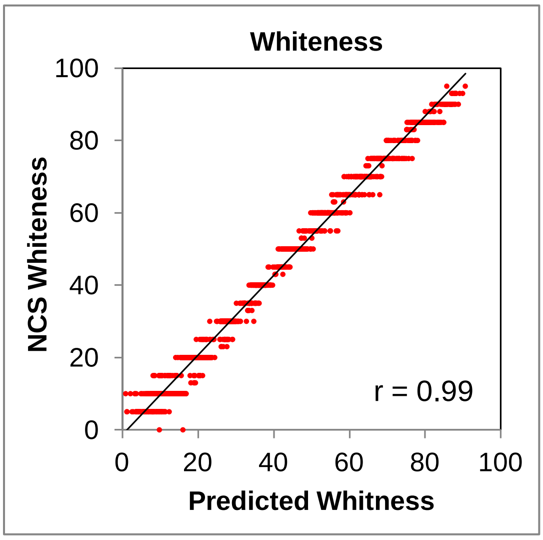
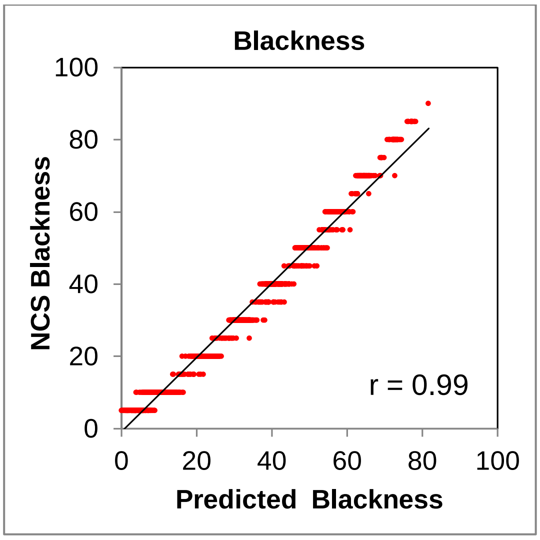


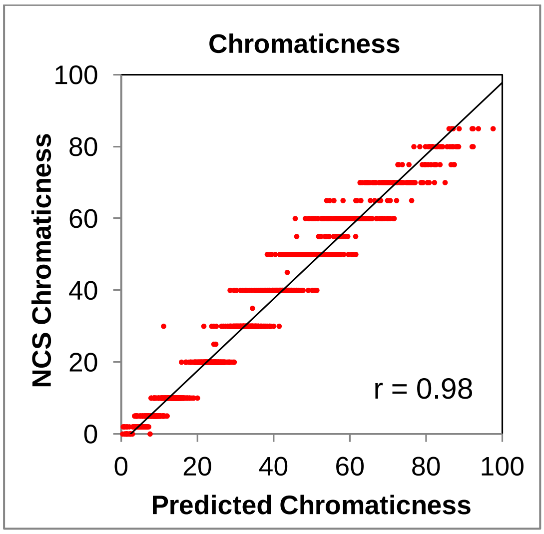
Figure 6.5 NCS data plotted against the predicted value from the NCS hue-based model in the CIELAB metric



(a)

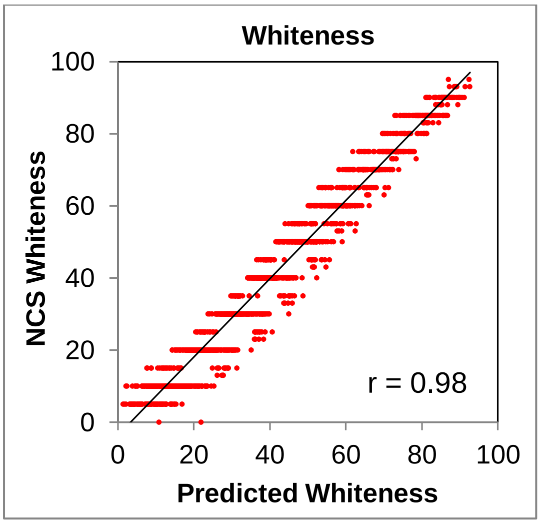


(b)

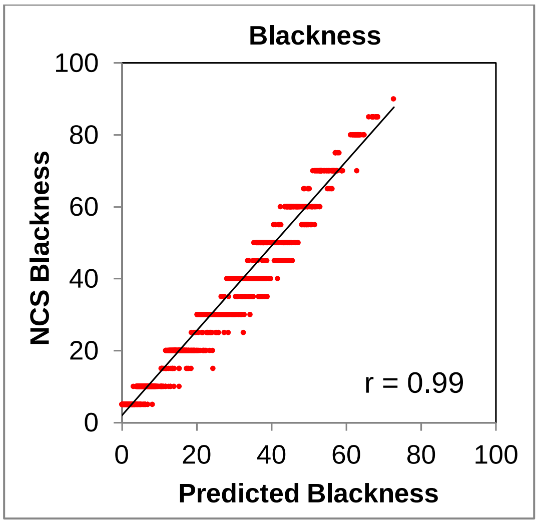


(c)

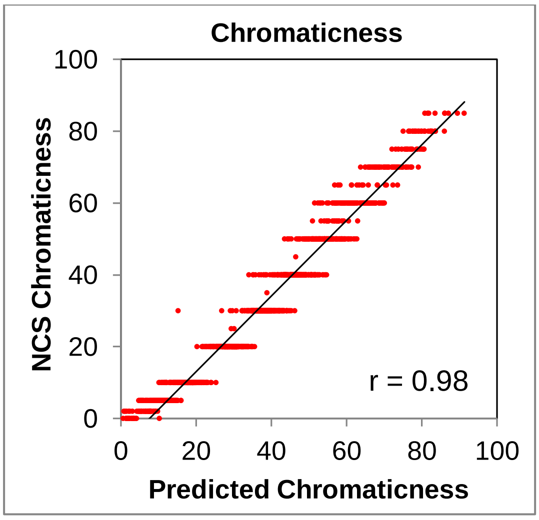
Figure 6.6 NCS data plotted against the predicted value from the NCS hue-based model in the CIECAM02 metric



(a)



(b)



(c)

Figure 6.7 NCS data plotted against the predicted value from the NCS hue-based model in the CAM02-UCS metric

6.4 Predictive Performance of the New Models

In this section, Luo, Cui and the author were involved in this project. The author contributed to the modelling of the NCS data using both Adams and ellipsoid models. The author also contributed to developing the Cho model and analysing the STRESS results. New blackness and whiteness models were derived based on the author's ellipsoid model shown in equation (6-10). These models and the NCS hue-based models, which are based on the NCS data, were compared to investigate their performance in terms of

STRESS (see Section 3.9.5). Also, different versions of NCS hue-based models were compared together.

The new NCS blackness (s) and whiteness (w) models are

$$s = 110.00 - 0.78\sqrt{2.44(\mathrm{J})^2 + 3.86(\mathrm{a} + 1.83)^2 + 2.15(\mathrm{b} - 4.95)^2} \quad (6\text{-}10)$$

$$w = 110.96 - 1.18\sqrt{1.20(J - 100)^2 + 0.91(a - 2.92)^2 + 1.20(b + 6.47)^2}$$

where *J*, *a* and *b* are the CIECAM02 lightness, redness-greenness, yellowness- blueness, respectively. Chromaticness is calculated by 100-*w*-*s*, which is defined by the NCS.

The equations are in the form of ellipsoid colour-difference formulae. The colour centres, in terms of J, a, and b values, for the two attributes were defined as the least white or the least black colours. This means that the further the colour departs from the colour centre, the whiter (or blacker) it appears.

It should be noted that the colour centre of whiteness is a bluish tinted white [J=100, a=2.92, b=-6.47]. This seems to agree with the visual phenomenon that a bluish white appears whiter than a tinted white having the same lightness. However, the blackness model did not seem to agree with previous findings (e.g. Tao *et al*. 2011 and Cho *et al*. 2012); the latter found that a bluish black appeared blacker than the other tinted blacks having the same lightness. A CAM02-UCS version of equation (6-10) is

$$s = 115.71 - 1.35\sqrt{0.76(\mathrm{J}')^2 + 3.68(\mathrm{a}' + 0.87)^2 + 2.19(\mathrm{b}' - 3.69)^2}, \quad (6\text{-}11)$$

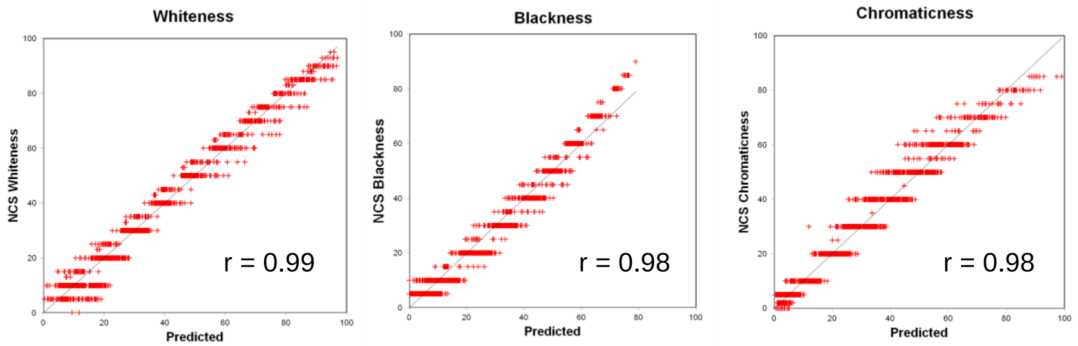
$$\mathrm{w} = 105.06 - 1.61\sqrt{0.82(\mathrm{J}' - 100)^2 + 1.60(\mathrm{a}' - 1.00)^2 + 2.02(\mathrm{b}' + 2.02)^2}.$$

Table 6.59 shows the models' performance at fitting the NCS data in terms of STRESS (García, 2007, see Section 3.9.5). The NCS hue-based models in CIECAM02 and CAM02-UCS versions are the equations (6-8) and (6-9) of Section 6.3, respectively. The simplified Lp and Cp of the NCS hue-based model in CIECAM02 and CAM02-UCS versions are simplified by using a constant for J_p and for C_p in CIECAM02 and CAM02-UCS space. The values of J_p and C_p for CIECAM02 space are 79 and 53.3, respectively. For CAM02-UCS space, J_p and C_p are 45.4 and 70.3, respectively. Table 6.59 shows that the NCS hue-based model of the CIECAM02 version outperforms other models. The simplified versions of the NCS hue-based model performed much worse than the full versions. Comparing the CAM02-UCS models, the Cho ellipsoid models performed the best. In general, the NCS hue-based models performed the best for both CIELAB and CIECAM02, respectively. This indicates that, although CAM02-UCS is modified from CIECAM02, the features of the colour spacing of the two models are different considering the full colours along the hue range.

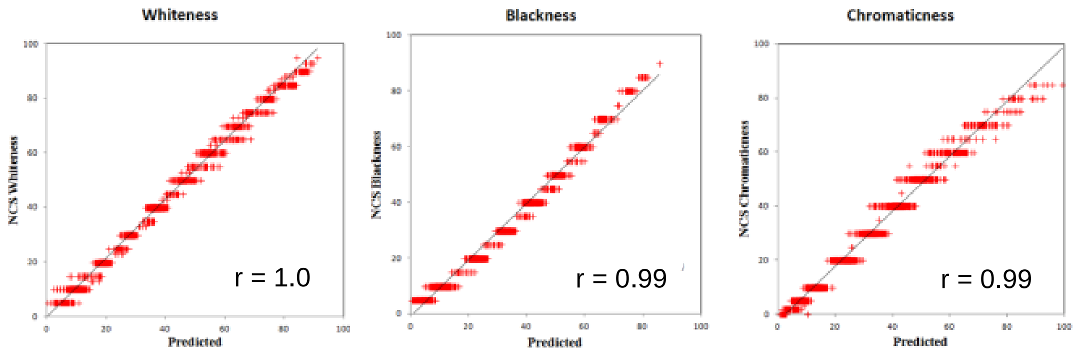
In Figure 6.8, the predictions of models in the CIECAM02 version are plotted against the NCS whiteness, blackness and chromaticness, respectively. It can be seen that the NCS hue-based models show the least scatter. CIECAM02 is preferred over CAM02-UCS. It performs better, and it is the basis of the comprehensive colour appearance model, rather than the development of new attributes from its derivation. Consequently, the NCS hue-based model of the CIECAM02 version was proposed due its superior performance in comparison with other models.

Table 6.59 Summary of the models' performance for blackness, whiteness and chromaticness attributes in terms of STRESS

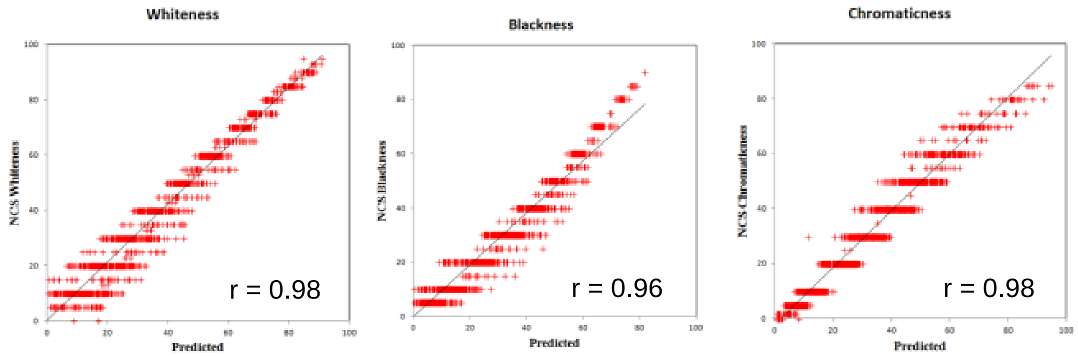
		Blackness	Whiteness	Chromaticness	Mean
CIELAB version	NCS ellipsoid model	11.2	10.2	12.5	11.3
	NCS hue-based model	7.6	12.1	10.4	10.0
CIECAM02 version	NCS ellipsoid model	12.1	8.3	11.2	10.5
	NCS hue-based model	8.7	6.1	10.3	8.4
	Simplified Lp and Cp of NCS hue-based model	15.9	11.8	12.2	13.3
	Equation (6-10)	12.1	8.3	20.2	13.5
CAM02-UCS version	NCS ellipsoid model	8.5	9.4	11.5	9.8
	NCS hue-based model	10.3	10.9	14.2	11.8
	Simplified Lp and Cp of NCS hue-based model	17.4	13.5	15.7	15.5
	Equation (6-11)	8.7	9.5	16.0	11.4



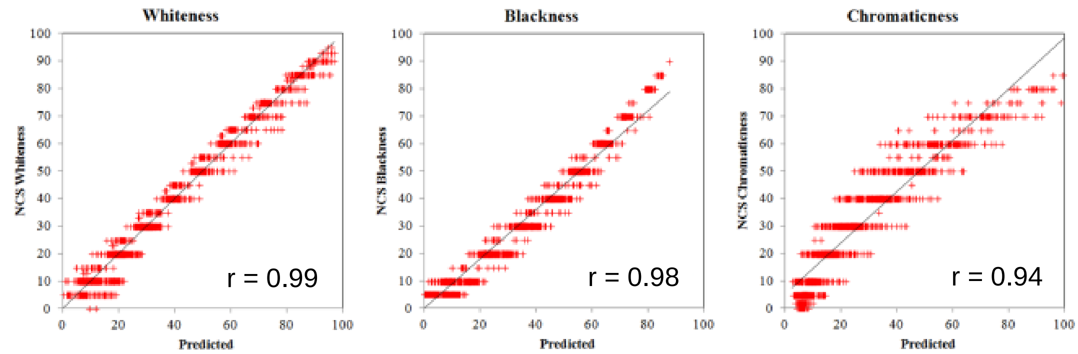
NCS ellipsoid model



NCS hue-based model



Simplified *Lp* and *Cp* of NCS hue-based model



Equation (6-10)

Figure 6.8 Plots of NCS visual data against predictions from the CIECAM02-based models

The performance of all models was compared in terms of correlation coefficient (r). This was to see how well each model fitted to its corresponding data in terms of r value. Tables 6.60 and 6.61 show the models' performance in terms of r. In general, all of the models agreed very well with the fitted data. Among the Cho models, the Cho blackness model performed the best. This indicates that the blackness model agrees very well with the blackness visual data. All of the NCS models performed very well with the NCS data. The three model versions (i.e. CIELAB, CIECAM02 and CAM02-UCS version) of the Cho and NCS models seemed to have similar performance.

Table 6.60 Summary of the models' performance for Cho ellipsoid and Cho hue-based models in terms of r

r		Cho saturation	Cho saturation (no neutral)	Cho vividness	Cho blackness	Cho whiteness
CIELAB version	Cho ellipsoid model	0.86	0.86	0.82	0.91	0.84
	Cho hue-based model				0.94	0.85
CIECAM02 version	Cho ellipsoid model	0.85	0.85	0.81	0.91	0.83
	Cho hue-based model				0.93	0.83
CAM02-UCS version	Cho ellipsoid model	0.86	0.86	0.81	0.92	0.85
	Cho hue-based model				0.93	0.86

Table 6.61 Summary of the models' performance for NCS ellipsoid and NCS hue-based models in terms of r

r		NCS blackness	NCS whiteness	NCS chromaticness
CIELAB version	NCS ellipsoid model	0.98	0.98	0.97
	NCS hue-based model	0.99	0.98	0.98
CIECAM02 version	NCS ellipsoid model	0.98	0.99	0.98
	NCS hue-based model	0.99	0.99	0.98
CAM02-UCS version	NCS ellipsoid model	0.99	0.98	0.98
	NCS hue-based model	0.99	0.98	0.98

6.5 Summary

Two sets of new models (i.e. the NCS hue-based and Cho hue-based models) based on the Adams equation were developed. The main difference between these new models and the ellipsoid models described in Chapter 5 is that the models based on the Adams equation are aimed to predict the NCS attributes, while the ellipsoid models are aimed to predict the observer response in terms of colour appearance. The latter (i.e. the ellipsoid models) were in the form of a colour difference formula that calculates the distance between a reference colour and the test colour.

An advantage of using the Adams equations is that they can easily convert the CIELAB lightness and chroma values to the NCS blackness and whiteness values. The predicted blackness and whiteness values can then be used to calculate NCS chromaticness values.

The main disadvantage of the Adams equations, however, is that they were not based on psychophysical experiments and they did not describe how to obtain L_p and C_p. For this reason in the new sets of models, as described in this chapter, L_p and C_p were defined as functions of CIELAB hue angles and were obtained from a particular experimental dataset. Lightness varies across different hue angles in CIELAB space. This hue effect is especially strong for highly saturated colours. For example, yellow with a high chromaticness has a high lightness, whereas blue with a high chromaticness has a low lightness. Thus, to convert CIELAB lightness and chroma to the NCS attributes requires the hue angle as a variable.

The new sets of models developed on the basis of both the Adams equations and the hue effect, as described in this chapter, were compared with those developed recently by Luo, Cui and the author (2013, also see Section 6.4) to investigate the predictive performance of the new models. These models were compared to the NCS data. The NCS hue-based models were found to perform best among all of the models tested (see Table 6.59). Of the two versions of the hue-based models, the CIECAM02 version was found to perform better as shown in Table 6.59. To determine the real predictive performance of these three versions of the models, however requires the use of an independent data set in the test, as will be described in the next chapter.

Chapter 7 Testing Models Using Independent Data Sets

7.1 Overview

In the previous two chapters, 4 types of new models (i.e. the Cho ellipsoid, NCS ellipsoid, Cho hue-based, and NCS hue-based models) were developed. The developed models needed to be tested with an independent data set to verify that these models are generally applicable.

The new models were tested to investigate their performance by using different data sets. This means that these models were tested using their counterparts. The Cho ellipsoid and Cho hue-based models were tested using the NCS data set, while the NCS ellipsoid and NCS hue-based models were tested using the visual results (the Cho data) obtained from the experiments. Note that there are two independent datasets here, one is from the present study and the other is from the NCS data. Although the present data were accumulated using the NCS samples, they are completely independent. For NCS data (as described in Section 2.3.8.2) such as the NCS blackness, whiteness and chromaticness, these were based on the work carried out at the Scandinavian Colour Institute many years ago. The visual data in the present study are obtained from the British and Korean observers. So, they are independent data sets.

The ellipsoid models that were fitted to the visual data (the Cho ellipsoid model) and to the NCS data (the NCS ellipsoid model) were compared. Also, the Cho hue-based and NCS hue-based models were compared. These comparisons were made to investigate the agreement between them.

7.2 Testing Cho Ellipsoid and Cho Hue-based Models Using the NCS Data

As mentioned in Section 2.3.8, the Natural Colour System (NCS) is arguably the most widely used colour atlas system for colour design and colour communication. It includes three unique attributes: whiteness, blackness and chromaticness. It is interesting to compare these attributes with the newly developed models to evaluate the predictive performance of the models. The Cho ellipsoid models were tested using 1,749 NCS data. The Cho ellipsoid saturation and vividness models were tested with the NCS chromaticness data, the Cho ellipsoid blackness models were tested with the NCS blackness data, and the Cho ellipsoid whiteness models were tested with the NCS whiteness data. Pearson's correlation coefficients were calculated to indicate the agreement between the predicted model and the NCS data. Tables 7.62 to 7.66 show the results in terms of correlation coefficients. Also, Figures 7.9 to 7.13 show the scatter plots between the NCS data and the predicted values from the model. It was found that almost all the model predictions correlated well with the NCS data except for the vividness model in the CAM02-UCS version.

Tables 7.62 and 7.63 show the tested results of the Cho ellipsoid saturation models. The models in Table 7.62 are the Cho ellipsoid saturation models, developed using the visual data including neutral data. The recommended models (see Section 5.8) in Table 7.63 are the Cho ellipsoid saturation models, developed using the visual data excluding neutral data. The saturation model developed without neutral data correlated with the NCS chromaticness data better than the saturation model developed with neutral data. This indicates that neutral colours were hard for observers to scale in terms of saturation. This may have influenced the model predictions of saturation.

Figures 7.9 to 7.11 show that the low chromaticness data do scatter more than the high chromaticness data. This implies that the chromaticness attribute has quite different characteristics compared to saturation and vividness attributes. It is not frequently used to describe the third dimensional scale.

The results show that all of the predicted values from the Cho ellipsoid blackness models correlated very well with the NCS blackness data for all three versions (CIELAB, CIECAM02 and CAM02-UCS) with the correlation coefficient value of 0.97. It was also found that the NCS whiteness data correlated very well with the Cho ellipsoid whiteness model predictions with correlation coefficient values ranging from 0.92 to 0.96. Figures 7.12 and 7.13 show that the predicted blackness and whiteness data are aligned on a diagonal line. According to the tested results, saturation and vividness showed lower correlation than blackness and whiteness. This may be because of high errors in intra- and inter-observer variability (see Tables 5.33 and 5.34).

Among the three colorimetric versions (e.g. CIELAB, CIECAM02 and CAM02-UCS) the models in the CIECAM02 version show the highest correlation with the NCS data. The figures show that the predicted data in the CIECAM02 version are less scattered and are more linearly plotted than the other versions of the data.

Table 7.62 Correlation coefficients (r) calculated between NCS chromaticness and the predicted value from the Cho ellipsoid saturation model

r	NCS Chromaticness
Cho Ellipsoid Saturation_$_{CIELAB}$	0.71
Cho Ellipsoid Saturation_$_{CIECAM02}$	0.74
Cho Ellipsoid Saturation_$_{CAM02\text{-}UCS}$	0.63

Table 7.63 Correlation coefficients (r) calculated between NCS chromaticness and the predicted value from the Cho ellipsoid saturation NN model (developed without neutral data)

r	NCS Chromaticness
Cho Ellipsoid Saturation$_{NN_CIELAB}$	0.71
Cho Ellipsoid Saturation$_{NN_CIECAM02}$	0.75
Cho Ellipsoid Saturation$_{NN_CAM02\text{-}UCS}$	0.64

Table 7.64 Correlation coefficients (r) calculated between NCS chromaticness and the predicted value from the Cho ellipsoid vividness model

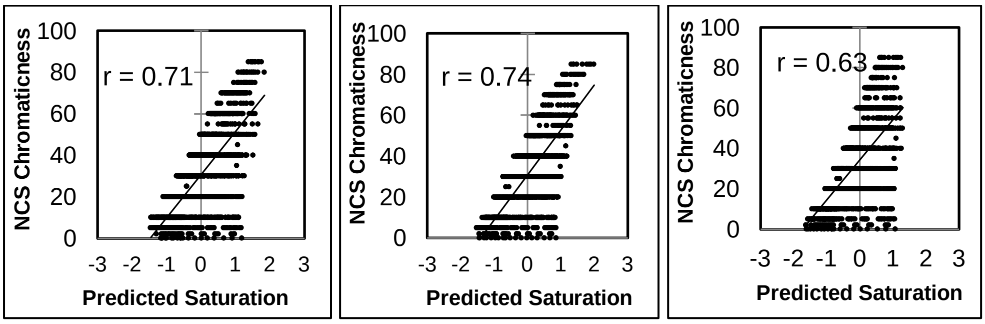
r	NCS Chromaticness
Cho Ellipsoid Vividness$_{_CIELAB}$	0.60
Cho Ellipsoid Vividness$_{_CIECAM02}$	0.62
Cho Ellipsoid Vividness$_{_CAM02\text{-}UCS}$	0.49

Table 7.65 Correlation coefficients (r) calculated between NCS blackness and the Cho ellipsoid blackness model

r	NCS Blackness
Cho Ellipsoid Blackness$_{_CIELAB}$	0.97
Cho Ellipsoid Blackness$_{_CIECAM02}$	0.97
Cho Ellipsoid Blackness$_{_CAM02\text{-}UCS}$	0.97

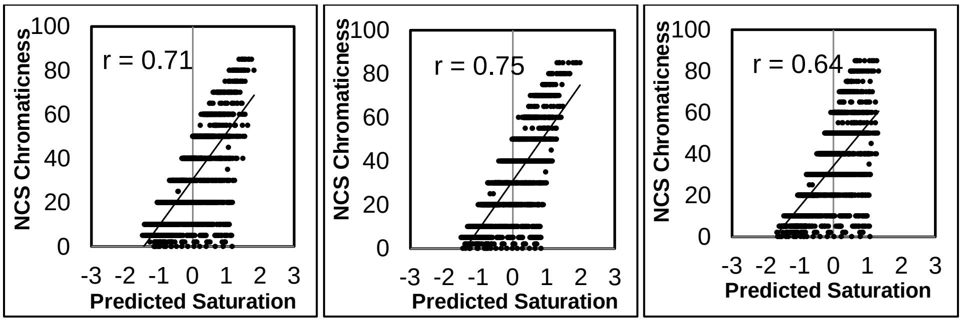
Table 7.66 Correlation coefficients (r) calculated between NCS whiteness and the predicted value from the Cho ellipsoid whiteness model

r	NCS Whiteness
Cho Ellipsoid Whiteness$_{_CIELAB}$	0.94
Cho Ellipsoid Whiteness$_{_CIECAM02}$	0.96
Cho Ellipsoid Whiteness$_{_CAM02\text{-}UCS}$	0.92



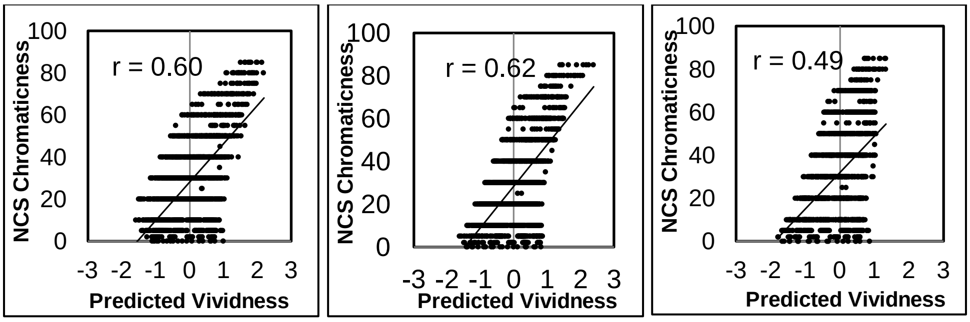
(a) (b) (c)

Figure 7.9 NCS chromaticness plotted against the predicted value from the Cho ellipsoid saturation model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics



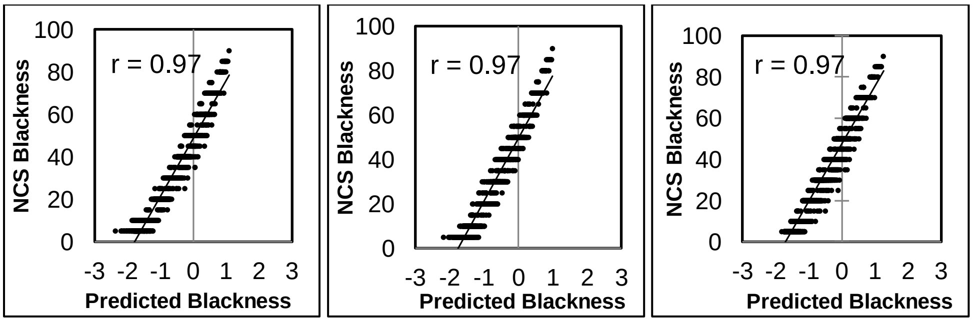
(a) (b) (c)

Figure 7.10 NCS chromaticness plotted against the predicted value from the Cho ellipsoid saturation model (developed without the neutral data) in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics



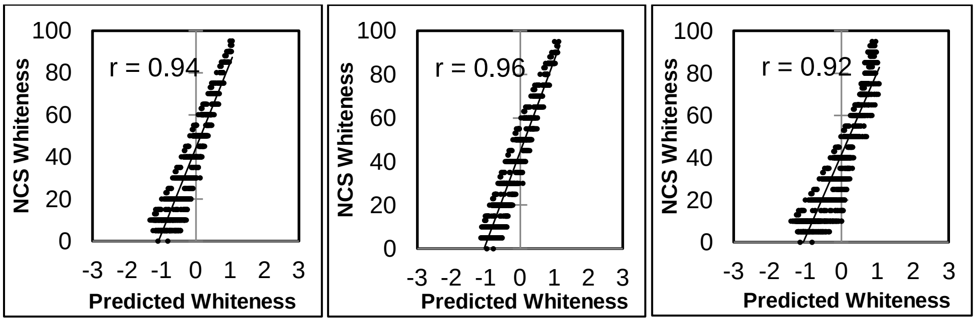
(a) (b) (c)

Figure 7.11 NCS chromaticness plotted against the predicted value from the Cho ellipsoid vividness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics



(a) (b) (c)

Figure 7.12 Scatter diagram of NCS blackness against the predicted value from the Cho ellipsoid blackness model in three metrics (CIELAB (a), CIECAM02 (b) and CAM02-UCS (c))



(a) (b) (c)

Figure 7.13 Plot of NCS whiteness against the predicted value from the Cho ellipsoid whiteness model in three metrics (CIELAB (a), CIECAM02 (b) and CAM02-UCS (c))

The Cho hue-based models based on visual data were also tested using the NCS data. They were evaluated using the Pearson's correlation coefficient (r) and these are plotted in Figures 7.14 to 7.16. The NCS whiteness data were compared with the predicted values from the Cho hue-based model of whiteness. The NCS blackness data were compared with the predicted values from the Cho hue-based model of blackness. The NCS chromaticness data were compared with the predicted values from the Cho hue-based model of chromaticness. Tables 7.67 to 7.69 show the correlation coefficient (r) results between the models' predictions and the NCS data. All the models' predictions show very high correlation with the NCS data with their coefficient values ranging from 0.95 to 0.99. This indicates that all the predicted values from the Cho hue-based models agree very well with the NCS data. It can be concluded that the Cho hue-based models successfully predict the NCS data.

The three versions (CIELAB, CIECAM02 and CAM02-UCS) of the Cho hue-based models performed similarly in terms of their relationship with the visual data. In the figures of the predicted blackness and whiteness models in the CAM02-UCS version, the predicted data were more scattered in the low NCS region than in the other versions. Thus, in general, the models in the CIELAB and CIECAM02 versions showed better prediction performance than the CAM02-UCS version.

Table 7.67 Correlation coefficients (r) calculated between NCS whiteness and the predicted value from the Cho hue-based whiteness model

r	NCS whiteness
Cho hue-based whiteness $_{CIELAB}$	0.99
Cho hue-based whiteness $_{CIECAM02}$	0.99
Cho hue-based whiteness $_{CAM02\text{-}UCS}$	0.95

Table 7.68 Correlation coefficients (r) calculated between NCS blackness and the predicted value from the Cho hue-based blackness model

r	NCS blackness
Cho hue-based blackness $_{CIELAB}$	0.99
Cho hue-based blackness $_{CIECAM02}$	0.99
Cho hue-based blackness $_{CAM02\text{-}UCS}$	0.97

Table 7.69 Correlation coefficients (r) calculated between NCS chromaticness and the predicted value from the Cho hue-based chromaticness model

r	NCS chromaticness
Cho hue-based chromaticness $_{CIELAB}$	0.98
Cho hue-based chromaticness $_{CIECAM02}$	0.98
Cho hue-based chromaticness $_{CAM02\text{-}UCS}$	0.97

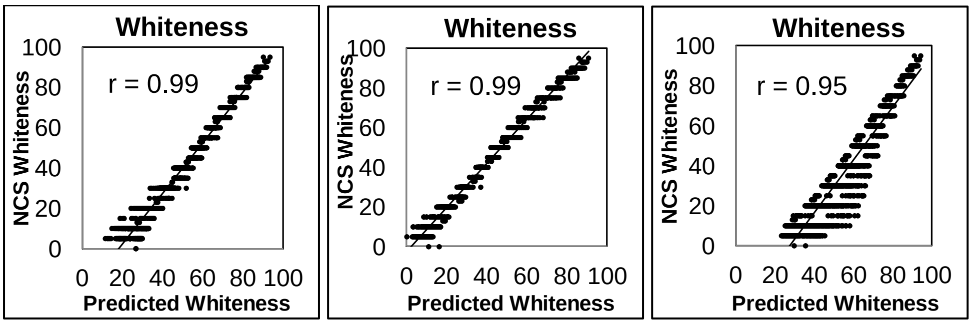
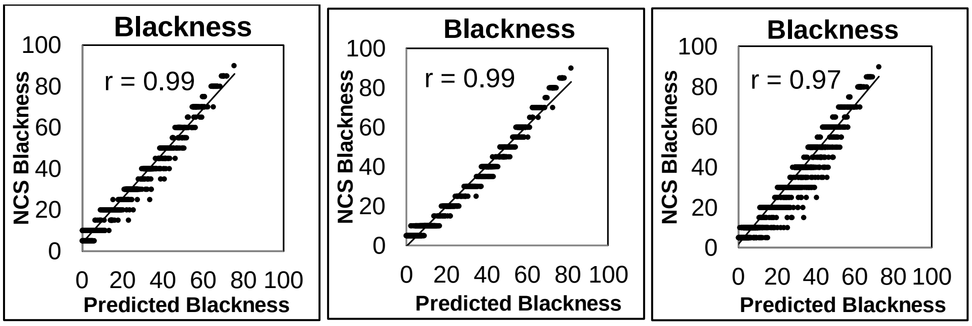
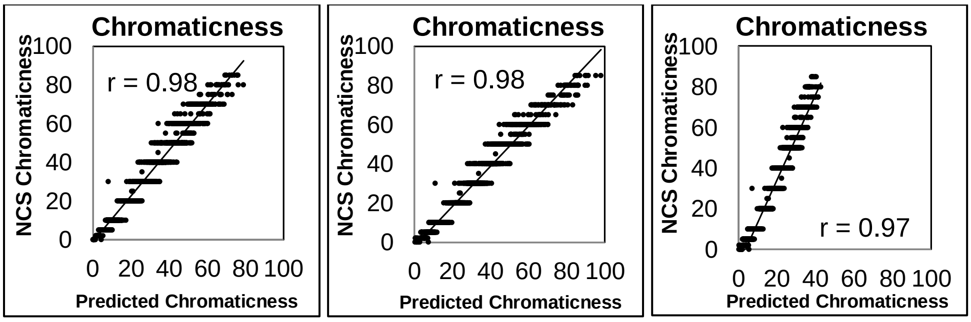


Figure 7.14 NCS whiteness data plotted against the predicted values from the Cho hue-based models in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions



(a) (b) (c)

Figure 7.15 NCS blackness data plotted against the predicted values from the Cho hue-based models in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions



(a) (b) (c)

Figure 7.16 NCS chromaticness data plotted against the predicted values from the Cho hue-based models in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions

7.3 Testing NCS Ellipsoid and NCS Hue-based Models Using the Cho Data

The NCS ellipsoid models of the three attributes (blackness, whiteness and chromaticness) were tested against the visual data (Cho data) obtained from the experiments to evaluate the model performance. The tested data set was the average data from the British and Korean observer response data. The Pearson's correlation coefficient (r) was calculated to indicate the agreements between the model predictions and the observer response. Tables 7.70 to 7.72 show the correlation coefficient results in the range of 0.53 to 0.92. The newly developed blackness and whiteness models were found to correlate very well with the visual data with correlation coefficients ranging from 0.83 to 0.92. The relationships between the visual data of saturation or vividness and the newly predicted chromaticness model showed less correlation than the blackness and whiteness results with r values ranging from 0.53 to 0.59. However, in general, the chromaticness models correlated well with the saturation and vividness data, respectively. The NCS ellipsoid chromaticness models predicted the saturation observer response better than the vividness observer response. This implies that the model prediction of NCS ellipsoid chromaticness fits the visual data of saturation more closely than the visual data of vividness. Figures 7.17 and 7.18 show the tested results of the predicted blackness and whiteness models plotted against the visual results. The linear relationships show that the models seem to predict reasonably well blackness and whiteness. Among the NCS ellipsoid models in three versions (CIELAB, CIECAM02 and CAM02-UCS), the CIELAB version is generally slightly better than the other models, except that the NCS ellipsoid blackness models show the same prediction performance.

Table 7.70 Correlation coefficients (r) calculated between the visual data and the predicted values from the NCS ellipsoid blackness model

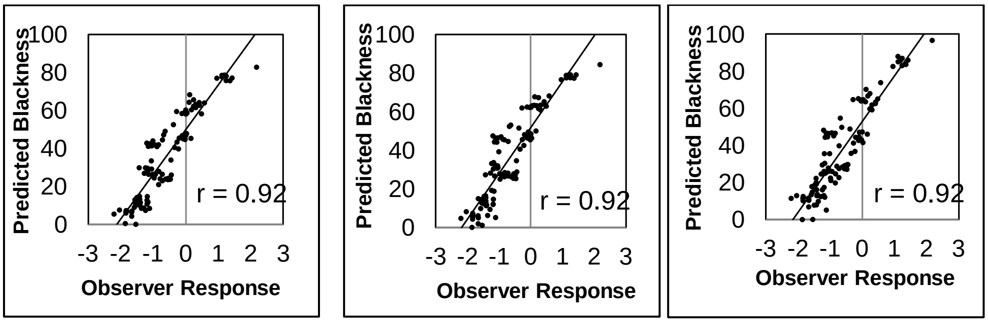
r	Blackness Observer Response
NCS Ellipsoid Blackness $_{CIELAB}$	0.92
NCS Ellipsoid Blackness $_{CIECAM02}$	0.92
NCS Ellipsoid Blackness $_{CAM02\text{-}UCS}$	0.92

Table 7.71 Correlation coefficients (r) calculated between the visual data and the predicted values from the NCS ellipsoid whiteness model

r	Whiteness Observer Response
NCS Ellipsoid Whiteness $_{CIELAB}$	0.85
NCS Ellipsoid Whiteness $_{CIECAM02}$	0.84
NCS Ellipsoid Whiteness $_{CAM02\text{-}UCS}$	0.83

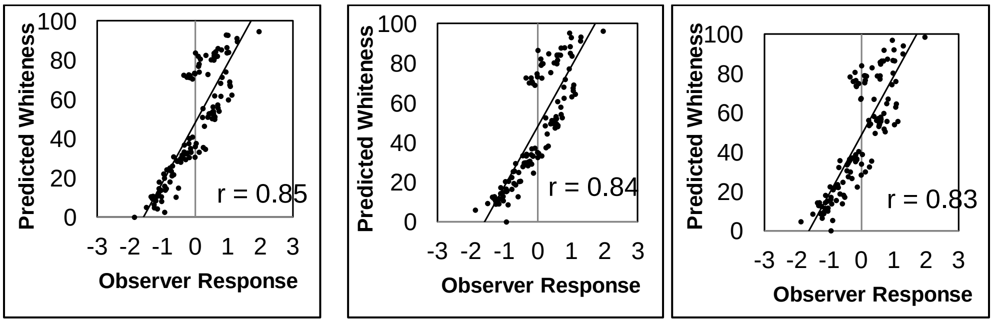
Table 7.72 Correlation coefficients (r) calculated between the visual data and the predicted values from the NCS ellipsoid chromaticness model

r	Saturation Observer Response	Vividness Observer Response
NCS Ellipsoid Chromaticness $_{CIELAB}$	0.59	0.56
NCS Ellipsoid Chromaticness $_{CIECAM02}$	0.59	0.54
NCS Ellipsoid Chromaticness $_{CAM02\text{-}UCS}$	0.58	0.53



(a) (b) (c)

Figure 7.17 Average observer response of blackness plotted against the predicted value from the NCS ellipsoid blackness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions



(a) (b) (c)

Figure 7.18 Averaged observer response of whiteness plotted against the predicted value from the NCS ellipsoid whiteness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions

The NCS hue-based models were also tested using the visual data. Pearson's correlation coefficients were also calculated between the predicted values from the NCS hue-based models and the observer response data (visual result). Tables 7.73 to 7.75 show the correlation coefficient results in the range of 0.54 to 0.93. The results show a pattern similar to that of previous tested results for the NCS ellipsoid models. In Figures 7.19 and 7.20, the NCS hue-based model predictions for blackness and whiteness are plotted against the visual results, respectively. It can be seen that the NCS hue-based models derived from the NCS data are also linearly correlated with the visual data. This implies that the two sets show good agreement.

The three versions (CIELAB, CIECAM02 and CAM02-UCS) of the NCS hue-based models show similar performance. The NCS hue-based blackness model in the CIELAB version shows slightly better performance than the other hue-based blackness models. In the hue-based whiteness models, the CIECAM02 version shows better performance than the other hue-based whiteness models. In Figure 7.19, most of the predicted data are aligned on the diagonal line. In Figure 7.20, the predicted data in the CAM02-UCS version are more scattered than the predicted data in other versions.

Table 7.73 Correlation coefficients (r) calculated between the visual data and the predicted values from the NCS hue-based blackness model

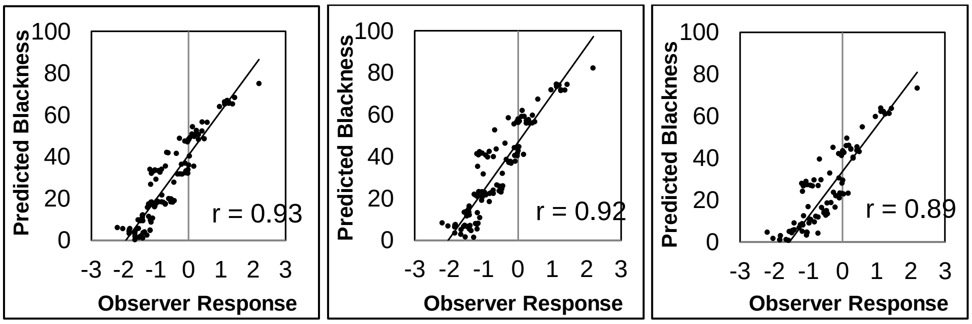
r	Blackness Observer Response
NCS hue-based blackness $_{\text{CIELAB}}$	0.93
NCS hue-based blackness $_{\text{CIECAM02}}$	0.92
NCS hue-based blackness $_{\text{CAM02-UCS}}$	0.89

Table 7.74 Correlation coefficients (r) calculated between the visual data and the predicted values from the NCS hue-based whiteness model

r	Whiteness Observer Response
NCS hue-based whiteness $_{\text{CIELAB}}$	0.80
NCS hue-based whiteness $_{\text{CIECAM02}}$	0.82
NCS hue-based whiteness $_{\text{CAM02-UCS}}$	0.68

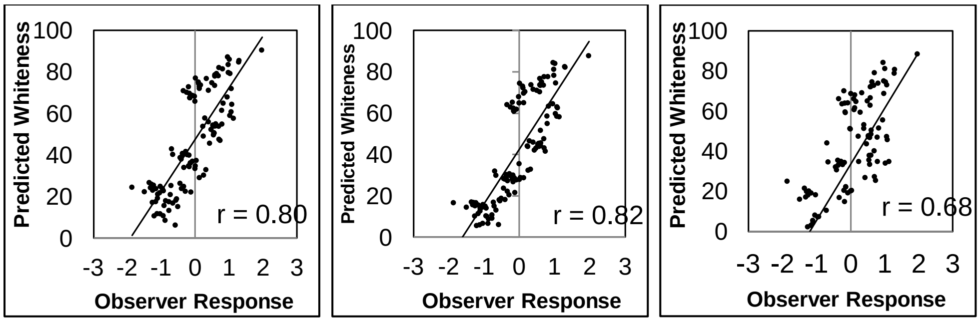
Table 7.75 Correlation coefficients (r) calculated between the visual data and the predicted values from the NCS hue-based chromaticness model

r	Saturation Observer Response	Vividness Observer Response
NCS hue-based chromaticness $_{CIELAB}$	0.55	0.54
NCS hue-based chromaticness $_{CIECAM02}$	0.56	0.54
NCS hue-based chromaticness $_{CAM02\text{-}UCS}$	0.56	0.54



(a) (b) (c)

Figure 7.19 Average observer response of blackness plotted against the predicted value from the NCS hue-based blackness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics



(a) (b) (c)

Figure 7.20 Average observer response of whiteness plotted against the predicted value from the NCS hue-based whiteness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS metrics

7.4 The Present Experimental Data vs. the NCS Data

The average observer responses of blackness and whiteness obtained from the experiments and the corresponding NCS data were compared. The comparisons were made to investigate the agreement between the two data sets by calculating Pearson's correlation coefficients. The results are scatter plotted in Figure 7.21. The visual results of blackness and whiteness were found to be highly correlated with the NCS data with correlation coefficients of 0.93 and 0.85, respectively. This implies that the visual data agree very well with the NCS data.

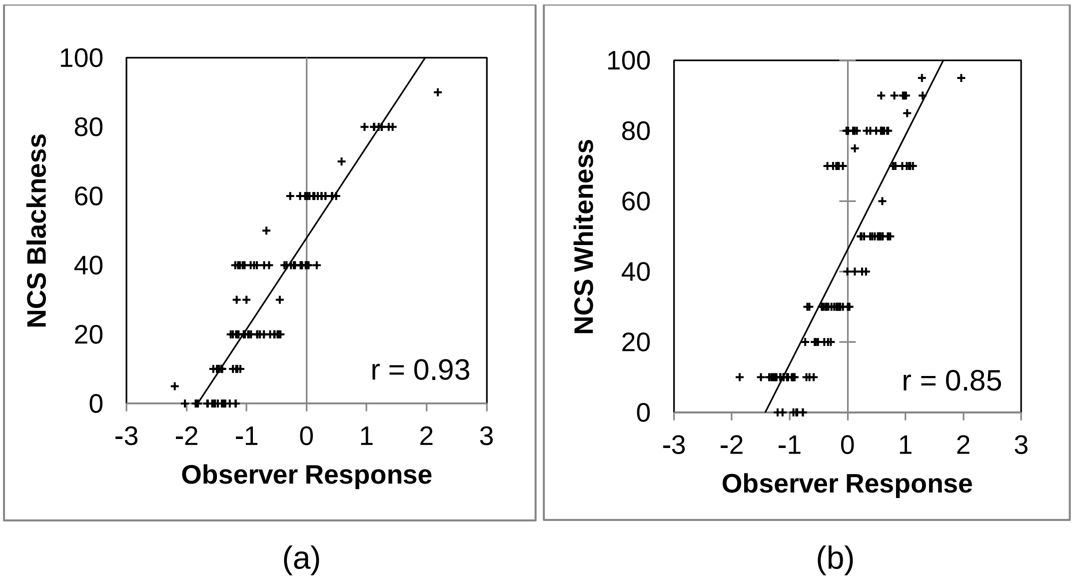
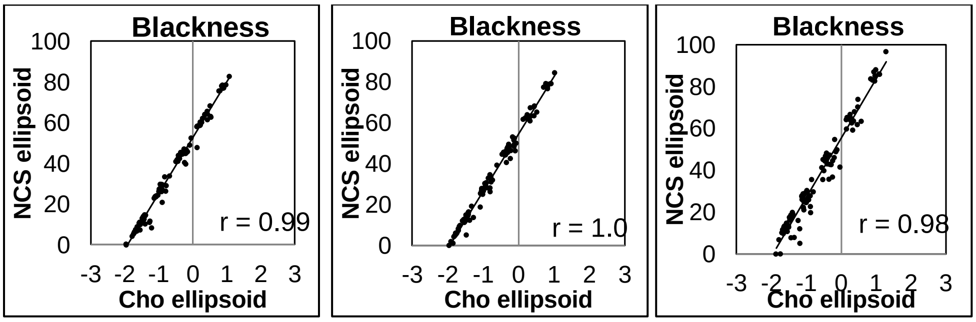


Figure 7.21 (a) Average observer response of blackness against NCS blackness; (b) average observer response of whiteness against NCS whiteness

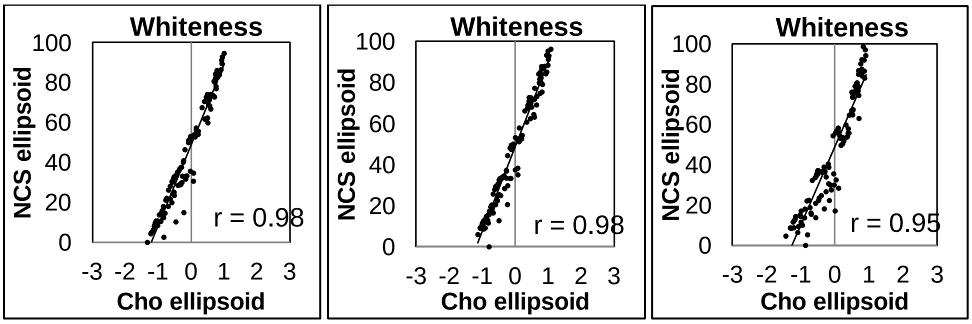
7.5 NCS Ellipsoid Models vs. Cho Ellipsoid Models and NCS Hue-based Models vs. Cho Hue-based Models

The NCS ellipsoid model predictions and the Cho ellipsoid model predictions for blackness and whiteness were compared to investigate the agreement between the two models. Both models were tested by using the independent visual dataset. The Pearson's correlation coefficient was used to indicate the agreement between the predicted value from the NCS ellipsoid model and the predicted value from the Cho ellipsoid model in three versions (CIELAB, CIECAM02 and CAM02-UCS). The results show very high correlation with correlation coefficients ranging from 0.95 to 1.0. In particular, the correlation is almost perfect between the NCS ellipsoid and Cho ellipsoid blackness models in the CIECAM02 version. This indicates that the NCS ellipsoid and Cho ellipsoid models agree with each other very well. In Figures 7.22 and 7.23, these models were plotted against each other. The figures show that the two models are linearly correlated with each other. In most of the figures, the predicted data were aligned on the diagonal line. The predicted data in the CAM02-UCS version was found to be more scattered in the low region than other versions.



(a) (b) (c)

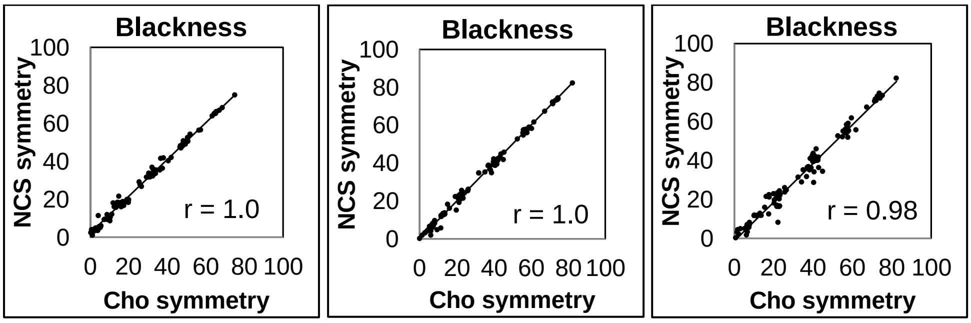
Figure 7.22 NCS ellipsoid blackness predictions plotted against Cho ellipsoid blackness predictions in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions



(a) (b) (c)

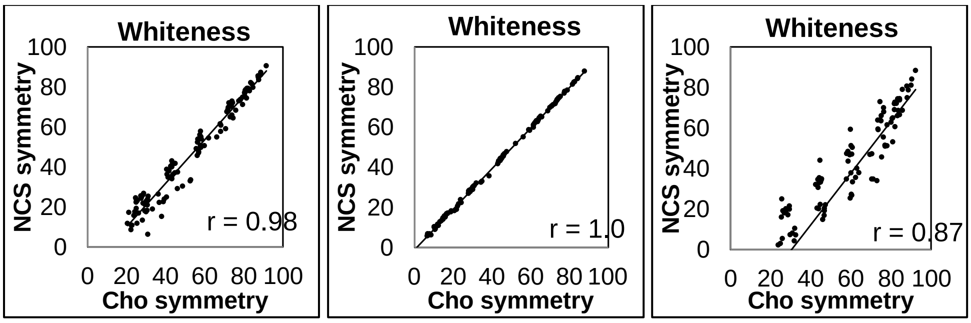
Figure 7.23 NCS ellipsoid whiteness predictions plotted against Cho ellipsoid whiteness predictions in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions

The NCS hue-based model and the Cho hue-based model in three versions (CIELAB, CIECAM02 and CAM02-UCS) were also compared to investigate the agreement between them. The results show very high correlation between the predicted values from both models with correlation coefficients of 0.87 to 1.0. Almost all of the models correlate very well with each other. In particular, the correlation is almost perfect between the Cho symmetry and NCS symmetry models in the CIELAB and CIECAM02 versions. Figures 7.24 to 7.26 display the scatter plots showing the NCS hue-based model predictions and the Cho hue-based model predictions of three attributes (blackness, whiteness and chromaticness) in three versions (CIELAB, CIECAM02 and CAM02-UCS). As seen in the figures, the two types of hue-based models agree with each other very well. Among the three versions, the predicted data in the CIECAM02 version shows more linearity with slight scattering, and they are more precisely aligned on the diagonal line than the other versions.



(a) (b) (c)

Figure 7.24 NCS hue-based blackness predictions plotted against Cho hue-based blackness predictions in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions



(a) (b) (c)

Figure 7.25 NCS hue-based whiteness predictions plotted against Cho hue-based whiteness predictions in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions

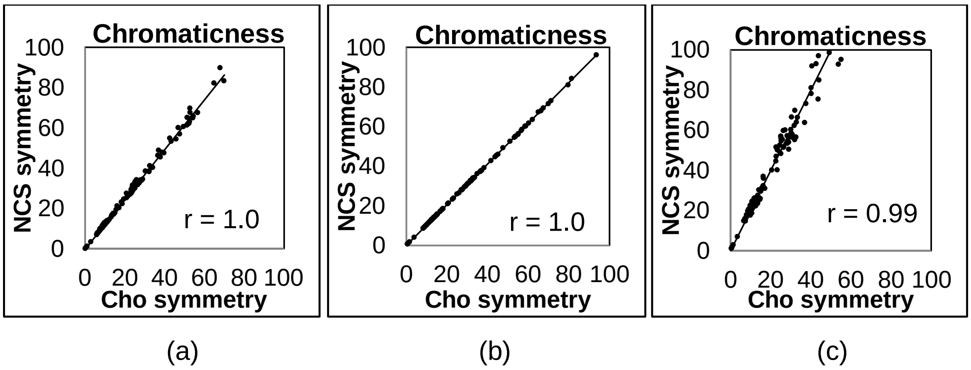


Figure 7.26 NCS hue-based chromaticness predictions plotted against Cho hue-based chromaticness predictions in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions

7.6 Model Performance

The developed models were compared in terms of Pearson's correlation coefficient. Tables 7.76 to 7.78 summarise the performance of each model. In Table 7.76, in general, most of the models were found to be highly correlated with the independent data set. However, the chromatincess models that were tested by the visual results of saturation and vividness were found be less strongly correlated than the other tested models. These results demonstrate that the variability of saturation and vividness according to observers affected the model predictions. In terms of chromaticnesss, the Cho hue-based chromaticnesss model performs the best among the saturation, vividness and chromaticness models. Also, all the blackness and whiteness models in Tables 7.77 and 7.78 were found to correlate very well with the tested data set. In terms of blackness, the Cho hue-based blackness model performs the best among the blackness models. In terms of whiteness, the Cho hue-based whiteness model performs the best among the whiteness models.

The Cho hue-based model is the best for the NCS data set because it is highly correlated with the NCS data among the other models. The NCS ellipsoid model is the best for the visual data set due to its high correlation with visual data. In terms of the model's structure, the ellipsoid model is a lot simpler than the hue-based model because it is basically formed by L*, a* and b* (or J, a_M and b_M; or J', a' and b';) attributes. This simplicity is the advantage of ellipsoid models. However, in terms of prediction performance, the hue-based models are better than the ellipsoid models according to the relationship with the testing data sets.

The Cho hue-based model which fitted well with the visual data also provided accurate predictions for the NCS data. This implies that the Cho hue-based model can cover both data sets, i.e. the visual data and NCS data sets. The Cho hue-based model outperformed the other models in terms of prediction performance. Hence, the Cho hue-based model is recommended among the newly developed models.

Among the three versions of the models (CIELAB, CIECAM02 and CAM02-UCS), in general, the CIECAM02 version shows better performance than the other versions. Thus, according to the performance and the linearity, it is suggested that the model in its CIECAM02 version is recommended over the other model versions.

Table 7.76 Summary of the model performance in terms of saturation, vividness and chromaticness

Version	Model	Tested Data Set	r
CIELAB	Cho ellipsoid saturation	NCS Chromaticness	0.71
CIECAM02			0.74
CAM02-UCS			0.63
CIELAB	Cho ellipsoid saturation (excluding neutral data)	NCS Chromaticness	0.71
CIECAM02			0.75
CAM02-UCS			0.64
CIELAB	Cho ellipsoid vividness	NCS Chromaticness	0.60
CIECAM02			0.62
CAM02-UCS			0.49
CIELAB	NCS ellipsoid chromaticness	Cho Saturation	0.59
CIECAM02			0.59
CAM02-UCS			0.58
CIELAB	NCS ellipsoid chromaticness	Cho Vividness	0.56
CIECAM02			0.54
CAM02-UCS			0.53
CIELAB	Cho hue-based chromaticness	NCS Chromaticness	**0.98**
CIECAM02			**0.98**
CAM02-UCS			**0.97**
CIELAB	NCS hue-based chromaticness	Cho Saturation	0.55
CIECAM02			0.56
CAM02-UCS			0.56
CIELAB	NCS hue-based chromaticness	Cho Vividness	0.54
CIECAM02			0.54
CAM02-UCS			0.54

Table 7.77 Summary of the model performance for blackness

Version	Model	Tested Data Set	r
CIELAB	Cho ellipsoid blackness	NCS Blackness	0.97
CIECAM02			0.97
CAM02-UCS			0.97
CIELAB	NCS ellipsoid blackness	Cho Blackness	0.92
CIECAM02			0.92
CAM02-UCS			0.92
CIELAB	Cho hue-based blackness	NCS Blackness	**0.99**
CIECAM02			**0.99**
CAM02-UCS			**0.97**
CIELAB	NCS hue-based blackness	Cho Blackness	0.93
CIECAM02			0.92
CAM02-UCS			0.89

Table 7.78 Summary of the model performance for whiteness

Version	Model	Tested Data Set	r
CIELAB	Cho ellipsoid whiteness	NCS Whiteness	0.94
CIECAM02			0.96
CAM02-UCS			0.92
CIELAB	NCS ellipsoid whiteness	Cho Whiteness	0.85
CIECAM02			0.84
CAM02-UCS			0.83
CIELAB	Cho hue-based whiteness	NCS Whiteness	**0.99**
CIECAM02			**0.99**
CAM02-UCS			**0.95**
CIELAB	NCS hue-based whiteness	Cho Whiteness	0.80
CIECAM02			0.82
CAM02-UCS			0.68

7.7 Summary

In this chapter, four new sets of models were tested using the two independent NCS and the present experimental data sets. In general, almost all of the models fitted the data well. The models provide good prediction for an independent data set, i.e. the NCS and the present data. In particular, the blackness and whiteness models provided good predictions for the tested data set, NCS and the present dataset.

The Cho ellipsoid saturation model which was developed excluding neutral data slightly better predicted the NCS chromaticness data than the model which was developed including neutral data. This implies that the observer variability in scaling neutral colour may have affected the model prediction performance.

The visual data of blackness and whiteness were also compared with the NCS blackness and whiteness data, respectively. Both sets of visual data showed very good agreement with the NCS data. In other words, these visual data can represent the NCS system. Intra- and inter-observer errors may have had an impact on the results. In particular, these factors may have had a strong impact on the vividness, saturation and chromaticness' results (see in Section 7.2) which were lower than those for blackness and whiteness. Observers may have had more difficulty understanding vividness and saturation in relation to the colours, and this may have affected the tested results. Nevertheless, the Cho ellipsoid models of saturation and vividness provided good predictions to the NCS data. This implies that ellipsoid models based on the visual data obtained from naive observers can predict NCS data well.

The Cho ellipsoid and NCS ellipsoid models were compared. Also, the Cho hue-based and NCS hue-based models were compared. Both comparison results showed very strong relationships between them. This implies that the models that cover visual data can reflect models based on NCS data.

Chapter 8 Conclusions

8.1 Overview

The aim of this study was given in Chapter 1: to develop a new model that may serve as an alternative to the third dimension of colour appearance based on colorimetric values and to develop new blackness and whiteness models based on colorimetric values. Specific tasks were carried out to achieve this aim:

(1) To understand and clarify the meaning of each chromatic attribute based on data obtained from Korean and British observer groups,

(2) To investigate the cultural differences between Korean and British groups in relation to visual results obtained from observers for four scales (saturation, vividness, blackness and whiteness),

(3) To investigate the relationships between the colour appearance scales of CIELAB, CIECAM02 and CAM02-UCS colour spaces and the observer responses for the four scales studied,

(4) To develop new colour models by fitting the present saturation, vividness, blackness and whiteness visual results. The new models are based on CIELAB, CIECAM02 and CAM02-UCS metrics.

(5) To test the models using an independent data set, NCS.

These tasks were successfully achieved and the major findings are summarised in the following section. Finally, directions for future work are given.

8.2 Summary of Major Findings and Contributions

Unique experiment design to reveal culture difference

The experiment was carried out to investigate words used to describe the third dimension of colour attributes (or chromatic attributes). All the objectives have been achieved due to the unique aspects of the experimental design.

These are summarised as follows:

1) To reveal TRUE cultural differences by using naive observers (rather than colour scientists). They can truthfully reflect their understanding of the words that can be used to describe a range of colours. If they are trained regarding the use of each word, it is highly likely they will be forced to use a new definition, and the results will not reveal the real meaning.

2) In the design of the experiment, observers were divided into two groups to scale adjectives having similar or dissimilar meanings in a session. It was found that the former group made more accurate assessments.

3) PCA analysis was used to find the most frequently used words in two underlying dimensions. One is related to the third-dimension attributes, and the two most frequently used by British people, i.e. saturation and vividness were identified.

4) Cultural differences regarding saturation and vividness were revealed.

5) The results also showed that quite a few observers assigned high saturation values for some neutral colours, i.e. a black colour could be considered highly saturated by members of both cultural groups.

The details of the results are given below.

Word translation

A survey was carried out to translate 23 English words (see Section 3.2). It is not easy to judge whether translated words are precise. Hence, the aim of this survey was to reduce the translation error by consulting people who are engaged in colour (or colour users). The survey was based on an English-Korean dictionary. The participants were asked to choose the most appropriate word according to the English-Korean dictionary because some of the English words were not familiar to them. In the survey results, for most of the English words, the participants responded with a variety of possible Korean meanings. This implies that most of the words had more than one Korean meaning even among people who work in the field of colour. A limitation of this survey is that it was limited to a certain group of people. It would have been interesting to survey people who are naive to colour to see how they understand the English terms and compare the results with those obtained in this study.

Note culture covers much wider scope than language. Culture covers various components such as communication, cognition, behaviours, materials, living style, history, and language is part of communication. The present study includes two different languages assessed by subjects from two cultures. Hence, the results should reflect the true culture difference.

Assessing colours using 15 scales by Korean observers

The visual data of the 15 scales in the Korean group were compared with the CIELAB chroma, lightness and hue angle to investigate the relationships between them and to find the third dimensional scale (see Section 4.3). Among the scales, “saturated” and “light-heavy” were found to be linked with the CIELAB chroma and lightness, respectively.

In this research, there were two principal components identified for the 15 responses to colour patches, i.e. lightness and chroma (see Section 4.4).

The two colour appearance attributes (i.e. lightness and chroma) agree well with those identified in the studies of Ou *et al*. (2004) and Gao *et al*. (2007), which used similar colour emotion scales, such as “light-heavy”, “passive-dynamic”, “vague-distinct”, “vivid-sombre” and “subdued-striking” (see Section 4.4).

Saturation and vividness scales are a function of the colour appearance attribute, such as chroma. In other words, similarities in colour appearance result in similarities in saturation and vividness responses to high chromaticness colours. This is supported by the result in the experiments in which “saturation” and “vividness” were found to be linked with the CIELAB chroma (see Sections 4.3 and 4.4). These are the two most familiar attributes to describe the third dimension of colour appearance.

Cultural difference between British and Korean

The “saturated” response given by the British group was found to have strong links with “full-thin” in the Korean group (r = 0.89), even better than its corresponding attribute from direct translation (r = 0.91) (see Section 4.5). Similarly, “vivid-dull” in the British group was found to have strong links with “striking” in the Korean group, instead of its corresponding attribute (r = 0.91) (see Section 4.5). This implies that more than one Korean word can represent the concepts of 'saturation' and 'vivid-dull' expressed in English words.

Comparison between the two cultural groups was carried out to see whether the four scales (i.e. “saturation”, “vividness”, “blackness” and “whiteness”) can be influenced by different cultures. Nationality difference did not have a significant impact on the visual results for blackness and whiteness. The responses of British observers were found to agree well with those of Korean observers (see Section 5.4). Also, there was no culture difference found between the British and Chinese observer groups in Tao *et al*.’s blackness study (see Section 5.4). These results verify the findings of Berlin and Kay (1969) that black and white are common words to all human languages (see Section 2.7) across all cultures.

In the present study, there was little culture effect found in saturation and vividness (see Section 5.4). There were small cultural effects on saturation and vividness responses by fitting these visual data to other existing models (see Section 5.5). Both British and Korean data showed some different visual results in comparison to other existing models, such as the British data for saturation fitting well with all the existing models. On the other hand, the Korean data of saturation did not fit well with the other models except lightness. For vividness, the Korean data seemed to fit well with chroma and colourfulness, while the British data did not. Although these two scales (i.e.

saturation, vividness) showed small differences, they agreed well between two groups (i.e. British and Korean) in terms of correlation coefficient (see Section 5.4). The two observer groups in general agreed well between the two groups.

Intra- and inter-observer variability

According to the mean result of intra- and inter-observer variability, “vividness” was the most difficult attribute for observers to scale (high observer variability), and “saturation” was the second most difficult (see Sections 5.3.1 and 5.3.2). Also, the difficulty of scaling saturation was found in Juan and Luo’s saturation study (see Section 2.4.1.1). As in Berlin and Kay’s finding (1969) that black is a widely used word in all human languages, 'blackness' was the easiest attribute for observers to scale in this study. On the whole, intra-observer variability was lower than inter-observer variability, as expected. Similar consistency was observed in the female and male groups. This means that there is little gender effect on the four visual scales (i.e. saturation, vividness, blackness and whiteness) (see Sections 5.3.1 and 5.3.2). It was also found that Korean observers seemed to show slightly more accurate results (smaller observer variability) than British observers according to the mean results.

A weakness of this study may be in the uncertainty over saturation and vividness for observers. However, this was intended to find the true understanding of these terms on the part of naive observers. However, during the experiment, it was found only two Korean observers did not understand the word of ‘saturated’ and they were given the definition. Nevertheless, the saturation and vividness models fit well with the NCS data set. Also, the observer responses for these words clearly fit well with the models in three colour spaces (i.e. CIELAB, CIECAM02 and CAM02-UCS) and other attributes (i.e. Berns’ depth (D_{ab}*) and clarity (T_{ab}*)) for both cultural groups (British and Korean).

In the future, if a new experiment was carried out using these words, training could be done before the experiment to compare the results obtained from the present and new experiments.

Colorimetric model's prediction vs. observer response

The existing colour appearance attributes were found to be linked with “saturation” (see Section 5.5). In addition, new attributes, such as Berns' vividness, depth and clarity, were found to be linked with the present blackness, whiteness and vividness results respectively (see Section 5.5). This indicates that his vividness scale does not have the same meaning that ordinary people expect it to have.

Comparing models that are derived from different bases with the visual responses, CIECAM02 saturation showed the highest correlation to the saturation response (see Section 5.5). It was also found that the visual data of saturation without neutral data showed a slightly better agreement to the attributes than the visual data including neutral data. This is expected because all colour science models define neutral colours to have zero saturation.

The vividness response was found to be linked with chroma and colourfulness (see Section 5.5). This result agreed with Kim *et al.*’s vividness study (2008), which showed that vividness is linked with chroma. Also, the present finding agrees with the findings of Fedorovskaya *et al*. (1997), Trémeau and Charrier (2000) that vividness is similar to colourfulness. However, this is different from Berns’ vividness scale.

The blackness and whiteness responses were found to be linked with lightness, depth and vividness (see Section 5.5).

Individual difference in scaling saturation

In the CIE colour science vocabulary (see Section 2.4), saturation for neutral colour was defined as zero. However, individual differences were found in scaling saturation especially for neutral colours (see Section 5.7). Some observers considered white or light grey or medium grey as the least saturated colour. Most of the observers considered black a very saturated colour. This finding of black agrees well with the finding of Juan and Luo's study (2000); in their pre-experiment, black was found to be a saturated colour (see Section 5.7). These findings imply that, in the real world, people believe that neutral colours have a different degree of saturation. This is highly relevant to their experience in using colours. For colourists, such as dyers and painters, they know that by adding colorants, the colour will become stronger and deeper leading to increased saturation. Frequently, they also add black colorant to increase depth. Hence, darker neutral colours could have saturation. This could only be found out by the untrained naive observers. However, it was also found that when modelling saturation with and without treating neutral colours to have saturation perception, the models do not change their performance very much. For industrial applications, we need to follow the CIE guideline to force saturation to be zero for greater accuracy and consistency.

Model developments

The first new type of model was based on ellipsoid equations to fit the saturation, vividness, blackness and whiteness of the present experimental data, and the blackness and whiteness of the NCS data. It was found that the models can fit the data well (see Sections 5.8 and 5.9). Another type of model based on the Louis Adams model (called "the hue-based model") was also used to fit the NCS and the present data sets. Finally, these models were tested using an independent dataset such as the model developed using the present dataset to be tested by a complete independent dataset (NCS is used here) (see Sections 7.2 and 7.3). The results were highly satisfactory. This means that the models work well, but most importantly, the blackness and whiteness from the two sets of data agree well with each other. Comparing the prediction performance of the models against the independent data, the Cho hue-based model in its CIECAM02 version outperformed the other models. It is recommended because the model reflects the understanding of naive observers and predicts the NCS data much better than other models.

The contributions of this thesis to the colour science field are the following:

1) To reveal the meanings of various scales to describe the third dimension. The two scales standing out are saturation and vividness. They are the most widely used and best understood by Korean and British observers.

2) To investigate the valuable attributes of whiteness and blackness. The present experimental data agree well with NCS data.

3) To develop new models for new colour appearance attributes, namely, saturation, vividness, blackness, whiteness and chromaticness. They could be used in various applications such as image enhancement.

8.3 Future Work

In this study, new attributes were developed for an alternative to the third dimension of colour appearance. In addition, new blackness and whiteness attributes were developed. They were tested with an independent data set (NCS) to investigate the model performance. Among the models, the Cho hue-based models are recommended based on their excellent test results. Further studies should extend or improve upon the present study as follows:

1) New experiment to scale saturation perception by training two groups of observers with zero or non-zero saturation for neutral colours.

2) The models that will be utilised for application require the development of an inverse model, e.g. from blackness to XYZ tristimulus values.

3) The newly developed models, such as the Cho hue-based models, need to be tested on images rather than just colour patches. It should be applied to images displayed on various devices, such as camera pipelines, printer drivers, organic light emitting diode (OLED) displays, liquid crystal displays (LCDs) and TV displays to enhance image quality. The processed images should be verified by conducting psychophysical experiments.

4) To unify the current method only predicting whiteness for limited white area. The whiteness model developed here can be tested to see whether it can predict near white sample.

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Appendices

Appendix A: Forward CIECAM02

Step 1: Chromatic Adaptation Transform

Convert the sample CIE 1931 tristimulus values to a long, medium and short wavelength sensitive space using the CAT02 forward matrix:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathrm{M}_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{9-1}$$

where

$$\mathrm{M}_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

Calculate the *D* factor or degree of adaptation to the white point:

$$D = F\left[1 - \left(\frac{1}{3.6}\right) e^{\left(\frac{-(L_A - 42)}{92}\right)}\right] \tag{9-2}$$

Apply *D* factor weighted chromatic adaption in the following equations:

$$R_C = \left[\left(Y_w\, {}^{\mathrm{D}}/_{\mathrm{R_W}}\right) + (1 - D)\right] R$$

$$G_C = \left[\left(Y_w\, {}^{\mathrm{D}}/_{\mathrm{G_W}}\right) + (1 - D)\right] G \tag{9-3}$$

$$B_C = \left[\left(\mathrm{Y_w}\, {}^{\mathrm{D}}/_{\mathrm{B_W}}\right) + (1 - \mathrm{D})\right] B$$

where R_w, G_w, B_w are the RGB values calculated for the white point.

Step 2: Calculate the viewing condition dependent constants (Luminance-level adaptation factor ($\mathrm{F_L}$), brightness induction factor ($\mathrm{N_{bb}}$) and chromatic background induction factor ($\mathrm{N_{cb}}$)):

$$k = 1/(5L_A + 1) \tag{9-4}$$

$$F_L = 0.2k^4(5L_A) + \ 0.1(1-k^4)^2(5L_A)^{1/3} \qquad (9\text{-}5)$$

$$n = Y_b/Y_w \qquad (9\text{-}6)$$

$$N_{bb} = N_{cb} = 0.725(1/n)^{0.2} \qquad (9\text{-}7)$$

$$z = 1.48 + \sqrt{n} \qquad (9\text{-}8)$$

Step 3: Convert to Hunt-Pointer space to apply the post-adaptation non-linear compression:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \mathrm{M}_{HPE}\mathrm{M}_{CAT02}^{-1}\begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix} \qquad (9\text{-}9)$$

where

$$\mathrm{M}_{HPE} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix}$$

$$\mathrm{M}_{CAT02}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix}$$

Step 4: Apply post-adaptation non-linear compression:

$$R'_a = \frac{400(F_L R'/100)^{0.42}}{27.13 + (F_L R'/100)^{0.42}} + 0.1$$

$$G'_a = \frac{400(F_L G'/100)^{0.42}}{27.13 + (F_L G'/100)^{0.42}} + 0.1 \qquad (9-10)$$

$$B'_a = \frac{400(F_L B'/100)^{0.42}}{27.13 + (F_L B'/100)^{0.42}} + 0.1$$

If any of the values of R', G' or B' are negative, then their absolute values must be used, and then the quotient term in the above three equations must be multiplied by a negative 1 before adding the value 0.1.

Step 5: Compute temporary Cartesian representations (a and b) and hue before computing eccentricity factor and perceptual attributes:

$$a = R'_a - 12G'_a/11 + B'_a/11 \quad (9\text{-}11)$$

$$b = (1/9)(R'_a + G'_a - 2B'_a) \quad (9\text{-}12)$$

$$h = \tan^{-1}(b/a) \quad (9\text{-}13)$$

The hue angle, h, should be calculated in degrees. If it is obtained in radians, multiplying by 180/π converts it into relative degrees, h_r. If a and b are both positive, h_r, is positive, and the angle in absolute degrees, h, is the same as h_r. If a is negative and b is positive, h_r, is negative, and $h = h_r + 180$. If a and b are both negative, h_r, is positive, and $h = h_r + 180$. If a is positive and b is negative, h_r, is negative, and $h = h_r + 360$.

Step 6: Compute eccentricity factor (e_t) and hue quadrature (H):

$$e_t = 1/4 \cos\left[\left(h\frac{\pi}{180} + 2\right) + 3.8\right] \quad (9\text{-}14)$$

Hue quadrature (H) is computed from linear interpolation of the data shown in Table 9.79.

If $h < h_1$, then $h' = h + 360$, otherwise $h' = h$. Choose a value of i so that $h_i \leq h' < h_{i+1}$.

Table 9.79 Unique hue data to calculate hue quadrature

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0.0	100.0	200.0	300.0	400.0

$$H = H_i + \frac{100(h' - h_i)/e_i}{(h' - h_i)e_i + (h_{i+1} - h')/e_{i+1}} \qquad (9-15)$$

Step 7: Compute lightness (*J*) and brightness (*Q*):

Calculate the achromatic response (A):

$$A = \left[2R'_a + G'_a + \left(\frac{1}{20}\right)B'_a - 0.305\right]N_{bb} \qquad (9\text{-}16)$$

Lightness (*J*) is computed from the achromatic signals of the stimulus (*A*) and white (A_W):

$$J = 100(A/A_w)^{cz} \qquad (9\text{-}17)$$

$$Q = (4/\mathrm{c})\sqrt{J/100}(A_w + 4)F_L^{0.25} \qquad (9\text{-}18)$$

Step 8: Calculate chroma (*C*), colourfulness (*M*) and saturation (*s*):

Temporary magnitude quantity (*t*) is computed for calculating *C* (and by extension *M*).

$$t = \frac{(50000/13)N_c N_{cb} e_t \sqrt{a^2 + b^2}}{R'_a + G'_a + (21/20)B'_a} \qquad (9-19)$$

$$C = t^{0.9}\sqrt{J/100}(1.64 - 0.29^n)^{0.73} \qquad (9\text{ - }20)$$

$$M = CF_L^{0.25} \qquad (9\text{ - }21)$$

$$s = 100\sqrt{M/Q} \tag{9 - 22}$$

Step 9: Calculate corresponding Cartesian coordinates as necessary

$$a_c = Ccos(h) \tag{9 - 23}$$

$$b_c = Ccos(h) \tag{9 - 24}$$

$$a_M = Mcos(h) \tag{9 - 25}$$

$$b_M = Mcos(h) \tag{9 - 26}$$

$$a_S = scos(h) \tag{9 - 27}$$

$$b_S = scos(\mathrm{h})$$

Appendix B: Backward CIECAM02

Step 1:

If starting from Q, J can be computed in the following:

$$J = 6.25\left(\frac{cQ}{(A_W + 4)F_L^{0.25}}\right)^2 \tag{10 – 1}$$

If starting from M, then C can be calculated:

$$C = M/F_L^{0.25} \tag{10 - 2}$$

If starting from s, then C can be computed:

$$Q = \frac{4}{c}\sqrt{J/100}(A_W + 4)F_L^{0.25} \tag{10 - 3}$$

$$C = (s/100)^2\frac{Q}{F_L^{0.25}} \tag{10 - 4}$$

Starting from H or h and Table 9.79, h' is calculated:

$$h' = \frac{(H - H_i)(e_{i+1}h_i - e_ih_{i+1}) - 100h_ie_{i+1}}{(H - H_i)(e_{i+1} - e_i) - 100e_{i+1}} \qquad (10-5)$$

Set $h = (h' - 360)$ if $h' > 360$ otherwise $h = h'$

Step 2:

Calculate *t*, *e*, p_1, p_2 and p_3:

$$t = \left(\frac{C}{\sqrt{J/100}(1.64 - 0.29^n)^{0.73}}\right)^{\frac{1}{0.9}} \qquad (10-6)$$

Note that if t is equal to zero, then set a and b to zero, calculate A, compute p_2 and go directly to equation R_a'.

$$e_t = 1/4\left(\cos\left(h\frac{\pi}{180} + 2\right) + 3.8\right) \qquad (10-7)$$

$$A = A_W(J/100)^{\frac{1}{cz}} \qquad (10-8)$$

$$p_1 = \frac{(50000/13)N_cN_{cb}e_t}{t} \qquad (10-9)$$

$$p_2 = (A/N_{bb}) + 0.305 \qquad (10-10)$$

$$p_3 = 21/20 \qquad (10-11)$$

Calculate a and b:

$$h_r = h\frac{\pi}{180} \qquad (10-12)$$

if $|\sin(h_r)| \geq |\cos(h_r)|$,

$$p_4 = p_1/\sin(h_r) \qquad (10-13)$$

$$b = \frac{p_2(2 + p_3)(460/1403)}{p_4 + (2 + p_3)(220/1403)[\cos(h_r)/\sin(h_r)] - (27/1403) + p_3(6300/1403)}$$

(10-14)

$$a = b[\cos(h_r)/\sin(h_r)] \qquad (10-15)$$

if $|\sin(h_r)| < |\cos(h_r)|$,

$$p_5 = p_1/\cos(h_r) \qquad (10-16)$$

$$a = \frac{p_2(2+p_3)(460/1403)}{p_5 + (2+p_3)(220/1403) - [(27/1403) - p_3(6300/1403)][\sin(h_r)\,/\,\cos(h_r)]}$$

(10-17)

$$b = a[\sin(h_r)\,/\,\cos(h_r)] \qquad (10\text{-}18)$$

Step 3:

Calculate R'_a, G'_a and B'_a:

$$R'_a = \frac{460}{1403}p_2 + \frac{451}{1403}a + \frac{288}{1403}b$$
$$G'_a = \frac{460}{1403}p_2 - \frac{891}{1403}a - \frac{261}{1403}b \qquad (10-19)$$
$$B'_a = \frac{460}{1403}p_2 - \frac{220}{1403}a - \frac{6300}{1403}b$$

Calculate R', G' and B':

$$R' = \frac{100}{F_L}\left(\frac{27.13|R'_a - 0.1|}{400 - |R'_a - 0.1|}\right)^{\frac{1}{0.42}}$$

$$G' = \frac{100}{F_L}\left(\frac{27.13|G'_a - 0.1|}{400 - |G'_a - 0.1|}\right)^{\frac{1}{0.42}}$$

$$B' = \frac{100}{F_L}\left(\frac{27.13|B'_a - 0.1|}{400 - |B'_a - 0.1|}\right)^{\frac{1}{0.42}} \qquad (10-20)$$

If any of the values of $(R'_a - 0.1)$, $(G'_a - 0.1)$ or $(B'_a - 0.1)$ are negative, then the corresponding value R', G' or B' must be made negative.

Calculate R_c, G_c and B_c:

$$\begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} = M_{CAT02} M_{HPE}^{-1} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \qquad (10\text{-}21)$$

where

$$M_{HPE}^{-1} = \begin{bmatrix} 1.910197 & -1.112124 & 0.201908 \\ 0.370950 & 0.629054 & -0.000008 \\ 0.000000 & 0.000000 & 0.000000 \end{bmatrix}$$

Step 6:

Calculate R, G, B, X, Y and Z:

$$R = \frac{R_c}{\left(Y_W\, {}^{D}\!/_{R_W} + 1 - D\right)}$$

$$G = \frac{G_c}{\left(Y_W\, {}^{D}\!/_{G_W} + 1 - D\right)} \qquad (10-22)$$

$$B = \frac{B_c}{\left(Y_W\, {}^{D}\!/_{B_W} + 1 - D\right)}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_{CAT02}^{-1} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad (10\text{-}23)$$

Appendix C: Observer response vs. predicted value from the Cho ellipsoid model

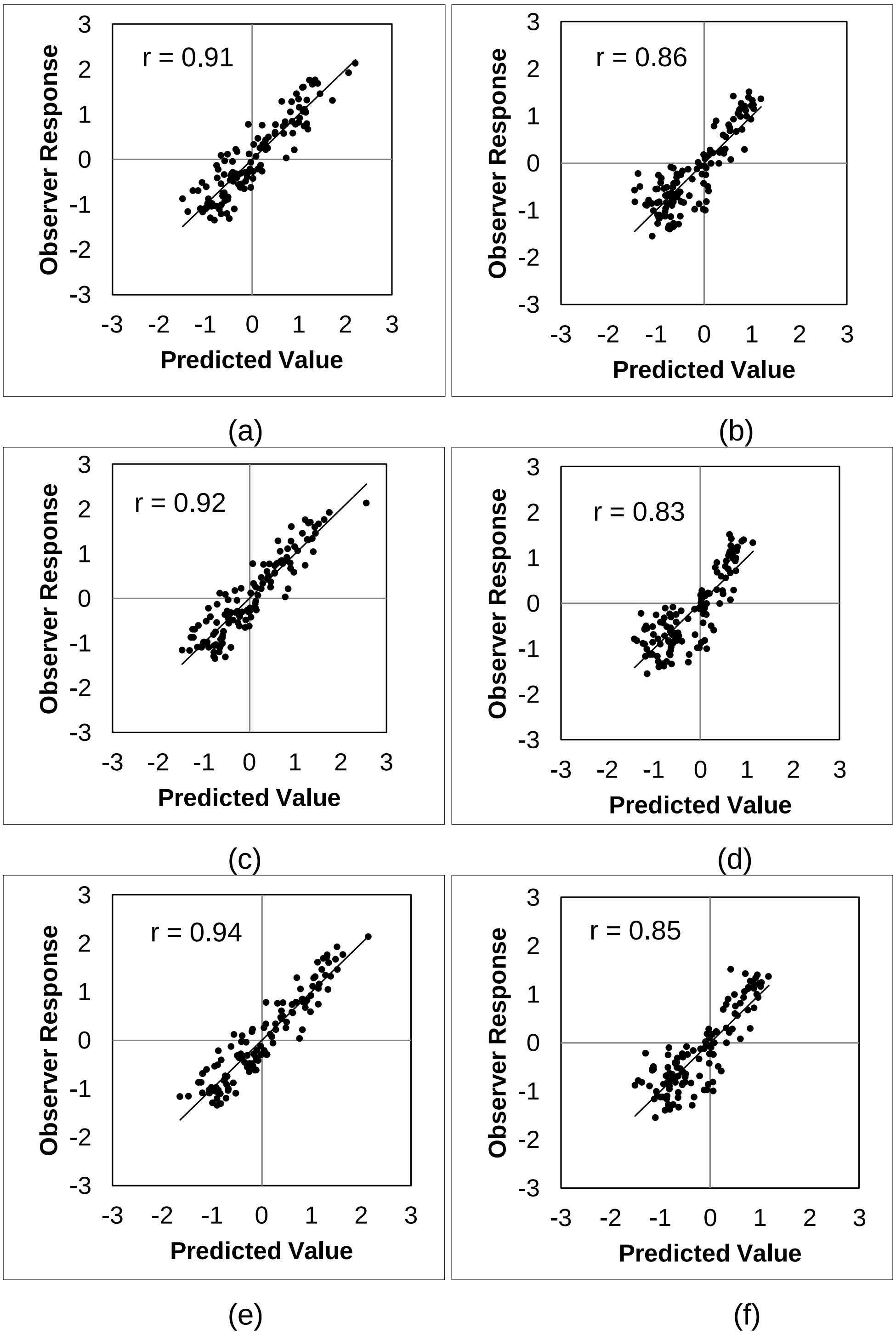
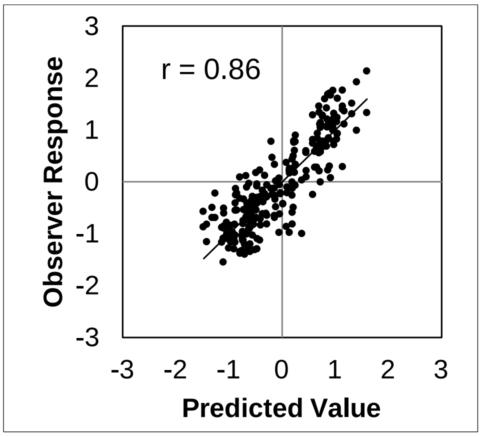
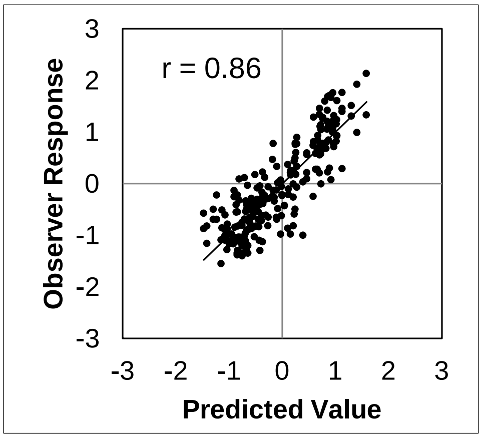


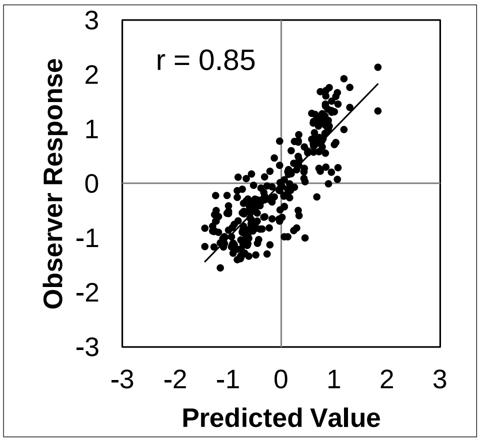
Figure 8.1 Left-column diagrams: British observer response against the predicted value of the Cho ellipsoid Saturation_$_{\text{British}}$ model in (a) CIELAB, (c) CIECAM02 and (e) CAM02-UCS versions. Right-column diagrams: Korean observer response against the predicted value of the Cho ellipsoid Saturation_$_{\text{Korean}}$ model in 3 versions.



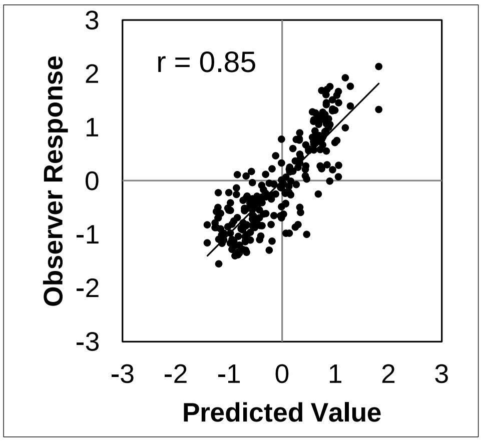
(a)



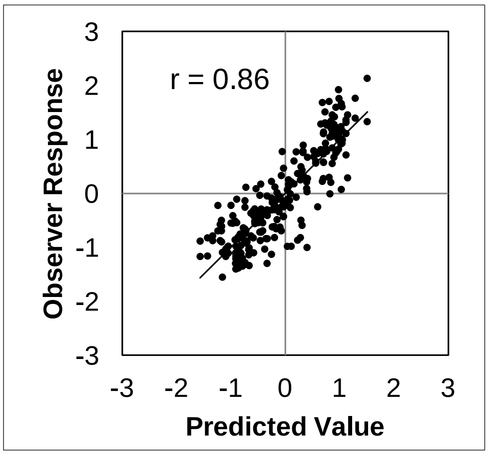
(b)



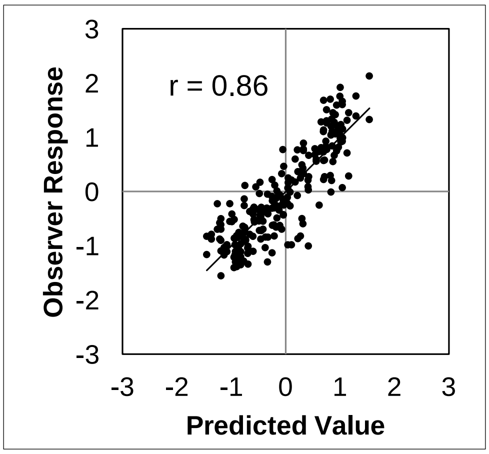
(c)



(d)



(e)



(f)

Figure 8.2 Left-column diagrams: Combined observer response against the predicted value of the Cho ellipsoid saturation model in (a) CIELAB, (c) CIECAM02 and (e) CAM02-UCS versions. Right-column diagrams are the same as the left-column diagrams except for the Cho ellipsoid saturation model (developed without neutral data)

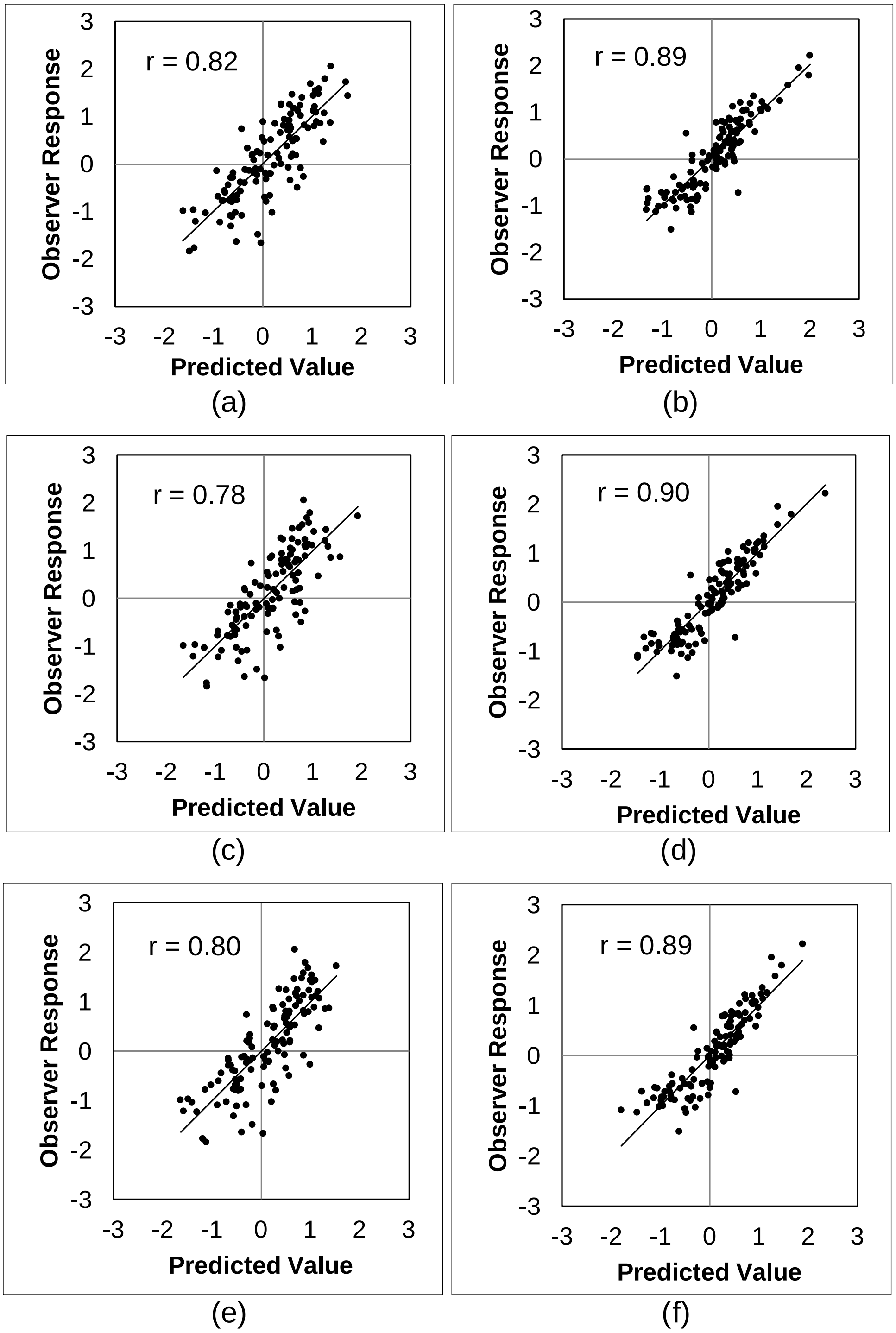
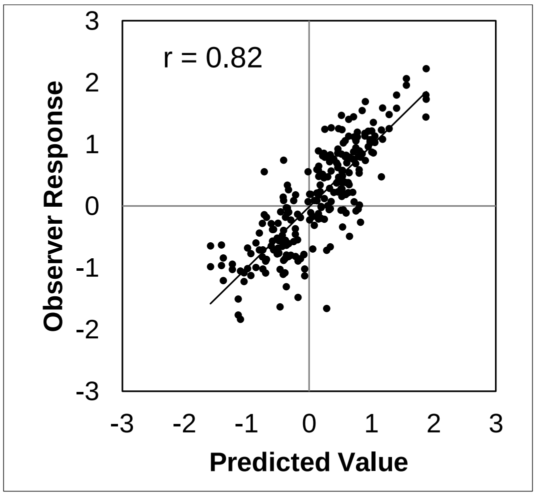
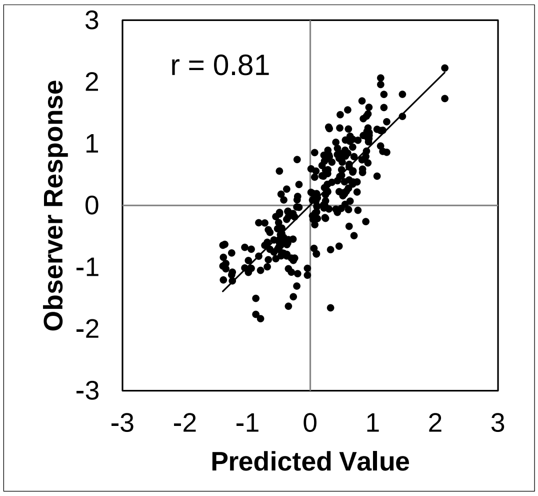


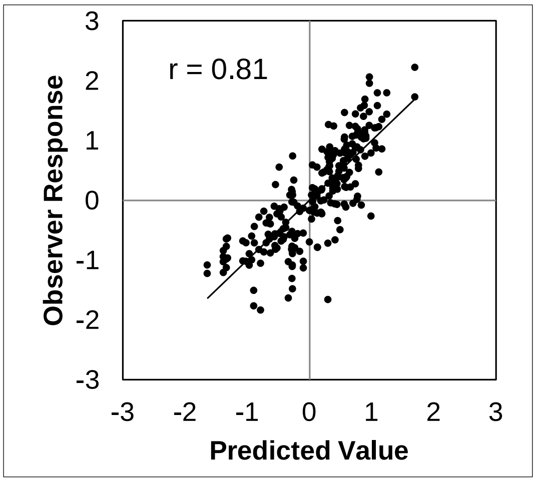
Figure 8.3 Left-column diagrams: British observer response against the predicted value of the Cho ellipsoid vividness$_{_British}$ model in (a) CIELAB, (c) CIECAM02 and (e) CAM02-UCS versions. Right-column diagrams: Korean observer response against the predicted value of the Cho ellipsoid vividness$_{_Korean}$ model in 3 versions



(a)



(b)



(c)

Figure 8.4 Combined observer response against the predicted value of the Cho ellipsoid vividness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions.

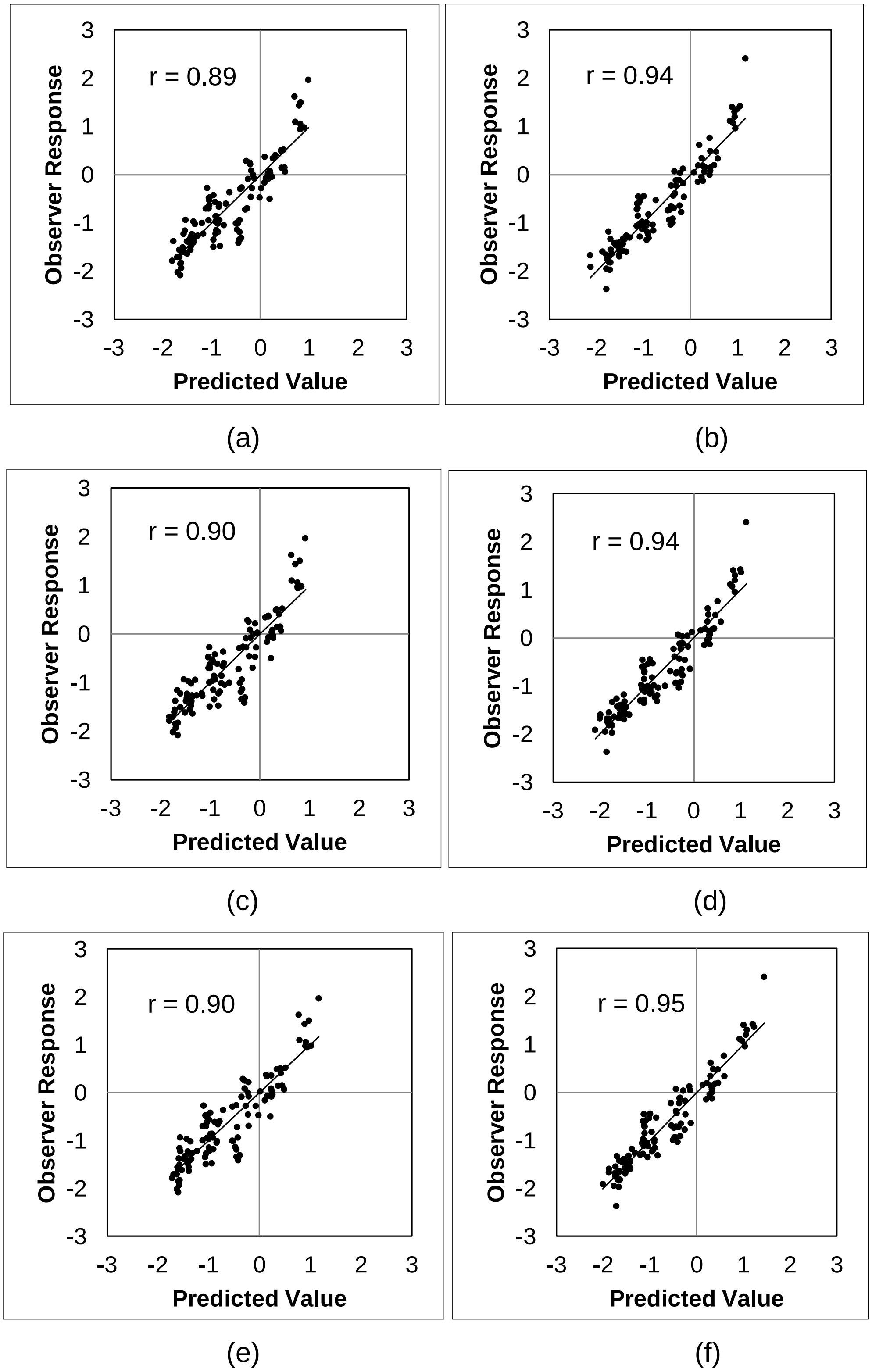
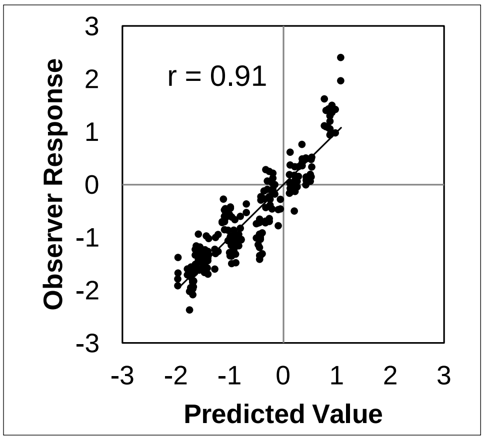
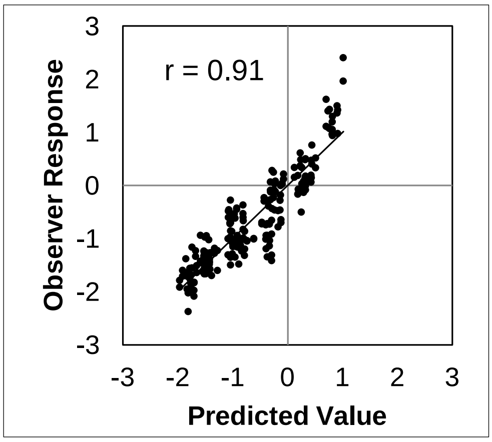


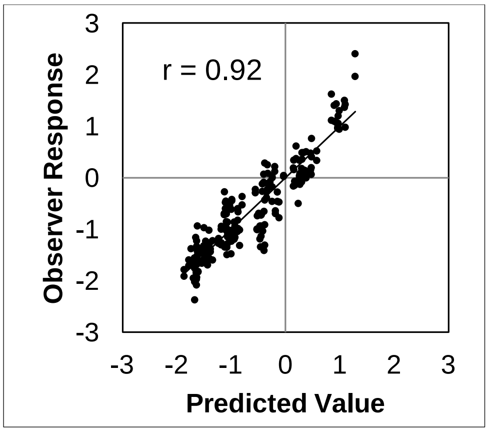
Figure 8.5 Left-column diagrams: the British observer response against the predicted value of the Cho ellipsoid blackness$_{_British}$ model in (a) CIELAB, (c) CIECAM02 and (e) CAM02-UCS versions. Right-column diagrams: the Korean observer response against the predicted value of the Cho ellipsoid blackness$_{_Korean}$ model in 3 versions



(a)

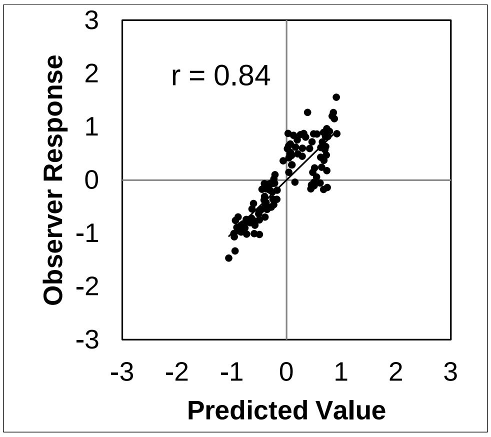


(b)

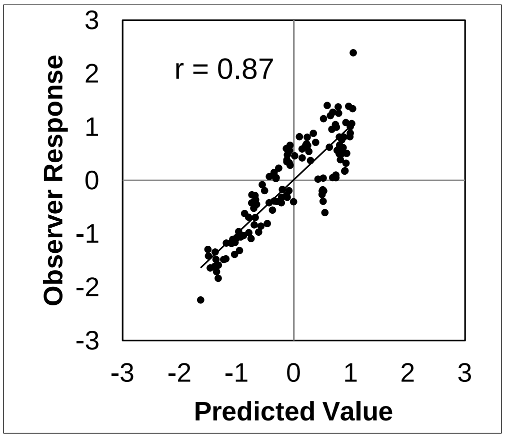


(e)

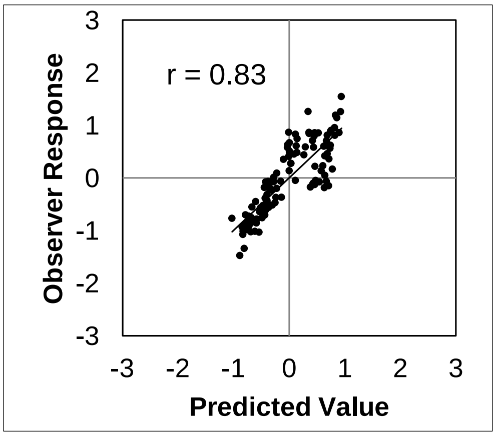
Figure 8.6 Combined observer response against the predicted value of the Cho ellipsoid blackness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions.



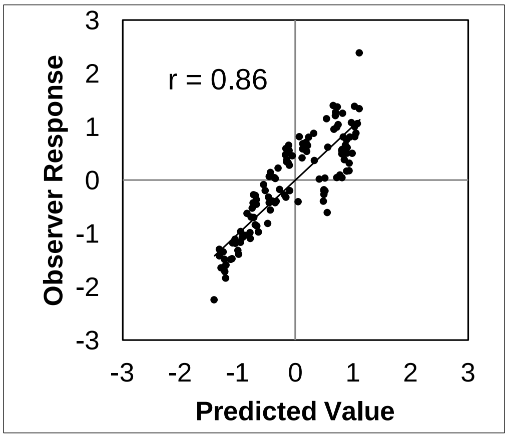
(a)



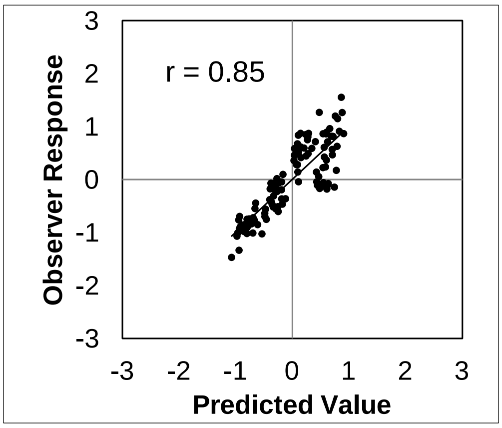
(b)



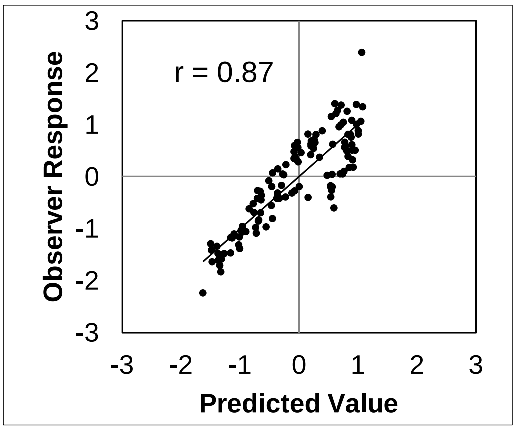
(c)



(d)

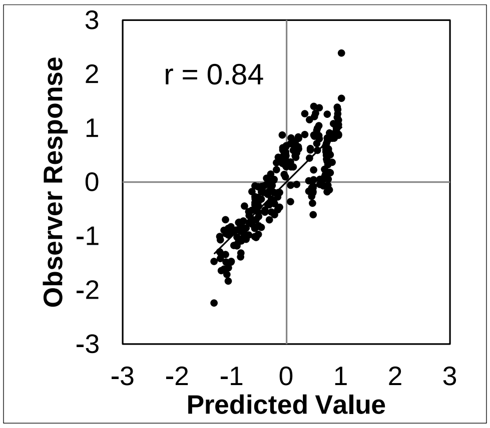


(e)

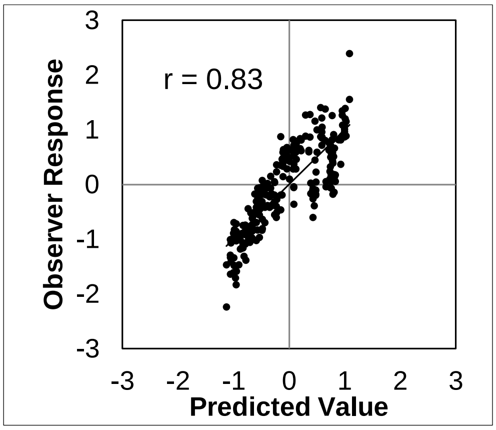


(f)

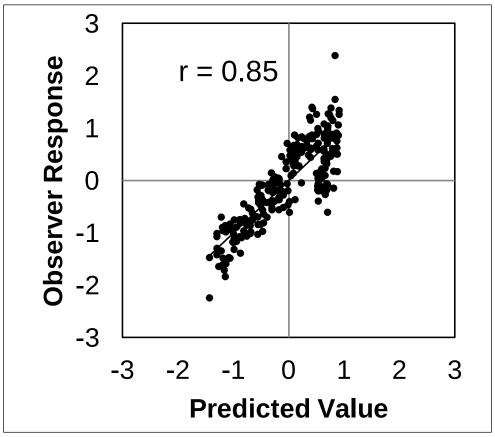
Figure 8.7 Left-column diagrams: British observer response against the predicted value of the Cho ellipsoid whiteness$_{_British}$ model in (a) CIELAB, (c) CIECAM02 and (e) CAM02-UCS versions. Right-column diagrams: Korean observer response against the predicted value of the Cho ellipsoid whiteness$_{_Korean}$ model in 3 versions



(a)



(b)



(e)

Figure 8.8 Combined observer response against the predicted value of the Cho ellipsoid whiteness model in (a) CIELAB, (b) CIECAM02 and (c) CAM02-UCS versions.

Appendix D: Visual Data Set of Saturation, Vividness, Whiteness and Blackness

	Saturation		Vividness		Whiteness	
Colour Sample	British	Korean	British	Korean	British	Korean
0030-Y10R	-0.62	-0.17	0.23	0.86	0.87	1.40
2030-Y10R	-0.34	-0.54	-0.78	-0.52	0.61	0.81
4030-Y10R	0.22	-1.13	-1.84	-1.06	-0.37	0.03
0080-Y10R	1.31	1.51	2.06	1.96	-0.61	-0.40
2060-Y10R	0.60	0.18	0.21	0.59	-0.47	-0.20
4060-Y10R	0.50	-0.50	-1.31	-0.03	-0.56	-0.97
0030-Y50R	-0.31	-0.08	0.23	0.34	0.44	1.15
2030-Y50R	-0.41	-0.84	-0.56	-0.10	0.28	0.59
2060-Y50R	0.78	-0.13	-0.14	0.55	-0.17	-0.40
0060-Y50R	0.21	0.09	0.94	1.07	0.09	0.42
4030-Y50R	0.03	-1.00	-1.66	-0.72	-0.23	-0.42
4060-Y50R	0.58	0.28	-0.66	0.83	-0.55	-0.98
0030-Y90R	-0.49	-0.42	0.48	0.64	0.71	0.95
2030-Y90R	-0.35	-1.03	-0.77	-0.56	0.28	0.81
4030-Y90R	0.07	-0.98	-1.64	-1.03	-0.07	-0.20
0060-Y90R	0.74	-0.25	1.18	1.13	-0.20	0.46
1090-Y90R	2.13	1.33	1.73	2.22	-0.77	-1.09
4060-Y90R	1.32	0.71	-0.27	0.79	-0.93	-1.47
2030-R30B	-0.29	-0.72	0.18	-0.82	0.75	0.65
0030-R30B	-0.56	-0.51	0.85	0.45	0.86	1.04
4030-R30B	0.22	-0.98	-1.48	-0.89	-0.18	-0.08
1060-R30B	1.69	0.23	1.59	1.08	-0.56	-0.32
2060-R30B	1.71	0.30	1.13	1.03	-0.64	-0.81
3060-R30B	1.46	0.29	0.47	1.23	-0.89	-1.17
0030-R90B	-0.30	-0.61	0.81	-0.04	0.86	1.27
2030-R90B	-0.29	-0.82	-0.19	-0.86	0.49	0.63
4030-R90B	0.25	-0.82	-1.02	-1.13	-0.05	0.07
1060-R90B	1.34	0.21	1.44	0.88	-0.07	-0.17
2060-R90B	1.60	0.75	1.09	0.69	-0.52	-0.56
3070-R90B	1.77	1.40	0.87	1.21	-0.72	-1.04
0030-B30G	0.12	-0.23	0.92	0.40	0.59	0.99
2030-B30G	-0.06	-0.65	0.19	-0.23	-0.05	0.54
4030-B30G	0.37	-0.87	-0.79	-0.79	0.01	-0.39
0040-B30G	0.47	-0.25	1.25	0.46	0.59	0.62
2060-B30G	1.05	-0.01	1.21	0.96	-0.70	-0.42

	Saturation		Vividness		Whiteness	
Colour Sample	British	Korean	British	Korean	British	Korean
3060-B30G	1.67	0.08	0.86	1.35	-1.01	-0.86
0030-G10Y	-0.39	-0.30	0.81	0.70	0.80	1.37
2030-G10Y	-0.54	-0.69	-0.14	-0.55	0.45	0.68
4030-G10Y	0.33	-0.69	-1.08	-0.86	-0.07	0.14
0060-G10Y	0.67	0.28	1.48	1.25	-0.06	0.71
1080-G10Y	1.92	0.99	1.44	1.80	-0.84	-0.32
4060-G10Y	1.07	1.42	-0.08	1.05	-0.92	-1.32
0030-G70Y	-0.27	-0.34	0.53	0.58	0.85	1.21
2060-G70Y	0.77	-0.07	-0.17	0.08	-0.52	-0.28
4030-G70Y	-0.05	-1.30	-1.77	-1.51	-0.20	0.05
0060-G70Y	0.79	0.68	1.80	1.58	-0.37	0.37
4060-G70Y	0.43	-0.59	-1.11	0.14	-1.03	-0.70
2030-G70Y	-0.46	-0.87	-0.80	-0.64	0.83	0.65
8010-Y90R	0.78	1.22	0.76	0.22	-1.07	-1.42
6030-Y90R	0.84	0.93	0.81	-0.06	-0.91	-1.18
4010-R30B	-0.84	-0.64	-0.77	-1.13	0.41	0.38
6010-R30B	-0.26	-0.01	-0.23	-0.80	-0.18	-0.69
8010-R30B	0.82	1.16	0.80	-0.05	-1.01	-1.30
6030-R30B	1.61	0.93	1.54	0.84	-0.90	-1.62
4050-R30B	1.76	1.05	1.69	0.74	-0.75	-1.07
4010-R90B	-1.10	-0.41	-1.02	-0.71	0.87	0.35
6010-R90B	0.25	0.17	0.26	-0.82	-0.31	-0.42
8010-R90B	0.92	1.24	0.89	0.01	-1.34	-1.64
6030-R90B	1.16	1.00	1.12	0.07	-0.83	-1.49
4010-B30G	-0.32	-0.82	-0.28	-0.83	0.14	0.33
6010-B30G	-0.21	-0.10	-0.18	-0.56	-0.47	-0.84
8010-B30G	0.84	1.12	0.82	-0.12	-0.96	-1.49
6030-B30G	1.28	0.67	1.23	0.27	-1.02	-1.19
4050-B30G	1.46	0.56	1.40	1.13	-0.78	-0.53
4010-G10Y	-0.74	-0.66	-0.68	-1.02	0.58	0.48
6010-G10Y	-0.62	-0.06	-0.57	-0.38	-0.09	-0.45
8010-G10Y	1.05	1.21	1.02	-0.06	-0.70	-1.35
6030-G10Y	1.29	0.81	1.24	0.79	-0.75	-1.11
4010-G70Y	-1.30	-1.10	-1.21	-0.84	0.48	0.66
6010-G70Y	-0.48	0.02	-0.44	-0.71	-0.43	-0.29
8010-G70Y	0.58	1.14	0.57	0.07	-0.86	-1.84
6030-G70Y	0.33	0.90	0.34	-0.03	-0.45	-0.96
S9000-N (Black)	1.11	1.36	1.07	1.04	-1.47	-2.24

	Saturation		Vividness		Whiteness	
Colour Sample	British	Korean	British	Korean	British	Korean
S7000-N	-0.13	0.22	-0.10	-0.61	-0.76	-0.62
S5000-N	-1.31	-0.72	-1.23	-1.08	0.35	0.23
S3000-N	-1.17	-0.88	-1.09	-0.90	1.26	0.88
S0500-N (White)	-0.54	-0.11	-0.49	0.79	1.55	2.39
4010-Y10R	-1.06	-0.84	-0.99	-0.65	0.67	0.28
6010-Y10R	-0.65	-0.12	-0.60	-1.00	-0.09	-0.36
8010-Y10R	0.73	1.11	0.72	0.28	-0.98	-1.59
6030-Y10R	0.76	0.79	0.74	0.09	-0.86	-1.06
4010-Y50R	-1.04	-0.82	-0.97	-0.63	0.51	0.56
6010-Y50R	-0.22	-0.23	-0.18	-0.87	-0.38	-0.43
8010-Y50R	0.78	1.27	0.76	0.22	-0.91	-1.71
6030-Y50R	0.56	0.60	0.55	0.07	-0.81	-1.39
4010-Y90R	-1.11	-0.96	-1.03	-0.94	0.63	0.59
6010-Y90R	-0.42	-0.43	-0.38	-0.71	-0.07	-0.27
0010-Y10R	-1.04	-1.14	0.38	0.56	0.36	0.81
1010-Y10R	-1.10	-1.28	-0.21	0.17	0.60	0.56
2010-Y10R	-0.87	-0.57	-0.68	-0.28	-0.11	-0.20
0020-Y10R	-0.03	-0.71	0.66	0.62	-0.07	0.05
0005-Y50R	-1.35	-1.38	-0.07	0.28	1.20	1.38
1005-Y50R	-1.09	-1.55	-0.70	-0.17	0.81	1.25
2005-Y50R	-1.16	-0.82	-0.76	-0.56	0.22	0.04
1010-Y50R	-0.51	-0.86	-0.11	0.19	0.23	0.10
0020-Y50R	0.09	-0.32	0.89	0.58	-0.05	0.05
0010-Y90R	-1.04	-1.33	-0.34	0.41	1.15	0.88
1010-Y90R	-1.10	-1.01	-0.32	0.09	0.46	0.81
2010-Y90R	-0.69	-0.22	-0.29	-0.65	-0.17	0.02
0020-Y90R	-0.13	-0.26	0.51	0.81	-0.18	0.38
0010-R30B	-1.21	-1.40	0.15	0.20	0.86	1.06
1010-R30B	-1.03	-1.17	-0.03	-0.01	0.91	0.51
2010-R30B	-0.87	-0.79	-0.40	-0.88	-0.11	-0.27
0020-R30B	0.12	-0.69	1.27	0.78	-0.15	0.18
0010-R90B	-1.20	-1.35	0.18	0.38	1.26	1.34
1010-R90B	-0.81	-1.13	0.12	-0.22	0.62	0.76
2010-R90B	-0.22	-0.55	-0.37	-0.46	-0.08	-0.61
0020-R90B	-0.36	-0.79	0.70	0.37	0.17	0.50
0010-B30G	-0.89	-0.90	0.48	0.58	0.81	0.81
1010-B30G	-0.75	-1.12	0.004	0.47	0.56	0.61
2010-B30G	-0.41	-0.55	0.09	-0.58	-0.13	-0.20

	Saturation		Vividness		Whiteness	
Colour Sample	British	Korean	British	Korean	British	Korean
0020-B30G	0.17	-0.43	1.47	0.84	-0.06	0.32
0010-G10Y	-0.92	-1.28	0.54	0.34	0.96	1.00
1010-G10Y	-0.98	-1.10	-0.20	-0.13	0.71	0.49
2010-G10Y	-0.61	-0.90	-0.12	-0.61	-0.10	-0.39
0020-G10Y	-0.29	-0.52	1.06	0.80	0.05	0.17
0010-G70Y	-1.01	-1.34	0.21	0.38	0.89	1.08
1010-G70Y	-0.98	-1.17	-0.20	-0.01	0.42	0.58
2010-G70Y	-0.69	-0.50	-0.66	-0.48	-0.11	-0.18
0020-G70Y	-0.32	-0.84	1.12	1.19	0.14	0.66

	Blackness	
Colour Sample	British	Korean
4010-Y10R	-1.19	-0.94
2030-Y10R	-1.15	-1.12
4030-Y10R	-0.09	0.07
0080-Y10R	-1.38	-1.67
2060-Y10R	-0.86	-1.06
4060-Y10R	-0.08	-0.12
6010-Y10R	-0.50	-0.05
2030-Y50R	-1.48	-1.05
2060-Y50R	-0.60	-0.83
0060-Y50R	-1.26	-1.69
4030-Y50R	0.08	-0.11
4060-Y50R	-0.28	-0.39
8010-Y10R	1.06	1.20
2030-Y90R	-1.05	-1.04
4030-Y90R	0.00	-0.18
0060-Y90R	-1.22	-1.60
1090-Y90R	-0.94	-1.26
4060-Y90R	0.02	0.04
2030-R30B	-0.86	-1.19
6030-Y10R	0.14	0.08
4030-R30B	0.22	0.12
1060-R30B	-1.00	-1.30
2060-R30B	-0.66	-0.99
4010-Y50R	-1.34	-0.94
6010-Y50R	-0.04	0.06
2030-R90B	-1.22	-1.23
4030-R90B	-0.27	-0.12

	Blackness	
Colour Sample	British	Korean
1060-R90B	-1.49	-1.35
2060-R90B	-0.94	-1.16
3070-R90B	-1.01	-1.00
8010-Y50R	0.97	0.96
2030-B30G	-1.35	-1.00
4030-B30G	-0.29	-0.23
6030-Y50R	0.49	0.14
2060-B30G	-0.97	-0.98
3060-B30G	-0.37	-0.53
4010-Y90R	-1.31	-0.91
2030-G10Y	-1.18	-1.12
4030-G10Y	0.28	-0.43
0060-G10Y	-1.64	-1.66
1080-G10Y	-1.27	-1.18
4060-G10Y	-0.47	-0.78
6010-Y90R	0.08	-0.13
2060-G70Y	-0.61	-1.02
4030-G70Y	0.25	-0.23
0060-G70Y	-1.78	-1.91
4060-G70Y	-0.28	-0.46
2030-G70Y	-0.57	-1.29
8010-Y90R	0.98	1.42
6030-Y90R	0.15	0.48
4010-R30B	-1.41	-0.65
6010-R30B	-0.08	0.18
8010-R30B	1.50	1.37
6030-R30B	0.52	0.33
4050-R30B	-0.46	0.04
4010-R90B	-1.14	-0.73
6010-R90B	0.37	0.61
8010-R90B	1.10	1.41
6030-R90B	0.36	0.49
4010-B30G	-1.01	-0.74
6010-B30G	-0.16	0.19
8010-B30G	1.62	1.11
6030-B30G	0.34	0.16
4050-B30G	-0.72	-0.69
4010-G10Y	-1.34	-1.03

	Blackness	
Colour Sample	British	Korean
6010-G10Y	-0.07	-0.15
8010-G10Y	1.44	1.07
6030-G10Y	0.51	0.00
4010-G70Y	-0.94	-0.72
6010-G70Y	0.03	0.34
8010-G70Y	0.94	1.30
6030-G70Y	0.06	0.20
S9000-N (Black)	1.97	2.41
S7000-N	0.41	0.76
S5000-N	-0.70	-0.64
S3000-N	-1.01	-1.32
S0500-N (White)	-2.02	-2.37
0010-Y10R	-1.61	-1.68
1010-Y10R	-1.23	-1.58
2010-Y10R	-0.47	-0.45
0020-Y10R	-1.16	-1.55
0005-Y50R	-1.93	-1.69
1005-Y50R	-1.38	-1.44
2005-Y50R	-0.63	-0.58
1010-Y50R	-1.02	-1.33
0020-Y50R	-0.97	-1.40
0010-Y90R	-1.85	-1.82
1010-Y90R	-1.41	-1.58
2010-Y90R	-0.42	-0.45
0020-Y90R	-1.32	-1.45
0010-R30B	-1.83	-1.82
1010-R30B	-1.56	-1.55
2010-R30B	-0.53	-0.54
0020-R30B	-1.38	-1.42
0010-R90B	-2.08	-1.97
1010-R90B	-1.48	-1.45
2010-R90B	-0.70	-0.72
0020-R90B	-1.62	-1.47
0010-B30G	-1.51	-1.64
1010-B30G	-1.41	-1.55
2010-B30G	-0.27	-0.69
0020-B30G	-0.94	-1.42
0010-G10Y	-1.56	-1.75

	Blackness	
Colour Sample	British	Korean
1010-G10Y	-1.27	-1.57
2010-G10Y	-0.70	-0.85
0020-G10Y	-1.23	-1.33
0010-G70Y	-1.71	-1.95
1010-G70Y	-1.26	-1.66
2010-G70Y	-0.48	-0.60
0020-G70Y	-1.71	-1.60

Appendix E: Colour Sample Measurement Data (XYZ)

Colour Sample	X	Y	Z
0030-Y10R	85.70	89.19	48.24
2030-Y10R	56.76	58.27	31.06
4030-Y10R	33.00	33.21	16.01
0080-Y10R	74.09	73.75	11.07
2060-Y10R	50.41	49.99	13.24
4060-Y10R	26.21	25.51	6.64
0030-Y50R	78.47	72.21	44.55
2030-Y50R	55.52	50.51	30.69
2060-Y50R	42.44	34.04	12.69
0060-Y50R	66.37	54.02	21.14
4030-Y50R	31.01	27.53	16.34
4060-Y50R	24.71	19.00	6.09
0030-Y90R	79.53	71.14	62.95
2030-Y90R	50.96	44.16	37.03
4030-Y90R	28.44	23.96	19.78
0060-Y90R	55.75	40.09	24.15
1090-Y90R	31.30	17.70	5.88
4060-Y90R	14.57	9.70	5.31
2030-R30B	52.33	45.08	55.26
0030-R30B	77.16	68.96	82.69
4030-R30B	26.16	21.56	26.28
1060-R30B	45.75	30.46	42.99
2060-R30B	33.87	22.23	29.23
3060-R30B	17.95	11.05	14.42
0030-R90B	60.29	65.15	99.26
2030-R90B	41.16	44.17	69.30
4030-R90B	22.64	24.02	42.56
1060-R90B	26.33	28.52	71.77
2060-R90B	23.03	24.33	64.64
3070-R90B	12.64	12.93	41.16
0030-B30G	58.83	69.50	88.38
2030-B30G	39.62	47.44	63.10
4030-B30G	21.59	26.46	37.18
0040-B30G	50.94	61.99	80.78
2060-B30G	19.53	28.17	45.44
3060-B30G	12.65	18.79	32.00
0030-G10Y	66.50	81.51	68.81
2030-G10Y	39.71	49.73	42.56
4030-G10Y	22.18	28.73	23.33

Colour Sample	X	Y	Z
0060-G10Y	39.09	58.64	35.23
1080-G10Y	17.44	33.57	14.45
4060-G10Y	8.54	14.21	8.75
0030-G70Y	83.77	95.36	53.55
2060-G70Y	39.91	47.28	13.26
4030-G70Y	29.16	32.83	18.00
0060-G70Y	73.70	88.21	26.40
4060-G70Y	20.39	23.84	6.72
2030-G70Y	52.02	58.97	31.74
8010-Y90R	6.26	5.76	5.42
6030-Y90R	12.55	10.11	7.82
4010-R30B	35.59	34.26	39.95
6010-R30B	17.56	16.28	19.63
8010-R30B	5.80	5.38	6.51
6030-R30B	9.35	7.16	9.51
4050-R30B	18.36	12.06	14.62
4010-R90B	32.33	33.85	44.10
6010-R90B	17.28	18.00	23.80
8010-R90B	5.55	5.81	8.59
6030-R90B	7.89	8.36	17.29
4010-B30G	32.31	35.60	43.02
6010-B30G	16.89	18.54	22.91
8010-B30G	6.26	6.97	8.68
6030-B30G	8.31	10.56	15.71
4050-B30G	12.27	16.99	26.76
4010-G10Y	31.50	35.41	35.51
6010-G10Y	17.59	20.01	19.93
8010-G10Y	6.27	7.32	7.13
6030-G10Y	8.82	11.92	9.49
4010-G70Y	35.57	38.46	32.41
6010-G70Y	18.52	20.06	16.35
8010-G70Y	7.48	8.02	6.62
6030-G70Y	13.15	14.73	7.83
S9000-N (Black)	4.18	4.30	4.99
S7000-N	14.80	15.29	16.65
S5000-N	29.12	30.10	33.38
S3000-N	51.01	52.93	57.28
S0500-N (White)	94.98	98.48	103.65
4010-Y10R	37.82	39.07	30.80

Colour Sample	X	Y	Z
6010-Y10R	19.95	20.27	16.55
8010-Y10R	8.05	8.05	6.41
6030-Y10R	15.71	15.33	7.05
4010-Y50R	38.32	37.87	32.80
6010-Y50R	19.10	18.55	15.28
8010-Y50R	8.12	7.72	6.04
6030-Y50R	15.59	13.44	7.42
4010-Y90R	36.04	34.99	34.11
6010-Y90R	19.47	18.40	17.64
0010-Y10R	93.38	98.05	80.04
1010-Y10R	80.72	84.47	68.76
2010-Y10R	61.93	64.55	54.77
0020-Y10R	89.13	93.71	63.28
0005-Y50R	93.55	95.79	92.03
1005-Y50R	78.09	79.96	77.31
2005-Y50R	61.69	63.14	60.79
1010-Y50R	79.48	79.59	68.70
0020-Y50R	83.37	80.14	59.21
0010-Y90R	94.79	95.38	95.20
1010-Y90R	79.82	79.16	79.13
2010-Y90R	58.83	57.76	56.82
0020-Y90R	85.72	81.76	76.25
0010-R30B	91.82	91.41	101.27
1010-R30B	80.57	79.83	89.27
2010-R30B	59.77	59.19	67.73
0020-R30B	86.40	80.95	91.32
0010-R90B	86.91	91.86	108.53
1010-R90B	73.10	77.39	94.51
2010-R90B	57.75	60.64	75.22
0020-R90B	76.45	81.79	104.06
0010-B30G	80.63	88.11	101.05
1010-B30G	73.34	79.51	92.46
2010-B30G	55.65	60.42	71.27
0020-B30G	71.65	81.14	96.98
0010-G10Y	88.56	97.37	96.49
1010-G10Y	72.29	78.95	80.24
2010-G10Y	56.43	62.26	62.27
0020-G10Y	77.62	89.72	82.56
0010-G70Y	92.35	99.78	84.91

Colour Sample	X	Y	Z
1010-G70Y	78.00	84.18	71.29
2010-G70Y	59.99	65.01	55.36
0020-G70Y	92.59	102.16	71.62

Note: the method to obtain the tristimulus values are described in Section 3.5.

Appendix F Definitions of Four Attributes in Dictionary

Saturated: Containing the largest possible amount of a particular solute.
(of colour) very bright, full, and free from an asmixture of white.
포화된, 채도, 색의 순수한 정도.

※ 포화된: 더 이상 채울 수 없을 만큼 가득 채움. (the greatest possible amount of the substance that has been dissolved in it).

※ 채도: 색의 순수한 정도 (the degree of colour purity).

Vivid: (of light, colours, etc) very bright.
선명한.

※ 선명한: (물체나 그 형태, 빛깔이) 뚜렷하고 밝다.

Black: of the very darkest colour owing to the absence of or complete absorption of light; the opposite of white

(Noun) 검정, (adjective) 검은.

White: of the colour of milk or fresh snow, due to the reflection of all visible rays of light; the opposite of black

(Noun) 하양, (adjective) 흰.