Modelling of colour appearance of textured colours and smartphones using CIECAM02

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Abstract

The international colour committee recommended a colour appearance model, CIECAM02 in 2002, to help to predict colours under various viewing conditions from a colour appearance point of view, which has the accuracy of an averaged observer. In this research, an attempt is made to extend this model to predict colours on mobile telephones, which is not covered in the model. Despite the limited size and capacity of a mobile telephone, the urge to apply it to meet quotidian needs has never been unencumbered due to its appealing appearance, versatility, and readiness, such as viewing/taking pictures and shopping online. While a smartphone can act as a mini-computer, it does not always offer the same functionality as a desktop computer.

For example, the RGB values on a smartphone normally cannot be modified nor can white balance be checked. As a result, performing online shopping using a mobile telephone can be difficult, especially when buying colour sensitive items. Therefore, this research takes an initiative to investigate the variations of colours for a number of smartphones while making an effort to predict their colour appearance using CIECAM02, benefiting both telephone users and makers. This thesis studies the Apple iPhone 5, LG Nexus 4, Samsung, and Huawei models, and compares their performance with a CRT colour monitor that has been calibrated using the D65 standard, to be consistent with the normal way of viewing online colours. As expected, all the telephones tested present more colourful images than a CRT. Work was also undertaken to investigate colours with a degree of texture. It was found that, on CRT monitors, a colour with a texture appears to be darker but more colourful to a human observer. Linear modifications have been proposed and implemented to the CIECAM02 model to accommodate these textured colours.

Acknowledgments

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1. Introduction

A smartphone is a mobile telephone with more advanced computing capability and connectivity than basic feature telephones, offering functionalities of typically personal assistance, media player, digital camera, and a GPS navigation unit in addition to the basic calling/receiving facilities. The global smartphone audience had reached 67.0 million units in 2011 and was expected to reach 248.6 million units by the end of 2015, [eMarkter, 2015]**.** The number of smartphone users worldwide is expected surpass 2 billion in 2016, according to new figures. As such, mobile sales are not only focusing heavily on smartphones, but also on the more affordable option of feature phones that do not have an operating system. As a result, mobile telephone penetration has surpassed 100% in many regions of the world, including North America, Western Europe, Central and South America, Central and Eastern Europe, and the Middle East [WeAreSocial, 2015].

One of the unexpected by-products of smartphones remains in the field of digital photography. It appears that more photographs are taken using smartphones than normal cameras. For example, among the few telephones used in this study, the Apple iPhone 5 is the most popular 'camera' on Flickr.com [Flickr, 2015]. As a direct result, a large amount of money is being invested by mobile developers to create photo apps in an attempt to satisfy the demands of 'serious' camera phone photographers.

While using a smartphone to perform everyday activities, colour remains one of the key factors, in particular in online shopping. Similar to any other digital device, a mobile telephone represents a digital image in a RGB colour space. Therefore when an image is to be processed, it is usually first converted into the colour space of, say, hue, lightness and colourfulness. In this way, the dependency of RGB space on hardware devices can be circumvented, i.e. a colour in one device usually does not appear nor measure the same as the one in another device even with the same RGB values in both devices. This is because the range of R, G, or B values are manually set to be the same (such as [0, 255] for an 8-bit computer) for all devices regardless of their physical measurements. Therefore in this research work, a number of smartphones are studied with their colour appearances modelled using the CIE colour appearance model, CIECAM02.

In this study, two phases of research work were conducted. Phase 1 was to train observers to estimate colours using a magnitude estimation method and at the same time to study a colour appearance model for modelling colour texture on CRT monitors. Phase 2 is for mobile telephones. The structure phase one of the thesis is as follows. Chapter 2 gives a comprehensive review of colour vision theory, colour texture, colour spaces, colour models and the trend of smartphones, which is then followed by Methodology in Chapter 3. Results and data analysis are explained in Chapter 4, followed by Chapter 5 where the conclusion is drawn up, and Chapter 6 where proposals for future work are presented. The thesis concludes with References and Appendices.

2. Literature Review

2.1 Overview of Colour Science

Colour is a visual experience generated primarily by three components, a visual system (e.g. an eye), a coloured object, such as an apple, and a light that shines on the object. Figure 2.1 illustrates the process of generating a colour. The light source generates light illuminating an object. Some part the light is reflected from the object to the eye and therefore the brain where the colour of the light is observed [Hunt, 1992; Fraser, 2003; Sangwine, 1998; Davis, 1998; Berns, 2000].

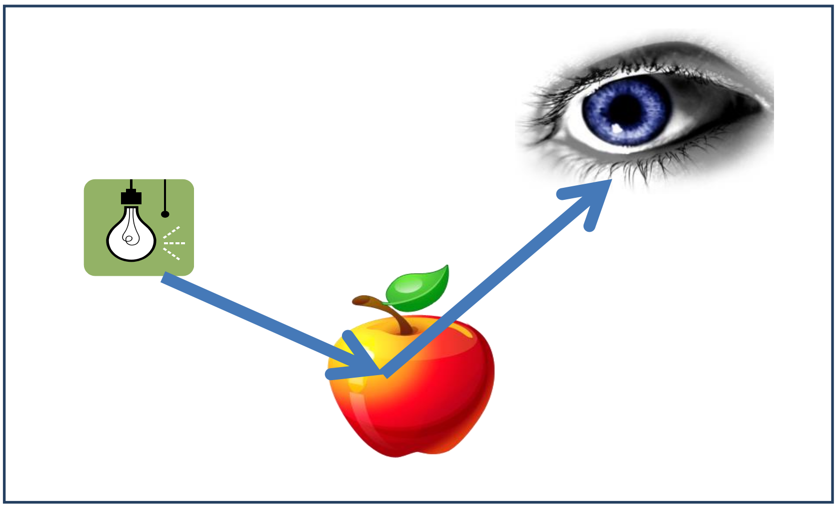


Figure 2.1: Three essential components to generate a colour. [1]

As a part of the human vision system that involves a light source, an object, and a processing system (e.g. brain), colour vision is the ability of the human eye to separate the various frequencies of light waves (380~740nm) to allow us to distinguish different colours through three colour cells, i.e. red, green and blue.

Accurate colour measurement requires reliable light sources, in order to make objects react to the components of the spectrum, and therefore colour vision properties of human observers involved in the measurement process as shown in Figure 2.2 [Neaves, 1998].

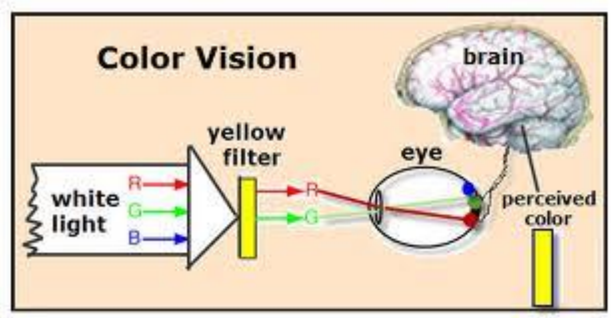


Figure 2.2: Three factors that are required to generate a colour. [2]

In 1666, Newton found that white light consists of a visible spectrum which includes all the visible colours ranging from red, orange, yellow, green and blue to violet [Luo, 1993a].

It was later found that colour is part of the electromagnetic spectrum with energy in the range of 380nm to 780nm wavelength, the range that human vision can see. Therefore the range between 380nm to 780nm is also known as 'visible light' as illustrated in Figure 2.3 [Wyszecki, 1982].

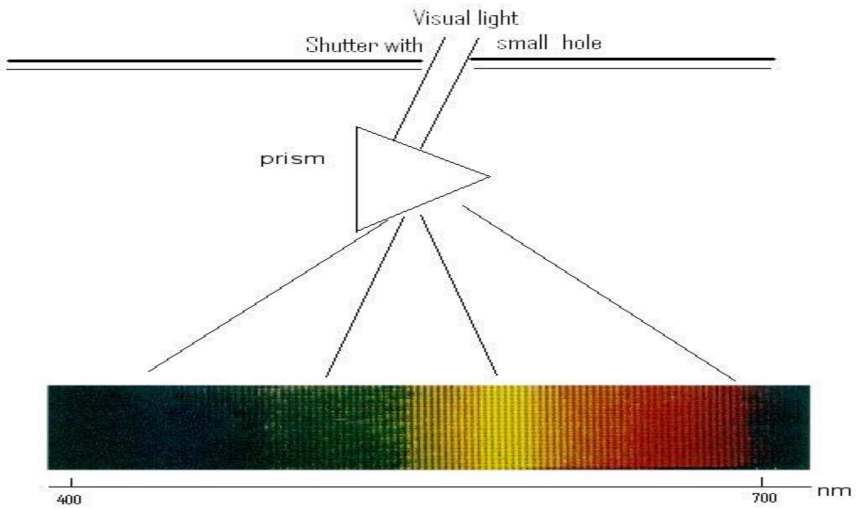


Figure 2.3. The Newton experiment. [3]

2.1.1 Light Source

The main light source is the Sun. In addition, there are a number of artificial light sources including fluorescent lamps, or by heating up materials. There are two ways to characterize a light source. One is to use a light spectral power distribution (SPD). SPD is the amount of radiant power at each wavelength represented by λ of the visible spectrum and denoted by $P(\lambda)$. The other common term to characterize light sources is colour temperature. Colour temperature corresponds to the temperature of a heated blackbody radiator. The colour of the blackbody radiator changes with the change of temperature. The absolute temperature is measured using K standing for Kelvin.

For example, the blackbody radiator changes from black at 0K, to red at about 1000K, white at 4500K to bluish white at about 6500K. The colour temperature of the Sun may vary during the time of the day (e.g. reddish at sunrise and bluish at noon) and the weather conditions (e.g., sky with/without clouds) [Gevers, 2001].

The Commission Internationale de L'éclairage (CIE) [CIE, 2015] has recommended that average daylight has the colour temperature of 6500K and is denoted by D65, whereas 5000K, or D50, represents overcast daylight. Figure 2.4 illustrates the relationship between colour temperature and spectral power distribution [Kelly, 1963].

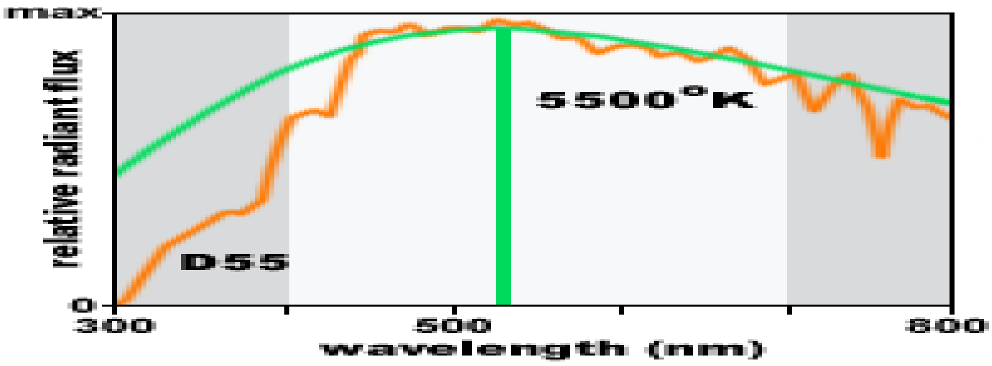


Figure 2.4: Relationship between colour temperature and spectral power distribution. [4]

2.1.2 Object

Coloured materials are called objects. The colour of an object is defined by the reflectance or transmittance that is a function of wavelength. Reflectance is the ratio of the light reflected from a sample to that reflected from a reference white board, and is denoted by R(λ) [Horne, 1998]

Usually, the colour reflected from or passed through an object is the product of the SPD of the illuminant (P(λ)) and the spectral reflectance of the object (R(λ)) is computed by the formula [Berns, 2000; Berlin, 1969] shown in Eq. (2.1).

$$P(\lambda) = I(\lambda)R(\lambda) \qquad (2.1)$$

2.1.3 Observer

The observer measures light coming directly from a light source *P* (*λ*) or light which has been reflected (or transmitted) from objects in the scene *R(λ).* The observer can be a colour camera or human eyes. For the human eye, the retina contains two different types of light-sensitive receptors, called rods and cones. Rods are more sensitive to monochromatic light and are responsible for vision in twilight. Cones are responsible for colour perception and consist of three types of receptors sensitive to Long (red), Middle (green) and Short (blue) wavelengths. The response of these three cones to different wavelengths is shown in the Figure 2.5 below [Color, 2010].

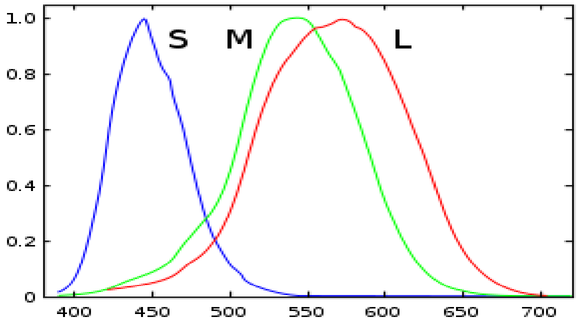


Figure 2.5: Response of three types of cone in relation to wavelength, where L, M, and S represent long (red), medium (green) and short (blue) wavelengths respectively. [5]

However, the sensation of a human observer cannot be measured by an objective instrument. Therefore, experiments have to be conducted to measure human observers' spectral sensitivities to colours. The observers are asked to match a test light, made of one single wavelength, by adjusting the energy levels of three separate primary lights which are Red (700nm), Green (546.1nm), and Blue (435.8nm) recommended by CIE. At each wavelength the amount of energy was recorded for the three primary colours. The results of this matching are called **colour matching functions**, usually denoted as $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$. Also these colour matching functions can be treated as the colour response of the eye [Hunt, 1995; Stitles, 2000] which are displayed in Figure 2.6. The tabulated numerical values of these functions are known collectively as the CIE standard observer.

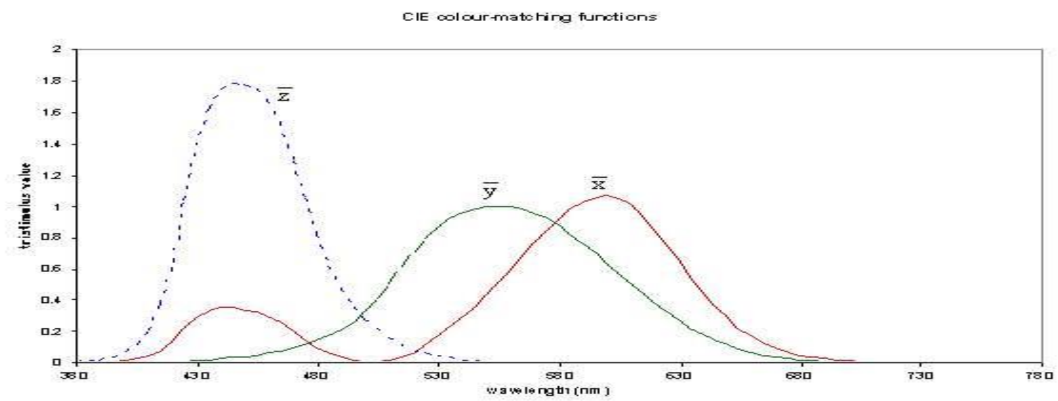


Figure 2.6: Human perception colour matching function
[Fairchild M.D., Colour Appearance Models, 2nd Ed., Wiley, Chichester (2005)] [6]

2.2 Colour vision

2.2.1 Human Eye Structure

In the process of colour vision, the human eye is the last element in the system. The retina is the light sensitive part of the eye. Its surface is coated with millions of photoreceptors. These photoreceptors sense the light and pass electrical signals through the optic nerve to stimulate the brain. There are two types of photoreceptors, rods and cones [Neaves, 1998].

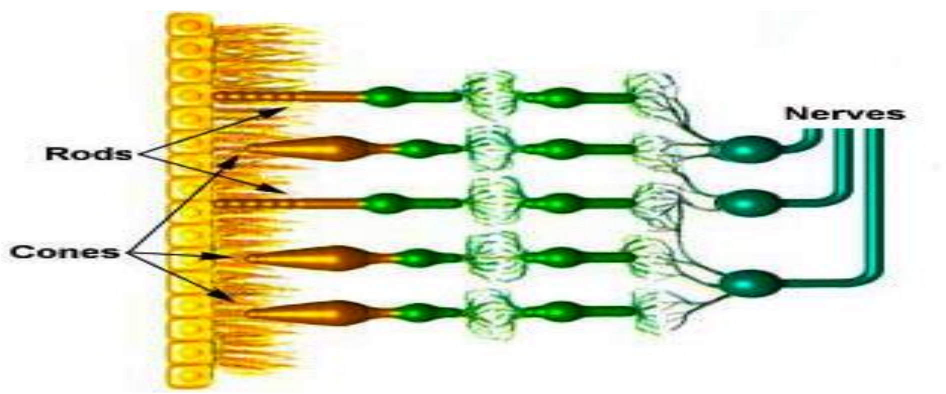


Figure 2.7: Human eye receptor. [7]
[https://luminous-landscape.com/color-vision/]

The human eye has a simple two element lens. The cornea is the front and the lens is the back. The main function of the lens is to alter the image by changing its shape; thinner for viewing far objects and thicker for near object. The cornea and lens acting together form a small inverted image of the outside world on the retina, the light-sensitive surface of the eye. [Neaves, 1998]

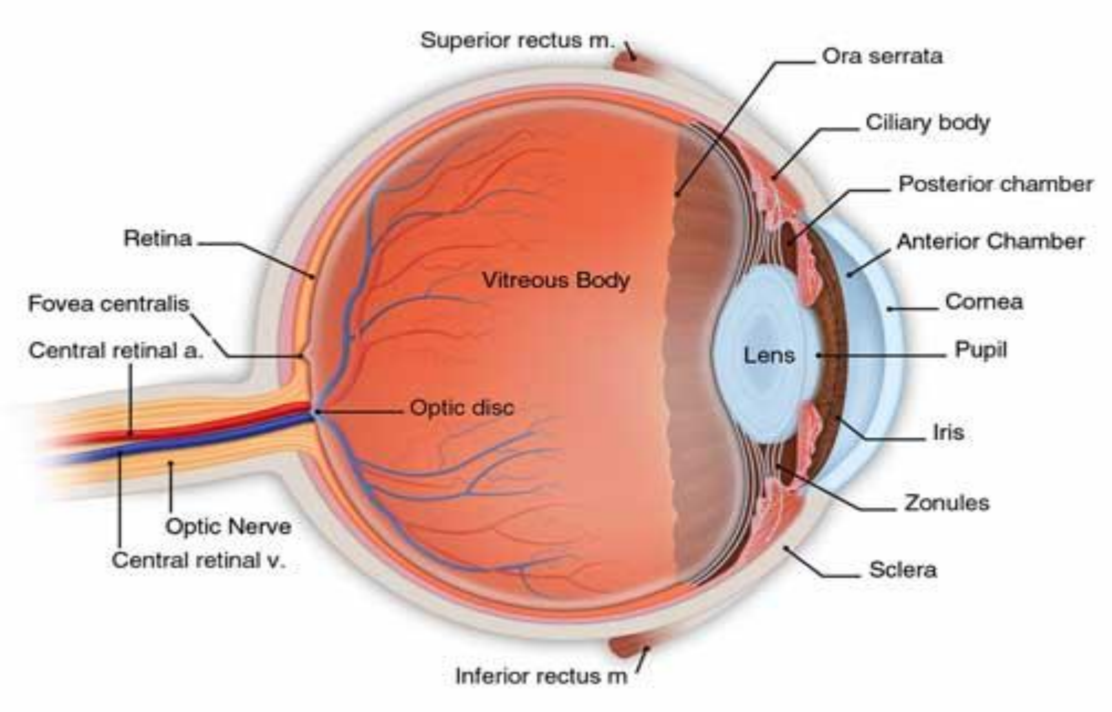


Figure 2.8: Anatomy of the Human Eye. [8]
(www.studenthealth.ucla.edu/FormsDocuments/LayereoftheHumanEye)

2.2.2 Colour Vision Theory

Colour vision is the result of a system comprising the eye, the nervous system, and the brain. Thomas Young [Young, 1802] first propounded the trichromatic theory of colour vision including three types of cone receptors (or colour receptors) in the eye, red, green, and violet, following Newton's earlier investigation. In 1852 it was revised and elaborated by Helmholtz. The modified theory is known as the Young-Helmholtz theory of colour vision [Helmhotz, 1924]. This assumed that the eye contained only three spectrally unique cone receptors, primarily red, green, and blue. In 1878 Edwald Hering provided additional insight, proposing six independent colours, red, green, yellow, blue, white, and black [Hering,1878]. These colours are registered by three opponent colour systems, black-white, red-green, and yellow-blue. Thus an observer sees colour in terms of redness or greenness, and yellowness or blueness. Both the Young-Helmholtz theory and Hering theory paved the road for subsequent research.

Since three types of independent receivers in the eye are required to match all possible colours, normal colour vision is called trichromatic [Burnham, 1963]. The spectral response curves are used to describe the response of the eye at different wavelengths. Curves plotting the amounts of R (red), G (green) and B (blue) required to match a constant amount of power per small constant-width wavelength interval at each wavelength of the spectrum for an observer are called colour-matching functions and designated by symbols $r(\lambda)$, $g(\lambda)$, and $b(\lambda)$ [Hunt, 1987].

The λ is the visible wavelength. These colour-matching functions were determined independently by Guild [Guild, 1932] and Wright [Wright, 1928]. Figure 2.9 schematically shows the basic experimental arrangement [Billmeyer 1981]. The test colour produced by the test lamp is to be matched and displayed in the bottom of the field of view. In the top, an observer sees an additive mixture of beams of red, green, and blue lights. The composition of the lights is then adjusted to match the test colour.

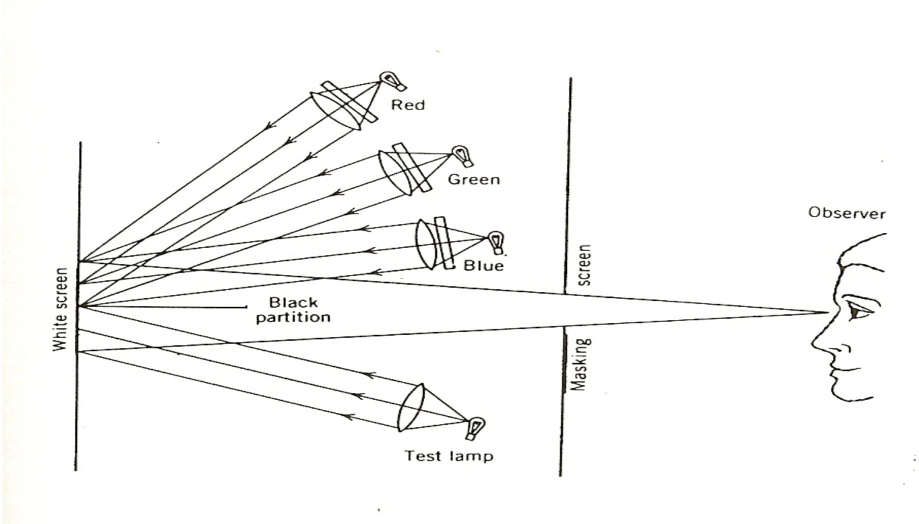


Figure 2.9: A visual arrangement for producing a colour by mixing the light from three different coloured lamps [Billmeyer 1981]. [9]

In Guild's investigation [Guild, 1932], 7 observers made colour matches throughout the visible spectrum. The amounts of red, green, and blue were obtained and were expressed in terms of Guild's instrumental stimuli (heterochromatic primaries obtained with coloured filters) after the units have been adjusted to give equal amounts of the primaries to match the National Physical Laboratory standard white at the National Physical Laboratory (NPL) at Teddington, U.K .

On the other hand, Wright [Wright, 1928], utilised monochromatic primaries at 650, 530, and 460nm. Their units (the quantity of each primary) were adjusted so that equal amounts of red and green stimuli were required in a match of a monochromatic yellow (582.5nm), and equal amounts of green and blue were required in a match of a monochromatic cyan (494nm). Using 10 observers, Wright carried out the experiment at Imperial College, London, England.

Although remarkably different techniques were applied by the two researchers, their results could be converted to the same set of primaries due to the algebraic nature of colour. The primaries chosen were R (700nm), G (546.1nm) and B (435.8nm). The units of R, G, and B were adjusted to be equal in a match on an 'equal-energy' white (a white in which the energy per unit wavelength was constant through the visual spectrum). The amounts of each primary used to obtain a match are known as tristimulus values, R, G, and B. Tristimulus values can be converted into chromaticity coordinates as given below.

$$r = \frac{R}{R+G+B},\ \ g = \frac{G}{R+G+B},\ \ b = \frac{B}{R+G+B} \qquad (2.2)$$

2.2.3 Colourimetry

As mentioned in Section 2.1, colour perception requires three factors: a source of light, an object and a detector, usually the eye and brain. Each of these can be described by an appropriate curve across the visible wavelength. The combination of these comprises a colour or colour stimulus. A quantitative method to describe a colour stimulus is shown in Figure 2.10 [Billmeyer, 1981].

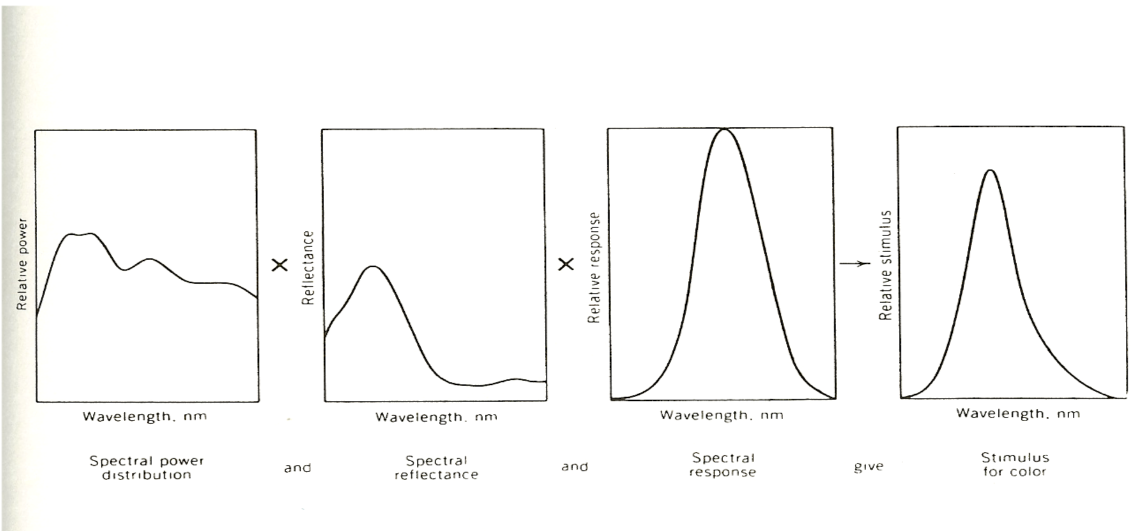


Figure 2.10: Quantitative definition of a stimulus [Billmeyer, 1981]. [10]

In 1931, the International Commission on Illumination (CIE) [CIE, 2007] adopted a system of colour specification which has lasted to the present time, known as the CIE system of colorimetry (see Section 2.3). In this system, a colour is defined by a set of X, Y, Z values, called tristimulus values. Two samples of identical material should be judged as an exact match when their tristimulus values are the same.

2.2.4 Subject Estimation

Colour can also be subjectively specified by means of visual percept. In the OSA Colour Committee terminology the word "colour' is clearly defined as follows: *"Colour consists of the characteristics of light other than spatial and temporal inhomogeneities; light being the aspect of radiant energy of which a human being is aware through the visual sensations which arise from the stimulation of the retina of the eye".* Colour appearance is defined by Judd as *"the colour perceived to belong to the visual object to which attention is directed*" [Judd, 1965]. The hue, colourfulness and lightness, abstracted from complete visual experiences, are used to represent dimensions along which colour may vary independently. ***Hue*** is defined as the attribute of a visual sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colours, red, yellow, green, and blue. ***Colourfulness*** is the attribute of a visual sensation according to which an area appears to exhibit more or less of its hue. ***Chroma*** is the colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting. ***Saturation*** refers to the colourfulness of an area judged in proportion to its brightness. ***Brightness*** implies the attribute of a visual sensation according to which an area appears to exhibit more or less light. ***Lightness*** is the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting [CIE, 1970; Evans, 1964].

There are two colour modes depending upon the colour being perceived. One is 'object mode' and another is 'aperture' (or 'light-source mode'). Object mode is when a visual object appears as being illuminated by an external emitting light. This may be observed when the object is viewed under the surrounding of the other objects. Aperture colour implies that the visual object is emitting light by itself. A colour is perceived as a hole filled with a colour light when the surrounding field of the visual object is completely dark. Colours seen in these special circumstances are often referred as 'unrelated colours'. An aperture colour may also be observed in its background to other visual objects which, however, are usually of a low luminance. The above two modes of colour, however, cannot be perceived simultaneously [Wyszecki, 1973].

2.3 Colour Space and Model

Although it is possible to represent a colour by using a spectrum of wavelengths, it is not convenient to represent a colour using so many parameters across visible wavelengths. Therefore in 1932, the very first mathematically defined colour space, CIEXYZ, was recommended [CIE, 1932].

Since then the CIE (Commission Internationale de l'Éclairage) has recommended several other standard colour spaces to represent a colour, including CIELUV [Colour Spaces, 1932], and CIELAB, and one colour appearance model, CIECAM02 [Moroney, 2002]. A colour space is a mathematical representation, which is a three-dimensional orthogonal coordinate system.

2.3.1 CIEXYZ

CIEXYZ was the first mathematical model recommended in 1931 by the Commission Internationale de l'Éclairage (CIE) to represent a colour, and is also called the CIE 1931 XYZ colour space.

The CIE XYZ colour space was derived from a series of experiments done in the late 1920s by W. David Wright and John Guild [Wright, 1928]. If a colour is given by I(λ), and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are matching functions, Eq. (2.3) gives the values of X, Y, and Z, which are also called tristimulus values for the colour, whereas λ is the wavelength measured in nanometres

$$X = \sum I(\lambda)\bar{x}(\lambda)$$

$$Y = \sum I(\lambda)\bar{y}(\lambda) \tag{2.3}$$

$$Z = \sum I(\lambda)\bar{z}(\lambda)$$

2.3.2 CIE xy chromaticity diagram

For each colour, three tristimulus values X, Y, and Z can be used to represent it. Therefore a full plot of all the visible colours is a 3-dimensional figure. On the other hand, in terms of colour perception, a colour can be divided into two parts: brightness and chromaticity, the colour content. For example, the colour white is a bright colour, while the colour grey is considered to be a less bright version of that same white.

In other words, the chromaticity of white and grey are the same while their brightness differs. The CIE XYZ colour space is therefore deliberately designed so that the Y parameter is a measure of the brightness or luminance of a colour. The chromaticity of a colour is then specified by the two derived parameters x and y, two of the three normalized values which are functions of all three tristimulus values X, Y, and Z as calculated in Eq. (2.4).

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

$$y = \frac{Y}{X+Y+Z} \qquad (2.4)$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

The plot of y against x for all the colours concerned is then called the xy chromaticity diagram as shown in Figure 2.11.

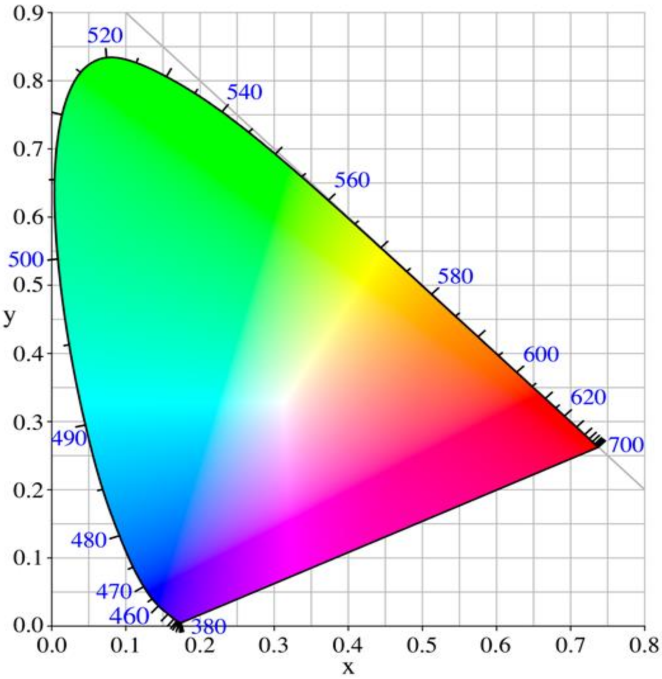


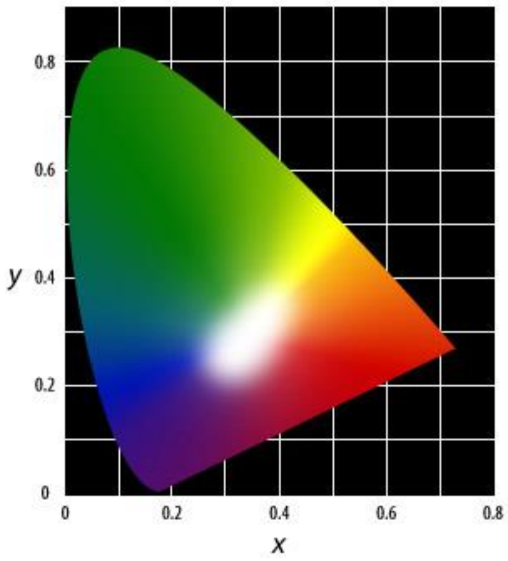
Figure 2.11: The xy chromaticity diagram for all the visible colours
[http://wolfcrow.com/blog/what-is-color-space-and-the-tristimulus-values-xyz] [11]

2.3.3 CIELUV

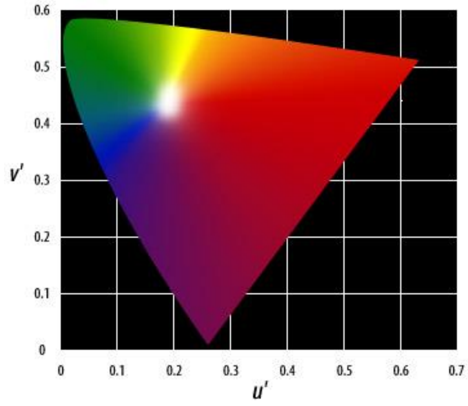
In 1976, the CIE defined a new colour space CIELUV to enable us to get more uniform and accurate models [CIE, 2009]. Sometimes, it is also called the universal colour space. This colour representation is derived from CIEXYZ. The CIE LUV colour space is a perpetually uniform derivation of a standard CIEXYZ space [Hunt, 1998].

As the distribution of the colours in xy chromaticity coordinates is not uniform, a new colour chromaticity coordinate, u'v', was recommended by CIE in 1976 [CIE, 2009], can be calculated using Eq. (2.5).

$$u' = \frac{4X}{X + 15Y + 3Z}$$
$$v' = \frac{9Y}{X + 15Y + 3Z} \qquad (2.5)$$



(a)



(b)

Figure 2.12: Chromaticity colour space xy (a) and u'v'(b).
[http://dba.med.sc.edu/price/irf/Adobe_tg/models/ciexyz.html] [12]

Chromaticity diagrams only show proportions of tristimulus values, and not their actual magnitudes. They are only strictly applicable to those colours with the same luminance.

Colours however, differ in both chromaticity and luminance, and some methods of combining these variables are required. In 1976, the CIE used the CIELUV colour space as the perceptually uniform colour spaces whose expressions are defined below [CIE, 2008].

$L^* = 116\left(\frac{Y}{Y_0}\right)^{1/3} - 16$, if Y/Y0 >0.008856, else $L^* = 903.3\left(\frac{Y}{Y_0}\right)$

$$u^* = 13L^*(u' - u'_0)$$ (2.6)

$$v^* = 13L^*(v' - v'_0)$$

$$H = \arctan(v^*/u^*)$$

$$C = \sqrt{(u^*)^2 + (v^*)^2}$$

where u'_0, v'_0 are the values of u', v' for the appropriately chosen reference white. The L component has the range of [0,100].

2.3.4 CIELAB

Another colour space recommended by CIE is CIELAB [CIE, 2008]. A lab colour space is a colour-opponent space with dimension (L) for lightness (a) and (b) for the colour-opponent dimensions, based on nonlinearly compressed CIE XYZ colour space coordinates. Eq. (2.7) gives the calculation of CIELAB.

$$\begin{aligned} L^* &= 116 f(Y/Y_n) - 16 \\ a^* &= 500\left[f(X/X_n) - f(Y/Y_n)\right] \\ b^* &= 200\left[f(Y/Y_n) - f(Z/Z_n)\right] \end{aligned}$$ (2.7)

where

$$f(u) = \begin{cases} \frac{841}{108}u + \frac{4}{29}, & u \le (6/29)^3 \\ u^{1/3}, & u > (6/29)^3 \end{cases}$$ (2.8)

The Chroma and hue are calculated as Eqs. (2.9) and (2.10).

$$C^* = \sqrt{{a^*}^2 + {b^*}^2}$$ (2.9)

H = arctan (b*/a*) (2.10)

CIELAB chromatic adaptation is compatible for near-daylight illuminants as well as medium grey background and surround and moderate luminance levels. The only weakness in CIELAB is that it cannot account for changes in background surround luminance cognition therefore it is unable to predict brightness and colourfulness. To overcome this limitation CIELAB can be replaced with a more accurate model such as CAT02.

While content-based image retrieval (CBIR) has been researched for nearly three decades, it remains debatable on whether it can ever meet users' expectations. On the one hand, due to the exponential increase of digital images, the demand for retrieving relevant data in an efficient, sufficient and effective way is high, especially amongst those images on the Internet that are not properly labelled, to complement the current text-based approaches. On the other, the subjectiveness of the interpretation of an image can lead to the association varying considerably between visual contents such as colour, texture and shape. To strengthen this gap, in general, the development of algorithms for extraction of those visual features has been endeavoured to endorse with human vision theories by considering colour textured samples. More importantly, colour, in many ways, among many visual features presented in an image, tends to be a decisive factor, such as in determining the purchase of clothes or the selection of wall papers. Additionally, with regard to internet retrieval, colour can be processed faster in real time due to the availability of many well established colour theories and models, which has led to much wider employment of colour spaces or models in content-based image retrieval (CBIR) systems than any other feature models. While colour-based approaches employ colour spaces of mainly RGB, HSV, CIELAB and CIELUV, those spaces do not take simultaneous texture into consideration.

Although an image begins by being represented using RGB colour space when it is in a digital form, it is usually converted into HSI (hue, saturation and intensity) colour space to circumvent the dependency nature of RGB space on hardware devices, i.e. a colour in one device usually does not appear nor measure the same as one in another device even with the same RGB values in both devices. This is because the range of R, G, or B values are manually set to be the same (such as [0, 255] for an 8-bit computer) for all monitors regardless of their physical measurements. On the other hand, HSI space agrees more with human vision theories. To further improve the fitness between users' perception and retrieved results, a colour appearance model has been proposed earlier in this section. In this study attention is paid to the development of distance formulae, with textured colour as the focus.

As mentioned above, the colour appearance model usually studied in a centre-surround 3-field paradigm consists of background, induction field and a test colour. Hence, this research comprises two parts with Phase 1 establishing a colour appearance model that in turn is employed for colour textured samples in order to establish the effect of texture in colour estimation by an observer, carried out in Phase 2. The same experiment was carried out on mobile telephones to evaluate their colour appearance by employing the CIECAM02 colour appearance model.

2.3.5 The Input and Output Information for CIECAM02

With regard to the representation of the colour appearance of an image, in this investigation, the perceptual colour attributes of lightness (*J*), colourfulness (*M*) and hue (H) are employed, which are detailed in Appendix B and briefly listed below.

Given a set of tristimulus values in XYZ, the corresponding LMS values can be determined by the $\mathbf{M}_{CAT02}$ transformation matrix:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \mathbf{M}_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \mathbf{M}_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

Once in LMS, the white point can be adapted to the desired degree by choosing the parameter D. For the general CAT02, the *corresponding* colour in the reference illuminant is:

$$L_c = \left(\frac{Y_w L_{wr}}{Y_{wr} L_w} D + 1 - D\right) L$$
$$M_c = \left(\frac{Y_w M_{wr}}{Y_{wr} M_w} D + 1 - D\right) M$$
$$S_c = \left(\frac{Y_w S_{wr}}{Y_{wr} S_w} D + 1 - D\right) S$$

where the Y_w / Y_{wr} factor accounts for the two illuminants having the same chromaticity but different reference whites. The subscripts indicate the cone response for white under the test (w) and reference illuminant (wr). The degree of adaptation (discounting) D can be set to zero for no adaptation (stimulus is considered self-luminous) and unity for complete adaptation (colour constancy).

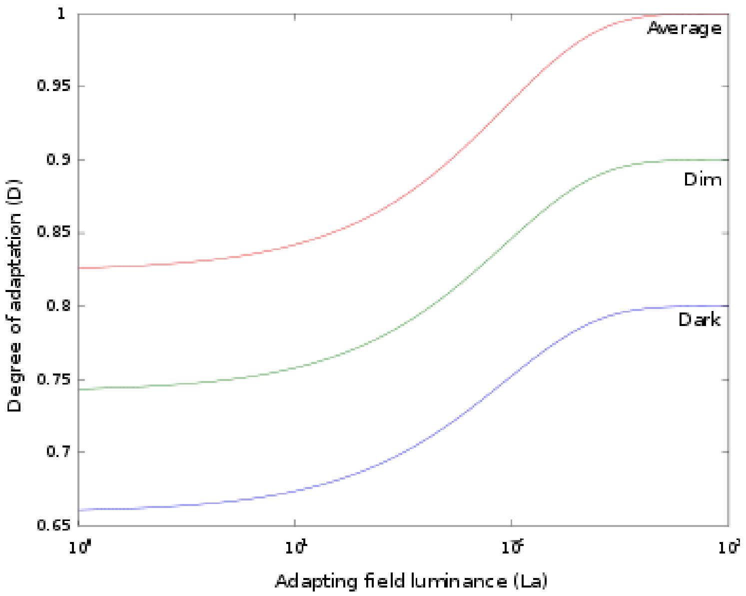


Figure 2.13: Colour constancy

[Moroney, Nathan; Fairchild, Mark, 2002] [13]

In practice, it ranges from 0.65 to 1.0, as can be seen from the diagram. Intermediate values can be calculated by:

$$D = F\left(1 - \frac{1}{3.6}e^{-(L_A+42)/92}\right)$$

where surround *F* is as defined above and L_A is the adapting field luminance in cd/m.

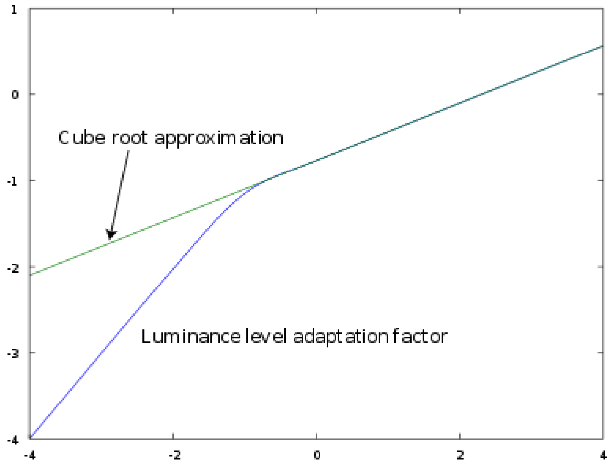


Figure 2.14: Post-adaptation

[Moroney, 2002] [14]

In CIECAM02, the reference illuminant has equal energy ($L_{wr} = M_{wr} = S_{wr} = 100$) and the reference white is the *perfect reflecting diffuser* (i.e. unity reflectance, and $Y_{wr} = 100$) hence:

$$L_c = \left(\frac{Y_w}{L_w}D + 1 - D\right)L$$
$$M_c = \left(\frac{Y_w}{M_w}D + 1 - D\right)M$$
$$S_c = \left(\frac{Y_w}{S_w}D + 1 - D\right)S$$

Furthermore, if the reference white in both illuminants have the *Y* tristimulus value ($Y_{wr} = Y_w$)

$$L_c = \left(\frac{L_{wr}}{L_w}D + 1 - D\right)L$$
$$M_c = \left(\frac{M_{wr}}{M_w}D + 1 - D\right)M$$
$$S_c = \left(\frac{S_{wr}}{S_w}D + 1 - D\right)S$$

After adaptation, the cone responses are converted to the Hunt–Pointer–Estévez space by going to XYZ and back:

$$\begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} = \mathbf{M}_H \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \mathbf{M}_H \mathbf{M}_{CAT02}^{-1} \begin{bmatrix} L_c \\ M_c \\ S_c \end{bmatrix}$$

$$\mathbf{M}_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix}$$

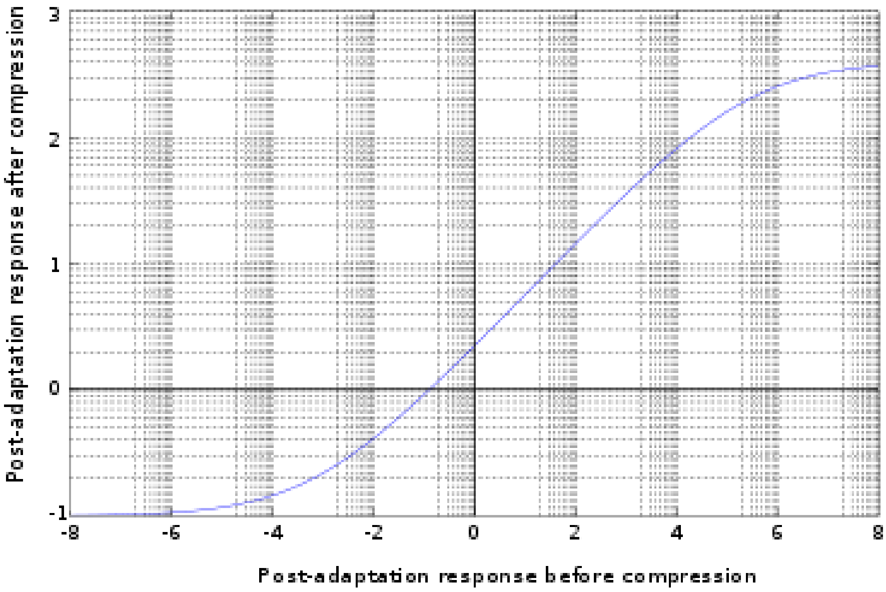


Figure 2.15: Log L'_a vs. log L' for L_A = 200 (F_L = 1)

[Moroney, 2002] [15]

Finally, the response is compressed based on the generalized Michaelis–Menten equation [Moroney, 2002]

$$k = \frac{1}{5L_A + 1}$$

$$F_L = \tfrac{1}{5}k^4\,(5L_A) + \tfrac{1}{10}(1-k^4)^2(5L_A)^{1/3}$$

where F_L is the luminance level adaptation factor.

$$L'_a = \frac{400(F_L L'/100)^{0.42}}{27.13 + (F_L L'/100)^{0.42}} + 0.1$$

$$M'_a = \frac{400(F_L M'/100)^{0.42}}{27.13 + (F_L M'/100)^{0.42}} + 0.1$$

$$S'_a = \frac{400(F_L S'/100)^{0.42}}{27.13 + (F_L S'/100)^{0.42}} + 0.1$$

As previously mentioned, if the luminance level of the background is unknown, it can be estimated from the absolute luminance of the white point as $L_A = L_W / 5$

using the "medium gray" assumption [Schanda, 2007] (The expression for F_L is given in terms of $5L_A$ for convenience.) In photopic conditions, the luminance level adaptation factor (F_L) is proportional to the cube root of the luminance of the adapting field (L_A). In scotopic conditions, it is proportional to L_A (meaning no luminance level adaptation). The photopic threshold is roughly L_W = 1 (see Figure 2.15).

CIECAM02 defines correlates for yellow-blue, red-green, brightness, and colorfulness. Let us make some preliminary definitions.

$$C_1 = L'_a - M'_a$$
$$C_2 = M'_a - S'_a$$
$$C_3 = S'_a - L'_a$$

The **correlate for red–green** (a) is the magnitude of the departure of C_1 from the criterion for unique yellow ($C_1 = C_2$ / 11), and the **correlate for yellow–blue** (b) is based on the mean of the magnitude of the departures of C_1 from unique red ($C_1 = C_2$) and unique green ($C_1 = C_3$).

$$a = C_1 - \tfrac{1}{11}C_2 \qquad = L'_a - \tfrac{12}{11}M'_a + \tfrac{1}{11}S'_a$$
$$b = \tfrac{1}{2}\left(C_2 - C_1 + C_1 - C_3\right)/4.5 \quad = \tfrac{1}{9}\left(L'_a + M'_a - 2S'_a\right)$$

The 4.5 factor accounts for the fact that there are fewer cones at shorter wavelengths (the eye is less sensitive to blue). The order of the terms is such that b is positive for yellowish colors (rather than blueish).

The **hue angle** (h) can be found by converting the rectangular coordinate (a, b) into polar coordinates:

$$h = \angle(a, b), \ (0 < h < 360^\circ)$$

To calculate the eccentricity (e_t) and hue composition (H), determine which quadrant the hue is in with the aid of the following table. Choose i such that $h_i \le h' < h_{i+1}$, where $h' = h$ if $h > h_1$ and $h' = h + 360°$ otherwise.

	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

Table 2.1 Hue angel chart
[Schanda, 2007]

$$H = H_i + \frac{100(h' - h_i)/e_i}{(h' - h_i)/e_i + (h_{i+1} - h')/e_{i+1}}$$
$$e_t = \frac{1}{4}\left[\cos\left(\frac{\pi}{180}h + 2\right) + 3.8\right]$$

Calculate the achromatic response A:

$$A = (2L'_a + M'_a + \tfrac{1}{20}S'_a - 0.305)N_{bb}$$

where:

$$N_{bb} = N_{cb} = 0.725n^{-0.2}$$
$$n = Y_b/Y_w$$

The correlate of **lightness** is:

$$J = 100\left(A/A_w\right)^{cz}$$

where c is the impact of surround (see above), and:

$$z = 1.48 + \sqrt{n}$$

The correlate of **brightness** is:

$$Q = (4/c)\sqrt{\frac{1}{100}J}\,(A_w + 4)\,F_L^{1/4}$$

Then calculate a temporary quantity t:

$$t = \frac{\frac{50\,000}{13} N_c N_{cb} e_t \sqrt{a^2 + b^2}}{L'_a + M'_a + \frac{21}{20} S'_a}$$

The correlate of **chroma** is:

$$C = t^{0.9}\sqrt{\frac{1}{100}J}(1.64 - 0.29^n)^{0.73}$$

The correlate of **colorfulness** is:

$$M = C \cdot F_L^{1/4}$$

The correlate of **saturation** is:

$$s = 100\sqrt{M/Q}$$

2.3.6 CIECAM

To model a colour appearance, CIE (Commission Internationale de l'éclairage) has recommended a colour appearance model, CIECAM02 [Moroney, 2002], Stemming from Hunt's early colour vision model [Luo 1993a, Luo 1993b, Luo 1993c] employing a simplified theory of colour vision for chromatic adaptation together with a uniformed colour space, CIECAM02 can predict the change of colour appearance as accurately as an average observer under a number of given viewing conditions, in which the way that the model describes a colour is reminiscent of subjective psychophysical terms, i.e., hue, colourfulness, Chroma, brightness and lightness.

To start with, the model takes into account of the tristimulus values (X, Y, and Z) of the stimulus, its background, its surround, the adapting stimulus, the luminance level, and other factors such as cognitive discounting of the illuminant. The output of the colour appearance model includes mathematical correlates for perceptual attributes. Table 2.2 summarises the input and output parameters from CIECAM02.

TABLE 2.2. THE INPUT AND OUTPUT INFORMATION FOR CIECAM02.

Input	Output
X,Y, Z: Relative tristimulus values of colour stimulus	Lightness (J)
$X_{W,}$ $Y_{W,}$ Z_W: Relative tristimulus values of white	Colourfulness (M)
La: Luminance of the adapting field (cd/m*m) = 1/5 of adapted D65;	Chroma (C)
	Hue angle (h)
Y_b: Relative luminance of the background = 0.2;	Brightness (Q)
Surround parameters: c, Nc, F = 0.41, 0.8, 0.9 respectively for luminous colours (i.e. monitor).	Saturation (S)

With regard to the representation of the colour appearance of an image, in this investigation, the perceptual colour attributes of lightness (*J*), Chroma (*C*), colourfulness (*M*) and hue angle (*h*) are employed, which are calculated in Eqs. 2.11 to 2.14 respectively.

$$J = 100(\frac{A}{A_w})^{cz} \tag{2.11}$$

$$C = t^{0.9}(\frac{J}{100})^{0.5}(1.64 - 0.29^{n})^{0.73} \tag{2.12}$$

$$M = CF_L{}^{1/4} \tag{2.13}$$

$$h = tan^{-1}(\frac{b}{a}) \tag{2.14}$$

where:

$$A = \left[2R'_a + G'_a + \frac{1}{20}B'_a - 0.305\right]N_{bb} \tag{2.15}$$

$$t = \frac{50\left(a^2+b^2\right)^{\frac{1}{2}}100e\left(\frac{10}{13}\right)N_cN_{cb}}{R'_a+G'_a+\frac{21}{20}B'_a} \tag{2.16}$$

$$a = R'_a - \frac{12G'_a}{11} + \frac{B'_a}{11} \tag{2.17}$$

$$b = \frac{1}{9}(R'_a + G'_a - 2B'_a) \tag{2.18}$$

and $R_a^{'}, G_a^{'}, B_a^{'}$ indicate the post-adaptation cone responses with detailed calculations specified in [Wu, 2007] whereas A_W refers to the A value for reference white. Constants N_{bb}, N_{cb} are calculated as:

$$N_{bb} = N_{cb} = 0.725(\frac{1}{n})^{0.2} \quad (2.19)$$

where n $= Y_b/Y_w$, with Y_b *and* Y_W representing the *Y* value for both background and reference white respectively. The work flow of CIECAM02 is illustrated in Figure 2.16 with its full formula given in Appendix A.

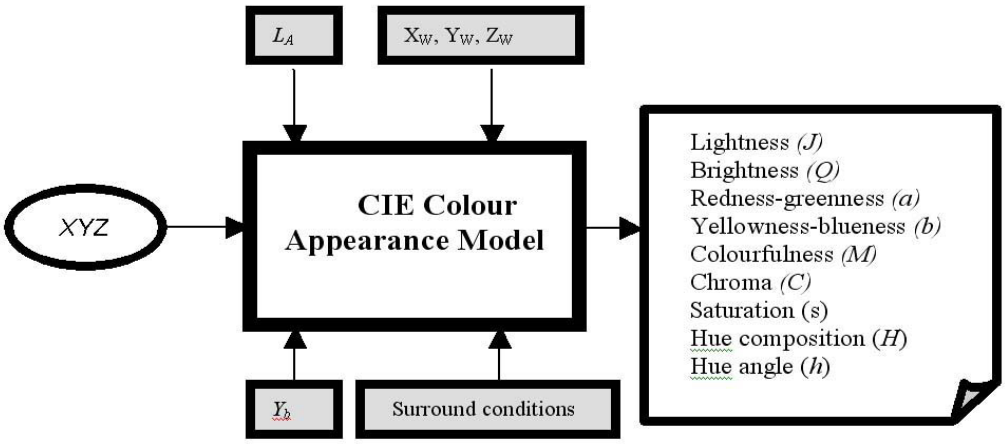


Figure 2.16: The work flow of CIE colour appearance models. [www.researchgate.net/publication/227991182] [16]

2.3.7 Colour Appearance Datasets

Colour appearance models based on colour vision theories has been developed to fit various experimental data sets, which were carefully produced to study particular colour appearance phenomena. Over the years, a number of experimental data sets were gathered to test and develop various colour appearance models. Luo [Luo, 1995] investigated a data set of saturation correlates using the magnitude estimation method. The data accumulated played an important role in the evaluation of the performance of different colour appearance models and the development of CIECAM97s and CIECAM02. In this study, the experimental design is similar to Luo’s [Luo, 1995] in order to be comparable.

2.4 Colour Appearance Phenomena

Colour perceived presentation is influenced by various colour appearance phenomena caused by any undetected change in viewing conditions in the colour reproduction process. Therefore to have a better understanding of colour research it is essential to analyse colour appearance phenomena to represent the colour appearance qualitatively and quantitatively and accurate colour reproduction in the easiest way possible. In this research, colour appearance and common colour appearance phenomena were analysed. Also the basic theory of colour appearance in colour reproduction was studied.

The important colour appearance phenomena were studied in this research based on the viewing conditions and the interaction of the colours. The results help to describe the colour appearance models significantly and accurately.

Almost all colour-appearance phenomena describe relationships between changes in viewing conditions and changes in appearance. If two stimuli do not match in colour appearance when (XYZ) 1 = (XYZ) 2, then some aspect of the viewing conditions is different.

Colour appearance phenomenon is that the perceived colour changes with changes in the viewing conditions. Even under the same viewing conditions, the colour appearance perceived is not always the same, as the perceived colour stimuli are influenced by the neighbourhood pixels [Qin-ling Dai, 2012].

Figure 2.17: Simultaneous Contrast/ Induction

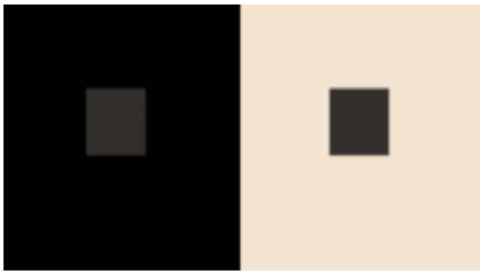


Fig 2.18: Influence of simultaneous contrast on colour. [17,18]

In Figure 2.17, the colour perception is inconsistent if the background is changed. As shown in Figure 2.18, with the dark background, the colour patch seems lighter but with a beige background it seems darker.

In Figure 2.19, two colour patches with the same chromatic colour value which lie on a dark background appear lighter and brighter than that sets where the background is of whiter shade.

Figure 2.19: Coloured object set in pink and white background. [19]

Figure 2.20: Object set in yellow and blue background. [20]

Simultaneous contrast or colour induction causes the colour vision implication of perception which causes the whole colour appearance to change by changing the background colour stimulus. It clearly shows that the colour stimulus will be darker on a lighter background while appearing darker on a lighter background. Red-green and yellow-blue will cause the corresponding induction colour vision, i.e. red will induct green, green will induct red, yellow will induct blue and blue will induct yellow.

2.4.1 Crispening Effect

The Crispening effect [Moroney, 2002] refers to the apparent increase in perceived magnitude of colour differences when the background is similar in colour to the object.

As shown below in Figure 2.21, the two blue stimuli give the impression of having greater lightness variance on the pale blue background than on either the white or dark blue backgrounds. [Moroney, 2002].

Figure 2.21: The pairs of blue patches are physically identical on all three backgrounds. [21]

2.4.2 Hunt Effect. (Colourfulness increases with luminance)

In general, colourfulness increases with luminance, this is known as the Hunt effect [Moroney, 2002]. It underlines the effect of absolute lightness on colour appearance. The Hunt effect is a common phenomenon in cross-media colour reproduction. However it is out of reflection in foundation colorimetry and should be predicted in colour appearance models. It has a very significant impact on CIECAM02, but because of its complexity the Hunt model itself is difficult to use [Moroney, 2002].

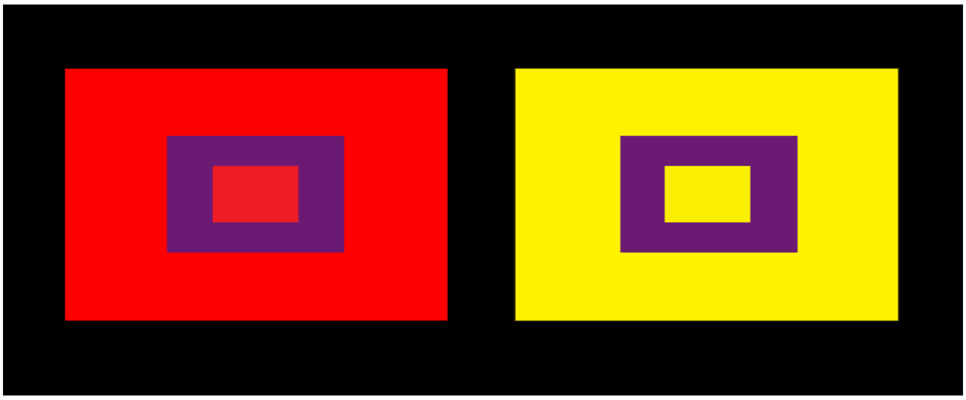


Figure 2.22: Hunt effect sample
[http://facweb.cs.depaul.edu/sgrais/color_context] [22]

2.4.3 Stevens Effect (contrast increases with luminance)

The Stevens's effect is that lightness relation increases with luminance of the adaptive field. It can be demonstrated in the figure below. The dark tone will be darker while the light tone will be lighter with the luminance increases, i.e. the contrast increases [Moroney, 2002].

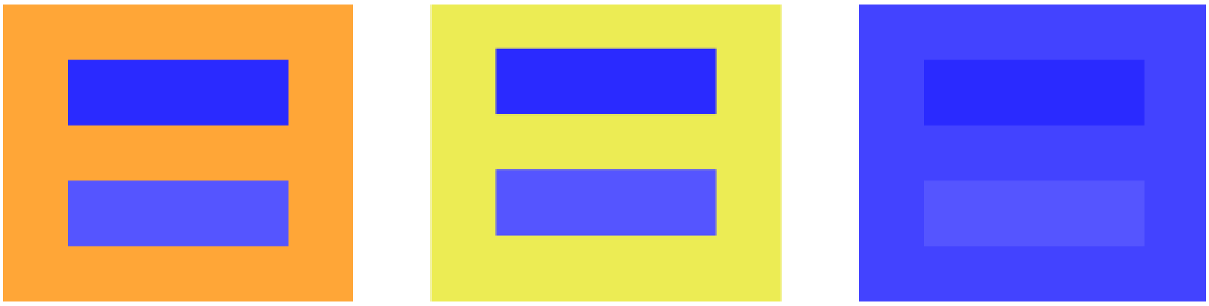


Figure 2.23: Stevens effect
[http://facweb.cs.depaul.edu/sgrais/color_context] [23]

2.4.4 Bezold Brucke Effect

Colorimetric purity of monochromatic light will change when it mixes with white light. The colour tone will change for monochromatic light with different lightness. According to Bezold Brucke, colour tune drift effects hue change with luminance. The phenomenon can be illustrated as in Figure 2.24 below. [Moroney, 2002].

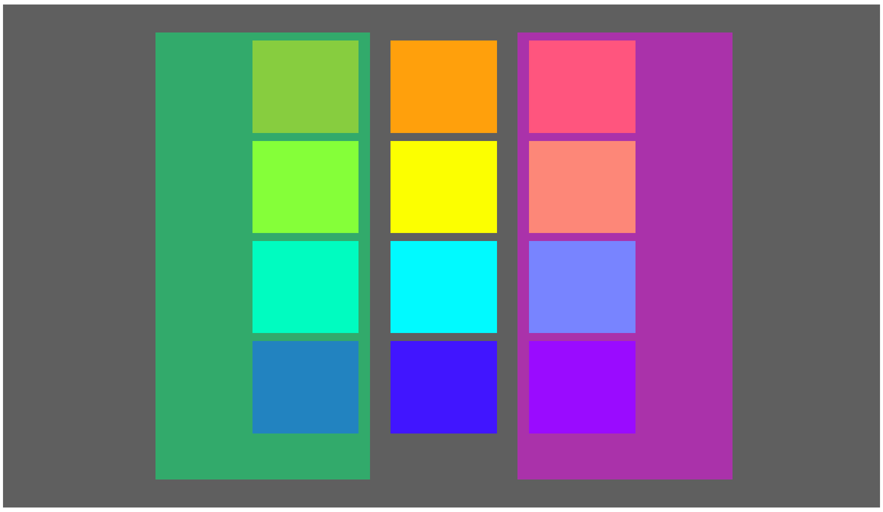


Figure 2.24 : Bezold Brucke effect
[http://facweb.cs.depaul.edu/sgrais/color_context] [24]

In colour reproduction and perception, there are also other colour appearance phenomena because of the changing viewing conditions, however, the above are the most common factors.

2.4.5 Colour Constancy

Colour Constancy is the ability to distinguish colours of objects, invariant to the colour of the light source, in other words, constancy of observed colour relations under dissimilar illuminants. The resulting changes in the spectrum of the light reflected from a scene are readily apparent over the course of a day [Romero, Hernández-Andrés, Nieves, & García, 2003], with the gamut of colours at sunset almost doubling under the mixture of direct and indirect illuminations [Hubel,D, 1995].

The human visual system is extremely capable of recognising the changes in both the level and the colour of the lighting which result in this capability known as *adaptation*; therefore objects tend to be recognized as having nearly the same colour in very many conditions. This human vision recognition system is well known for its *colour constancy*. Having said that, colour constancy is only estimated, and considerable changes in colour appearance can sometimes occur, as in the tendency for colours that appear navy in daylight to appear distinctly bluish in tungsten light; but still colour constancy is an extremely powerful and important effect in colour perception.

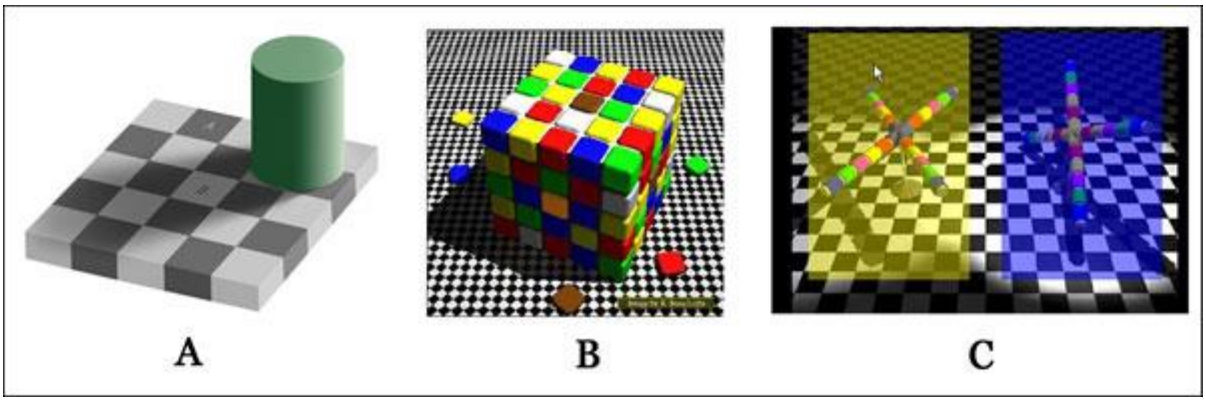


Figure 2.25. Three optical illusions demonstrating colour constancy in action. A. The checkerboard illusion of Edward Adelson. B. The cube illusion of R. Beau Lotto. C. The cross-piece illusion of R. Beau Lotto [Dimension of colour by Dr David. J.C. Briggs [Briggs, 1998]. [25]

2.4.6 Metamerism

Metamerism is the phenomenon wherein two coloured samples will seem to be of the same shade under one light source but will appear to have different shades under a second source. The two different colours have identical colour appearance under one light source (metameric match) but look different under another light source (metameric mismatch). Metamerism is the dissimilarity of the reflection curves of two colours which look identical under a given form of lighting (e.g. Florescent light, electric bulb light, daylight).

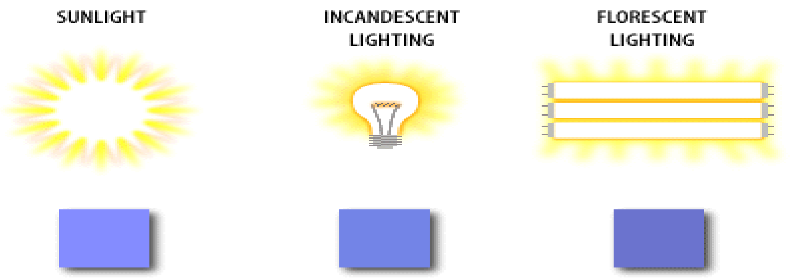


Figure 2.26: When two colours having different spectral compositions match one another, they are said to be *metameric*, or *metamers*, and the phenomenon is called *metamerism*. [http://dba.med.sc.edu/price/irf/Adobe_tg/color/variables.html]. [26]

The CIE has recommended that the degree of metamerism for changes of illuminant can be allowed for and can be found by calculating an Illuminant

Metamerism Index, *M*, consisting of the size of the colour difference between a metameric pair caused by substituting, in place of a reference illuminant, which in this case is the test illuminant having a different spectral composition. The preferred reference illuminant is known as the Standard illuminant D65 for daylight illumination. [Hunt, 1998].

Colour perception is different when the same colour is viewed under different conditions. Mostly the viewing conditions include lighting condition, medium, background, surround and the observer.

The reason for conducting colour experiments under controlled viewing conditions is to have the most accurate result by overcoming the issues that have been raised. Associated with the specification of viewing fields for colour appearance models are the various definitions of standard viewing conditions used in different situations. This attempts to minimize difficulties with colour appearance by outlining appropriate viewing field configurations [Moroney, 2002].

2.5 Chromatic-adaptation models

Chromatic-adaptation models offer nominal scales for colour appearance. Two stimuli in their relative viewing conditions match each other but might be more or less different in their colour properties. To verify the colour difference and have more accurate results, we need colour-appearance models to evaluate and measure: Lightness, Brightness, Hue, Chroma, and Colourfulness. The Colour Appearance Model provides mathematical formulae to transform physical measurements of the stimulus and viewing environment into different attributes of colour, e.g. lightness, colourfulness and hue.

In the vision subject area, three types of adaptation are considered important issues, namely light, dark, and chromatic.

Light adaptation tells us that increases in the overall level of illumination has a negative effect on visual sensitivity. In other words, increasing the illumination level will decrease visual sensitivity [Moroney, 2002].

Dark adaptation is similar to light adaptation, as dark adaptation is the increase in visual sensitivity experienced upon decreases in luminance level.

Time-course is one of the important features of chromatic adaptation mechanisms. This issue in regard of colour appearance judgements has been explored in detail [Fairchild, 1992], [Fairchild, 1995]. The outcome of these studies suggests that the sensory mechanisms of chromatic adaptation are about 90% complete after 60 seconds for changes in adapting chromaticity at constant luminance. As a result, the minimum time for making critical judgments for an observer have been suggested as around 60 seconds. Adaptation is slightly slower when significant luminance changes are involved [Hunt, 1952]. Cognitive mechanisms of adaptation rely on knowledge and interpretation of the stimulus configuration. Having said that, in some unusual viewing situations, the time required to interpret the scene can be substantially longer than mentioned above.

2.5.1 Colorimetry

Colorimetry is the branch of colour science dealing with specifying statistically the colour of a physically defined visual stimulus by the observer. In particular, it is concerned with:

1) when an object is viewed by an observer with normal colour vision, under the same observing conditions, readings and measurements of the same object should appear similar.

2) stimuli that appear similar should have the same specification.

3) the numbers comprising the specification are functions of the physical parameters defining the spectral radiant power distribution of the stimulus *Trichromatic generalization* (R,G,B).

2.5.2 Colour-matching functions

Given a monochromatic stimulus **Q**λ wavelength, it can be written as

$\mathbf{Q}_\lambda = R_\lambda \mathbf{R} + G_\lambda \mathbf{G} + B_\lambda \mathbf{B}$

where R_λ, G_λ, and B_λ are the spectral *tristimulus values* of $\mathbf{Q}_\lambda$.

Assume an equal-energy stimulus $\mathbf{E}_\lambda$ whose mono-chromatic constituents are E_λ (equal-energy means $E_\lambda \equiv 1$).

The equation for a colour match involving a mono-chromatic constituent E_λ of E is. $E_\lambda = r_\lambda \mathbf{R} + g_\lambda \mathbf{G} + b_\lambda \mathbf{B}$, where rλ, gλ, and bλ, are the spectral tristimulus values of Eλ.

The sets of such values are called *colour-matching functions*

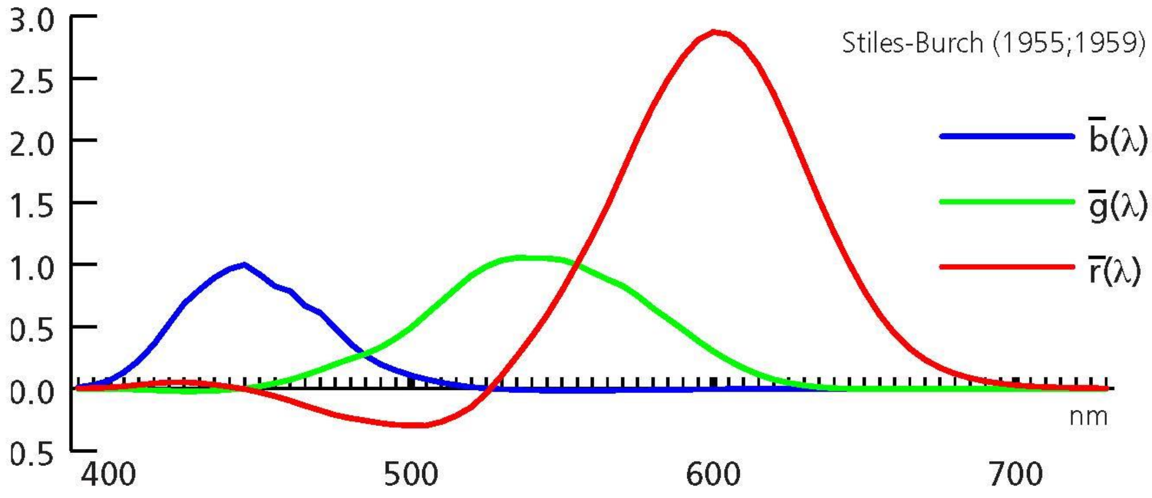


Figure 2.27: Colour-matching Diagram.
[Harris, 1990] [27]

2.5.3 Chromaticity Diagrams

We can normalize the colour-matching functions and thus obtain new quantities.

r (λ) = r (λ) / [r (λ) + g(λ) + b(λ)]

g(λ) = g(λ) / [r (λ) + g(λ) + b(λ)]

b(λ) = b(λ) / [r (λ) + g(λ) + b(λ)]

with r(λ) + g(λ) + b(λ) = 1

The locus of chromaticity points for monochromatic colours so determined is called the *spectrum locus* in the (*r, g*) - chromaticity diagram.

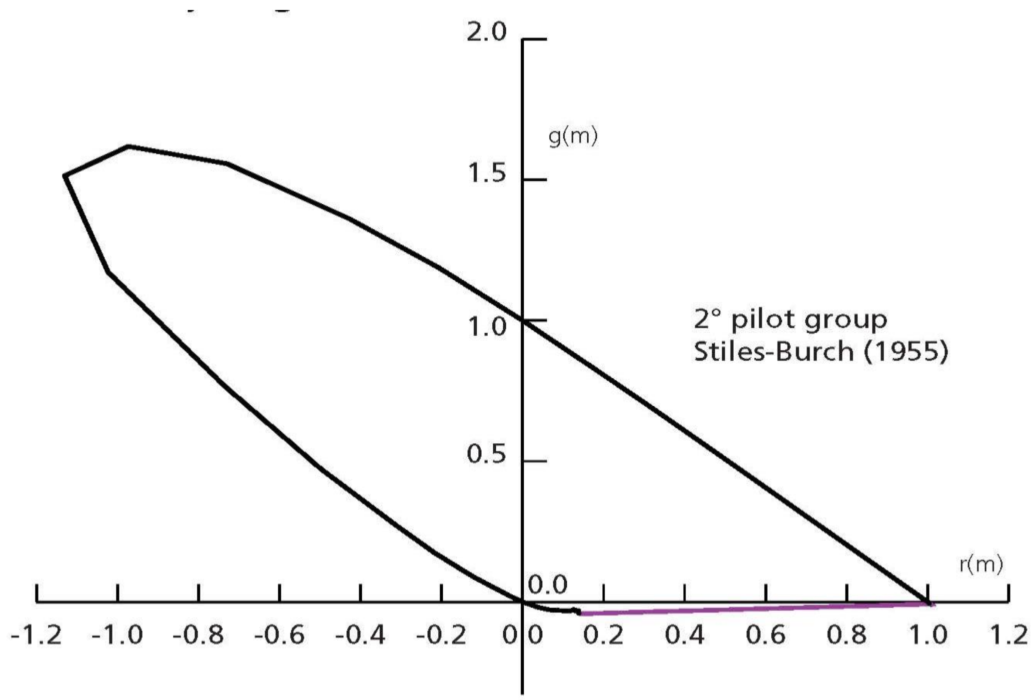


Figure 2.28: Chromaticity diagrams.
[Hunt, (2011). "The Colour Triangle"]. [28]

2.6 Experimental Method of Magnitude Estimation to Determine Colour Appearance

In this research, the magnitude estimation method is applied to estimate the appearance of each colour. Each observer is asked to make a subjective estimate of the magnitude of visual attributes. The attributes might be lightness, brightness, colourfulness, saturation, chroma, and hue. The observer simply assigns a number that in his or her view corresponds to the magnitude of the chosen attribute in the sample being viewed. Alternatively, the observer might be asked to make a subjective estimate of the attribute on some more clearly defined scale, usually an equal-interval scale, or to compare two samples for an estimating parameter [Ishak,1970; Stevens, 1957].

The magnitude estimation technique was first tested by Stevens et al. [Stevens,1957] and has recently gained in general acceptance. It is a subjective scaling technique by which the magnitudes of perceived attributes are scaled. Rowe [Rowe,1973] and Padgham [Padgham,1973] carried out their work to scale hue and saturation. They concluded that a surprising degree of precision can be achieved using this technique. In Ishak et al's study [Ishak, 1970], two observers made estimations in terms of hue, saturation and lightness for 60 surface colours on seven backgrounds (Black, Grey, White, Red, Yellow, Green, and Blue background). They compared their results to those of Helson et al. [Helson,1952] (using the memory method), and Wassef, Hunt and Gibson [Gibson, 1967] (using the binocular matching method). The results showed that the magnitude estimation method was reliable in producing results similar to those found using other methods. They concluded that the method was suitable for measuring colour appearance under a variety of viewing conditions. Following their study, Nayatani et al. [Nayatani,1972] examined the precision of this method between and within observers, and reconfirmed its effectiveness. They made assessments for three attributes of 100 object colours by a panel of fifteen observers. A fluorescent lamp with a high colour-rendering index was used. Results showed a good agreement with those obtained by Ishak et al. This method was later employed by Bartleson [Bartleson,1979], Pointer [Pointer, 1980], and Luo et al [Luo 1991a, Luo 1991b].

In using a magnitude estimation technique, an observer simply views the test sample and assigns numbers or names that correspond to the colour attributes of its subjective appearance. Normally they are lightness, brightness, saturation, colourfulness, and hue.

Lightness is a subjective attribute that has been studied thoroughly by Stevens et al. and by many others [Stevens 1957; Luo 1991a, Luo 1991b]. As far as the method applied to reflecting surfaces, it was mainly grey content that was examined [Stevens, 1963].

Brightness is defined by the CIE as the attribute of a visual sensation according to which an area appears to exhibit more or less light [Bartleson,1980]. It is a perceptually absolute quantity and has an absolute zero modulus without upper limit. For many years attempts have been made to characterise perceived brightness as a function of stimulus luminance. A variety of predictive equations has been proposed. Stevens et al. [Stevens, 1963] specified brightness as a power function of luminance. Bartleson's brightness-scaling experiments with a complex stimulus field showed that the resulting brightness vs luminance functions are not simple power functions but are nonlinear in log-log coordinates [Indow, 1966].

For estimating hue, four to six names of basic or unique colours are commonly used among which are Red, Yellow, Green, Blue and the two intermediate hues orange and yellowish-green. For colour appearance between the unique colours interpolations are used either in numerical form [Indow,1966] such as "80% green, 20% yellow", or as combination names such as Blue-Green. This method is closely associated with the NCS Colour System.

Earlier magnitude estimation experiments were conducted using saturation rather than colourfulness. Saturation assessments were reported by many researchers [Indow,1966]. In these studies, observers were asked to scale the saturation of a test colour on a scale which had fixed points at both ends. One end (zero) represented a colour with no saturation (a neutral colour), and the other end (100) represented the most saturated colour that the observer could imagine having the same hue as the test colour. The test colour was then scaled as a number between these two end points. This led to difficulties in analysing the data because the most saturated colour varied in absolute saturation for different hues, for example, a most saturated blue could be more saturated than a most saturated yellow [Pointer,1980].

The concept of colourfulness was introduced by Hunt [Hunt, 1952] to denote the attribute of a visual sensation according to which an area appears to exhibit more or less chromatic colour. Pointer's [Pointer,1978] results showed that this concept is meaningful to the observers who were asked to rank colour chips in order of colourfulness and also able to scale the colourfulness of each individual chip. In his experiment, colourfulness was scaled under various luminance levels and backgrounds. A correlation coefficient of 0.97 was obtained between the mean of saturation and colourfulness. This suggested that there was a high degree of correlation between these two attributes. He concluded that colourfulness was a useful concept which observers were well able to scale, and may be more easily scaled than saturation or Chroma. If a full measure of the appearance of a colour is required, colourfulness can provide changes in chromatic response caused by the luminance levels.

2.7 Summary

In summary, a magnitude estimation method as described below was used to scale each colour in terms of lightness, colourfulness, and hue. In other words, lightness represents the degree of brightness a colour is showing. With the reference white being 100 and an imaginary black being zero, observers are asked to give an estimation between 0 and 100 that is in proportion to the reference white. For example, if a test colour appeared half as bright as the reference white to a subject, 50% of lightness was assigned to the colour.

On the other hand, colourfulness shows the amount of hue appearing in a test colour, which is in proportion to the reference colourfulness that is given colourfulness of 40, e.g. if a colour has a colourfulness of 60, this colour should display 1.5 times as colourful as the reference colourfulness colour. Neutral colours, including white, black, and grey colours have zero colourfulness. For hue estimation, four opponent hue scales were employed, which were red against green and yellow against blue. The hue of a test colour was then estimated with reference to any two neighbouring colours. For example, a hue can appear 80% yellow and 20% red or 50% green and 50% blue. A colour cannot show the contents of opponent hues, i.e. an answer of ‘30% green and 70% red’ is invalid (red and green are opponent hues), whilst neutral colours have no content of hue at all. This hue scale was later converted into a hue angle of 0 to 400 with 0 (400) being red, 100 yellow, 200 green and 300 blue for data analysis.

Furthermore, all observers' vision was tested before conducting the experiment. Figure 2.29 shows an example of colour plate used for colour vision tests, by which a subject with normal vision can see '6' that cannot be perceived by a person without.

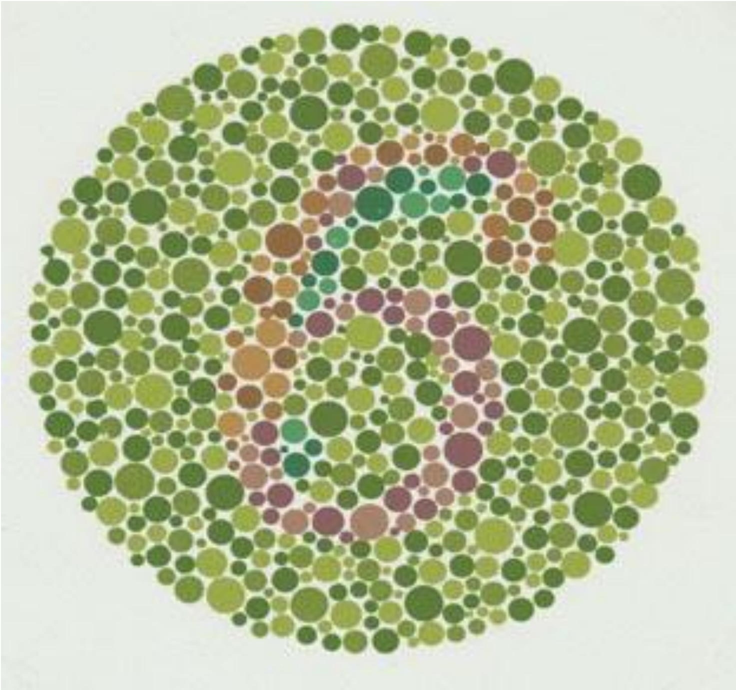


Figure 2.29. An example of the plate in the Ishihara colour vision test [Ishihara, 2004]. [29]

2.8 Literature Review on chromatic texture

In this research, the initial observer training is conducted on CRT (cathode ray tube) monitors to be in line with the existing studies [Gao, 2015]. In addition, textured colours are studied to evaluate both subjects' consistency and the performance of the CIECAM02 model.

As a part of the human vision system that involves a light source, an object, and a processing system (i.e. brain), colour vision is the ability of the human eye to separate various frequencies of light waves (380~740nm) to allow us to differentiate different colours through three colour cells, i.e. red, green, and blue, positioned on the retina. Usually all colour models are established in a laboratory environment, where, typically, the background is usually of a certain colour with a uniform light source and test stimuli of single colours in a way that is different from natural viewing situations.

2.8.1 Texture definition

Texture is a measure of the variation of the intensity of a surface, quantifying properties such as smoothness, roughness and regularity. It is often used as a region descriptor in image analysis and computer vision [Julesz,1962]. The three principal approaches used to describe texture are statistical, structural and spectral. Texture perception is important for colour perception and regarded as one of the early steps towards identifying objects and understanding scene through textural variations on the surface of an object. Largely attributed to [Julesz, 1981] conjecture that observers were sensitive only to differences in the first- and second-order statistics of constituent textures (though counter examples to this conjecture have been found at a later stage). Texture segregation has been represented extensively using computational models with a common form simulating cortical cells (simple or complex) including a set of linear spatial filters, a point-wise nonlinearity, and further linear spatial filtering to turn the textural difference into a difference in response strength.

These biologically inspired models accept grey-level images as an input, working exclusively on the luminance domain. As a result, they concentrate on differences in the figural, or form, features of the texture elements (texels), while all the other attributes of the texels (luminance, colour, stereo disparity, etc.) remain fixed.

However, recently study has shown that the interaction between colour, luminance and orientation can be attributed to the texture process. Furthermore, the typical experimental settings differ considerably from those in our natural environment. It has been shown that colour sensitivity and appearance is influenced by adaptation to the colour distribution of natural images [Webster, 1997].

2.8.2 Chromatic texture

Many natural objects are categorized not only by shape and colour, but also by their particular chromatic textures. While the roles of colour and shape have been well explored in object recognition, chromatic texture has not. In this investigation, the roles of colour and texture and their interaction are studied, in an object classification task using familiar objects.

The use of joint colour-texture features has been a popular approach to colour texture analysis. At present, it appears, there have not been many published articles in this area which certainly shows colour and texture should be processed jointly.

The issue has been touched on by a few scientists [Julesz, 1981], in terms of the contribution of colour information to the classification of colour textures, but the amount of data that has been considered is limited and the experiments take place under limited conditions.

Therefore, in this research, **Phase 1** is dedicated to study textured colours to measure the significance of texture in contributing to the perception of colours, specifically to estimation using the CIECAM02 model, whereas **Phase 2** will focus on the investigation of the modelling of the colour appearance on mobile telephones.

2.9 Literature Review on Smartphones

2.9.1 Introduction to Smartphone Global trends

Thanks to the advances of computer technology, our world at present is becoming increasingly more mobile. Global sales of mobile devices have been rising year by year, driven in particular by purchases in developing economies, where the mobile device market is yet to reach a saturation point.

It was estimated that by the end of 2015 the global smartphone users would reach 1.75 billion. One billion consumers had been recorded in 2012 [eMarket, 2015], which is demonstrated in Figure 2.27.

The total amount of mobile devices is already larger than PC desktop computers. Global mobile device sales are not only focused on smartphones alone, but also on feature phones which are classified as non-operating system devices. Since these types are more affordable than current smartphones, these are still a popular choice in countries such as India and China [eMarket, 2015].

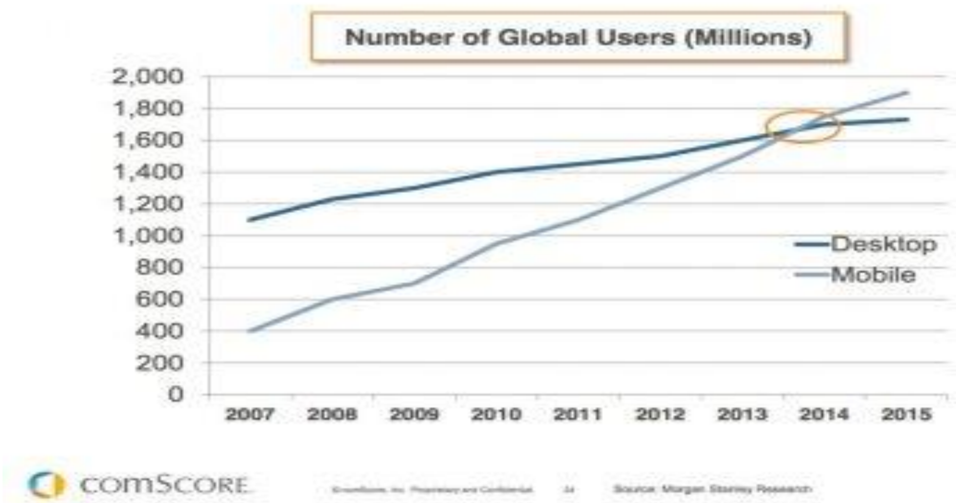


Figure 2.30. (Number of global users (2007-2015) [smartinsights.com, 2015][30]

2.9.2 The rise of mobile internet worldwide

Mobile Internet users form a significant part of overall mobile subscriptions worldwide. According to the estimation given by ITU, in 2013 there were 2.1 billion active mobile broadband subscriptions in the world. That means 29.5% of the global population is online, and this number is sure to keep growing [Walk digital, 2015].

According to the research by 'We Are Social', mobile overload has exceeded 100% in many regions of the world, including North America, Western Europe, Central and South America, Central and Eastern Europe, and the Middle East also. This means there are at least as many mobile subscriptions as citizens in those regions, including users of all smartphones, feature phones, and regular phones [WeAreSocial, 2015].

Figure 2.31: Comparison between mobile devices and fixed devices [IPcarrier, 2015]. [31]

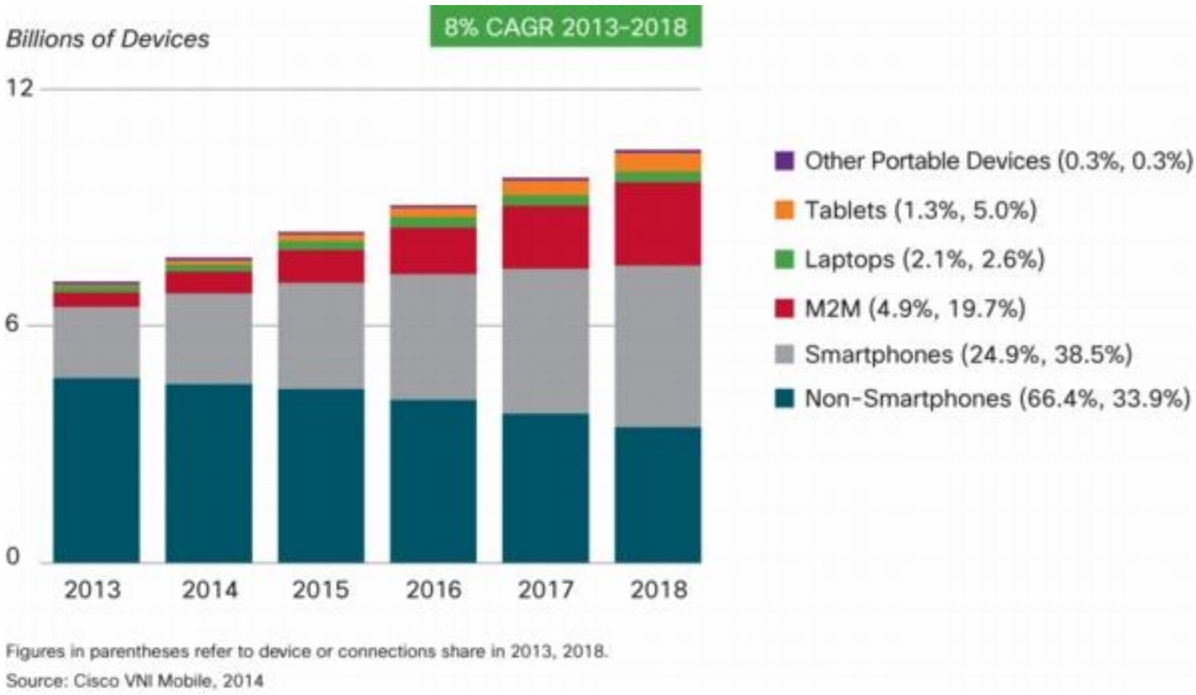


Figure 2.32: Device comparison (2013-2018) [CISCO, 2015]. [32]

Almost two-fifths of all mobile phone users, close to one-quarter of the worldwide population, used a smartphone at least monthly in 2014. By the end of the forecast period, smartphone penetration among mobile phone users globally will near 50%.

Regarding the internet, more than 2.23 billion people worldwide, or 48.9% of mobile phone users, went online via mobile at least monthly in 2014, and over half of the mobile audience will use the mobile internet next year [Cisco, 2015].

As a result, it has been estimated that the total number of mobile phone internet users rose 16.5% in 2014 and will maintain double-digit growth through 2016 [idc.com, 2015].

2.9.3 Mobile and user expectations

User expectations are increasing in line with the introduction of more advanced devices along with the huge exposure those consumers have with regard to mobile websites and mobile apps, which contribute to the change of behaviour patterns. Due to the change of users' activities, digital mobility and connectivity become ever more important every day as the smartphone continues to transform what people demand. In a recent study by Salesforce, reported in 2014, 85% of respondents said that mobile devices were central to their everyday life [Saleforce, 2015] as demonstrated in Figure 2.33.

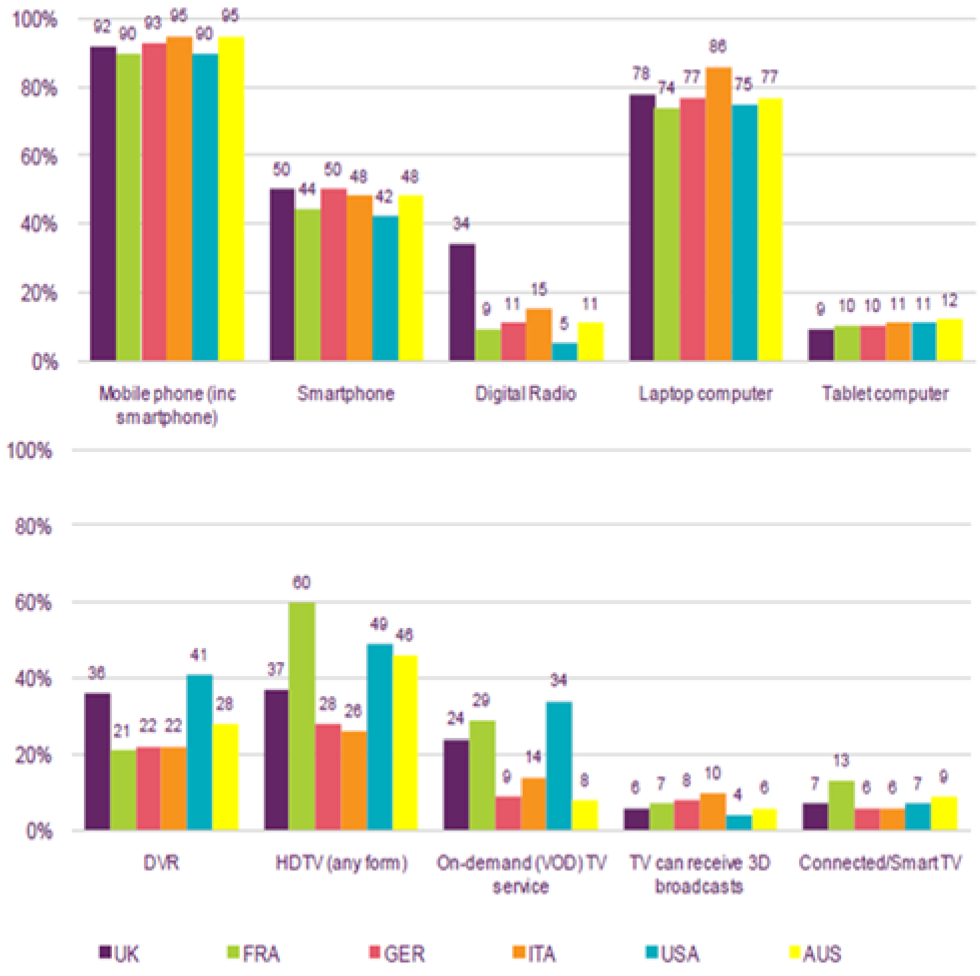


Figure 2.33: Mobile usage comparison between UK and middle Europe and USA companies [Digital-stats, 2015]. [33]

2.9.4 Smartphone UK trends

A smartphone is a mobile phone with more advanced computing ability and connectivity than basic feature phones. Smartphones typically include the features of a telephone, as well as the features from other popular user devices, such as a personal assistant, a media player, a digital camera, and / or a GPS navigation unit. Mobile telecommunications have been available in the UK since the mid-1980s.

There are now 83.1 million mobile handsets and data connections in the UK. In 2000, just half of the UK adults said that they have a mobile phone. That figure now stands at 93%. In the UK, there has been a steady but slowing growth of smartphone usage; latest research from YouGov's Technology and Telecoms team confirms that almost half of mobile owners now use smartphones (47%) [Portioresearch, 2015].

In the UK, it was believed that the number of smartphone users was expected to reach 42 million people or 65% of the population [Mobilemastinfo, 2015]. Figure 2.34 projects this trend.

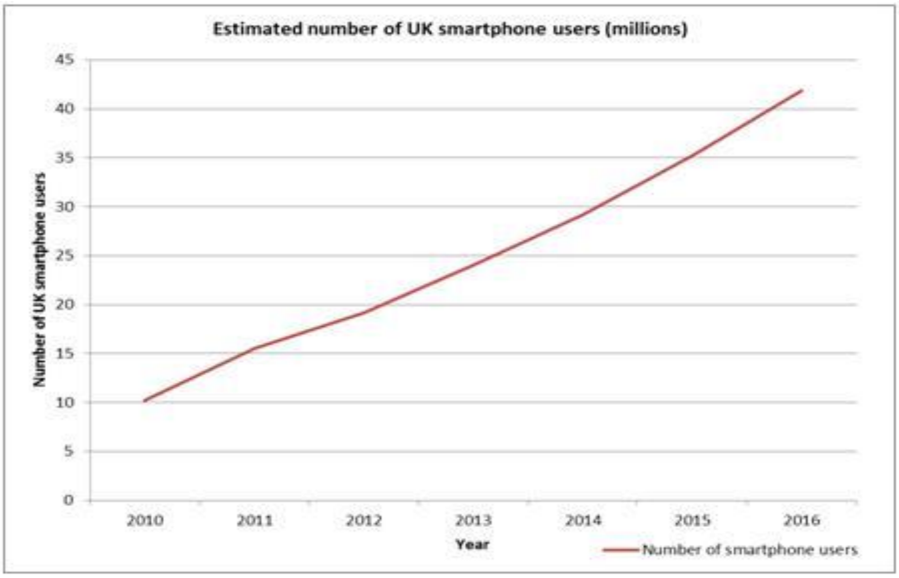


Figure 2.34: The estimated growth of UK mobile smartphone users [Pharmaphorum, 2015]. [34]

2.9.5 Smartphone changing photography

The huge growth in popularity of smartphones in the past three years has led to many consequences, some of which were easy to predict, and some of which are not yet fully understood. This is true especially in the field of digital photography. Smartphone users, it appears, take a lot of photographs.

The Apple iPhone 4 is currently the most popular 'camera' on Flickr.com [Flickr, 2015]. As a direct result, millions of dollars are being made by mobile developers to develop photo apps to satisfy this new trend of demands.

2.9.6 Smartphone popularity

According to a new survey by market researcher Counter Point, the iPhone 5s sold 7 million units in May, creating the bestselling smartphone in the world. Secondly was Samsung's Galaxy S5, which sold 5 million units across 35 countries. Table 2.3 lists the top 10 most popular smartphones on the market. [Counter Point Research, 2014].

Table 2.3. Top 10 smartphone list as of May 2014 [Counter Point Research, 2014], [3]

Rank	Brand	Model
1	Apple	iPhone 5s
2	Samsung	Galaxy S5
3	Samsung	Galaxy S4
4	Samsung	Note 3
5	Apple	iPhone 5c
6	Apple	iPhone 4S
7	Xiaomi	MI3
8	Samsung	Galaxy S4 mini
9	Xiaomi	Hongmi Redrice
10	Samsung	Galaxy Grand 2

Due to the adaptability and convenience of current mobile telephones, people are constantly using a telephone to perform various tasks more than just making a call, including viewing / taking pictures and shopping online. While a smartphone can act as a mini-computer and can be utilized to search the internet in the same way as using a desktop computer, it does not always offer the same functionality as a computer due to its inherent limitations. For example, the colour of a desktop computer can be adjusted to its desired colour temperature, i.e. D65, whereas the RGB values on a smartphone normally cannot be modified nor can the white balance be checked. As a result, performing online shopping using a mobile phone can be tricky, especially when buying colour sensitive items.

Therefore, this research takes an initiative to investigate the variations of colours for a number of smartphones while making an effort to model their colour appearance using CIECAM02. Phase 2 studies the Apple iPhone 5 as a starting point but also considers the LG Nexus 4, Samsung, and Huawei models, and makes a comparison with a CRT colour monitor, that has been studied extensively in Phase 1 and that has been calibrated using the D65 standard.

In this study, the iPhone 5 (6), Samsung (1), Huawei (1), and LG Nexus 4(1) are investigated due to their availability.

3. Methodology

In this Chapter, experimental setup procedures, methodologies and the apparatus applied for measuring colours are explained in detail, including the setup of experiments and the magnitude estimation method. Table 3.1 gives an overview of the experiments carried out in this study. In total, 19,510 data values have been collected in this research.

Table 3.1 Overview of the psychophysical experiments carried out in the study. [4]

Phase	Number of samples	Number of observers	Lighting source	Device	No of Experiments	Scaling attributes	No of estimation
0 Training	30	7	D65	CRT	1	Lightness Colourfulness Hue	630 (=30x7x3)
1 Textured Colours	30	7	D65	CRT Textured colours	5	Lightness Colourfulness Hue	3,150 (=30x7x3x5)
2 Mobile phones	30	3-7	D65	IPhone5 (3) LG Nexus Samsung Huawei	6	Lightness Colourfulness Hue	3,780 (=30x7x6x3)
Total							**7,560**

3.1 Apparatus

3.1.1 Viewing cabinet

Colours appear differently under different lighting sources. To avoid and reduce the assessment error, the Verivide colour viewing cabinet is used to simulate different light sources to obtain an objective assessment of colour and colour difference under controlled viewing environments, as illustrated in Figure 3.1.

Figure 3.1: Colour viewing cabinet. [35]

3.1.2 Colour meter, CA-100

The phones and CRT were calibrated and measured before starting the experiment. A Minolta Chroma Meter CS-100A, as shown in Figure 3.2, was employed to measure each colour in terms of CIE tri-stimulus values, i.e. x, y, Y and is in the position of the observers' view.

Figure 3.2: Colour meter, CA-100A. [36]

3.1.3 Monitoring calibration (Spyder)

Experiments are conducted on a 19” CRT monitor that was calibrated daily using Pantone ColorVision OptiCAL Spyder software [Spyder]. Figure 3.3 illustrates the calibration procedure using the Spyder software where the Gamma value is set to 2.2.

Figure 3.3: Spyder sensor attached to the computer screen to perform the calibration. [37]

The illuminant in these experiments is set to D65 to be consistent with the other existing studies. Thirty test colours were selected to cover a wide range of colours and were plotted in a CIE chromaticity xy diagram as given in Figure 3.4, which is consistent with many existing studies [Gao, 2015].

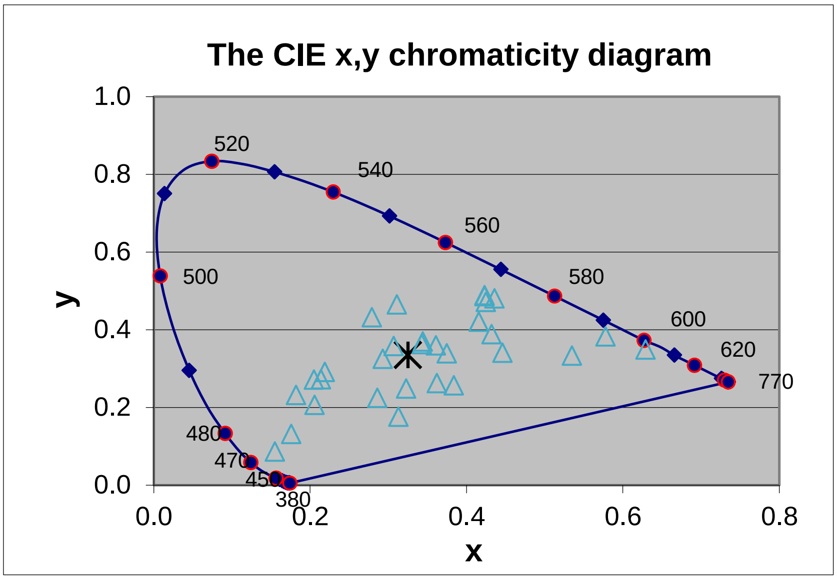


Figure 3.4: Thirty test colours presented on a CIE xy Chromaticity diagram. The '*' refers to reference white under D65 illuminant. [38]

Throughout all the experiments, the reference white, reference colourfulness and surrounding colours remain the same. The test field in the centre in Figure 3.5 subtends a visual angle of 2^{o} at a viewing distance of ~ 60 cm. Figure 3.5 shows the difference of 2^{o} and 4^{o} vision defined by CIE when viewing them at a distance of 45 cm.

The test field in the centre in Figure 3.6 subtends a visual angle of 2^{o} at a viewing distance of ~ 60 cm.

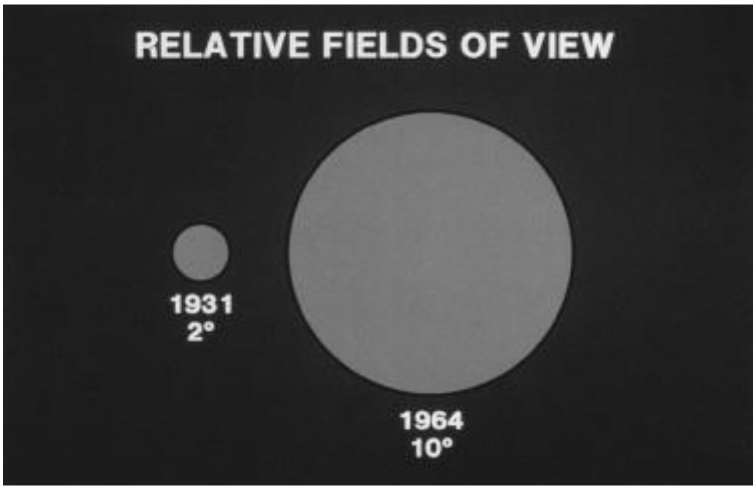


Figure 3.5: A viewing angle on 1931 CIE and 1964 CIE standard. [39]

3.2 Experimental setup

Figure 3.6 illustrates the experimental pattern applied in all the experiments.

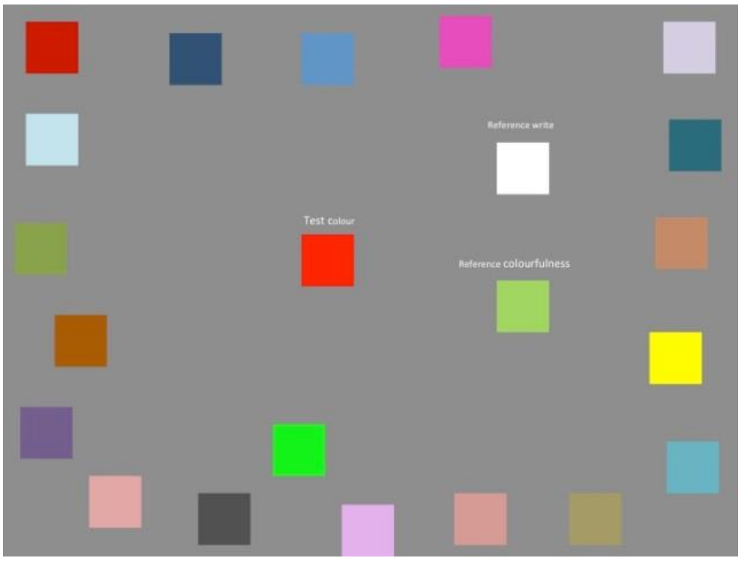


Figure 3.6: The paradigm of the experimental pattern. [40]

Throughout each experiment, only the test sample in the centre changes from sample 1 to sample 30, whereas the rest remains the same. The reference white is assigned as having lightness of 100 whilst reference colourfulness has a colourfulness of 40.

Ten subjects with normal colour vision according to the Ishihara colour vision test [Ishihara, 2004] were selected from 23 to conduct psychophysical experiments, aged between 17 to 40 years old mixed with both males and females who have different culture backgrounds and chosen from undergraduates, postgraduates and post-doc researchers. Figure 2.14 shows an example of a colour plate used for colour vision tests, by which a subject with normal vision can see a '6' that cannot be perceived by a person without.

3.3 Subject training

Since all the observers are new to the scaling experiment, a training experiment was carried out first with a total of 23 subjects. Those who did not perform well during the training experiment, showing big variations in their performance, were not invited to take part in the subsequent formal experiments. The magnitude estimation method as described in Section 2.4 is used to scale each colour in terms of lightness, colourfulness, and hue. In other words, lightness represents the degree of brightness a colour is showing. With the reference white being 100 and an imaginary black being zero, observers are asked to give an estimation between 0 and 100 that is in proportion to the reference white. For example, if a test colour appears half as bright as the reference white to a subject, 50% of lightness should be assigned to the colour. On the other hand, colourfulness shows the amount of hue appearing in a test colour, which is in proportion to the reference colourfulness that is given colourfulness of 40, e.g. if a colour has a colourfulness of 60, this colour should display 1.5 times as colourful as the reference colourfulness colour.

Neutral colours, including white, black, and grey colours have zero colourfulness. For hue estimation, four opponent hue scales are employed, which are red against green and yellow against blue. The hue of a test colour is then estimated with reference to any two neighbouring colours. For example, a hue can appear 80% yellow and 20% red or 50% green and 50% blue. A colour cannot show the contents of opponent hues, i.e. an answer of '30% green and 70% red' is invalid (red and green are opponent hues), whilst neutral colours have no content of hue at all. This hue scale is later converted into a hue angle of 0 to 400 with 0 (400) being red, 100 yellow, 200 green and 300 blue for data analysis.

Detailed descriptions are given below.

Lightness -- Lightness represents the degree of brightness a colour is showing. Alternatively, lightness can be considered as an estimate of the lightness or darkness of a colour. With the reference white being 100 and an imaginary black being zero, observers are asked to give an estimation between 0 and 100 that is in proportion to the reference white.

Colourfulness -- Colourfulness describes the purity and strength of a colour, e.g. bright red or dull red. Colourfulness shows the amount of hue appearing in a test colour, which is in proportion to the reference colourfulness that is given a colourfulness of 40, e.g. if a colour has a colourfulness of 60, this colour should display 1.5 times as colourful as the reference colourfulness colour.

Hue -- Hue or shade is the colour name, e.g. red, yellow, blue. For hue estimation, four opponent hue scales are employed, which are red against green and yellow against blue. The hue of a test colour is then estimated with reference to any two neighbouring colours. For example, a hue can appear 80% yellow and 20% red or 50% green and 50% blue. A colour cannot show the contents of opponent hues.

To analyse these subjective data, arithmetic means for both hue and lightness are applied as an averaged value between all the observers whereas a geometric mean is employed for colourfulness as colourfulness is scaled using an open-ended approach, which are defined as below.

Mean Value Definition: For a data set, the mean, or *arithmetic mean,* is the sum of the values divided by the number of values, which is given in Eq. (3.1).

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \qquad (3.1)$$

Geometric Mean Definition: The geometric mean is an average that is useful for sets of positive numbers that are interpreted according to their product and not their sum (as is the case with the arithmetic mean), and is given in Eq. (3.2).

$$\bar{x} = \left(\prod_{i=1}^{n} x_i \right)^{\frac{1}{n}} \qquad (3.2)$$

Standard Deviation Definition: A standard deviation refers to the measure of the dispersion of a set of data from its mean. The more spread apart the data, the higher the deviation. Standard deviation (s) is calculated as the square root of variance and is formulated in Eq. (3.3).

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2}, \qquad (3.3)$$

CV Value Definition: In this study, the variations are expressed in CV values. The coefficient of variation (CV) is defined as the ratio of the standard deviation s to the mean m, and is shown as Eq. (3.4).

$$CV = \frac{s}{m} \times 100\% \qquad (3.4)$$

4. Results on subject training and textured colours

4.1 Evaluation of Colour Monitor

The CRT Phillips Brilliance 201B colour monitor was calibrated and measured every day during the period of experiment that lasted 12 months. A Minolta Chroma Meter CS-100A was employed to measure each colour in terms of CIE tri-stimulus values, i.e. x, y, Y from the position of an observers' view. For each experiment, although the test colours are different from the other experiments, the reference white (RW), reference colourfulness (RC), and the background should remain the same. The averaged colour difference of those measurements in terms of CIELAB for reference white and reference colourfulness is 3 ΔE^*_{ab} units, which is similar to the literature [Luo ,1995], indicating the monitor is in a consistent colour condition.

4.2 Evaluation of Subjects' Data

Seven subjects were chosen for each experiment to have an age variation between 20 to 40 years old and mixed gender, as given in Table 4.1. The selection of the subjects aims to represent a wide age range group of subjects while remaining comparable with studies in the literature [Luo, 2005].

Table 4.1 Subject's information. [5]

Subjects	**Age**	**Gender**
subject 1	31	Female
Subject 2	32	Female
Subject 3	28	Female
Subject 4	37	Male
Subject 5	19	Male
Subject 6	28	Male
Subject 7	36	Male

The first study therefore is trying to find out any difference between gender groups. Figure 4.1 illustrates the comparison results for the estimation of lightness, colourfulness, and hue between the averaged female and male subjects. It can be seen from the graph that there are no significant differences between gender groups since all the points are close to the middle straight line.

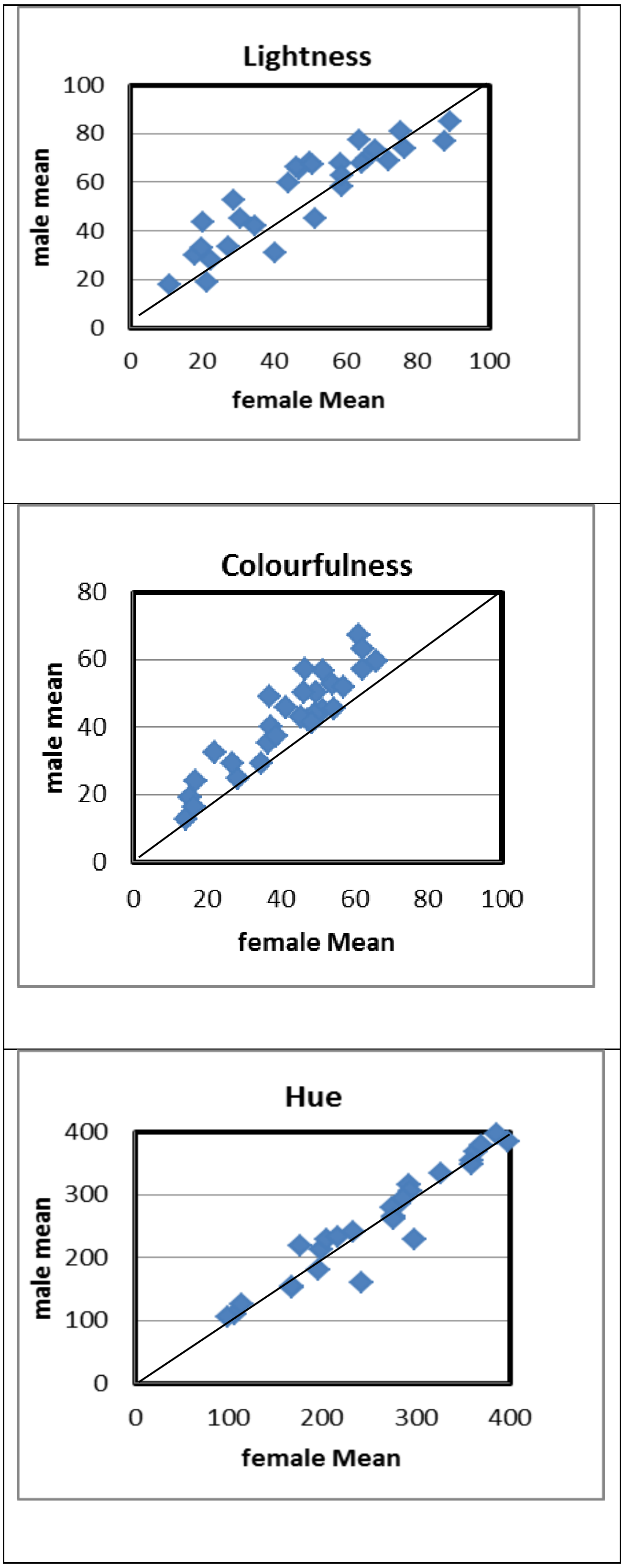


Figure 4.1: The comparison results between female (x-axis) and male (y-axis) observers on the mean estimation of lightness (top), colorfulness (middle) and hue (bottom). [41]

4.3 Experiments of textures

Thirty samples were displayed and estimated. In the first stage of the experiment, the sets included 30 colour sample slides from a database. The initial experiment (Experiment 1) is conducted on the 30 test colour samples without any texture. The following six experiments add a number of grey textures into those test colours as demonstrated in Figure 4.2. For example, in experiment 2, a cross is added to the colours where the shade of the dot is the same grey as the background.

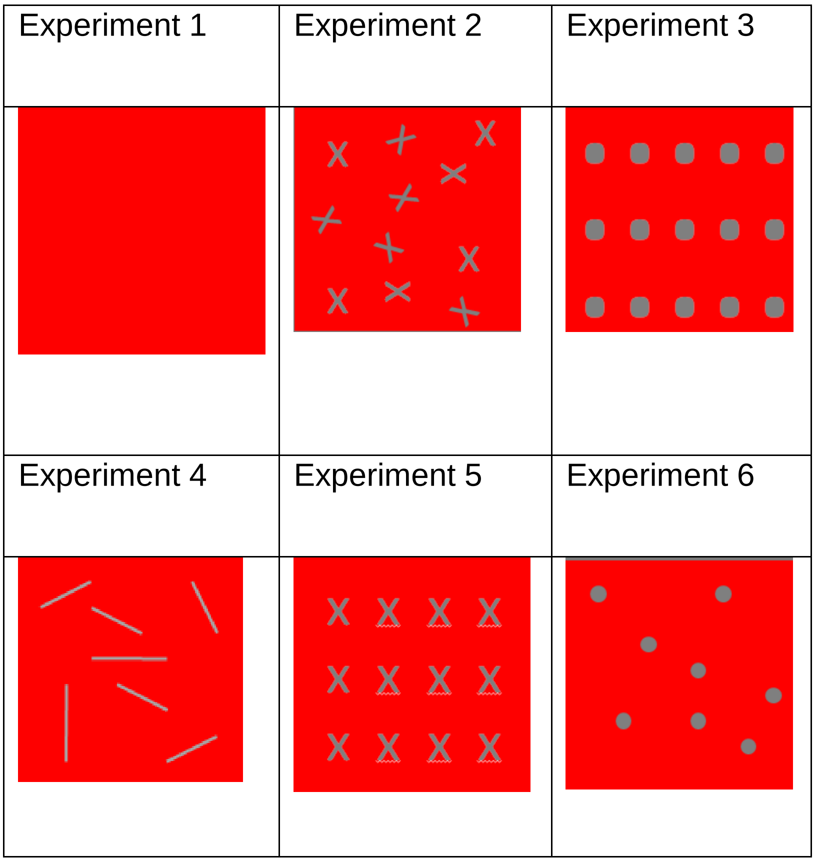


Figure 4.2: An example of experimental patterns in the 6 colour and textured experiments where Experiment 1 has no texture at all. [42]

In the second stage of the experiment, 5 sets of 30 colours with different textures were tested, which aims to be similar to the texture database at VisTex [VisTex,1995]. Figures 4.3 and 4.4 exemplify the experimental patterns in the real experimental settings whereas Figure 4.5 depicts the tristimulus values of 30 samples for all 6 experiments.

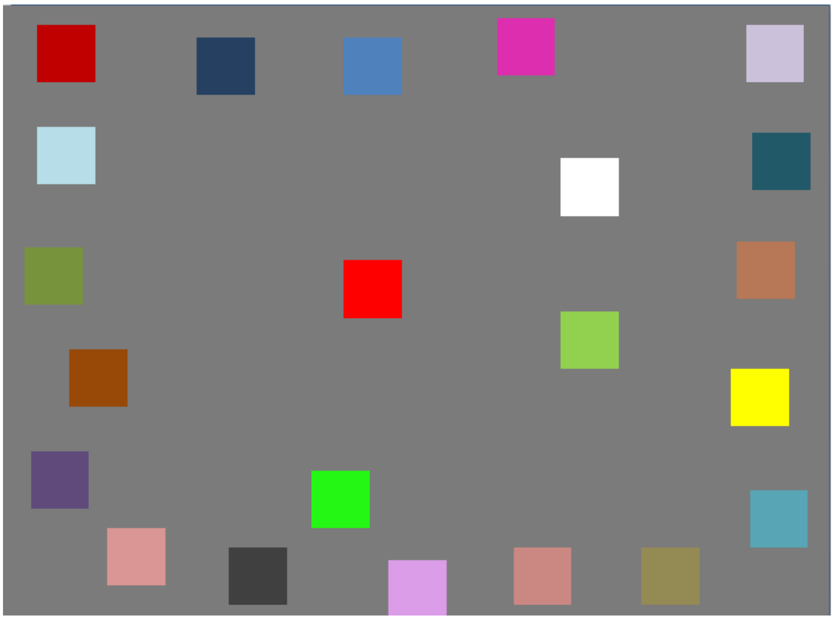


Figure 4.3: Experimental pattern for Experiment 1 (no texture) where only central test colour changes from sample 1 to sample 30. [43]

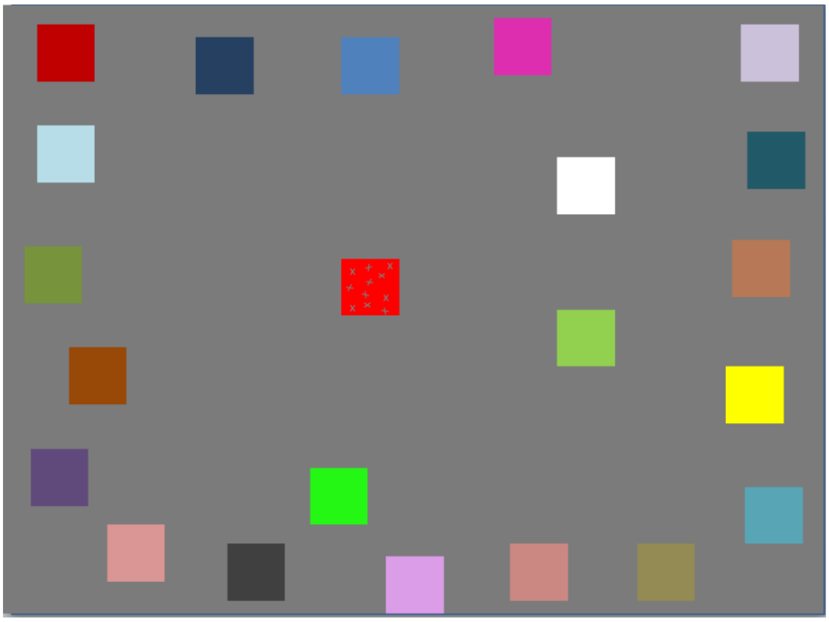


Figure 4.4: Textured colour samples (Experiment 2). [44]

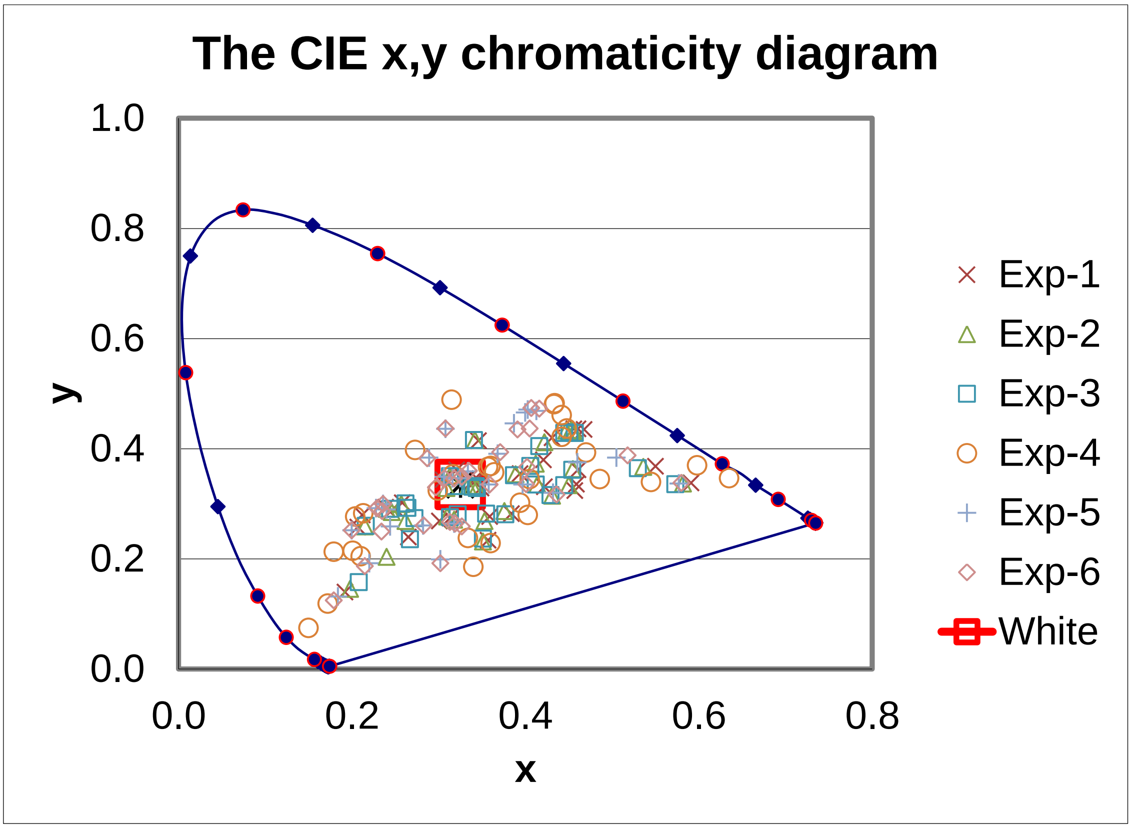


Figure 4.5: The tristimulus values (x, y) of thirty test colour samples for the six experiments conducted in Phase 1. The big red square in the centre represents the reference white under D65 that remains the same for all the experiments. [45]

As illustrated in Figure 4.5, the colour measurements do appear differently when presented with different texture patterns but not as significant as the same colour being presented on different telephones as will be seen in Figure 5.2 in Phase 2. The reference white remains the same for all six experiments and for all 30 colour samples in each experiment. The six experiments use the texture patterns that are demonstrated in Figure 4.2.

4.4 User study

As described in Section 3, for calculation of the averaged visual estimates, arithmetic means were employed for the attributes of lightness and hue, whilst geometric means were used for colourfulness as colourfulness was scaled using an open-ended approach. The coefficient of variation (CV) was applied to measure the agreement between each individual's estimation of the three attributes against the actual values measured by the Chroma Meter, over the 30 test samples. Table 4.2 lists the mean CV values for the colour experiment and Tables 4.3 lists the CV values for the different textured colour experiments. Figure 4.6 shows figuratively the comparison between mean CV values for Subject A (1), the rest of the figures are given in Appendix B. It shows the variation of individual subject's estimations in comparison with the mean estimations for the attributes of lightness, colourfulness and hue.

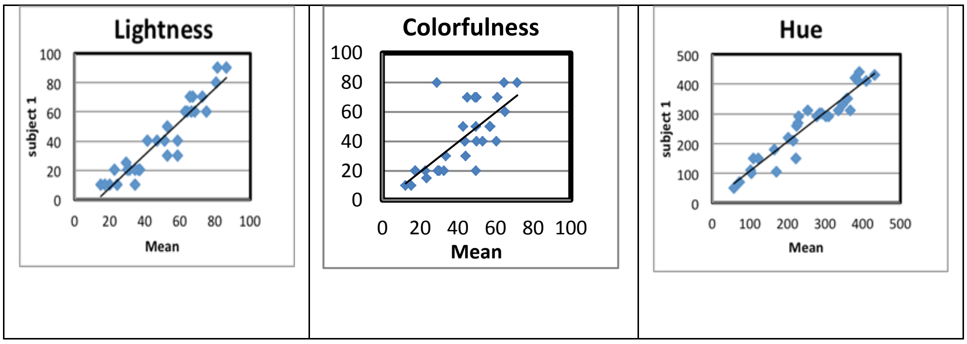


Figure 4.6: Comparison of estimation between Subject 1 (A) and means. [46]

A total of 7 subjects were recruited and took part in Experiment 1. All 7 subjects remained available to take part in Experiments 2 up to 6. Table 4.2 lists the CV values for all 7 subjects in performing Experiment 1 which contains colour samples without any texture, whereas the CV values for the rest of the experiments, i.e. Experiments 2 to 6 are given in Appendix C.

Table 4.2. The CV values of all seven subjects who performed Experiment 1 (Colour Sample). [6]

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	a	B
A	20	0.88	1.05	-2.7	32	0.62	1.6	1.15	9	0.95	1.04	-17.7
B	17	0.87	0.76	11.8	26	0.44	0.54	18.23	11	0.94	1.06	-15.6
C	36	0.89	1.18	-21.9	26	0.61	0.789	4.05	13	0.92	1.08	15.67
D	**41**	0.89	1.14	-11.2	20	0.81	1.14	-6.72	9	0.96	0.95	12.92
E	29	0.62	0.58	29.78	20	0.64	1.06	7.94	14	0.93	1.02	-11.7
F	25	0.91	1.26	-3.21	16	0.64	0.76	6.83	16	0.95	1.07	-34.3
G	23	0.9	1.18	-10.3	63	0.60	0.779	25.66	9	0.95	1.06	2.3
Mean	**27**	0.82	1	0.003	29	0.62	0.902	12.72	**11**	0.90	1.466	0.01

As shown in Table 4.2, each estimate by the subject is measured using three values, a, b and r (correlation coefficient). A regression equation allows us to find out the relationship between two (or more) variables to be expressed algebraically. It indicates the nature of the relationship between two (or more) variables.

A linear regression equation is usually written as Eq. (4.1):

$$Y = aX + b \tag{4.1}$$

where (a) is the slope and (b) is the intercept and r is the independent variable to measure the linear relationship between datasets X and Y, which lies within -1 to 1.

For example, for Subject 1 (A in Table 4.2), the linear equation is written and calculated as shown below.

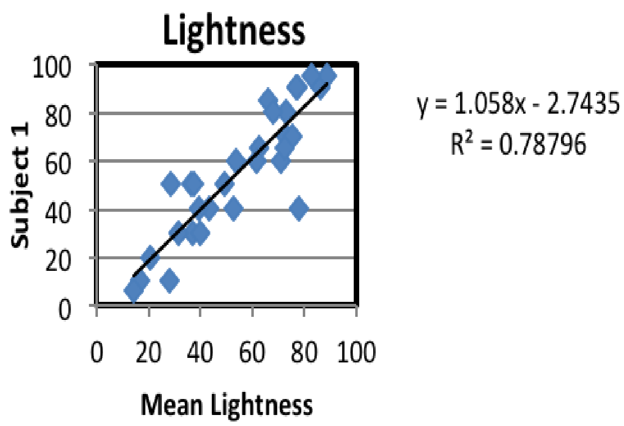


Figure 4.7: Plot between mean lightness (x) with lightness estimation by Subject 1 (y). [47]

Therefore, in this case, $a = 1.05$; $b = -2.74$; and $r = 0.88$. In the ideal perfect situation, a should be 1 and b should 0 and r should be 1.

In Table 4.2, according to the CV values, all subjects perform well on hue estimations with the average of 11% errors and worst on the estimation of colourfulness with the average error of 29%. The average error on the estimation of lightness is 27%. In comparison with the other studies [Luo 1993a, Luo 1995], which have errors of 17%, 25% and 10% for the estimation of lightness, colourfulness and hue respectively, the errors are very similar for colourfulness and hue. The estimation of lightness is much larger in this study with 27% error. This is mainly because most of the subjects were new to the magnitude estimation technique whereas in Luo's studies, those subjects are very experienced observers. For example, for Subject D and Subject G, their estimation of lightness and colourfulness respectively constitute the largest errors, which contribute to the final mean values.

On the other hand, although the CV value for colourfulness is 29%, which is similar to Luo's study, the correlation coefficient (r) is only 0.62 whereas in Luo's study, it is greater than 0.8, implying that for this study the estimation has larger scattering around the central line.

In this study, the subjects become more skilled during the subsequent experiments. As the subjects become more experienced, they perform better with decreasing CV values. For example, in Table 4.3, the CV values are improved significantly for lightness estimation, i.e. from 29% down to 21%, which is consistent with those in Luo's studies. In particular, the r value for colourfulness in Table 4.3 has increased to 0.77 from 0.62, implying that observers have much less scattering estimations. Table 4.4 summaries CV values for all subjects while conducting the six experiments whilst Appendix A lists all the CV values for each individual experiment.

Table 4.3. CV values for Experiment 2 (textured Colour Sample). [7]

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	A	b
A	24	0.94	1.14	-15.4	29	0.72	1.00	-1.04	11	0.74	0.91	-4.74
B	17	0.95	1.13	-9.52	31	0.79	1.1	-7.65	11	0.81	1.05	-24.2
C	14	0.93	0.9	3.43	20	0.88	1.06	-4.77	14	0.89	1.19	-16.3
D	24	0.84	1.05	-3.44	23	0.79	0.92	-0.96	13	0.7	0.85	37.2
E	27	0.74	0.73	12.4	27	0.77	0.94	5.66	14	0.91	1.23	-51.2
F	23	0.88	1.08	3.38	43	0.74	0.93	16.5	15	0.74	1.94	33.9
G	22	0.9	0.94	9.09	43	0.7	0.68	24.7	18	0.74	0.87	25.4
Mean	21	0.88			30	0.77			13			

From Table 4.3, it can be seen that Hue is the easiest attribute to estimate with the least CV values, ranging from 11% to 15%, whereas colourfulness is the most difficult one with CV values ranging from 26% to 30%. The CV values for lightness estimation are between 21% to 27%. Overall, all the subjects seem to perform to a similar standard, which is as expected.

Table 4.4. Summary of the CV values for Subjects A to G while performing Experiments 1 to 6. [8]

Subject	A	B	C	D	E	F	G	Mean
Exp-1 L	24	17	36	41	29	25	23	**27**
C	32	26	26	20	20	16	63	**29**
H	9	11	13	9	14	16	9	**11**
Exp-2 L	24	17	14	24	27	23	22	**21**
C	29	31	20	23	27	43	43	**30**
H	11	11	14	13	14	15	18	**13**
Exp-3 L	38	22	27	53	32	12	29	**30**
C	49	30	28	40	34	21	29	**33**
H	11	11	7	19	11	8	16	**11**
Exp-4 L	20	17	36	41	29	25	23	**27**
C	32	26	26	20	20	16	28	**24**
H	9	11	13	9	14	16	9	**11**
Exp-5 L	26	21	20	27	37	18	19	**24**
C	26	38	24	22	30	32	29	**28**
H	18	24	12	12	16	12	14	**15**
Exp-6 L	17	16	17	17	12	29	22	**18**
C	21	20	35	24	30	31	26	**26**
H	15	15	11	10	13	14	19	**13**

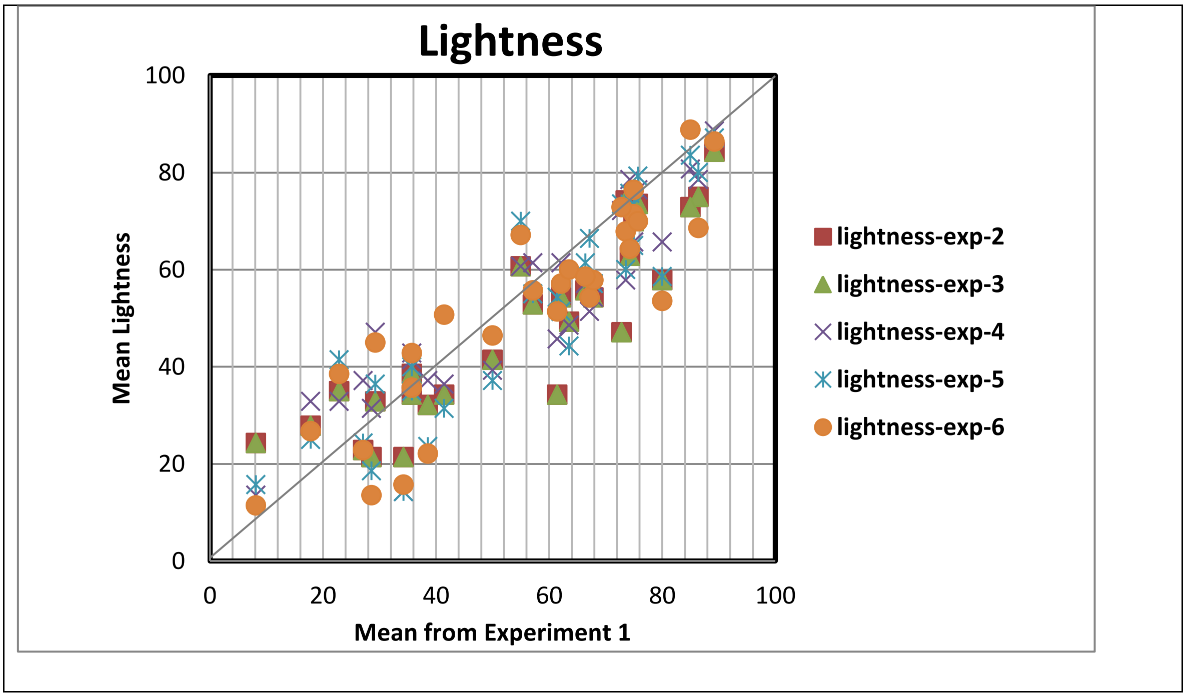
Table 4.5 compares the CV values across all six experiments. Again, a similar tendency occurs, i.e. colourfulness is the most difficult attribute to estimate. Specifically, as the experiments progress, the CV values are getting smaller for both lightness (from 27% to 22%) and colourfulness (from 29% to 18%), suggesting that subjects are getting more experienced and producing more consistent estimations.

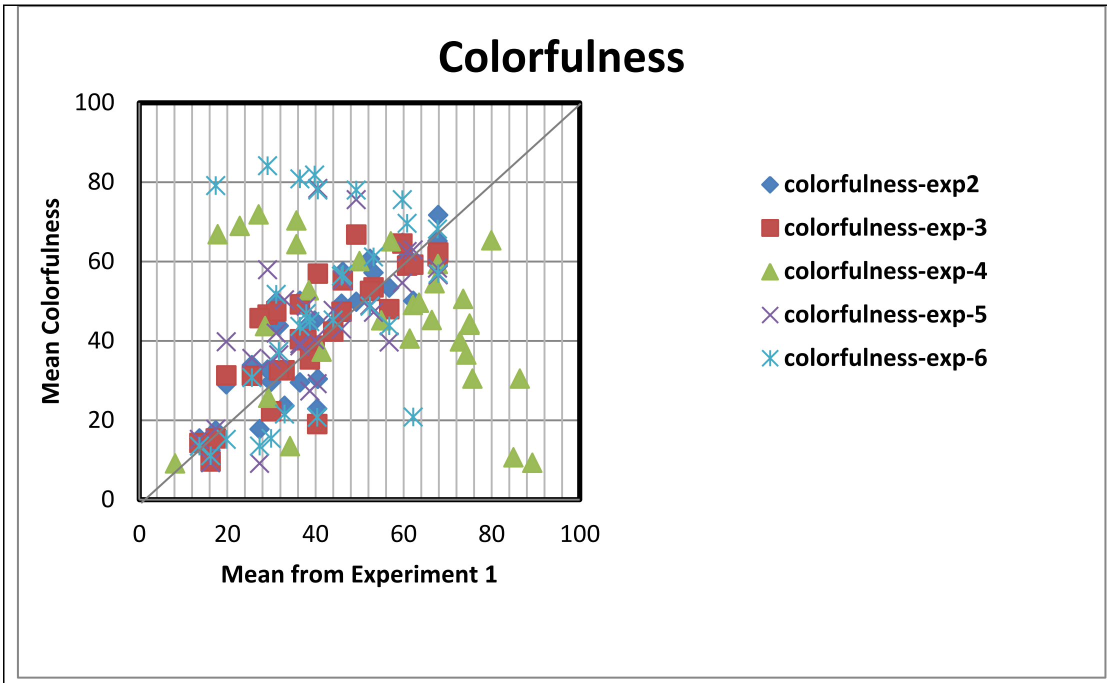
Table 4.5. Summary of the mean CV (%) values of subjects' estimations for the 6 experiments. [9]

Name	**Lightness**	**Colourfulness**	**Hue**
Experiment 1	27	29	11
Experiment 2	21	30	13
Experiment 3	30	33	11
Experiment 4	27	24	11
Experiment 5	24	28	15
Experiment 6	22	18	13
Mean	**25**	**27**	**12**

4.5 The effect of texture on the appearance of colours

Experiments 2 to 6 are performed on textured colour samples as illustrated in Figure 4.2. A graphical comparison of the variability between the sets of samples in terms of the three attributes is shown in Figure 4.8 where comparison between Experiment 1 (x-axis without texture) and the other 5 experiments are given.





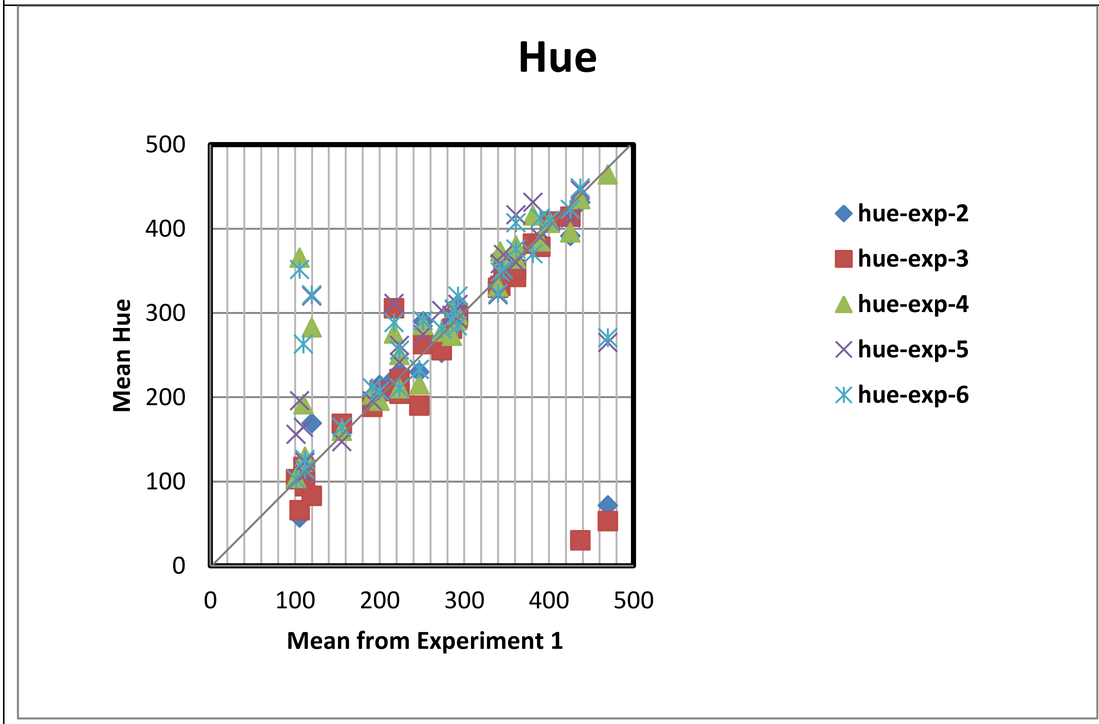


Figure 4.8: Comparison results between mean estimations of lightness (top), colourfulness (middle) and hue (bottom) for Experiment 1 (x-axis) and Experiments 2-6 (y-axis). [48]

As can be seen from Figure 4.8, the largest discrepancies occur on colourfulness estimations, in particular for Experiments 4 (Δ) and 6 (*), which contain patterns of random lines and random dots as depicted in Figure 4.2, which could be explained on the basis that random patterns make colourfulness more difficult to estimate. Although Experiment 2 also contains patterns scattered around the colour sample, the texture pattern itself, i.e. X, is symmetrical. Otherwise, all the points in Figure 4.8 are slightly above the central line for the colourfulness estimation, suggesting that texture has some effect on colourfulness estimations and makes colours appear to be more colourful.

For lightness, the textured colours appear to be darker than the colours without textures, which indicate the texture decreases the lightness contrast and makes colours appear darker.

On the other hand, little effect is found for hue estimation, which is expected as the texture patterns are neutral colour, the same grey as the background.

Therefore it is concluded in this study that texture that shares the same grey level with that in the background has little effect on hue estimation, makes a colour appear more colourful and darker, while under the D65 viewing condition on CRT monitors.

A comparison between texture patterns was also carried out, which is demonstrated in Figures 4.9 where estimation results from Experiment 6 (with dot texture, x-axis) are compared with the results from Experiments 5 (with cross texture) and 4 (with line texture) respectively.

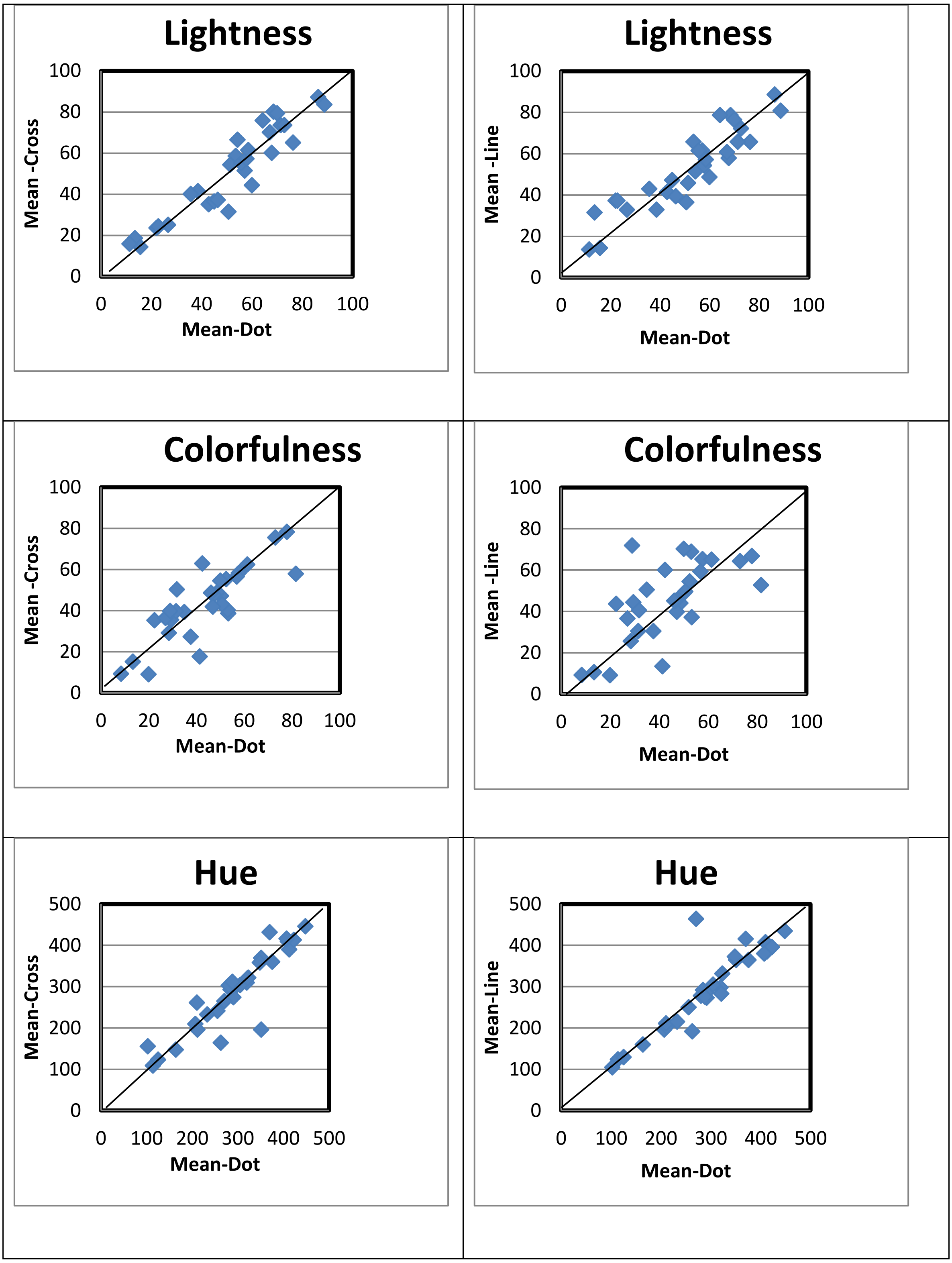


Figure 4.9: Comparison results between Experiment 5 (dot pattern, x-axis)) with Experiment 6 (cross pattern) and Experiment 4 (line pattern). [49]

The figure shows the estimation results are very similar, implying that texture patterns have little effect on the colour appearance in this study. Similar results can also be found when comparing between patterns of crosses (Experiment 5) and lines (Experiment 4) as depicted in Figure 4.10.

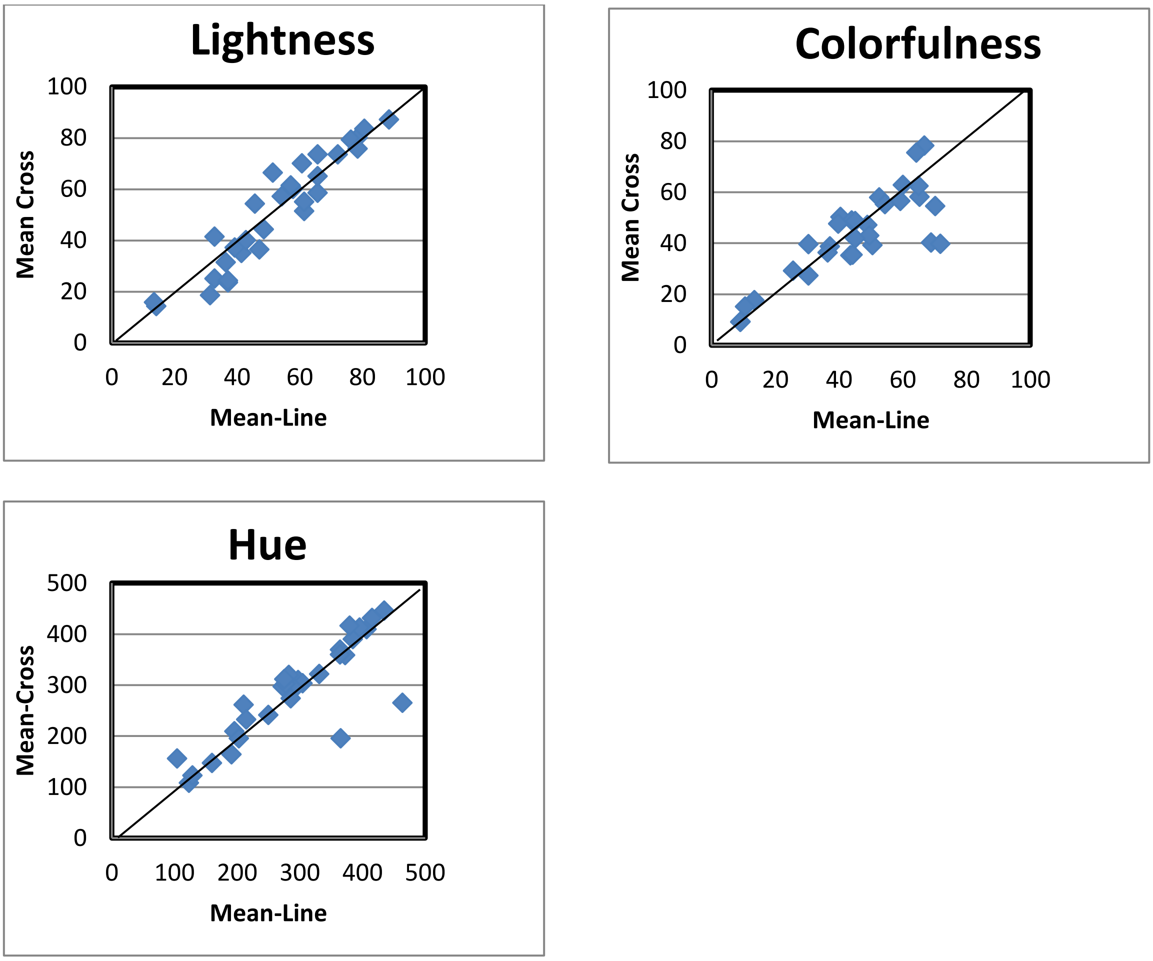


Figure 4.10: Comparison results between Experiment 4 (line pattern, x-axis) with Experiment 6 (cross pattern). [50]

From Section 4.5, it can be seen that the added texture appears to have some effects on estimated colour appearance. Therefore this analysis focuses on the study of the performance of CIECAM02 on the prediction of these colour appearances. The graphs in Figures 4.11 illustrate the comparison results between observers' estimation and the predictions by CIECAM02. That is the data estimated by subjects (x-axis) from each experiment is plotted against the predications by CIECAM02 for each of three colour attributes of lightness, colourfulness, and hue. The input data of XYZ of CIECAM02 are measured in advance for each colour sample under each experimental setting as presented in Figure 4.5.

With regard to hue, the predictions from CIECAM02 fit well with subjects' estimations. Because of the presence of grey texture patterns presented in each test colour sample, the estimations of lightness by subjects appear to be higher, which could be due to the fact that the presence of texture makes colours appear darker. On the other hand, the estimated colourfulness appears to be less colourful than that of predictions by CIECAM02 due to the fact that textures make colour more colourful as observed in Section 4.5. Note: Experiment 1 does not have any texture pattern; therefore the top left graph appears to be a good fit. With regard to the modelling of textured colours using CIECAM02, a linear modification has been carried out on Eqs. (4.2) and (4.3) for both lightness and colourfulness respectively as it gives the biggest correlation coefficient values compared to other non-linear approaches.

$$L_{texture} = 0.82\, L_{CIECAM02} \quad (4.2)$$

$$C_{texture} = 1.40\, C_{CIECAM02} \quad (4.3)$$

In this way, the average correlation coefficient (r) values are 0.86 and 0.61 for lightness and colourfulness respectively. Obviously textured colours have more complex characteristics than linear representations. More study will be conducted in the future to investigate more textured patterns.

The same experiment on colour samples was also conducted on mobile phones and as the result of data comparison and fitting CIECAM02 model to this phase of the study, the conclusion and changes in CIECAM02 model is as follows.

Since the colour appearance model CIECAM02 was developed for the medium of a CRT, which feature refection and transparency, it is not well equipped to predict smartphones. After setting the environmental parameters to 'dim' conditions where F = 0.9, c = 0.59, and Nc = 0.90 to compensate for lightness differences between a CRT and iPhone, the comparison results are given in Figure 5.6 for the three iPhones, where colourfulness was adjusted according to Eq (4.4) below.

$$\text{Colourfulness\_smartphone} = 1.8 * \text{Colourfulness\_CIECAM02} \quad (4.4)$$

When comparing with the other smartphones, in terms of hue, all three types of phones tend to be more reddish for purplish colours than those displayed on an iPhone, whereas the rest maintains near the same. With regard to lightness, for lighter colours, all three phones unanimously appear darker than on iPhones with the LG-Nexus being the darkest with 25% darker, whereas 18% and 16% darker are evidenced for HuaWei and SamSung respectively. However, the opposite phenomenon occurs when it comes to the representation of colourfulness.

The images on all three phones, the LG-Nexus4, SamSung, and HuaWei, appear more colourful than those displayed on an iPhone. For example, the colours on a LG-Nexus4 phone appear systemically 10% more colourful than those depicted on an iPhone. In addition, for both the HuaWei and SamSung phones, they appear again to be 17% and 22% more colourful, especially for colourful samples, the tendency presenting across all three smartphones.

4.6 Data prediction using CIECAM02

From Section 4.5, it can be seen that the added texture appears to have some effects on estimated colour appearance. Therefore this analysis focuses on the study of the performance of CIECAM02 on the prediction of these colour appearances. The graphs in Figures 4.11 illustrate the comparison of results between observers' estimation and the predictions by CIECAM02. That is the data estimated by subjects (x-axis) from each experiment is plotted against the predications by CIECAM02 for each of three colour attributes of lightness, colourfulness, and hue. The input data of XYZ of CIECAM02 are measured in advance for each colour sample under each experimental setting as presented in Figure 4.5.

Understandably, CIECAM02 is not designed for textured colour samples. Therefore its predictions may vary to a large extent. Interestingly, with regard to hue, the predictions from CIECAM02 fit well with subjects' estimations. Because of the presence of grey texture patterns presented in each test colour sample, the estimations of lightness by subjects appear to be higher, which could be due to the fact that the presence of texture makes colours appear darker. On the other hand, the estimated colourfulness appears to be less colourful than that of predictions by CIECAM02 due to the fact that textures make colour more colourful as observed in Section 4.5. Note: Experiment 1 does not have any texture pattern, therefore the top left graph appears to be a good fit.

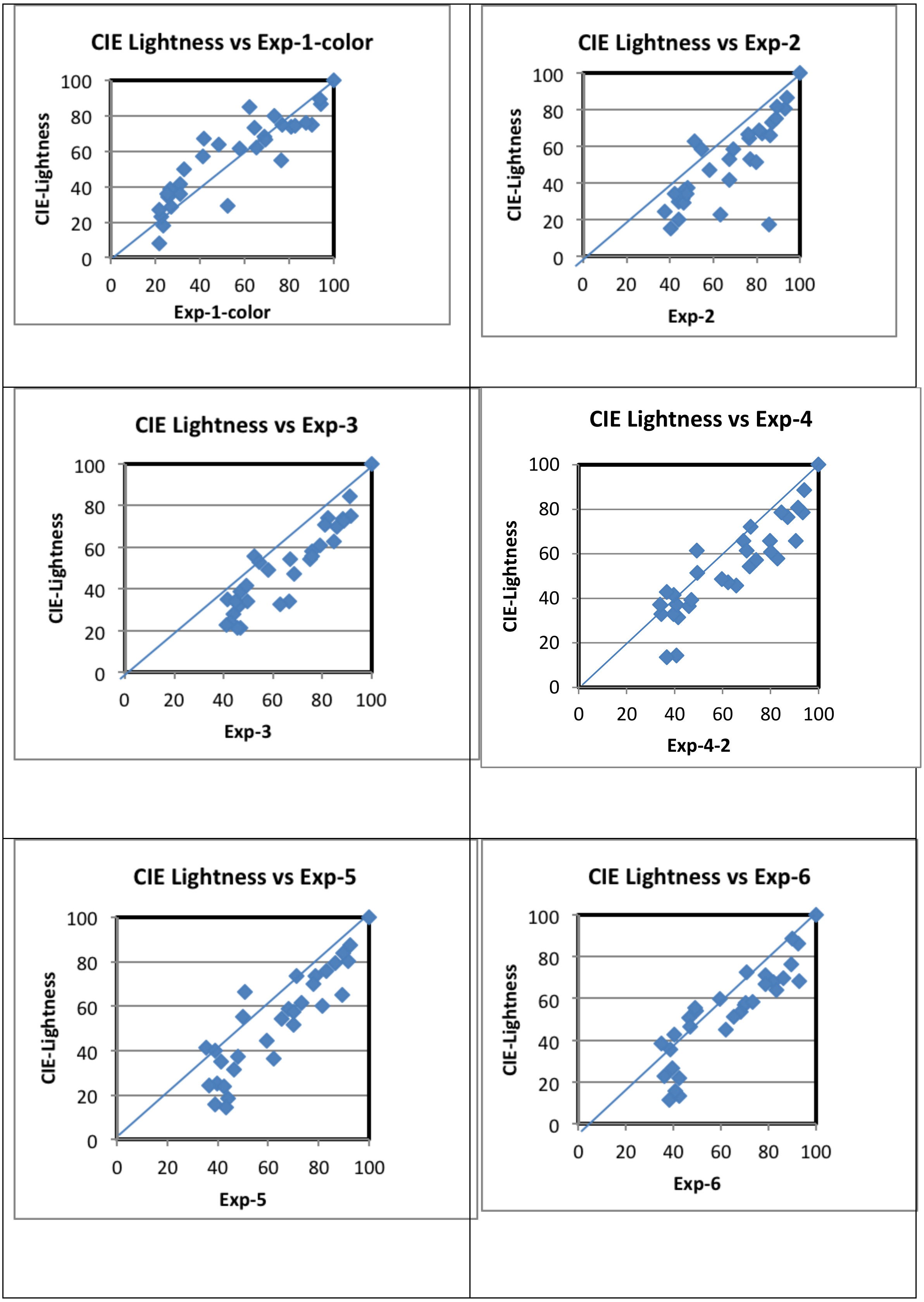


Figure 4.11: The prediction of lightness by CIECAM02 (y-axis) are compared with subjects' estimations of lightness for Experiments 1 to 6 (x-axis). [51]

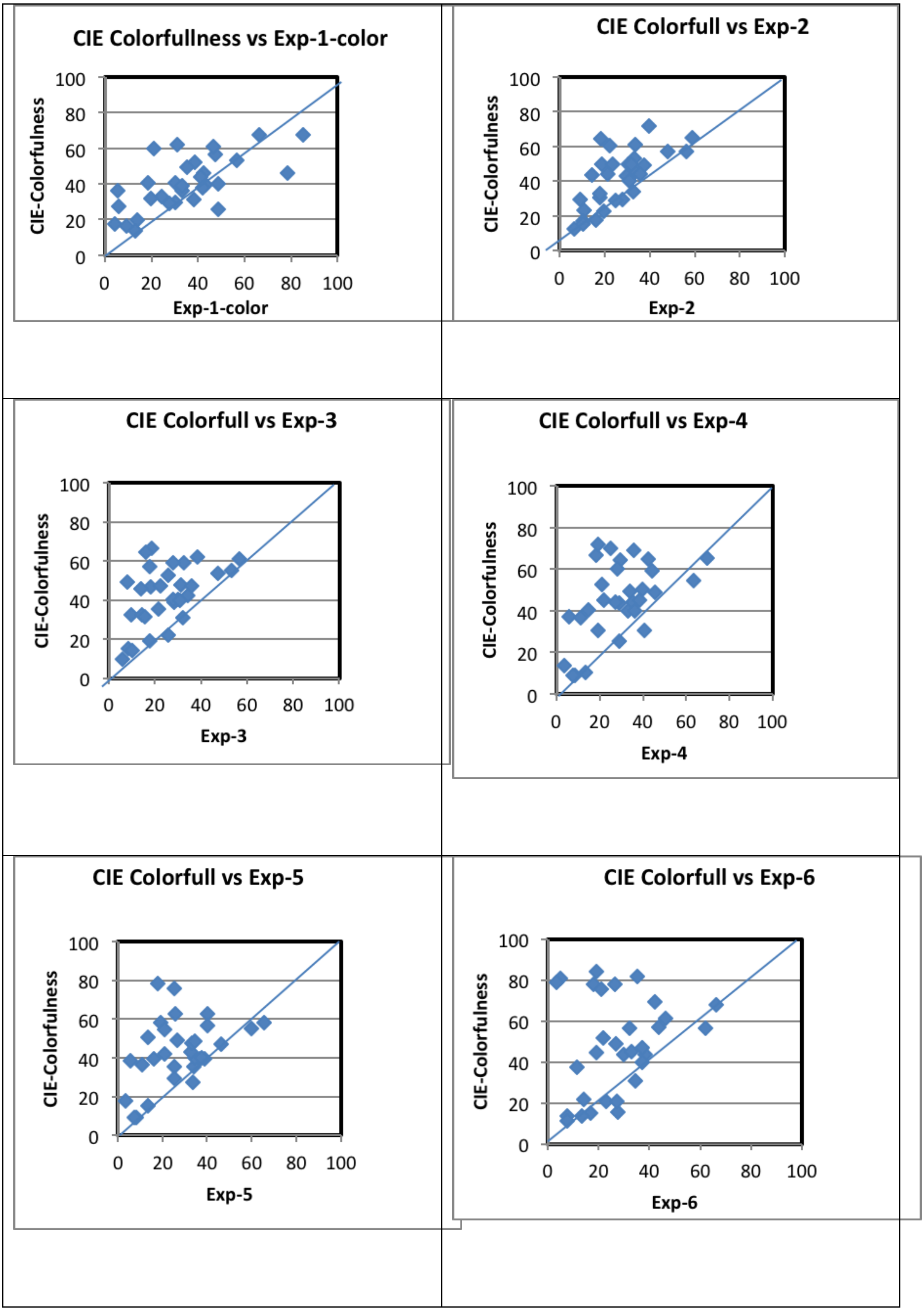


Figure 4.12: The prediction of Colourfulness by CIECAM02 (y-axis) are compared with subjects' estimations of colourfulness for Experiments 1 to 6 (x-axis). [52]

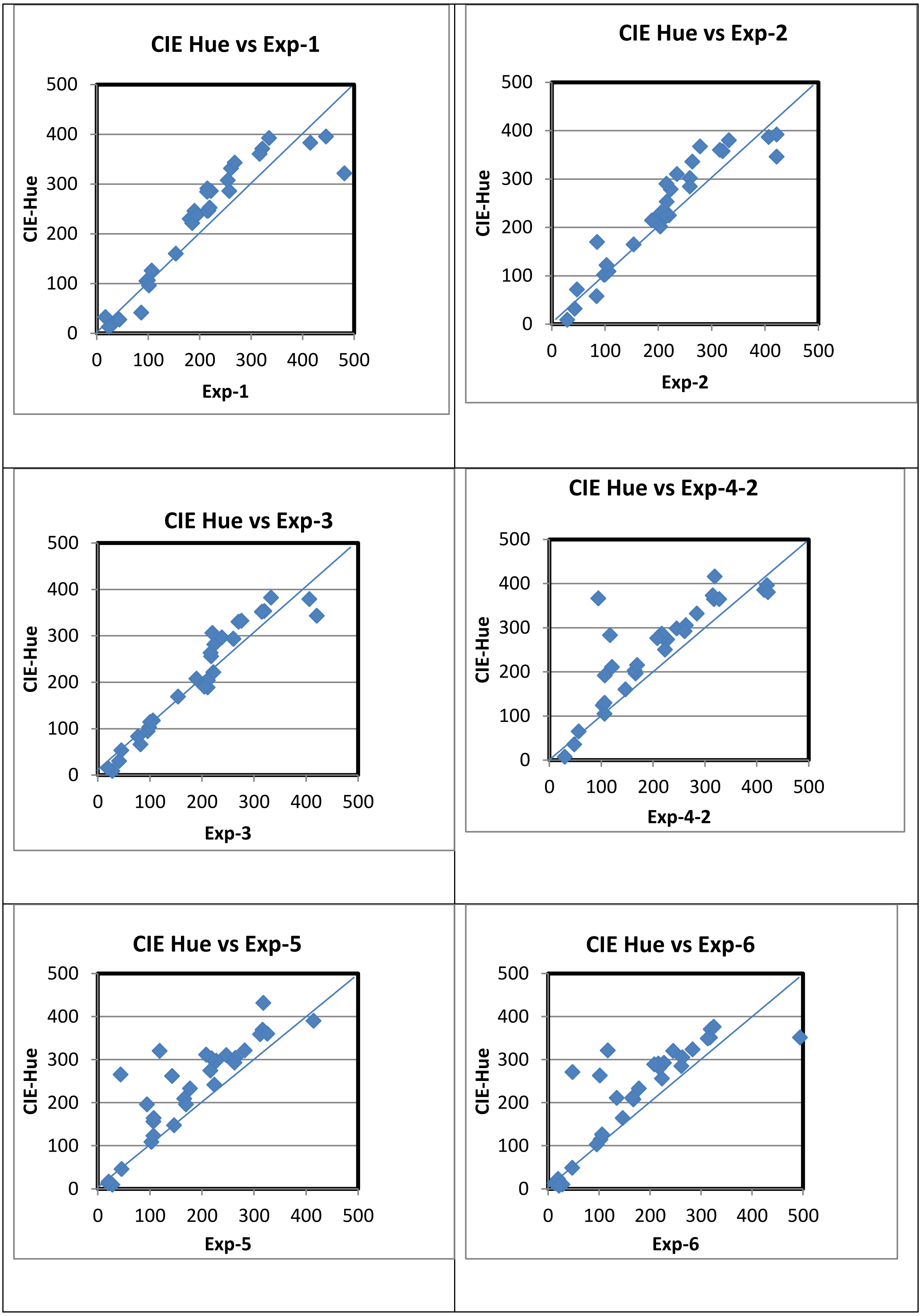


Figure 4.13: The prediction of Hue by CIECAM02 (y-axis) are compared with subjects' estimations of Hue for Experiments 1 to 6 (x-axis). [53]

Because the calculation of Hue is cycling between 0-400, i.e. 420 is equivalent to 20, the same data in Figure 4.11 appears to be scattered widely in comparison with Figures 4.9 and 4.10, whereas in fact the scattering is smaller.

In summary, the data collected from experiments 1 to 6 are based on 30 test colour samples estimated by 7 subjects after being trained and under a controlled environment by measuring and visual estimations of lightness, colourfulness and hue. The comparison takes place between the mean values of each attribute and the corresponding ones predicted by the CIE colour appearance model, i.e. the CIECAM02 model.

In Experiment 1, all lightness, colourfulness and hue values estimated by the observers appear to agree well with CIECAM02 predictions, indicating the experiments reported in this thesis are in line with the published work.

For experiments 2 to 6, a variety of simple texture patterns have been added to the test colour samples. The comparison results between the predictions by CIECAM02 and the observers' estimations show that they agree very well for the attributes of hue. For lightness, the predictions appear to be darker, whilst for colourfulness, the predictions appear to be more colourful, which is in line with the results Section 4.5.

4.7 Summary of Phase 1

The added texture does make changes to the appearance of a colour. Although the hue content does not change, a colour does appear darker and slightly more colourful when it has a texture in it than without. The pattern of the textures has no effect on the appearance of a colour.

The predictions by CIECAM02 follows the same trend, the textured colour samples appearing darker and more colourful.

Phase 2 of this study focuses on conducting similar experiments on mobile telephones whereas Phase 1 was conducted on a CRT monitor. Again, CIECAM02 will be investigated for the fitness to subjects' estimations.

5. Results on smartphones

5.1 Summary of the experimental setting

This study introduced refined versions of CIECAM02 for mobile displays. The images were processed based on CIECAM02 phenomena (lightness, colourfulness and hue). The experiment was conducted by comparing the original images viewed in a viewing cabinet with the predicted image viewed on mobile displays. The refined CIECAM02 with colourfulness* correction performed much better than original CIECAM02 versions. Many colour appearance studies were carried out using household TV or PC displays viewed under controlled viewing conditions. However, the colour appearance of mobile displays is affected by a many of viewing conditions. First of all, the display size is much smaller than the other displays such as TV. Secondly, the portability and the size of the device allows the display to be viewed under surrounding conditions varying from day light to bright sunlight, and indoor and outdoor conditions.

This phase of the study, describes the modelling of a few well known smart phones by using coloured image samples based on individual image statistical measurements for mobile phone displays (LCD). Thirty natural images were measured and analysed in terms of lightness, colourfulness and hue attributes. Each of the images was displayed on a mobile LCD and assessed by a panel of 10 observers. The visual results were used to evaluate the CIE colour appearance model, CIECAM02. The model was then modified specifically for mobile display viewing conditions.

Colour has been recognised as one of the top considerations in recognising an image. Human colour recognition is psychological, and is therefore subjective, hence it can be classified according to human visual perception. Objective evaluation involves physical measurement of images but generally fails to consider human visual characteristics. Therefore, psychophysical experimental results are required for developing metrics.

A number of these metrics have been suggested and widely used such as the CIELAB colour difference equation and CIECAM02 was developed in 1996 as an image difference metric factor for colour image properties.

In phase 1, affective attributes in modelling of colour image followed by colour textured image were investigated. These included lightness, colourfulness and hue measurement of the samples by observers. The experiment was designed to develop two types of colour and textured samples.

In phase 2, only colour attributes were considered and the statistical values of images were used to develop a colour model.

Although an image begins by being represented using RGB colour space when it is in a digital form, it is usually converted into hue, lightness and colourfulness colour space to circumvent the dependency nature of RGB space on hardware devices, i.e. a colour in one device usually does not appear nor measure the same as one in another device even with the same RGB values in both devices. This is because the range of R, G, or B values are manually set to be the same (such as [0, 255] for an 8-bit computer) for all monitors regardless of their physical measurements. On the other hand, hue, colourfulness and lightness, space agrees more with human vision theories. To further improve the fitness between users' perception and retrieved results, colour appearance based retrieval has been proposed in [Qui, 2002], attention is paid to the development of distance formulae, whereas in [Othman, 2008], patterned colour is the focus.

Usually, colour effect can be subjectively specified by means of visual perception [Judd, 1965]. By the definition given by the CIE (Commission Internationale de l'éclairage) [CIE: Publication No 17,1970], the hue, colourfulness and lightness, abstracted from complete visual experiences, are employed to represent dimensions along which colour may vary independently. For example, ***Hue*** is defined as the attribute of a visual sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colours, red, yellow, green, and blue, whereas ***Colourfulness*** constitutes the attribute of a visual sensation according to which an area appears to exhibit more or less of its hue. ***Brightness*** implies the attribute of a visual sensation according to which an area appears to exhibit more or less light, and ***Lightness*** refers to the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting [CIE: Publication No. 17, 1970].

In this Chapter, experimental setup procedures, methodologies and the apparatus applied for measuring colours are explained in detail, including the setup of experiments and the magnitude estimation method.

Thirty test colours are randomly selected from the Munsell colour book [Munsell] while making an effort to cover as much of the CIE 1931 colour space as possible. Psychophysical experiments are then carried out on both a 19" CRT colour monitor with its illuminant calibrated to D65, and mobile telephones. As illustrated in Figure 5.1, each test colour is placed at the centre against a grey background (with 20% of the luminance of reference white) and surrounded by the reference white, reference colourfulness and surrounding colours. The test field in the centre subtends a visual angle of 2^o at a viewing distance of ~60cm. Ten subjects with normal colour vision are selected to conduct the experiments using the technique of magnitude estimation which they have been trained in advance to apply skilfully. Specifically, for each test colour, each subject is asked to estimate its appearance in terms of lightness, colourfulness and hue contents verbally that are then recorded by an operator sitting nearby.

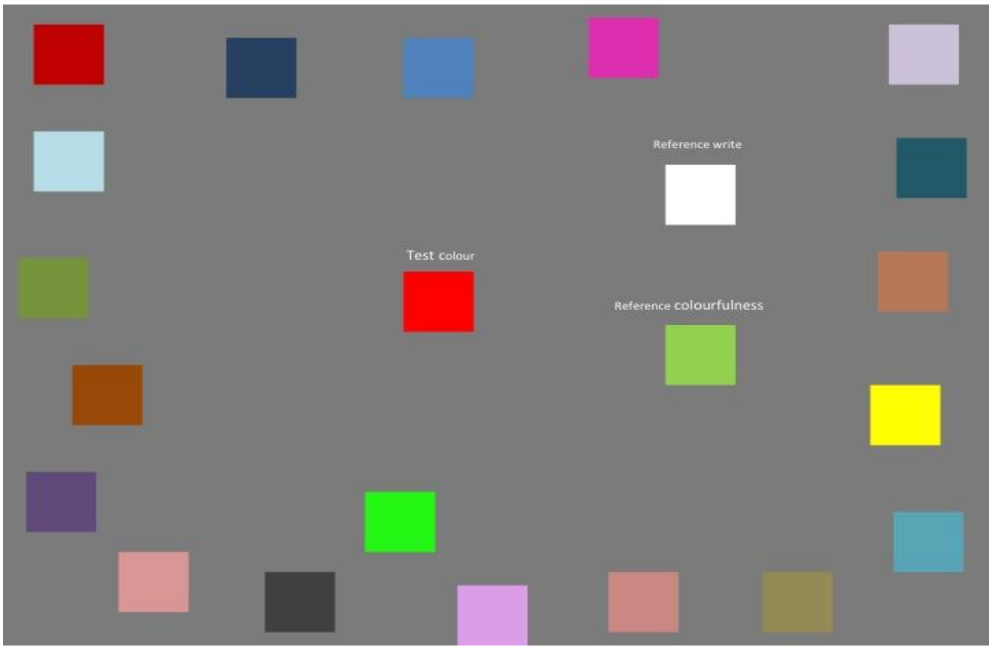


Figure 5.1: The paradigm of the experimental pattern. [54]

The above paradigm has been used to display on the mobile telephones and the tests were carried out by using the coloured sample on each mobile telephone using the same experimental procedure as phase 1. Different colours were selected in different samples to give a practical coverage of the CIELAB space. Neutral grey background colours were used in each phase to clearly show the colours on the monitor with the right contrast. The sample was placed inside a viewing booth and the observers with normal colour vision, according to the Ishihara test, participated in all experimental phases. All observers were familiar with the magnitude estimation method. Each was asked to estimate test colours in terms of lightness, colourfulness and hue closely following the method used by Luo et al [Luo, 1995].

Lightness was scaled against the reference white having a lightness of 100 and an imaginary black, 0. An anchor patch that was assigned a colourfulness of 40 and brightness of 100 was shown in a viewing cabinet. Each observer had to estimate the colourfulness of the reference patch in the beginning of each phase. The brightness was judged according to the anchor patch having a value of 100. The hue was judged by reporting the percentage of the two colours from the four psychological hues (red, yellow, green, and blue). The measured data are presented in a CIE xy chromaticity diagram as illustrated in Figure 5.2.

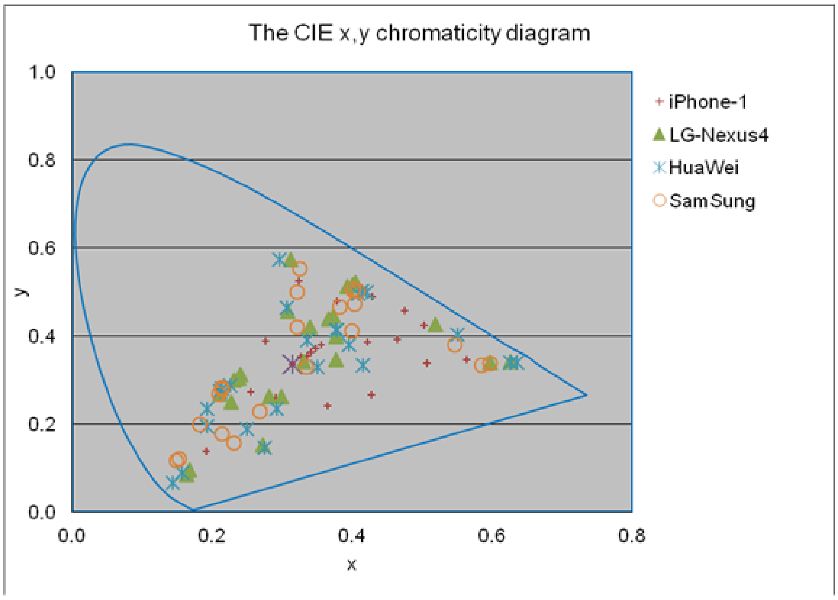


Figure 5.2: The x, y data of the thirty sample colours plotted on the CIE xy chromaticity diagram for the four telephones studied in this research. The big * refers to the reference white. [55]

5.1.1 Smartphones Colour Gumet

The measured data are presented in a CIE xy chromaticity diagram for each individual smart phone as illustrated in Figure 5.3.

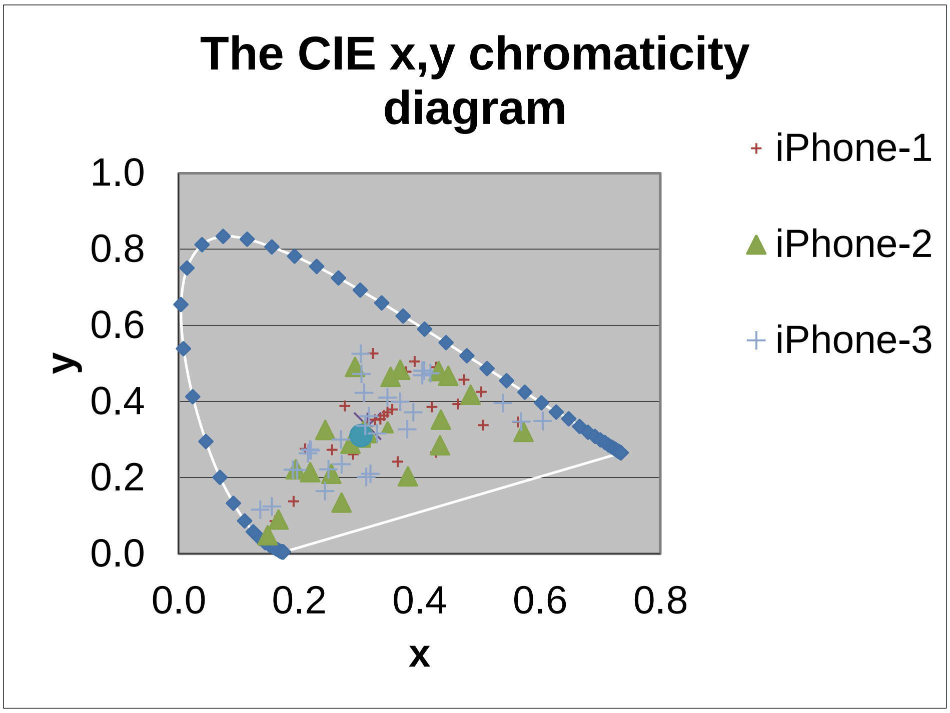


Figure 5.3: The x, y data of the thirty sample colours plotted on the CIE xy chromaticity diagram for the three iPhones studied in this research. The big * refers to the reference white. [56]

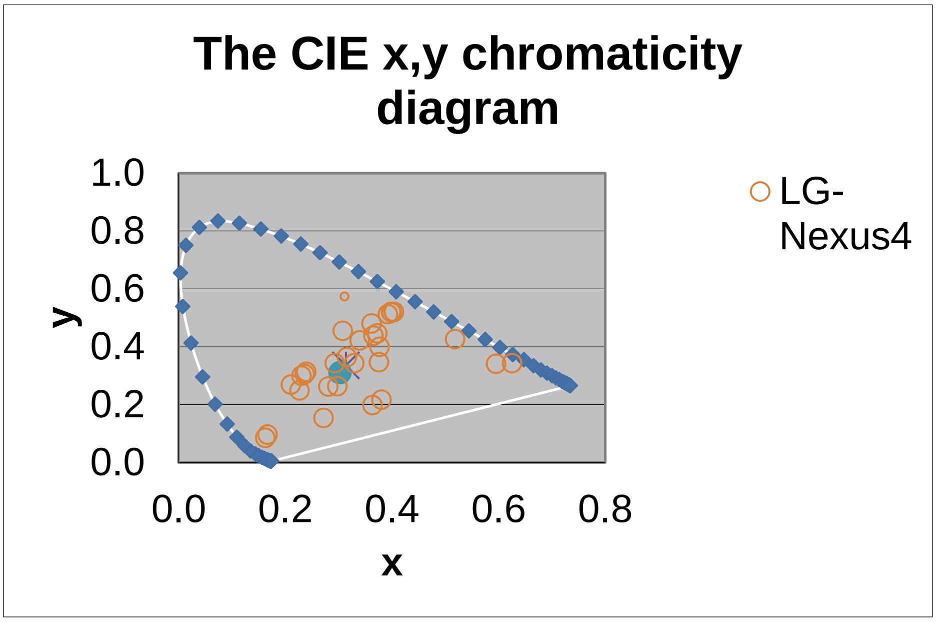


Figure 5.4: The x, y data of the thirty sample colours plotted on the CIE xy chromaticity diagram for the LG-Nexuse4 studied in this research. The big * refers to the reference white. [57]

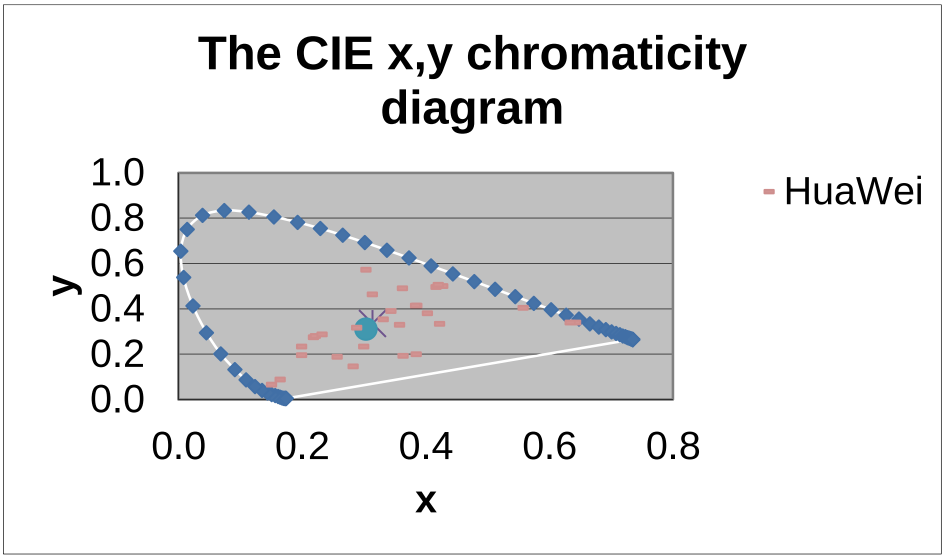


Figure 5.5: The x, y data of the thirty sample colours plotted on the CIE xy chromaticity diagram for the HuaWei studied in this research. The big * refers to the reference white. [59]

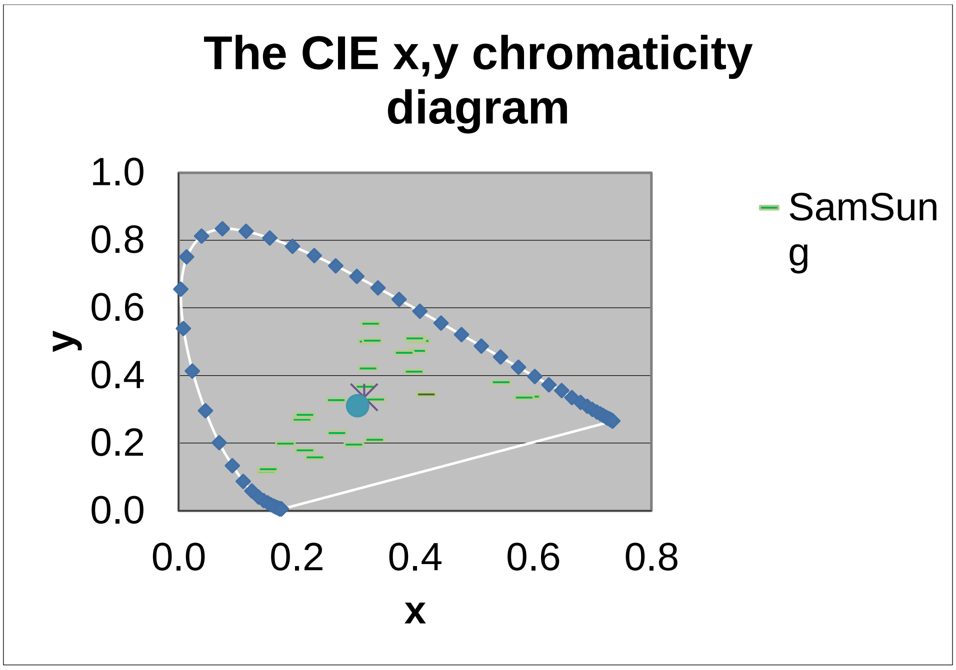


Figure 5.6: The x, y data of the thirty sample colours plotted on the CIE xy chromaticity diagram for the Samsung studied in this research. The big * refers to the reference white. [60]

In addition, comparison between subjects' estimation is also conducted, particularly with regard to hue, the estimated hue values of the colours presenting on a mobile telephone appear to be similar between all telephones and between phones and the CRT monitor. Similarly, the colourfulness and lightness vary significantly on subjects' estimations. For the iPhone 5, double values of lightness and double colourfulness have been witnessed. As a result, the CIECAM02 model has been modified to convert an image taken by a mobile telephone to its colour corrected using both forward and backward models. In doing so, an image is firstly converted into XYZ representation using the correlation between the RGB space and XYZ from a mobile telephone that has been measured in advance. Then using the forward model of CIECAM02, the predictions of lightness, colourfulness and hue are obtained.

After the alteration of these values, i.e. halving (or doubling if showing on a computer monitor) the lightness and colourfulness values of the image, the final XYZ values of the image can be calculated using the reverse model of CIECAM02. Subsequently, the RGB values and the final image will be displayed with truthful colours.

5.1.2 Observer Variations

Observer variations in terms of observer accuracy were examined. The accuracy was compared between each individual observer and mean visual results. The measure of Coefficient of Variation (CV) was used to indicate the disagreement between two sets of data. The more the points are scattered about the line, the poorer the agreement. For a perfect agreement, CV should be zero and the larger the value, the poorer the agreement.

The Figure 5.7 below shows the above sample on the mobile telephone screen which had been used for all the subjects during the test.

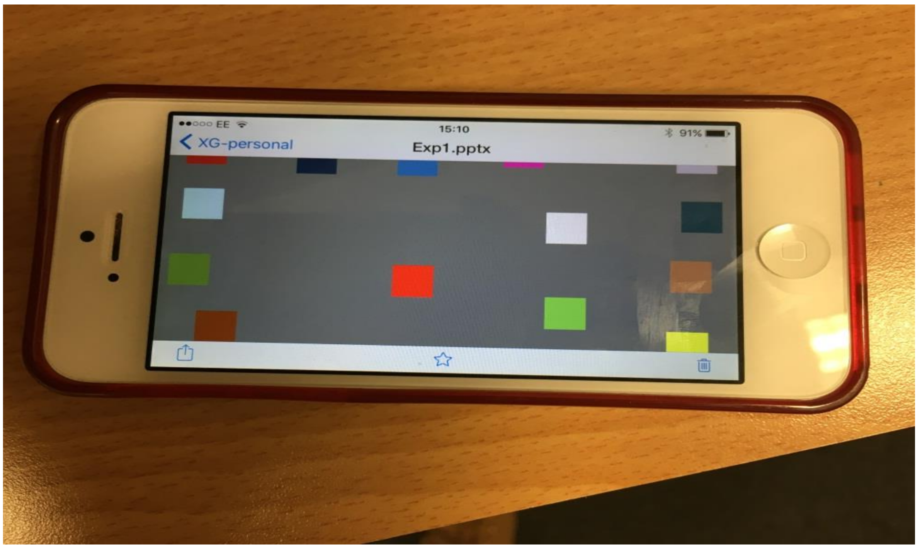


Figure 5.7: Sample test on mobile phone screen. [61]

5.1.3 Setup on a Smartphone

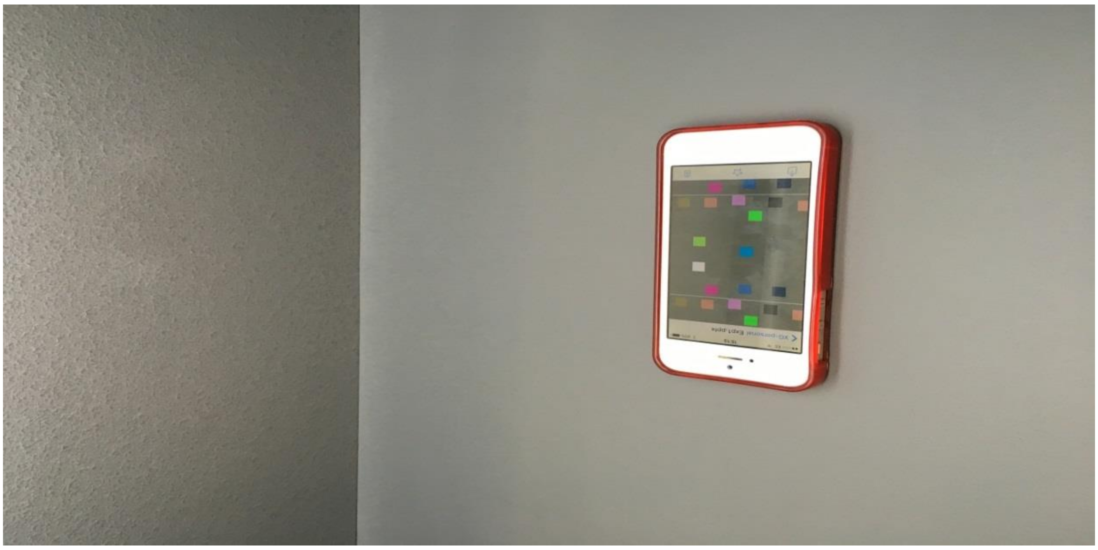
Test samples were displayed on a mobile telephone. The colour gamut is similar to RGB as shown in the CIE 1931 xy chromaticity diagram. A Minolta CS-1000 telespectro radiometer was used for measurement.

The CIECAM02 model is the colour appearance model recommended by CIE. The model's performance is evaluated using the present experimental data in terms of CV calculated between the model's predicted and visual results.

5.1.4 Apparatus

Colours appear differently under different lighting sources. To avoid and reduce the assessment error, a colour **viewing cabinet** is used to simulate different light sources to obtain an objective assessment of colour and colour difference under controlled viewing environments, as illustrated in below Figure 5.8 (a) and (b).

(a)



(b)

Figure 5.8 (a,b): Mobile telephone under viewing cabinet position. [62]

Figure 5.9 below shows the mobile telephone experimental procedure which was carried out by 10 subjects under viewing cabinet conditions and demonstrate the subject position and the environmental situation during the experiment.

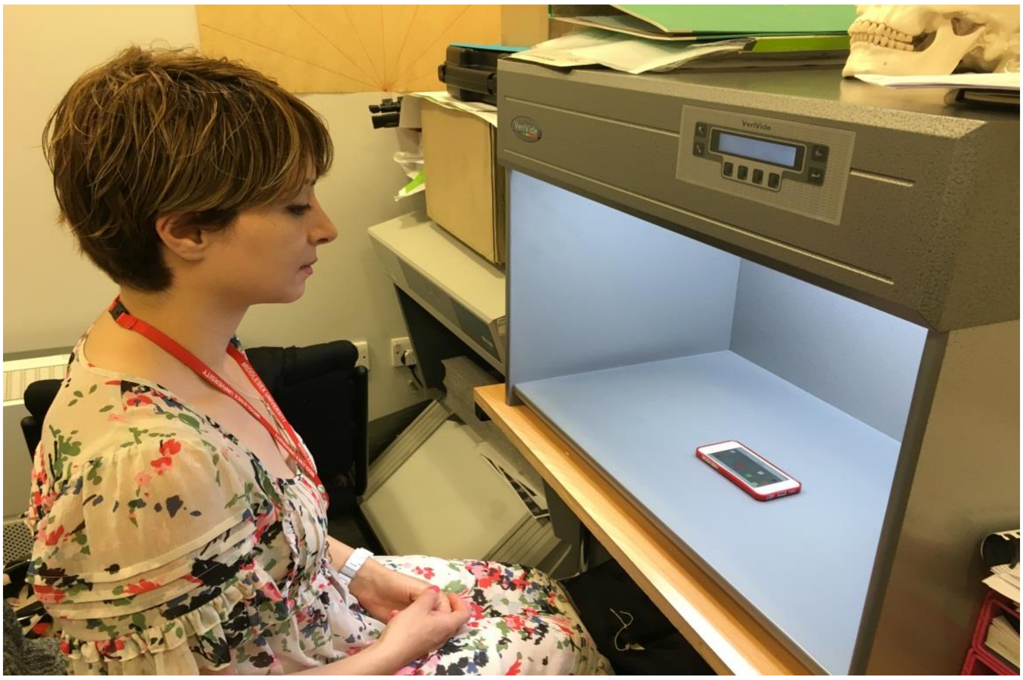


Figure 5.9: Subject's viewing position. [63]

The telephones and CRT were calibrated and measured before starting the experiment. A **Minolta Chroma Meter CS-100A**, as shown in Figure 5.10, was employed to measure each colour in terms of CIE tri-stimulus values, i.e. x, y, Y and was in the position of the observers' view.

Figure 5.10: Colour meter, CA-100A. [64]

In addition, each colour on each phone has been measured using a colour meter CS-100A, simulating the subjects' viewing position. In particular, the reference white, reference colourfulness, and background were measured at least 3 times, e.g. at the beginning, the middle and the end of the colour sample sequence, to check the repeatability of the telephone. In total, 6 iPhone 5s, 1 Huawei, 1 Samsung, 1 LG Nexus4, are measured and estimated. The same work is also performed on the CRT monitor, Philips Brilliance 201B.

5.2 Comparison of Experimental Data

In Phase 2, the experimental setting is the same as Experiment 1 in Phase 1 in terms of measurement using the CS-100A colour meter on a series of colour samples displayed on each telephone. Encouragingly, the variations among the same kind of telephone are not significant with less than 3 ΔE CIELAB units when measuring reference white and background of a test pattern. Figure 5.3 demonstrates the comparison results between 2 iPhones using CIELUV L*C* as formulated by Eq. (2.6) since CIELAB is mainly used for the calculation of colour differences.

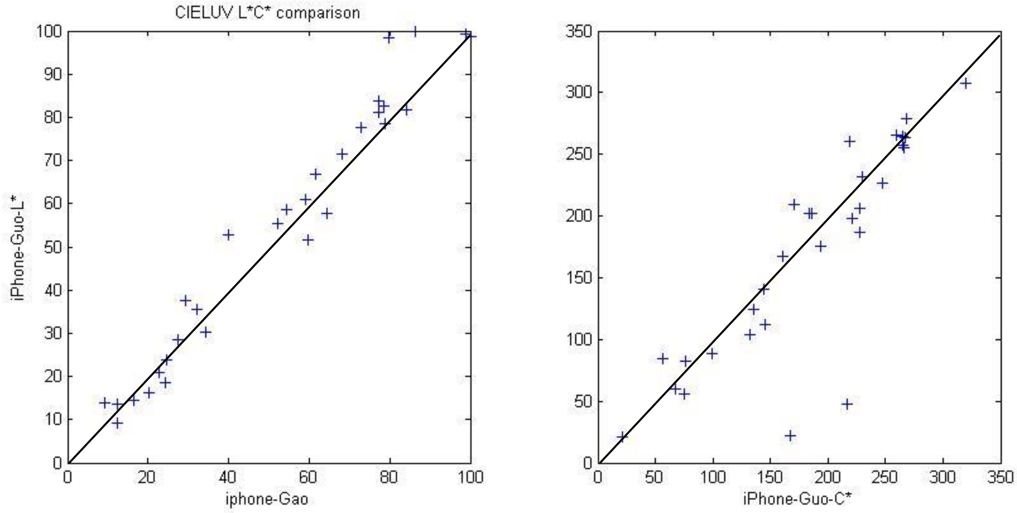


Figure 5.11: The comparison results between 2 iPhones using CIELUV L* and C*. [65]

It can be seen from Figure 5.11 that all the data points are located around the central line for both L* and C*, suggesting that the 2 iPhones have similar colour attributes.

Figure 5.12 compares the measurement of each telephone (i.e. xyY values using Colour Meter CA-100) represented using CIELUV L*C* with the measurement of the CRT applied in Phase 1.

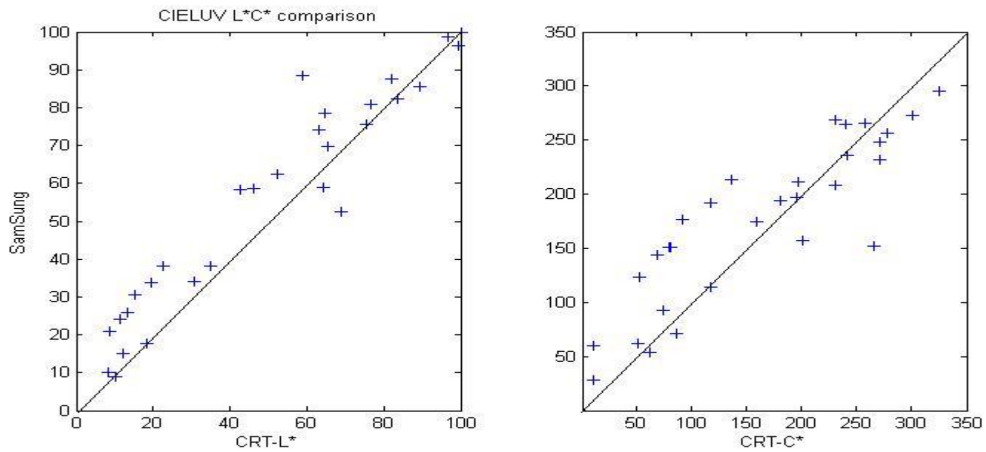


Figure 5.12: The comparison of CIELUV L* and C* between the SamSung phone and CRT. [66]

Figure 5.12 shows that the L* of the SamSung is larger than that of the CRT monitor. For C*, the less colourful colours have bigger C* and more colourful colours have less C* on the SamSung telephone. Similar results can also been found in Figure 5.13 where 2 mobile iPhones are compared with the CRT monitor.

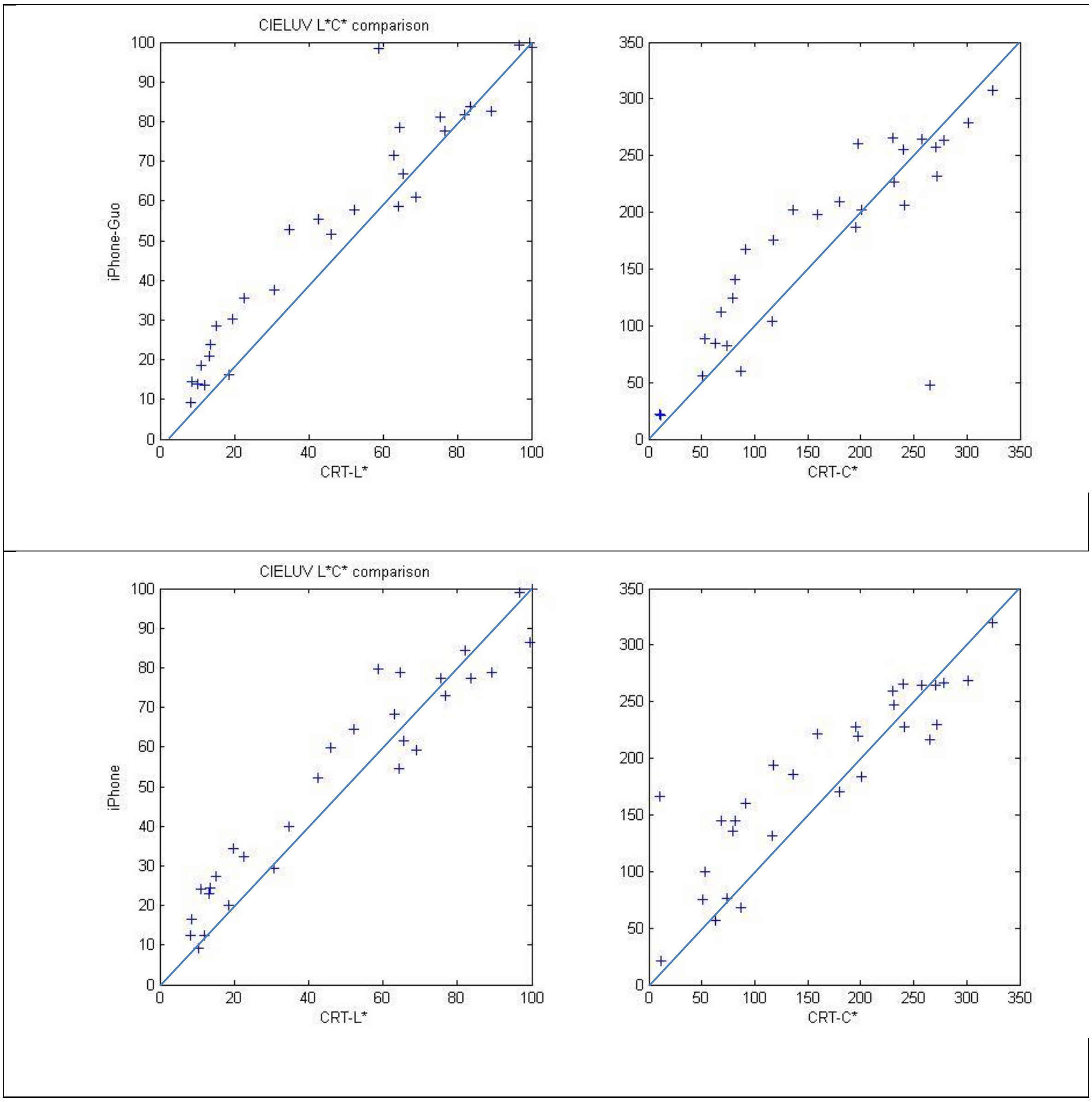


Figure 5.13: The comparison of CIELUV L* and C* between 2 iPhones and CRT. [67]

Figure 5.13 reiterates the effect that is found in Figure 5.4, i.e. the L* is larger for both iPhones than the L* for the CRT. Also for most colours, the C* is larger for iPhones than for the CRT, suggesting colours on mobile telephones might appear lighter and more colourful than on CRTs.

In addition, Figure 5.14 exemplifies the estimation results by subjects between the CRT and an iPhone.

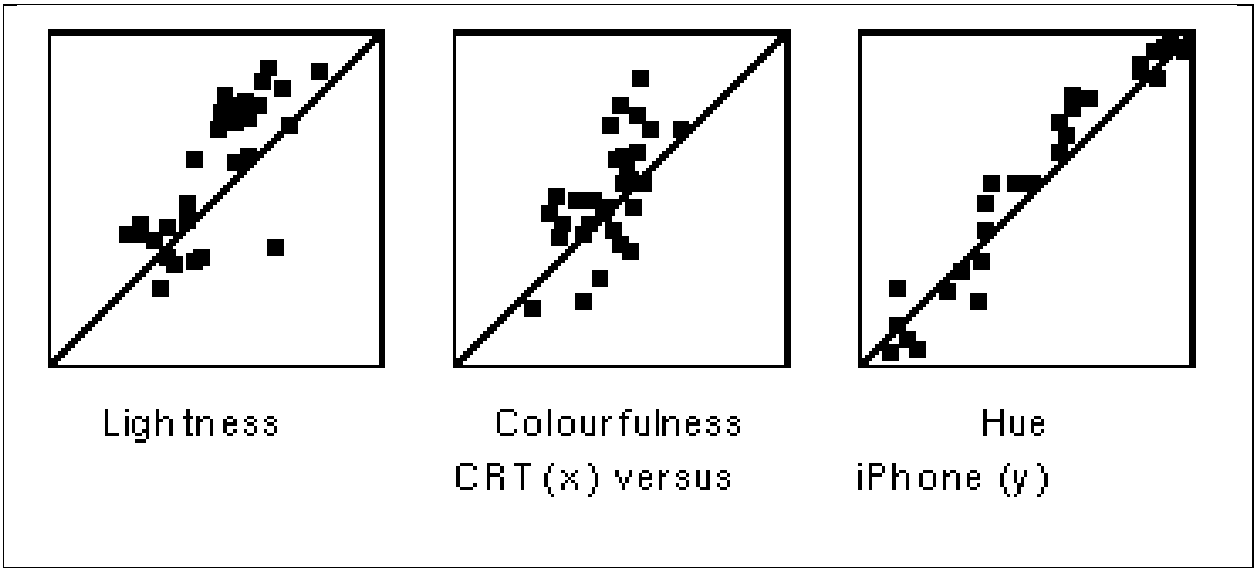


Figure 5.14: Comparison of the estimation results by subjects between CRT (x-axis) and iPhones 1 studied in this research. [68]

The above figure illustrates the colours on the iPhone appear lighter and slightly more colorful than on CRT monitors.

For lightness, the estimation on a mobile iPhone tends to be 16% more than that on CRT monitors, whereas an 11% increase of colourfulness for mobile telephones is evidenced. In Figure 5.15, a hue-colourfulness plot is presented, where small circles (o) represent the colours from the CRT and big squares (□) from an iPhone 5.

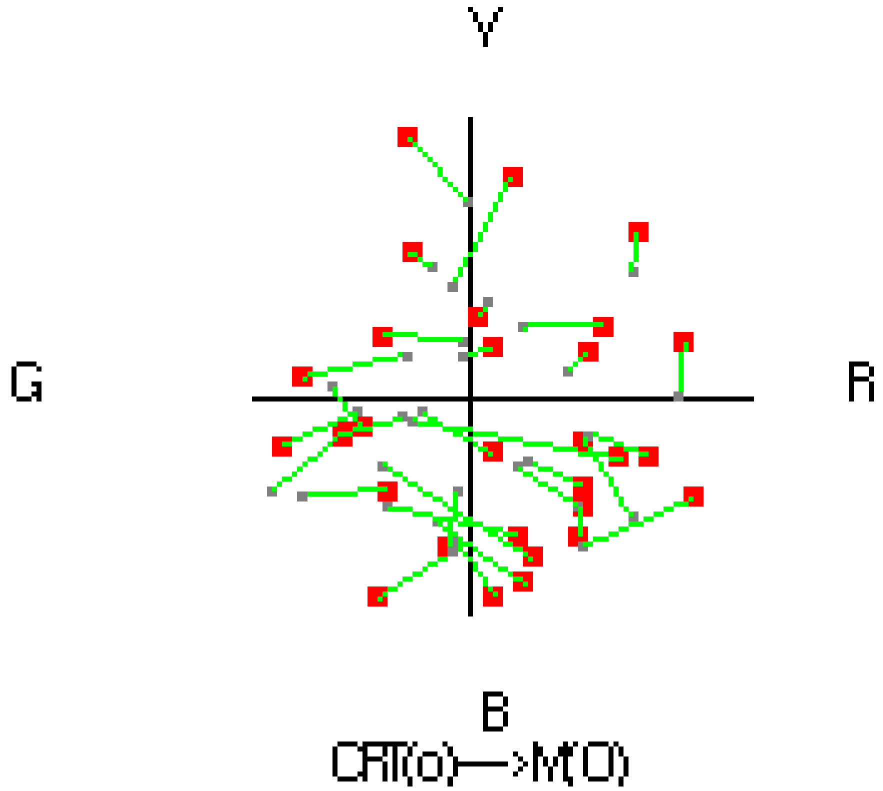


Figure 5.15: Subjects' estimation for the same group of colours on both CRT and iPhone5. A small circle (o) refers to the estimation for the CRT whereas big solid square (■) on iPhone. [69]

With regard to hue estimations, although the correlation for Hue remains the highest (i.e. r = 0.96) between the iPhone and CRT, i.e. greenish colours appear to be greener and blue colours bluer as shown in Figure 5.15. All colours tended to be more colourful while depicted on the telephone. Figure 5.16 demonstrates visually the differences between the iPhone (top) and the CRT (bottom) when a colour checker image is displayed.

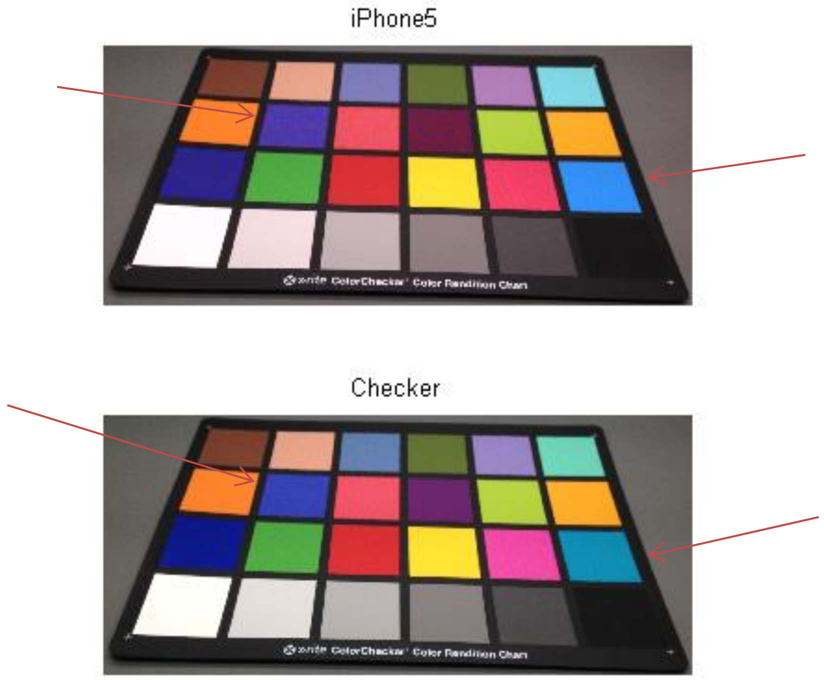


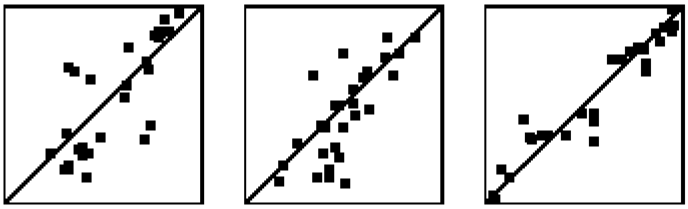
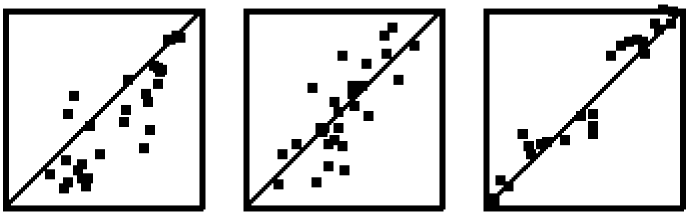
Figure 5.16: Colour checker appears on both CRT (bottom) and iPhone 5 (top). [70]

As pointed by arrows, the blueish colours appear differently when displayed on different media.

6. Modelling of iPhone Appearance using CIECAM02

Since the colour appearance model CIECAM02 was developed for the medium of a CRT, which features refection and transparency, it is not well equipped to predict smartphones. After setting the environmental parameters to 'dim' conditions where F = 0.9, c = 0.59, and Nc = 0.90 to compensate for lightness differences between a CRT and iPhone, the comparison results are given in Figure 6.1 for the three iPhones, where colourfulness was adjusted according to Eq. (6.1).

$$\text{Colourfulness\_smartphone} = 1.8 * \text{Colourfulness\_CIECAM02} \qquad (6.1)$$

Phone	The Experiments
1	 Lightness Colourfulness Hue Subjects' Estimation r = 0.81 r = 0.72 r = 0.95
2	 Lightness Colourfulness Hue CIECAM02 (y) vs Subject r = 0.85 r = 0.73 r = 0.97

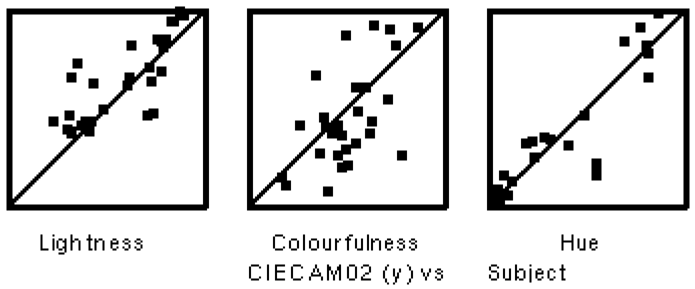
3	 r = 0.80 r = 0.59 r = 0.88

Figure 6.1: Comparison of CIECAM02 predictions with subject's estimations. [68]

After correction using Eq. (6.1), the modified CIECAM02 can predict smartphones accurately, which appear to be satisfactory.

6.1 iPhone data analysis

The data analysis and comparison of iPhone experiments was carried out to understand the colour reproduction consistency between them by adding three more iPhones to this stage of the study and also investigating iPhone colour reproduction consistency mainly focused on cyan colours, with setting up 10 more new samples to the experiment. Referring to the first step of the iPhone colour experiment, there was a scattering of hue points mainly in the cyan colour which was worth more investigation. Following further experimentation, no significant change was recorded therefore the reason of scattering in the hue chart remains inconclusive and so must be put down to a subject reading error or recording error .

iPhone Lightness graphs

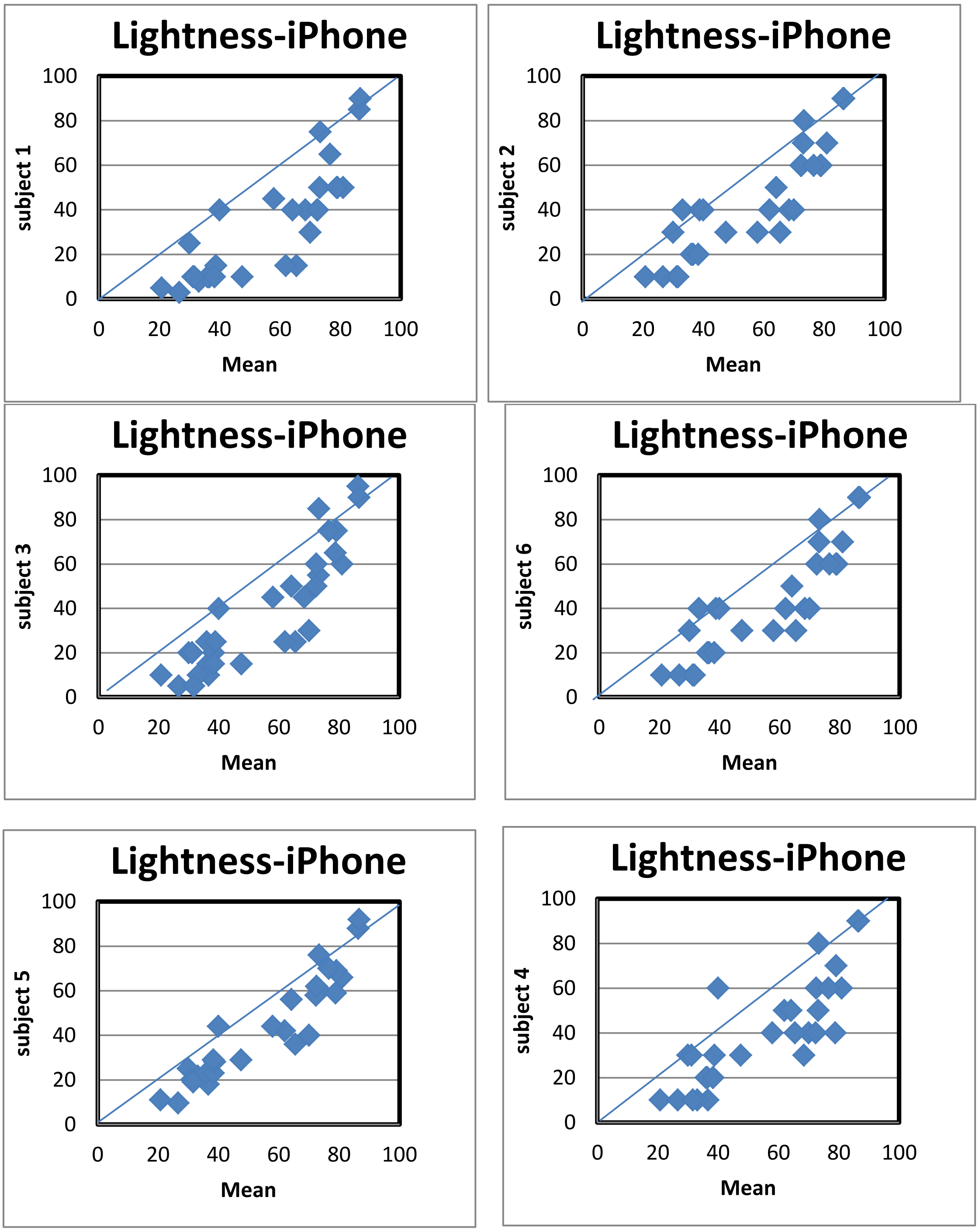


Figure 6.2: The prediction of iPhone lightness. [72]

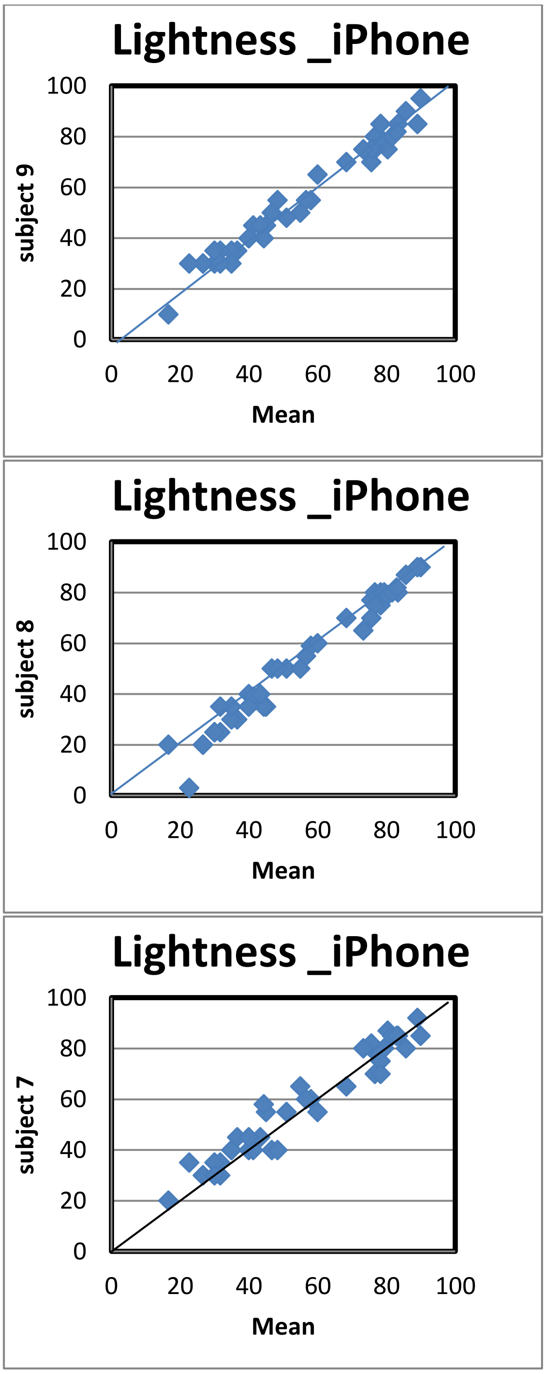


Figure 6.3: iPhone lightness prediction for cyan samples. [73]

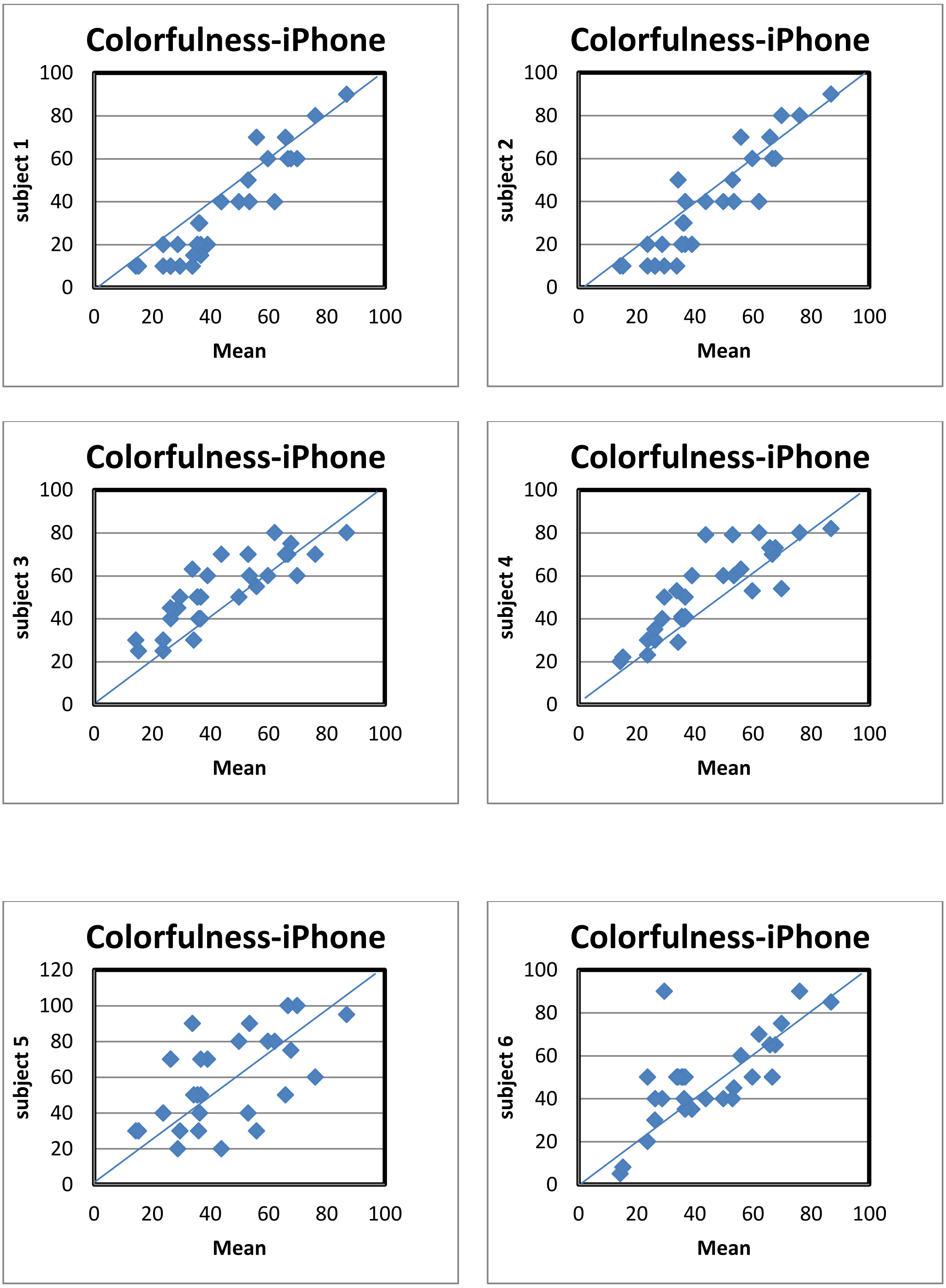


Figure 6.4: The prediction of iPhone colourfulness. [74]

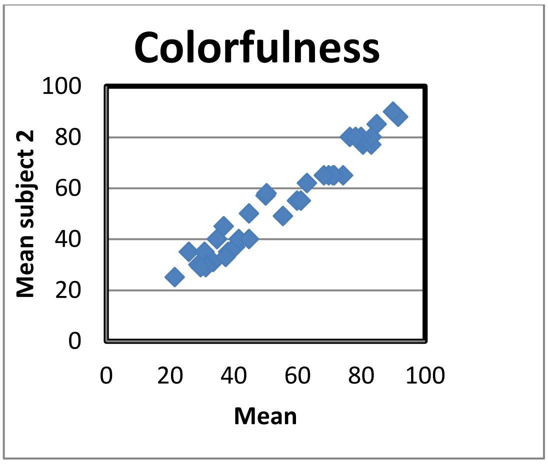


Figure 6.5: iPhone colourfulness prediction for cyan samples. [75]

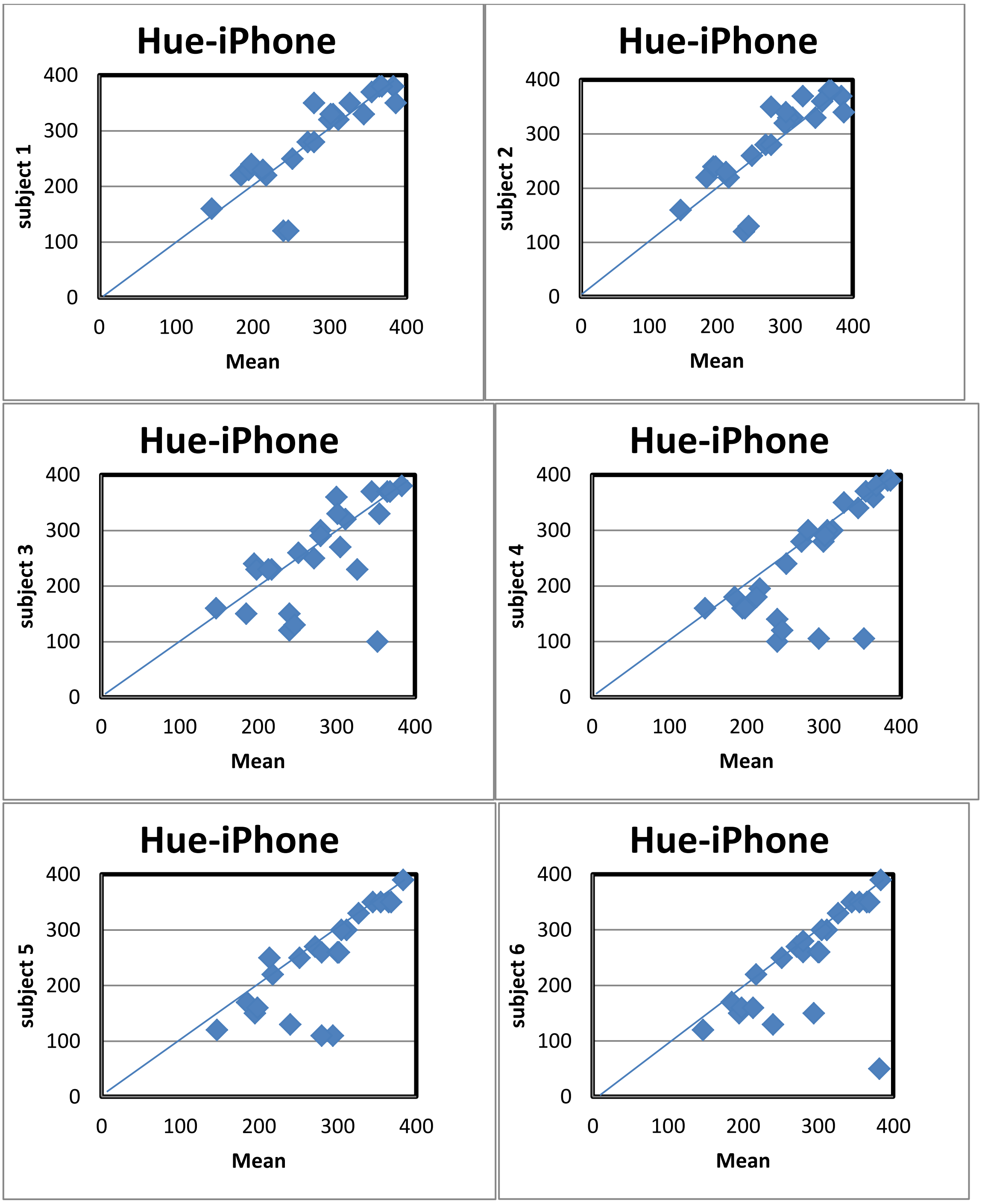
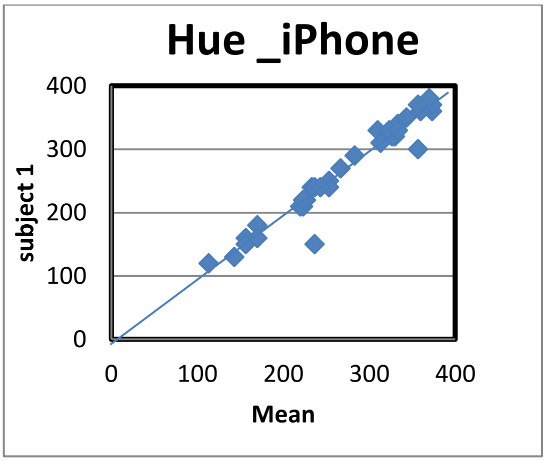
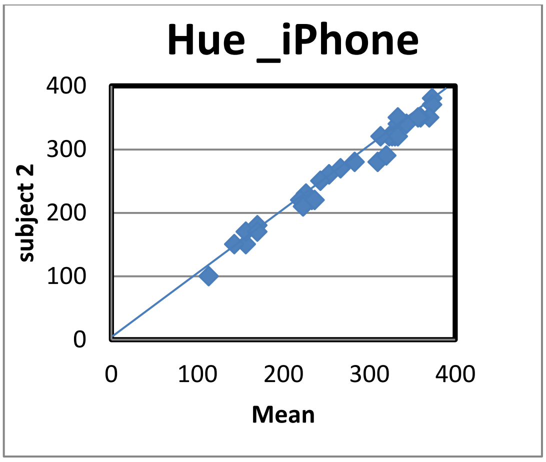


Figure 6.6: The prediction of iPhone hue. [76]





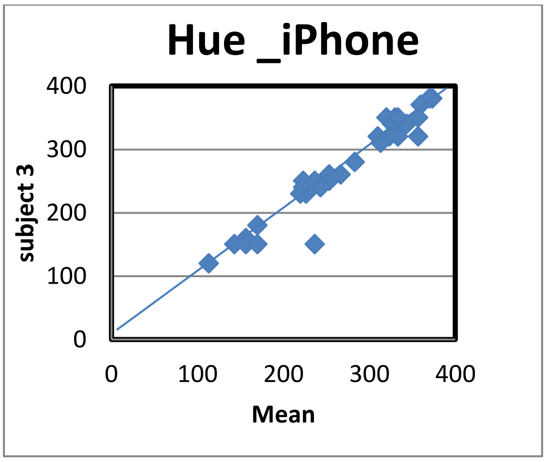
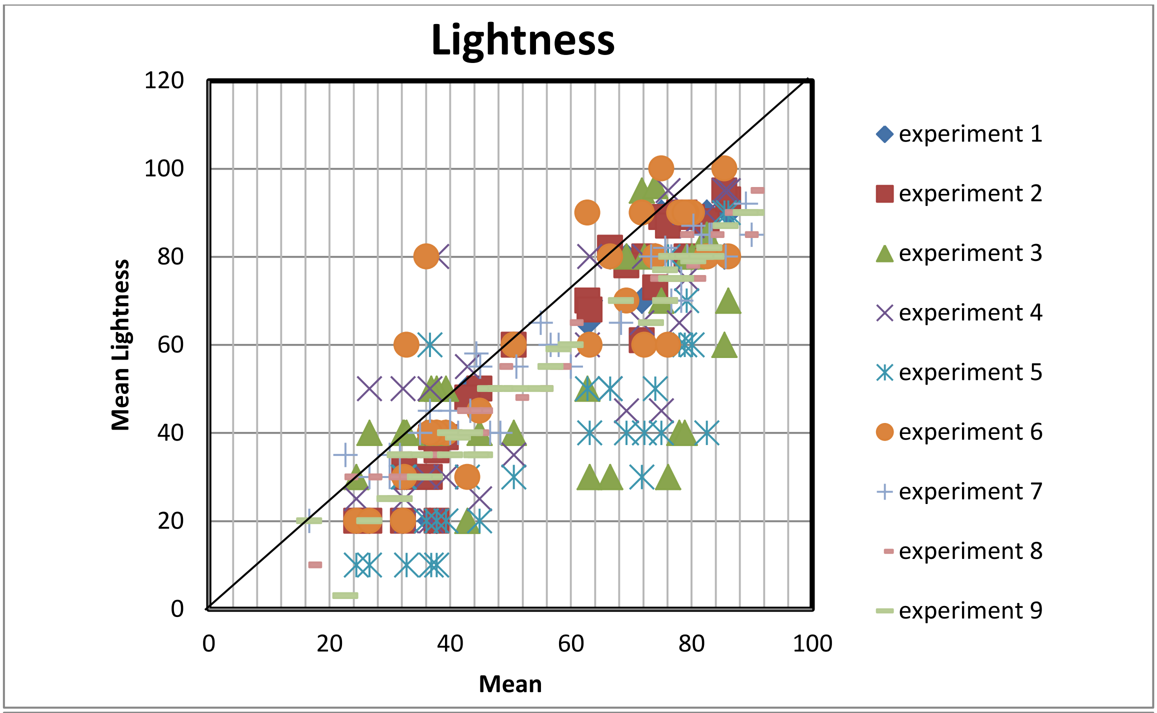
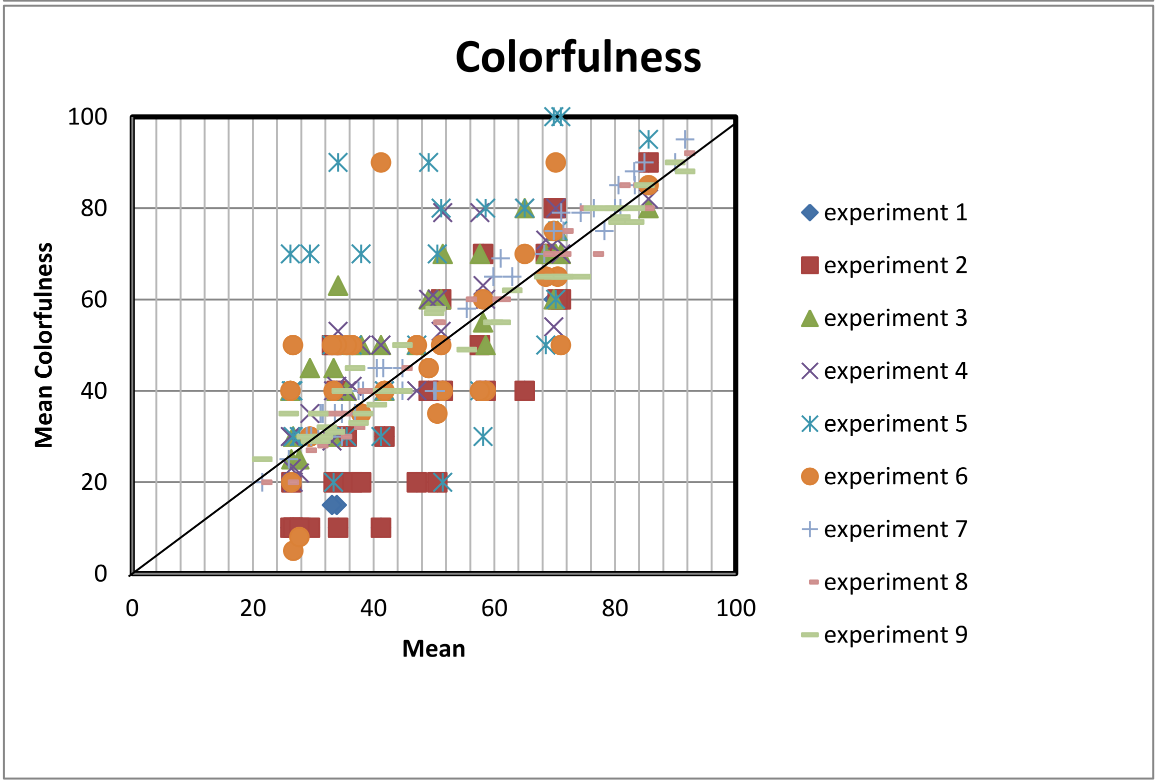


Figure 6.7: iPhone hue prediction for cyan samples. [77]

Experiments 1 to 9 are performed on colour samples by iPhone as illustrated in Figure 6.8 below, with a graphical comparison of the variability between the sets of samples in terms of the three attributes through comparison between Experiment 1 (x-axis) and the other 8 experiments.





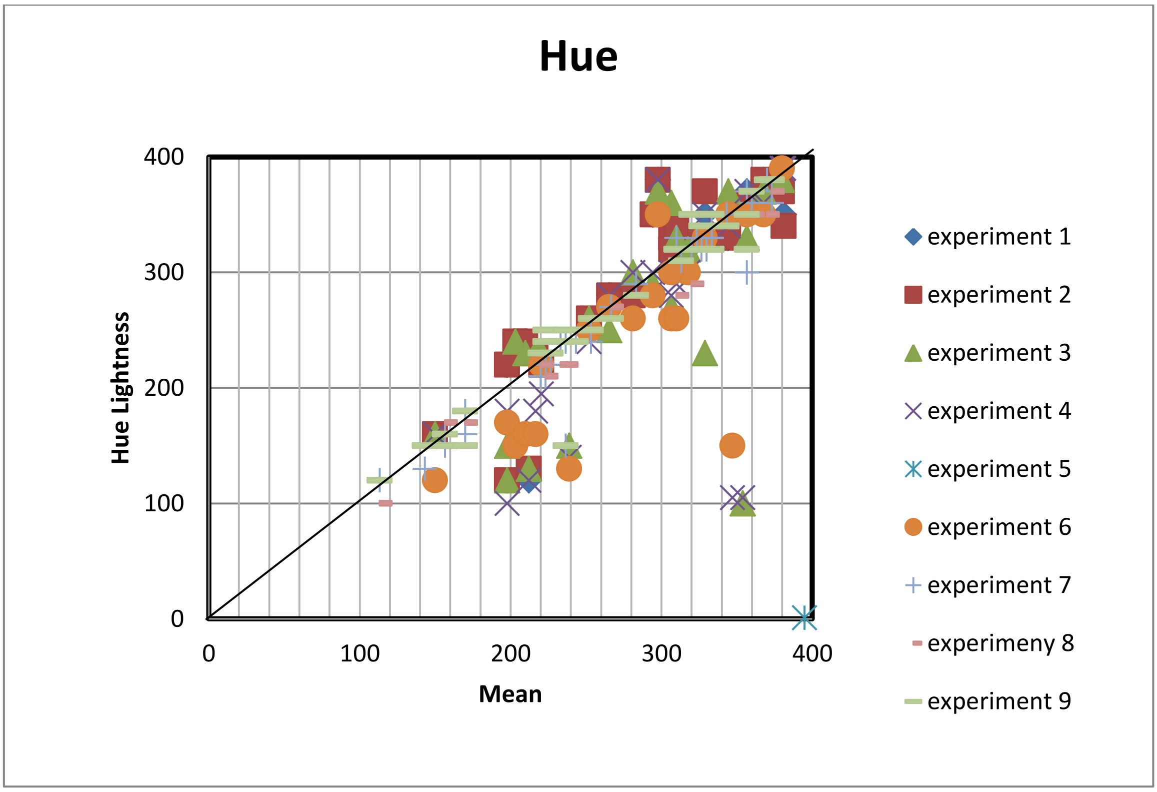


Figure 6.8: Comparison results between mean estimations of lightness (top), colourfulness (middle) and hue (bottom) for iPhone Experiment 1 (x-axis) and Experiments 2-9 (y-axis). [78]

7. Results and Discussions

7.1 Testing CIECAM02

The CIECAM02 model is the colour appearance model recommended by CIE. The model's performance is evaluated using the present experimental data in terms of CV calculated between the model's predicted and visual results.

The results shows that the model gave a reasonable prediction for *the brightness and hue visual results, but performed poorly for predicting colourfulness visual results, i.e.* the correlation coefficient (r) for CIELUV L* are 0.963, 0.959, 0.960, and 0.940 for the iPhone, LG Nexus4, HuaWei and SamSung respectively, and are 0.890, 0.876, 0.761, and 0.764 respectively for CIELUV C* when comparing with the counterparts on the CRT monitor.

To predict a colour on a mobile telephone using CIECAM02, the predictions rest on a number of environmental parameters settings, e.g., f = 0.9, c = 0.59, and nc = 0.90, which gives closer results with less scattering.

Figure 5.6 presented a plot of a hue-colourfulness with regard to hue estimations, although the correlation for hue remains the highest (i.e. r = 0.96) between the iPhone and CRT, i.e. greenish colours appear to be greener and blue colours bluer as shown in Figure 5.15. All colours tended to be more colourful when depicted on the phone.

Figure 5.16 shows the plots for lightness, colourfulness and hue visual results against the corresponding CIECAM02 predictions, respectively.

Figure 6.1 shows that by modifying CIECAM02, we can predict smartphone colours accurately, which appear to be satisfactory when viewed.

Figure 8.1 shows a comparison of the iPhone (x-axis) with mobile telephones form LG-Nexus4 (top), Samsung (middle) and Huawei (bottom) by modified CIECAM02. When comparing with the other smartphones, in terms of hue, all three types of phones tend to be more reddish for purplish colours than those displayed on an iPhone, whereas the rest remains nearly the same. With regard to lightness, for lighter colours, all three telephones unanimously appear darker than on iPhones with the LG-Nexus being the darkest, 25% darker, whereas 18% and 16% darker are evidenced for Huawei and Samsung respectively. However, the opposite phenomenon occurs when it comes to the representation of colourfulness. The images on all three telephones, the LG-Nexus4, Samsung, and Huawei, appear more colourful than those displayed on an iPhone. [Park, 2006].

7.2 Refinement of CIECAM02

In the last section, it was found that the performance of CIECAM02 is not completely satisfactory, i.e. the results in terms of CV in predicting current results are much better than those in predicting smartphones data. Hence, new trials were made to try to improve the model's performance for predicting visual data. The general strategy was to add 10 more samples to the whole experiment and use 3 more iPhones in order to repeat the experiment and mainly focus on 10 new sample slides which had been carefully chosen from cyan and blueish colours as by analysing the results, in the iPhone there is a slight confusion around cyan colour. Comparison between the new set of samples and the old samples has also been taken into account in order to have a better and clearer understanding of the issues so far.

Table 7.1 below summarises the values for the iPhone based on experimental data obtained from subject's readings.

Table 7.1: Values for iPhone Experiment. [10]

Subject	Lightness			Colourfulness			Hue		
	r	a	b	r	a	b	r	a	b
A	0.84	1.00	-23.5	0.94	1.21	-18.7	0.75	0.97	30
B	0.88	1.00	-13.95	0.92	1.21	-16.6	0.74	0.94	39.3
C	0.88	1.14	-24.3	0.84	0.73	20.3	0.72	1.01	-10.7
D	0.82	0.93	-11.6	0.85	0.88	12.65	0.8	1.1	-8.1
E	0.93	1.04	-14.25	0.57	0.75	24.35	0.66	1.03	-9.1
F	0.88	1.00	-13.95	0.71	0.77	14.64	0.55	0.86	30.5
Mean	0.87	1.01	-13	0.80	0.92	12.34	0.70	0.98	11.9

As shown in Table 7.1, each estimate by the subject is measured using three values, a, b and r (correlation coefficient).

8. Modelling of iPhone appearance using CIECAM02

Since the colour appearance model CIECAM02 was developed for the medium of a CRT, which features refection and transparency, it is not well equipped to predict smartphones. After setting the environmental parameters to ‘dim’ conditions where F = 0.9, c = 0.59, and Nc = 0.90 to compensate for lightness differences between a CRT and iPhone, the comparison results are given in Figure 6.1.

The general strategy was to modify the CIECAM02 model as little as possible. The modification was made for the three iPhones, where colourfulness was adjusted according to equation below:

$$\text{Colourfulness\_smartphone} = 1.8 * \text{Colourfulness\_CIECAM02}$$

The new equations were used to replace the fixed parameters used by CIECAM02 for the iPhone experiment. Its predictions and visual results are plotted in Figures 6.1 for lightness, colourfulness and hue results respectively. After correction using the equation above, the modified CIECAM02 can predict smartphones accurately.

Figure 6.1 shows that there is a good prediction by the refined CIECAM02. It can be seen clearly in Figures 6.1 that the largest improvement can be found in colourfulness, followed by lightness and hue the smallest.

8.1 Comparison with other smartphones

After the modelling of an iPhone using CIECAM02, a number of other smartphones can be evaluated as well in terms of colour appearance, including a LG-Nexus4, Samsung, and Huawei.

Figure 8.1 presents the comparison results from the calculations using CIECAM02 for all the telephones when the settings are given as F = 0.9, c = 0.59, and Nc = 0.90 and the colourfulness applies Eq. (8.1).

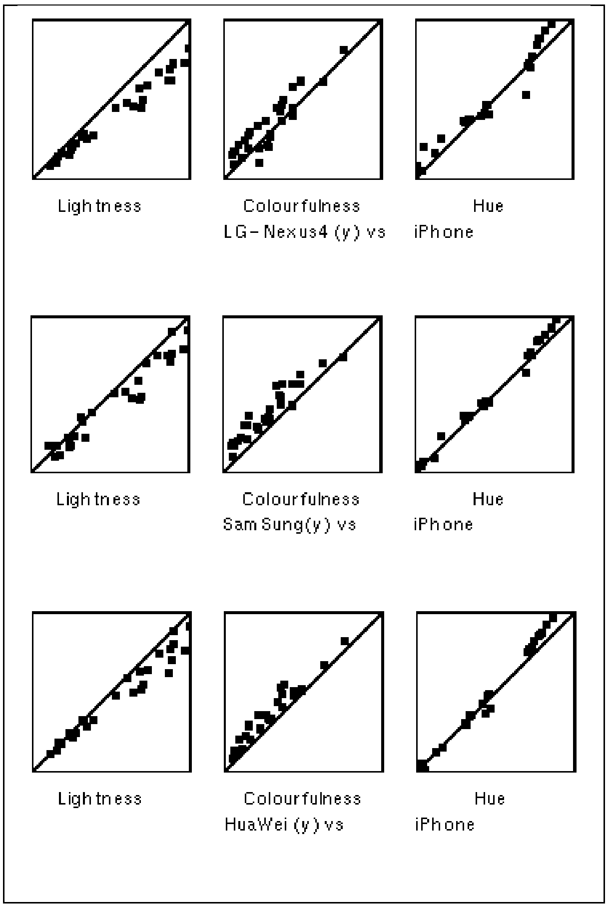


Figure 8.1: Comparison of iPhone (x-axis) with phones of LG-Nexus4 (top), Samsung (middle) and Huawei (bottom) by modified CIECAM02. [80]

When comparing with the other smartphones, in terms of hue, all three types of telephone tend to be more reddish for purplish colours than those displayed on an iPhone, whereas the rest maintains near the same. With regard to lightness, for lighter colours, all three telephones unanimously appear darker than on iPhones with the LG-Nexus being the darkest, 25% darker, whereas 18% and 16% darker are evidenced for HuaWei and SamSung respectively. However, the opposite phenomenon occurs when it comes to the representation of colourfulness. The images on all three telephones, the LG-Nexus4, SamSung, and HuaWei, appear more colourful than those displayed on an iPhone. For example, the colours on a LG-Nexus4 telephone appear systemically 10% more colourful than those depicted on an iPhone. In addition, for both the HuaWei and SamSung phones, they appear again to be 17% and 22% more colourful, especially for colourful samples, the tendency presenting across all three telephones. Since these findings are based on only one telephone of each type, future study is needed to focus on the investigation of large samples with more similar phones.

Figure 8.2 demonstrates the colour check images that are displayed on each mobile telephone together with one from a CRT. As indicated by arrows, the purple colour appears to be slightly different on different telephones.

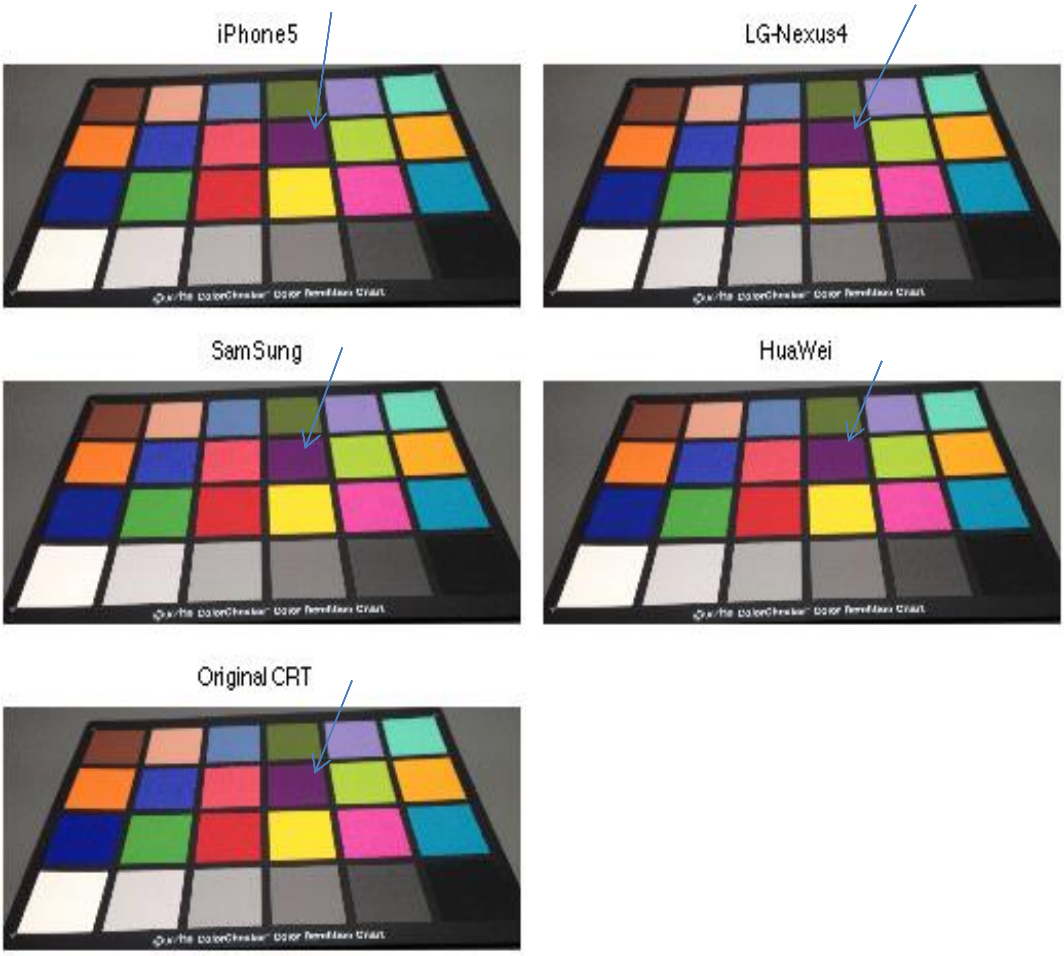


Figure 8.2: Colour checker depicted using four phones and a CRT. [81]

9. Summary of Phase 2

With 85% of smartphone users performing their everyday tasks using the device due to its ability and connectivity, the smartphone continues to revolutionize how people perform their everyday activities. It is expected that this work will contribute to this revolution and complement users with some information when they perform online shopping buying colour sensitive goods.

In summary, in terms of the measurement on each mobile telephone, encouragingly, the variations among the same kind of phones are insignificant, being less than 3 ∆E CIELAB units.

In addition, when comparing with subjects' hue estimations, all phones and the CRT monitor appear to have similar hue values, indicating that the hue values have been well preserved on those phones although some variations are observed. However, when it is viewed on a mobile telephone, a colour appears to show a variance with colourfulness by appearing much more colourful. Furthermore, the correlation coefficients (r) for CIELUV L* are 0.963, 0.959, 0.960, and 0.940 for the iPhone, LG Nexus4, HuaWei and SamSung respectively, and are 0.890, 0.876, 0.761, and 0.764 respectively for CIELUV C* when comparing with the counterparts on the CRT monitor. Therefore, the iPhone tends to be the best with fewer scatterings. To predict a colour on a mobile telephone using CIECAM02, the predictions rest on a number of environmental parameter settings, e.g. f = 0.9, c = 0.59, and nc = 0.90, which gives closer results with less scattering. Consequently, for an image with truthful colour to be displayed on a mobile phone, the forward and reverse model of

CIECAM02 will have to be applied. Specifically, for the iPhone 5, nearly half of the colourfulness predicted by CIECAM02 needs to be factored in. Further studies are in place to take a bigger number of mobile telephones into consideration.

10. Conclusion and future work

The colour appearance model CIECAM02 was standardised in 2002 and has since been widely applied to predict colour appearance under varying viewing environments. However, it does not cover mobile devices that have become available and popular in the last decade or so. To fill the gap, this research aimed to ensure the CIECAM02 model can predict colours on mobile telephones. Also, the study of textured colours was carried out in order to fill another gap that CIECAM02 is missing.

For texture colours, liner modification appears to be adequate since textured colours appear to be darker and more colourful. However, only 5 texture patterns are studied in this research, more experiments should be designed in the future to further understand the effect of texture on human perception.

10.1 Measuring the Impact of Texture to Colour Appearance model using CIECAM02

Research into colour measurement using a calibrated colour imaging systems is investigated by measuring and analysing the effect of texture on colour appearance. The analysis is based on measured colour and the CIE co-ordinate colour definitions of coloured image phenomena. Colour phenomena are used to define the variation in colour appearance of different textures introduced in this study.

The study is designed to establish as separate variables of colour appearance, a model of colorant formulations, and a model of the colour appearance of that formulation when applied to a given texture. The CIECAM02 model was validated using a visual simulation of colour appearance on a computer screen that has been calibrated so that each colour phenomena could be controlled and reproduced to within an average D65 CIE 10 degree Observer colour difference.

Colour textured samples with a range of 6 different textures have been used in all the experiments in this research. They focus on shapes such as dots, lines and crosses, etc. The measuring and analysing properties of Tristimulus values leads to the modelling of the relationship between variations in colour appearance due to texture, and the fundamental colour represented by a colorant formulation. The study looks to establish computational relationships between colour and texture as distinct contributing variables of colour appearance.

The results of visual matching experiments (Experimental 2-6) are the basis for colour modelling, and have been used to define the psychophysical attributes of the human sensation of colour, such as lightness, colourfulness and the hue of the colour as well as the modification of the colour model by using texture and comparing the interaction of it in the colour model. Both the colorimetric accuracy of the data derived from images, and the accuracy of the matching process itself is assessed.

Surface texture effects are responsible for significant visual colour shifts as is shown in the results. The variability of such observer trials requires output to be generated from multiple observations (See Results tables 1 & 2), and it is important for the results of on-screen matching experiments to be subjected to statistical analysis for significance. In the following discussion, some results are reported for the effects of texture on colour appearance. In a separate series of experiments [2-6], multiple observations were carried out in a variety of matching tasks, ranging from the simple texture such as dots and line to more complex texture in the samples under viewing cabinet conditions. Full details and the calculation are reported separately in the appendix, and the results are summarized here for reference.

From Table 4.2, the reasonable mean values can be seen. Experiment 4 and, to a lesser extent Experiment 6, were reported as ‘difficult to measure’ as they had a more complex texture present. By looking at the Mean and CV values of the experiments, the appearance of the texture will move more smoothly through colour-space. Table 4.2 indicates that the presence of texture in the simulation, has some effects on an observer’s measurements.

10.2 Analysis of more complex Texture effects

From Experiment 4 results it can be seen that the collected data are not consistent with other performed texture-related experiments. The complex texture is viewed and quantified as consistently less colourful in all 30 samples, compared to the other textured experiments. It viewed as more colourful than all cases and more colourful than Experiment 6 as shown in Figure 4.8 that represents the higher colourfulness reading.

As can be seen from Figure 4.8, the largest discrepancies occur on colourfulness estimations, in particular for Experiments 4 (Δ) and 6 (∗), which contain patterns of random lines and random dots as depicted in Figure 4.2, which could be explained on the basis that random patterns make colourfulness more difficult to estimate. Although Experiment 2 also contains patterns scattered around the colour sample, the texture pattern itself, i.e. X, is symmetrical. Otherwise, all the points in Figure 4.8 are slightly above the central line for the colourfulness estimation, suggesting that texture has some effect on colourfulness estimations and makes colours appear to be more colourful.

For lightness, the textured colours appear to be darker than the colours without textures, which indicates that the texture decreases the lightness contrast and makes colours appear darker. On the other hand, little effect is found for hue estimation, which is expected as the texture patterns are neutral colour, the same grey as the background. Therefore it is concluded in this study that texture that shares the same grey level with that in the background has little effect on hue estimation, makes a colour appear more colourful and darker, while under the D65 viewing condition on CRT monitors.

The primary application of phase 1 of this study was to calculate colour differences between two sets of experiments and study six different texture patterns under the same backgrounds. In the future it would be ideal to perform content-based image retrieval on a variety of patterns overlaid on various coloured backgrounds (e.g. a collection of wallpaper images http://www.moda.mdx.ac.uk/collections/wallpapers) as extensive investigation has been carried out in this study only on a grey background with simple textured pattern.

Phase 2 of this study introduces measures of colour appearance in smartphones based on visual matching methods. Colour based colorimetric analysis was facilitated in these experiments, by the availability of measuring the samples on the smartphone screen under controlled viewing conditions. Images have been classified according to the colour appearance descriptions which humans understand. In the future this will allow people to find coloured images more easily on devices. Overall, the metrics developed using in the CIECAM02 colour model, to mark-up images with colour appearance concepts, show positive results on smartphones and more strongly on iPhones.

In conclusion for mobile telephones, it appears that colours appear lighter and more colourful than on CRT monitors. However, only a limited number of mobile telephones were tested i.e. 6 iPhone5s and one Samsung, Huawei and LG Nexus, these conclusions might be limited. In the future, it is planned that more mobile telephones are to be studied to confirm the results achieved in this work. In particular, the iPhone5 seems to be prevalent, especially among those observers who helped doing the experiments.

The results from the proposed methods show that this is a contribution to bridging the semantic gap in the area of whole-scene colour appearance in smartphones as they now become a daily use machine in a wide range of procedures from watching a movie to purchasing items online.

Initial small-scale human observation tests have been carried out and extensive tests are planned for future developments such as using more complex sample texts with patterns. Subjective trials are important to determine quality of the algorithms and classifications. These colour appearance classifications can be integrated into a smartphone image browsing system which allows them to also be used to refine browsing. For example, in browsing certain collections, e.g. multi-coloured items such as a mug with bright and intense colours, or to search for some single colour chair or shoes. These descriptors can therefore help the searching process. Finally, in the future, it would be ideal to plan to use this modification, with the aim that the analysis will take into account the colour appearance more accurately in smartphones particularly in popular devices such as the iPhone.

Appendixes:

Appendix A: The calculation of CIECAM02

Appendix B: The comparison of each individual's estimations with the mean results for Experiment 1 in Phase 1.

Appendix C: The CV values of 7 subjects for performing six experiments in Phase 1.

Appendix A: The calculation of CIECAM02

1. Firstly, the measurement using a colour meter for luminance, reference white, background, test colour samples take place to obtain L_A, $L_{A\text{-}bg}$, and X, Y, Z values.
2. View conditions and notations where λ is a newly introduced factor in the CAMcc model for the calculation of simultaneous contrast.

Surround	F	C	Nc
Average	1.0	0.69	1.0
Dim	0.9	0.59	0.95
Dark	0.8	0.525	0.8
Luminous computer monitor	0.2	0.41	0.80
L_A	Luminance of reference white in cd/m^2		
$L_{A\text{-}bg}$	Luminance of background in cd/m^2		
Y_b	Y value for background ranging within [1,100].		
Y_w	Y value for reference white and close to 100.		
$k = \frac{1}{5L_A + 1}$			
$F_L = 0.2k^4(5L_A) + 0.1(1 - k^4)^2(5L_A)^{1/3}$			
$n = \frac{Y_b}{w}$			
$N_{bb} = N_{cb} = 0.725(\frac{1}{n})^{0.2}$			
$z = 1.48 + \sqrt{n}$			

3. Chromatic adaption

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{A.1}$$

$$M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & 0.1624 \\ 0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \tag{A.2}$$

$$D = F\left(1 - \frac{1}{3.6} e^{-(L_A+42)/92}\right) \tag{A.3}$$

$$R_c = R\left[D\frac{Y_w}{R_w} + 1 - D\right] \tag{A.4}$$

$$G_c = G\left[D\frac{Y_w}{G_w} + 1 - D\right] \tag{A.5}$$

$$B_c = B\left[D\frac{Y_w}{B_w} + 1 - D\right] \tag{A.6}$$

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_H M_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \tag{A.7}$$

$$M_{CAT02}^{-1} = \begin{bmatrix} 1.0961 & 0.2788 & 0.1827 \\ 0.4543 & 0.4735 & 0.0720 \\ 0.0009 & 0.0056 & 1.0153 \end{bmatrix} \tag{A.8}$$

$$M_H = \begin{bmatrix} 0.3897 & 0.6889 & 0.0786 \\ 0.2298 & 1.1834 & 0.0464 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix} \tag{A.9}$$

4. Non-linear Response Compression

$$R'_a = \frac{400\left(\frac{F_L R'}{100}\right)^{0.42}}{27.13 + \left(\frac{F_L R'}{100}\right)^{0.42}} + 0.1 \tag{A.10}$$

$$G'_a = \frac{400\left(\frac{F_L G'}{100}\right)^{0.42}}{27.13 + \left(\frac{F_L G'}{100}\right)^{0.42}} + 0.1 \tag{A.11}$$

$$B'_a = \frac{400\left(\frac{F_L B}{100}\right)^{0.42}}{27.13+\left(\frac{F_L B'}{100}\right)^{0.42}} + 0.1 \tag{A.12}$$

5. Perceptual attribute correlates

$$a = R'_a - \frac{12G'_a}{11} + \frac{B'_a}{11} \tag{A.13}$$

$$b = \frac{1}{9}(R'_a + G'_a - 2B'_a) \tag{A.14}$$

Hue angle:

$$h = tan^{-1}(\frac{b}{a}) \tag{A.15}$$

Eccentricity factor:

$$e_t = \left[\frac{12500}{13} N_c N_{cb}\right]\left[\cos\left(h\frac{\pi}{180} + 2\right) + 3.8\right] \tag{A.16}$$

$$t = \frac{50\left(a^2+b^2\right)^{\frac{1}{2}} 100 e_t\left(\frac{10}{13}\right) N_c N_{cb}}{R'_a + G'_a + \frac{21}{20} B'_a} \tag{A.17}$$

Hue response:

$$H = H_i + \frac{\frac{100(h-h_i)}{e_i}}{\frac{h-h_i}{e_i} + \frac{h_{i+1}-h}{e_{i+1}}} \tag{A.18}$$

where $h_i \leq h < h_{i+1}$ and if $h > h_5$, $h = h - 360$.

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0	100	200	300	400

Achromatic Response:

$$A = \left[2R'_a + G'_a + \left(\frac{1}{20}\right)B'_a - 0.305\right]N_{bb} \tag{A.19}$$

Lightness:

$$J = 100\left(\frac{A}{A_w}\right)^{cz} \tag{A.20}$$

where A_w is the A value for reference white.

Brightness:

$$Q = \frac{4}{c}\left(\frac{J}{100}\right)^{0.5}(A_w + 4)F_L^{0.25} \tag{A.21}$$

where A_w is the A value for reference white.

Chroma:

$$C = t^{0.9}\left(\frac{J}{100}\right)^{0.5}(1.64 - 0.29^{n})^{0.73} \tag{A.22}$$

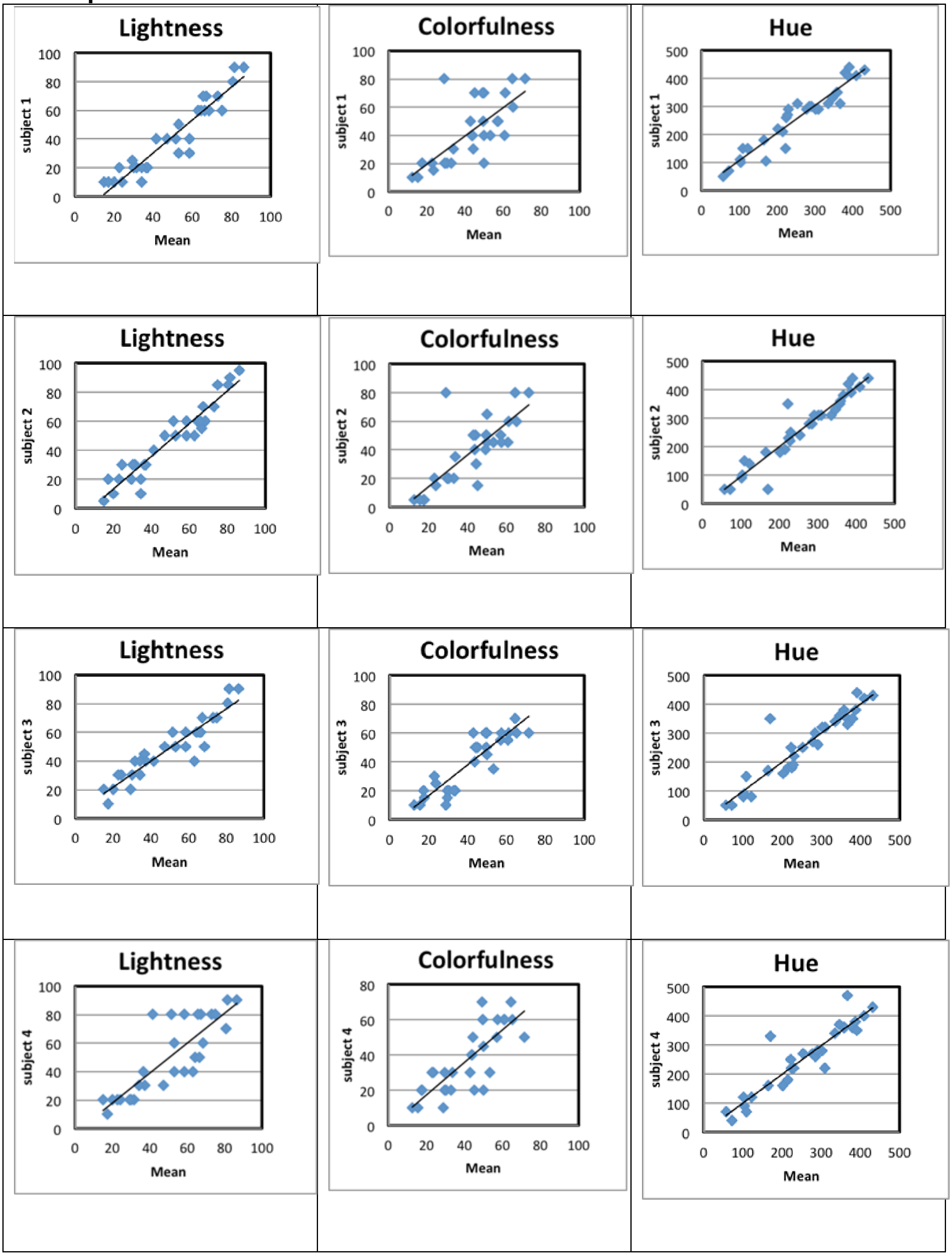
Colourfulness:

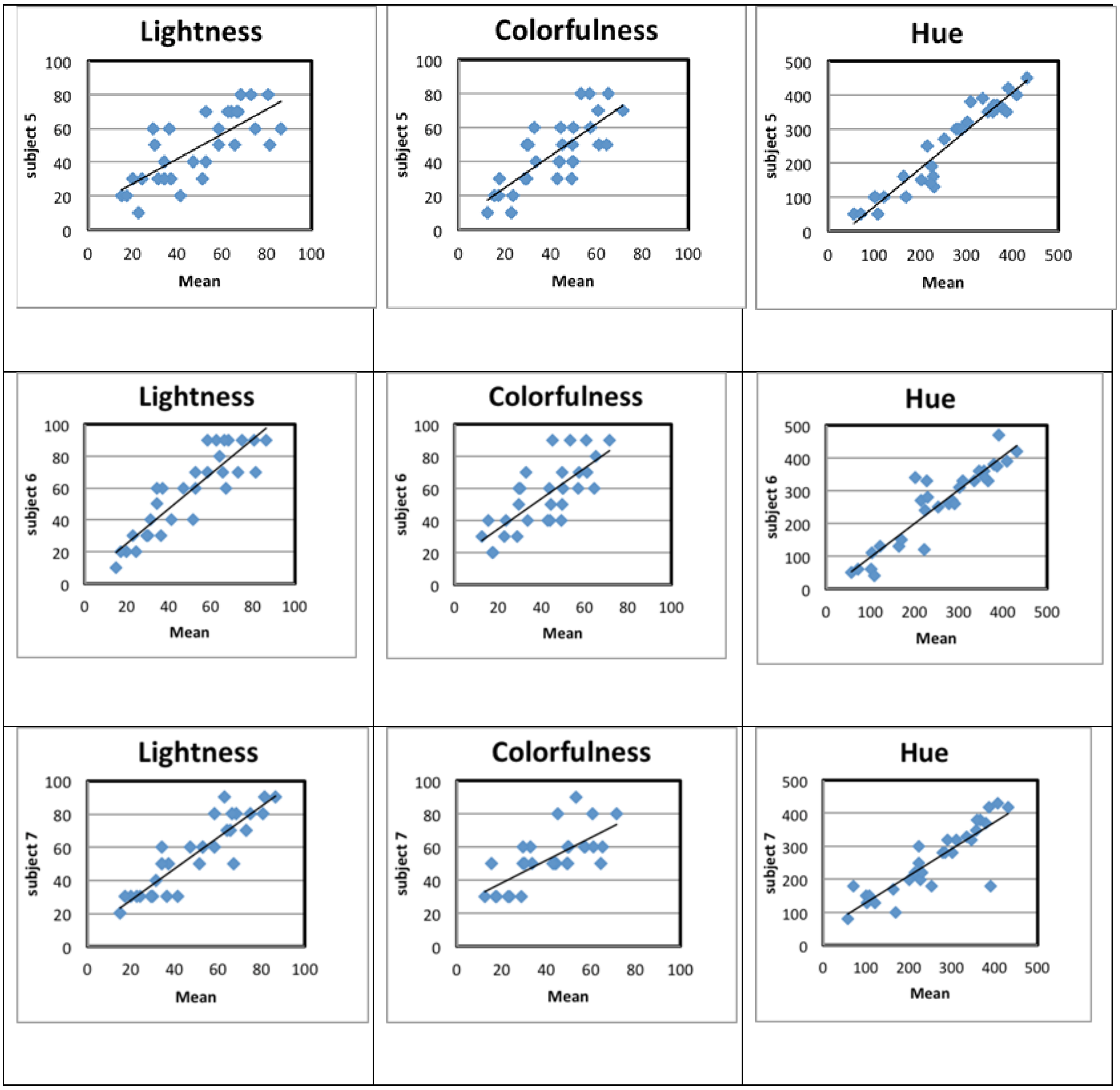
$$M = C{F_L}^{1/4} \tag{A.23}$$

Saturation:

$$s = 100\sqrt{\frac{M}{Q}} \tag{A.24}$$

Appendix B: The comparison of individual estimation with the mean results for Experiment 1 in Phase 1.




Lightness
subject 5
Mean
Colorfulness
subject 5
Mean
Hue
subject 5
Mean
Lightness
subject 6
Mean
Colorfulness
subject 6
Mean
Hue
subject 6
Mean
Lightness
subject 7
Mean
Colorfulness
subject 7
Mean
Hue
subject 7
Mean

Appendix C: The CV values of 7 subjects for performing six experiments in Phase 1.

Table C-1: The CV values of all seven subjects who performed Experiment 1 (Colour Sample).

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	a	b
A	20	0.88	1.05	-2.7	32	0.62	1.6	1.15	9	0.95	1.04	-17.7
B	17	0.87	0.76	11.8	26	0.44	0.54	18.23	11	0.94	1.06	-15.6
C	36	0.89	1.18	-21.9	26	0.61	0.789	4.05	13	0.92	1.08	15.67
D	**41**	0.89	1.14	-11.2	20	0.81	1.14	-6.72	9	0.96	0.95	12.92
E	29	0.62	0.58	29.78	20	0.64	1.06	7.94	14	0.93	1.02	-11.7
F	25	0.91	1.26	-3.21	16	0.64	0.76	6.83	**16**	0.95	1.07	-34.3
G	23	0.9	1.18	-10.3	**63**	0.60	0.779	25.66	9	0.95	1.06	2.3
Mean	**27**	**0.82**	1	0.003	**29**	**0.62**	0.902	12.72	**11**	**0.90**	1.466	0.01

Table C-2. CV values for Experiment 2 (Textured Colour Sample)

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	a	b
A	24	0.94	1.14	-15.4	29	0.72	1.00	-1.04	11	0.74	0.91	-4.74
B	17	0.95	1.13	-9.52	31	0.79	1.1	-7.65	11	0.81	1.05	-24.2
C	14	0.93	0.9	3.43	20	0.88	1.06	-4.77	14	0.89	1.19	-16.3
D	24	0.84	1.05	-3.44	23	0.79	0.92	-0.96	13	0.7	0.85	37.2
E	27	0.74	0.73	12.4	27	0.77	0.94	5.66	14	0.91	1.23	-51.2
F	23	0.88	1.08	3.38	43	0.74	0.93	16.5	15	0.74	1.94	33.9
G	22	0.9	0.94	9.09	43	0.7	0.68	24.7	18	0.74	0.87	25.4
Mean	21	0.88			30	0.77			13			

Table C-3. CV values for Experiment 3 (Textured Colour Sample)

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	a	b
A	38	0.51	0.52	40.9	49	0.76	0.89	1.17	11	0.67	0.92	26.2
B	22	0.93	1.12	-6.08	30	0.83	1.09	-8.11	11	0.71	0.89	38.2
C	27	0.87	1.19	-17.3	28	0.78	0.85	4.59	7	0.71	0.95	11.4
D	53	0.94	1.16	-7.88	40	0.83	1.09	0.04	19	0.85	1.16	-61.4
E	32	0.94	1.16	-7.88	34	0.59	0.74	15	11	0.85	1.18	-40.6
F	12	0.77	0.83	0.42	21	0.8	0.95	-0.7	8	0.74	0.91	27.5
G	29	0.92	1.1	-6.37	29	0.77	1.15	14.2	16	0.78	0.96	-1.16
Mean	30				33				11			

Table C-4. Experiment 4 (Textured Colour Sample)

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	a	b
A	20	0.89	1.36	-27.9	32	0.89	1.31	-11.1	9	0.86	0.98	-7.71
B	17	0.81	0.92	3.41	26	0.87	1.01	5.84	11	0.9	1.05	-17.6
C	36	0.92	1.08	-5.37	26	0.93	1.2	-7.05	13	0.92	1.11	-24.7
D	41	0.75	0.84	17.8	20	0.72	0.78	14.7	9	0.68	0.74	76.7
E	29	0.84	0.94	-2.27	20	0.82	0.69	6.52	14	0.84	0.99	-6.66
F	25	0.91	1.05	-2.61	16	0.93	1.11	-4.49	16	0.91	1.09	-17.0
G	23	0.85	0.79	16.9	28	0.9	0.86	5.59	9	0.87	1.01	-3.78
Mean	27				24				11			

Table C-5. Experiment 5 (Textured Colours Sample)

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	a	b
A	26	0.94	1.25	-20.5	26	0.83	1.21	-4.87	18	0.75	0.94	6.31
B	21	0.87	0.9	5.34	38	0.59	0.72	20.3	24	0.57	0.67	112.
C	20	0.88	0.95	3.59	24	0.84	1.13	-6.01	12	0.9	1.15	-41.2
D	27	0.93	1.17	-17.5	22	0.86	1.14	-1.79	12	0.89	1.13	-34.7
E	37	0.79	0.89	14.7	30	0.76	1.02	-4	16	0.82	1.02	-1.29
F	18	0.91	0.93	6.92	32	0.65	0.79	13.2	12	0.88	1.04	-31.5
G	19	0.9	0.87	7.56	29	0.62	0.7	12.6	14	0.88	1.02	-10.2
Mean	24				28				15			

Table C-6. Experiment 6 (Textured Colours Sample)

Subject	Lightness				Colourfulness				Hue			
	CV	r	a	b	CV	r	a	b	CV	r	a	b
A	17	0.96	1.02	0.97	21	0.88	0.9	2.04	15	0.78	0.99	11.8
B	16	0.97	1.02	1.85	20	0.88	0.93	-0.54	15	0.78	0.98	14.2
C	17	0.98	1.21	-11.5	35	0.86	1.2	-23.2	11	0.84	1.05	-5.97
D	17	0.96	1.1	-3.92	24	0.89	1.25	-17.1	10	0.87	1.11	-32.1
E	12	0.97	1.08	-5.58	30	0.89	1.2	-0.9	13	0.82	1.03	-16
F	29	0.86	0.67	17.5	31	0.73	0.68	23.9	14	0.82	0.96	-11.0
G	22	0.93	0.78	11.0	26	0.78	0.82	15.9	19	0.67	0.84	39.0
Mean	18				26				13			

Appendix D: The Paper published at AIC 2015, Tokyo, May 2015.

Evaluation of colour appearances displaying on smartphones

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ABSTRACT

Despite of the limited size and capacity of a mobile phone, the urge to apply it to meet quotidian needs has never been unencumbered due to its appealing appearance, versatility, and readiness, such as viewing/taking pictures and shopping online. While a smartphone can act as a mini-computer, it does not always offer the same functionality as a desktop computer does. For example, the RGB values on a smartphone normally cannot be modified nor can white balance be checked. As a result, performing online shopping using a mobile phone can be tricky, especially when buying colour sensitive items. Therefore, this research takes an initiative to investigate the variations of colours for a

number of smartphones while making an effort to predict their colour appearance using CIECAM02, benefiting both phone users and makers. The paper studies models of Apple iPhone5, LG Nexus 4, Samsung, and Huawei, by capitalising on comparisons with a CRT colour monitor that has been calibrated under the illuminant of D65, to be in keeping with the usual way of viewing online colours. As expe cted, all the phones present more colourful images than a CRT does.

1. Introduction

A smartphone is a mobile phone with more advanced computing capability and connectivity than basic feature phones, offering functionalities of typically personal assistance, media player, digital camera, and a GPS navigation unit in addition to the basic calling/receiving facilities. At present, the global smartphone audience has reached 1 billion consumers [eMarkter] and expects to arrive at 1.75 billion by the end of 2014. As such, mobile sales are not only focusing heavily on smartphones, but also on the more affordable option of feature phones that do not have an operating system. As a result, mobile penetration has surpassed 100% in many regions of the world, including North America, Western Europe, Central and South America, Central and Eastern Europe, and the Middle East [WeAreSocial]. Among those smartphone users, about half of them go online by using the phone regularly. Table 1 lists the top 10 most popular smartphones on the market.

Table 1. Top 10 smartphone list as of May 2014 [Counter].

Rank	Brand	Model
1	Apple	iPhone 5s
2	Samsung	Galaxy S5
3	Samsung	Galaxy S4
4	Samsung	Note 3
5	Apple	iPhone 5c
6	Apple	iPhone 4S
7	Xiaomi	MI3
8	Samsung	Galaxy S4 mini

9	Xiaomi	Hongmi Redrice
10	Samsung	Galaxy Grand 2

One of the unexpected by-products of smartphones remains in the field of digital photography. It appears that more photos are taken by using Smartphones than normal cameras. For example, the Apple iPhone 5 is currently the most popular 'camera' on Flickr.com [Flickr]. As a direct result, large amount of money are being investigated by mobile developers to create photo apps in an attempt to satisfy the demands of 'serious' camera phone photographers.

While using smartphone to perform everyday activities, colour remains one of the key factors, in particular in online shopping. Similar to any other digital device, a phone represents a digital image in a RGB colour space. Therefore when an image is to be processed, it is usually firstly converted into the colour space of, say, hue, lightness and colourfulness. In this way, the dependency of RGB space on hardware devices can be circumvented, i.e., a colour in one device usually does not appear nor measure the same as the one in another device even with the same RGB values in both devices. This is because the range of R, G, or B values are manually set to be the same (such as [0, 255] for an 8-bit computer) for all devices regardless their physical measurements. On the other hand, hue, colourfulness and lightness, space agrees more with human vision theories. To further improve the fitness between users’ perception and retrieved results, CIE has recommended a colour appearance model CIECAM02 to predict colours appear on any media under a number of viewing conditions [Moroney]. Stemmed from Hunt's early colour vision model [Luo (a) 1993, Luo (b) 1993] employing a simplified theory of colour vision for chromatic adaptation together with a uniformed colour space, CIECAM02 can predict the change of colour appearance as accurately as an average observer under a number of given viewing conditions. In particular, the way that the model describes a colour is reminiscent of subjective psychophysical terms, i.e., hue, colourfulness, Chroma, brightness and lightness.

To begin with, CIECAM02 takes into account of measured physical parameters of viewing conditions, including tristimulus values (X, Y, and Z) of a stimulus, its background, its surround, the adapting stimulus, the luminance level, and other factors such as cognitive discounting of the illuminant. The output of the colour appearance model predicts mathematical correlates of perceptual attributes.

With regard to the representation of the colour appearance of an image, in this investigation, the perceptual colour attributes of lightness (*J*), colourfulness (*M*) and hue (*H*) are employed.

2. Method

Thirty test colours are randomly selected from the Munsell colour book while making an effort to cover as much CIE 1931 colour space as possible. Psychophysical experiments are then carried out on both 19" CRT colour monitor with its illuminant calibrated to D65 and mobile phones. As illustrated in Figure 1, each test colour is placed at a centre against a grey background (with 20% of luminance of reference white) and surrounded by the reference white, reference colourfulness and surrounding colours. The test field in the centre subtends a visual angle of 2^{o} at a viewing distance of ~60cm. Ten subjects with normal colour vision are selected to conduct the experiments using the technique of magnitude estimation which they have been trained in advance to apply skilfully. Specifically, for each test colour, each subject is asked to estimate its appearance in terms of lightness, colourfulness and hue contents verbally that are then recorded by an operator sitting nearby.

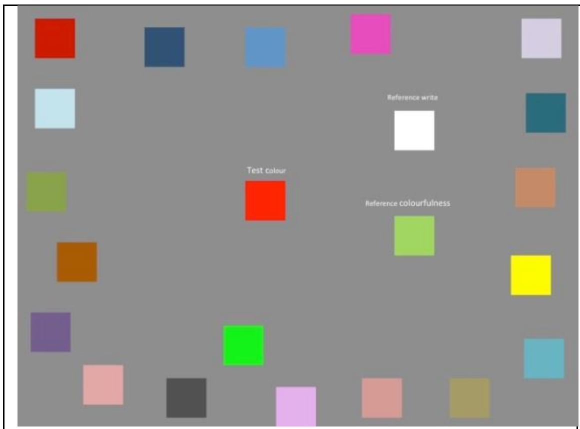

Figure 1. The paradigm of the experimental pattern.

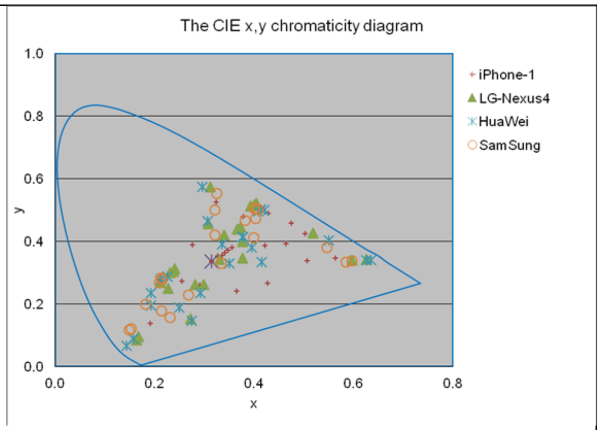

Figure 2. The x, y data of the thirty sample colours plotted on the CIE xy Chromaticity diagram for the four phones to be studied in this research. The big * refers to the reference white.

In addition, each colour on each phone has been measured using a colour meter CS-100A, simulating subjects' viewing position. Specifically, the reference white, reference colourfulness, and background are measured at least 3 times, e.g., at the beginning, the middle and the end of the colour sample sequence, to check the repeatability of the phone. In total, 6 phones, including three iPhone5, one Huawei, one SamSung, and one LG Nexus4, are measured and estimated. The same work is also performed on the CRT monitor, Philips Brilliance 201B. The measured data are presented in a CIE xy Chromaticity diagram as illustrated in Figure 2.

3. Results and Discussion

3.1 iPhone

Three handsets of iPhone 5 are investigated in this paper. Figure 2 compares the subjects' estimation results between CRT and iPhone 5 where correlation coefficient (r) values are 0.76, 0.62 and 0.96 respectively for Lightness, colourfulness, and hue estimations.

For lightness, the estimation on mobile iPhone tends to be 16% more than that on CRT monitors, whereas 11% increase of colourfulness for mobile phones is evidenced. In Figure 4, a hue-colourfulness plot is presented, where small circles (o) represent the colours from CRT and big square (□) from iPhone5.

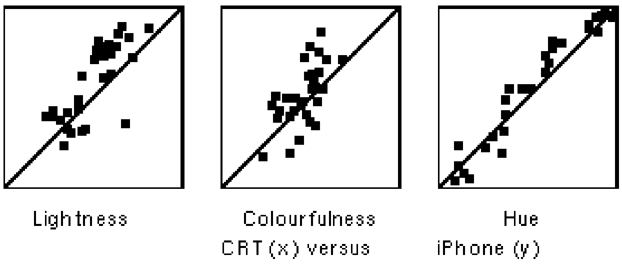

Figure 3. Comparison of subjective estimations of the thirty samples for CRT (x-axis) and iPhone 5 (y-axis).

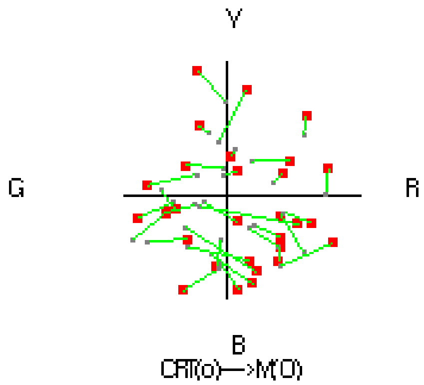

Figure 4. Subjects' estimation for the same group of colours on both CRT and Iphone5. Small circle(o) refers to the estimation for CRT whereas big solid square (▪) on Iphone.

3.2 Modelling of Iphone appearance using CIECAM02

Since the colour appearance model CIECAM02 is developed for the media of CRT, refection and transparency, it may not be well equipped to predict smartphones. After the setting of environmental parameters to ‘dim’ condition where F =0.9, c = 0.59, and Nc=0.90 to compensate lightness differences between CRT and iPhone, the comparison results are given in Figure 6 for the three phones, where colourfulness is adjusted according to Eq. (1).

$$Colourfulness\_smartphone = 1.8 * Colourfulness\_CIECAM02 \qquad (1)$$

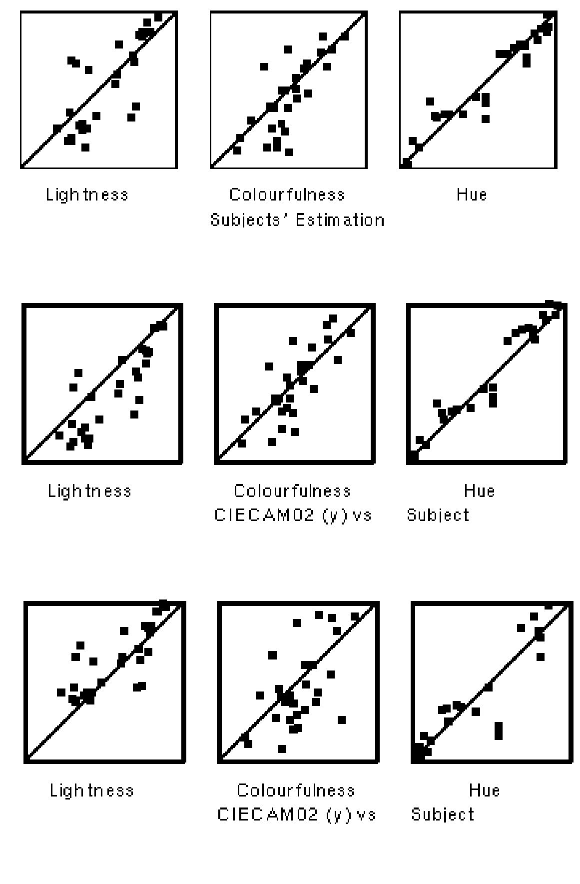

Figure 6. Comparison of CIECAM02 predictions with subjects estimations.

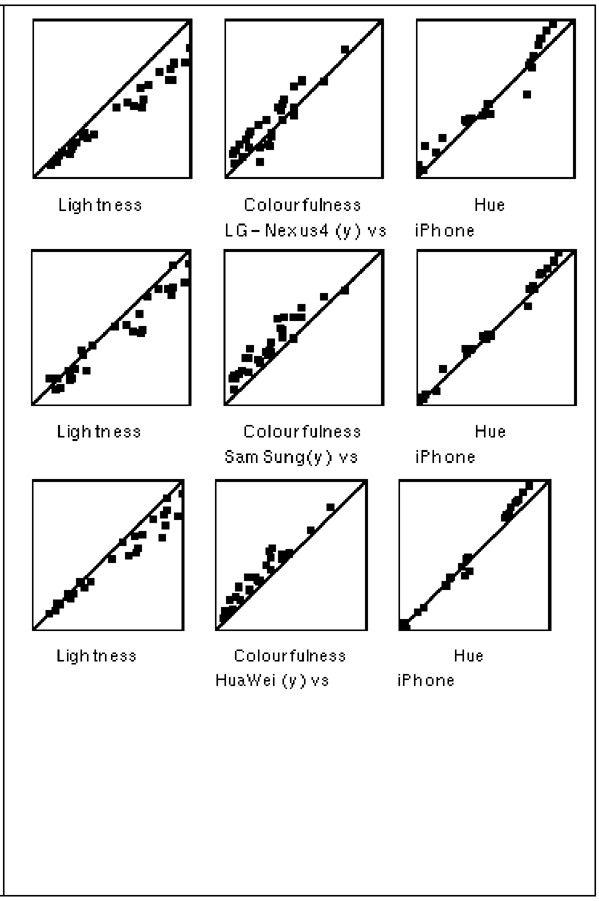

Figure 7. Comparison of iPhone (x-axis) with phones of LG-Nexus4 (top), Samsung (middle) and Huawei (bottom) by modified

It can be seen that after the correction using Eq. (1), the modified CIECAM02 can predict smartphones accurately.

3.3 Comparison with other smart phones

After the modelling of iPhone using CIECAM02, a number of other smartphones are evaluated as well, including, a LG-Nexus4, SamSung, and HuaWei. Figure 7 presents the comparison results by the calculations using CIECAM02 for all the phones, whereas Figures 8 demonstrates a colour checker depicted on these phones.

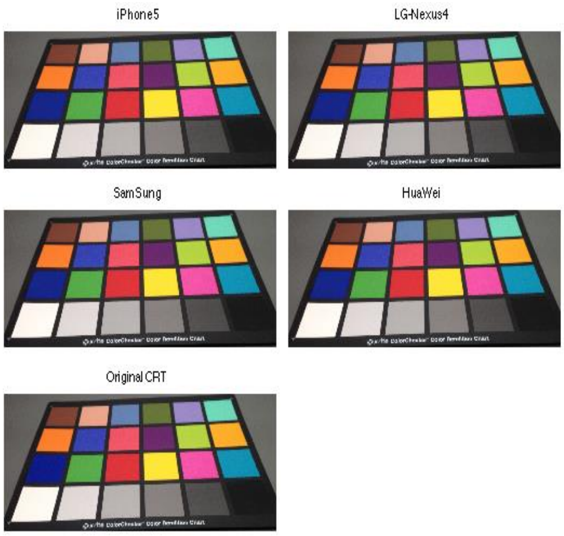

Figure 8. Colour checker depicted using four phones and CRT

When comparing with the other smartphones, in terms of hue, all three phones tends to be more reddish for purplish colours than those displayed on an iPhone, whereas the rest maintains near the same. With regard to lightness, for lighter colours, all three phones unanimously appear darker than on iPhones with LG-Nexus being the darkest with 25% darker, whereas 18% and 16% darker are evidenced for HuaWei and SamSung respectively. However, the opposite phenomenon occurs when it comes to the representation of colourfulness. All three phones of LG-Nexus4, SamSung, and HuaWei appear more colourful than those displayed on an iPhone. For example, the colours on a LG-Nexus4 phone appears systemically 10% more colourful than those depicted on an iPhone. In addition, for both HuaWei and SamSung phones, they appear again to be 17% and 22% more colourful, especially for colourful samples, the tendency presenting across all three phones. Since these findings are based on only one phone of each type, future study will focus on the investigation of large samples with more similar phones.

4. Conclusions

With 85% smartphone users perform their everyday tasks [Salesforce] using the device due to its ability and connectivity, smartphone continues to revolutionize how people perform their everyday activities. It is expected that this work will contribute to this revolutionary and complement users with some information when they perform online shopping buying colour incentive goods.

In summary, in terms of the measurement on each phone, encouragingly, the variations among the same kind of phones are insignificant with less than 3 ΔE CIELAB units. In addition, when comparing with subjects' hue estimations, all phones and the CRT monitor appear to have similar hue values, indicating that the hue values have been well reserved on those phones although some variations among phones are observe red. However, when it is viewed on a phone, a colour appears to show at variance with colourfulness by appearing much more colourful. Furthermore, the correlation coefficient (r) for CIELUV L* are 0.963, 0.959, 0.960, and 0.940 for iPhone, LG Nexus4, HuaWei and SamSung respectively, and are 0.890, 0.876, 0.761, and 0.764 respectively for CIELUV C* when comparing with the counterparts on the CRT monitor. Therefore, the iPhone tends to be the best with fewer scatterings. To predict a colour on a mobile phone using CIECAM02, the predictions rest on a number of environmental parameters settings, e.g., f = 0.9, c = 0.59, and nc = 0.90, which gives closer results with less scattering. Consequently, for an image with truthful colour to be displayed on a mobile phone, the forward and reverse model of CIECAM02 will have to be applied. Specifically, for iPhone5, nearly half of the colourfulness predicted by CIECAM02 need to be factored into. Further studies are in place to take more number of phones into consideration.

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