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EFFECTS OF LIGHTNESS AND CHROMA ON COLOUR HARMONY OF COLOUR PAIRS

Miss Parnsiri Ngammaneewat

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Thesis Title	EFFECTS OF LIGHTNESS AND CHROMA ON COLOUR HARMONY OF COLOUR PAIRS
By	Miss Parnsiri Ngammaneewat
Field of Study	Imaging Technology
Thesis Advisor	Assistant Professor Suchitra Sueeprasan, Ph.D.

Accepted by the Faculty of Science, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

.... Dean of the Faculty of Science

(Professor Supot Hannongbua, Dr.rer.nat.)

THESIS COMMITTEE

.... Chairman

(Associate Professor Aran Hansuebsai, Ph.D.)

.... Thesis Advisor

(Assistant Professor Suchitra Sueeprasan, Ph.D.)

.... Examiner

(Associate Professor Pontawee Pungrassamee)

.... External Examiner

(Professor Tetsuya Sato, Ph.D.)

พรรณสิริ งามมณีวัฒน์ : ผลของความสว่างและความอิ่มตัวสีต่อความกลมกลืนสีของคู่สี. (EFFECTS OF LIGHTNESS AND CHROMA ON COLOUR HARMONY OF COLOUR PAIRS) อ.ที่ปรึกษาวิทยานิพนธ์หลัก : ผศ.ดร. สุจิตรา สื่อประสาร, 99 หน้า.

นอกจากคุณภาพผลิตภัณฑ์และสมบัติการใช้งานแล้ว สีเป็นอีกปัจจัยหนึ่งที่มีผลในการเลือกซื้อของผู้บริโภค นักออกแบบจึงควรออกแบบและคำนึงถึงการใช้สีร่วมกัน เพื่อสร้างความโดดเด่นและความสวยงามให้เกิดกับตัวผลิตภัณฑ์ ให้เป็นที่ดึงดูดใจของผู้บริโภคมากที่สุด

งานวิจัยนี้จึงศึกษาผลของค่าความสว่างและค่าความอิ่มตัวสีของคู่สีที่มีต่อระดับความกลมกลืนสี ซึ่งรับรู้ได้จากการมองเห็น ตัวอย่างสีที่ใช้แบ่งออกเป็น 2 กลุ่ม คือ กลุ่มแรกมี 42 สี และกลุ่มที่สองมี 33 สี นำสีเดี่ยวนั้นจับคู่กัน ทำให้กลุ่มแรกและกลุ่มที่สองมีคู่สี 861 คู่ และ 528 คู่ ตามลำดับ แสดงภาพคู่สีทีละคู่ ซึ่งมีรูปร่างเป็นลักษณะของสี่เหลี่ยมจัตุรัสสองแผ่นวางชิดกันกลางจอซีอาร์ทีที่มีพื้นหลังสีเทา โดยให้ผู้สังเกตคนไทยจำนวน 20 คน ทุกคนมีการมองเห็นสีปกติ ประเมินและบอกค่าระดับความกลมกลืนสีของคู่สีเหล่านั้นด้วยสเกล 10 ระดับ ตั้งแต่ไม่มีความกลมกลืนสีเลย (-5) ถึงมีความกลมกลืนสีมากที่สุด (5) จากการทดลองพบว่า ความสว่างและความอิ่มตัวสีมีผลต่อค่าความกลมกลืนสีของคู่สี โดยที่คู่สีที่มีความสว่างสีสูงจะมีความกลมกลืนสีมากกว่าคู่สีที่มีความสว่างสีต่ำ และคู่สีที่มีความอิ่มตัวสีสูงก็มีความกลมกลืนสีมากกว่าคู่ที่มีความอิ่มตัวสีต่ำเช่นกัน และสีที่ก่อให้เกิดความกลมกลืนกันของคู่สีมากที่สุด คือ สีขาว ซึ่งตรงกันข้ามกับสีเทาเป็นสีที่ไม่ก่อให้เกิดความกลมกลืนสีเลย

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ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก
สาขาวิชา เทคโนโลยีทางภาพ
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In addition to quality and usability of products, colour is an important factor which affects a customer's decision when buying a product. Designers should therefore consider a combination of colours in order to design most outstanding and pleasing products.

This study aimed to investigate impacts of lightness and chroma of colour pairs on the degree of perceived colour harmony. Colour samples were divided into 2 sets: 42 single colours were chosen for the lightness investigation, and 33 single colours for the chroma. All possible combinations of single colours were generated to obtain 861 and 528 colour pairs, respectively. The colour pairs were shown one by one on a CRT monitor as two colour squares placed next to each other against a uniform grey background. Twenty Thai observers, all having normal colour vision, participated in the experiments in which they were asked to rate the degree of colour harmony for each colour pair using a 10-point scale (-5 means completely disharmonious to 5 means completely harmonious). Experimental results indicated that lightness and chroma had impacts on colour-harmony scores of colour pairs. Colour pairs with high lightness were more harmonious than those with low lightness and similar results were also found in the case of chroma. The most harmonious colour was white and the grey was the most disharmonious.

Department :	Imaging and Printing Technology	Student's Signature	พรรณศิริ งามมณีวัฒน์
Field of Study :	Imaging Technology	Advisor's Signature	
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CHAPTER I

INTRODUCTION

If everything in the world had no colour, only black and white or levels of grey had been seen every day, our lives would have been depressed, cheerless, and unhappy. We are surrounded by colours and experience them throughout all stages of life. Without colour, life would have been less colourful, less cheerful, and less fun.

Colour is something that has many benefits in the way of life. It is an element of all things. With a touch of colour, things can look good and feel good. Taking a colour television as an example, moving pictures on a colour TV look far better than those on a black-and-white TV. This is because viewers can feel them like what they experience in daily life. Colour enhances the world just as cosmetics enchant white faces to be beautiful and fascinating. Colour can also help products to look attractive to customers. Designers use colour to make products look outstanding and interesting. Colour also plays an important role in fashion, and it is one of major aspects that customers consider when buying goods. Moreover, colour is used as symbols, to communicate status, feeling and emotion. For example, most logos of companies use colour or colour with text, but not only text, so that their brands are easy to memorize, such as coke, canon, Kbank, DTAC, MK, etc. The traffic light has three colour lights: red light tells us to stop the car, yellow light to prepare to stop, and green to proceed in the denoted direction. Different coloured rooms can create atmospheres [1]: peacefulness, drama or even excitement such as soft blue in bedroom helps you to release tension and also aids peaceful sleep. Each colour can influence our mood [2], for example, red affects us physically to activate; blue affects the intellect, promoting thought and “higher order” activity; yellow affects the emotions and the ego; green affects the essential balance between mind, body and emotions.

Colour is defined by The *International Lighting Vocabulary* [3] as *“Attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange,* *brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, gray, black, etc., and qualified by bright, dim, light, dark, etc., or by combinations of such names."* That means colour can not be alone, it is always seen in the context of other colours or it consists of any combination of chromatic, achromatic, or degrees of bright. Therefore, if there are many colours that can be used in the world, a number of colour combinations will even be greater.

Colour combinations usually appear around us such as colours of clothes, cosmetics, decoration, catalogue, poster, product and design, or even food. So, the combinations of colour should be considered carefully in order to obtain proper colours that are attractive, beautiful, and harmonious. As colour is a significant factor in art and design and viewers may have different colour preferences when they look at the same colour, there is one principle that helps when designing appropriate colours. It is called colour harmony.

Colour harmony has long been studied in various fields (e.g. art, architecture, science, etc.). However, no acceptable model exists for explaining the concept of colour harmony. One possibility of a definition of colour harmony is as suggested by Judd and Wyszecki [4]: "when two or more colours seen in neighbouring areas produce a pleasing effect, they are said to produce a colour harmony". This concept is very useful to help designers, architects, and decorators in order to create various works of art such as web and design, clothes and fashion, cosmetics, decoration, carpet, townscape, and packaging.

At present, the advanced technology such as the use of computer brings some electronic devices for helping designers due to the fact that it is very convenient, easy to edit, and quick. Artwork can be seen on a monitor's screen before producing the real work. Knowledge of colour in science has taken on a role of arts and it has been applied to computer software. For example, booria's software uses the concept of colour harmony to design the colour carpets [5]; CAD (Computer-Aided Design) can search for an ideal colour combination [6]. The concept of colour harmony is also used in a guidebook such as “more than 800 colourways for package designs that work” by James Mousner [7], “The Principles Of Interior Decoration” by Bernard C. Jakway [8].

Burchett [9] found that there are many attributes that affect colour harmony such as order, tone, configuration, area, interaction, association, similarity, and attitude. The research by Ou and Luo [10] on a study of a colour harmony model for two-colour combinations indicated that differences of colour pairs in lightness, chroma, and hue affected the degree of colour harmony. They developed a model for predicting the colour harmony of colour pairs. Moreover, Ou et al. [11] investigated the effect of culture on colour emotion and preference. The result showed that nationality and culture can influence the viewers’ emotional response and preference of colours.

This study investigated the effects of lightness and chroma on colour harmony of colour pairs. The colour stimuli were displayed on CRT monitor and assessed by Thai observers. Observers selected the number that represents the degree of colour harmony for each colour pair. The stimuli were separated into two groups: lightness group with fixing chroma value, and chroma group with fixing lightness value. All of the stimuli were systematically selected from CIECAM02 colour appearance model.

1.1 Objectives

To investigate an impact of lightness attribute as well as chroma attribute on perceived colour harmony for two-colour combinations.

1.2 Scope

Forty-two single colours were selected to investigate lightness factor of colour harmony. A series of colour pairs was then generated and simulated on a CRT monitor. Twenty Thai observers participated in the visual assessments. In the case of chroma factor, 33 single colours were selected. All colour samples were systematically distributed in the CIECAM02 colour appearance space and were analytically converted to display on the CRT monitor via the GOG model. For lightness group of samples, chroma values were fixed at 15, and for chroma group lightness values were fixed at 50. Seven lightness levels and five chroma levels were included in the present study. These levels were varied for 6 hues: red, orange, yellow, green, blue and purple.

1.3 Expected Outcomes

1. Relationship between lightness attribute and colour harmony of two-colour combinations.

2. Relationship between chroma attribute and colour harmony of two-colour combinations.

1.4 Contents

Chapter 2 consists of the theoretical considerations and literature reviews that relate to this research. Chapter 3 describes the methodology that can be divided into three parts: apparatus, observers, and experimentation. The experimentation consists of pre-experiment, experimental procedures, and analysis of the results from the visual assessments. For Chapter 4, this chapter reports the result from testing of the CRT monitor, the result from the visual assessments, and reliability of the visual data. The last chapter is Chapter 5 that gives conclusions and suggestions for the future work.

CHAPTER II

THEORETICAL CONSIDERATIONS AND LITERATURE REVIEWS

2.1 Theoretical Considerations

This thesis studied about the impacts of lightness and chroma on colour harmony of colour pairs. Colorimetric values of samples were selected from CIECAM02 appearance model because this model is recommended by CIE (Commission Internationale de l' Eclairage) as the model capable of predicting the appearance of colours, taking into account the effect of viewing conditions. The CRT monitor was used to display the desired colours, so the characterisation of CRT monitor was required. Thus the GOG model was applied. The theoretical considerations are described in this chapter.

2.1.1 Colour Wheel

A colour circle, based on red, yellow and blue, is traditional in the field of art. Sir Isaac Newton developed the first circular diagram of colours in 1666. Since then scientists and artists have studied and designed numerous variations of this concept. Differences of opinion about the validity of one format over another continue to provoke debate. In reality, any colour circle or colour wheel which presents a logically arranged sequence of pure hues has merit. [12]

The colour wheel is the basic tool for combining colours. It is designed so that virtually any colours you pick from it will look good together. Over the years, many variations of the basic design have been made, but the most common version is a wheel of 12 colours based on the RYB (or artistic) colour model as shown in Figures 2-1 (a) and (b). Traditionally, there are a number of colour combinations that are considered especially pleasing. These are called colour harmonies or colour chords and they consist of two or more colours with a fixed relation in the colour wheel [13] which is consisted of primary colours, secondary colours, and tertiary colours. [12, 14-15]

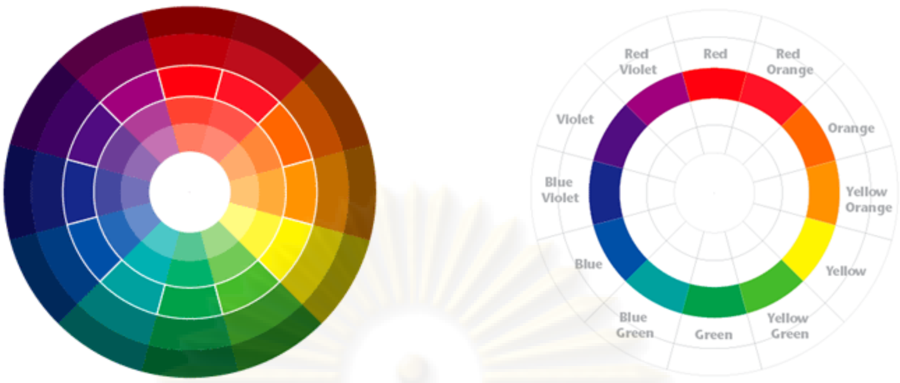


Figure 2-1 RYB colour wheel (a) including tint and shade, (b) name of each colour. [16]

2.1.1.1 Primary Colours

The three primary colours are red, yellow, and blue. In traditional colour theory, these are the three pigment colours that can not be mixed or formed by any combination of other colours or they are pure, unmixed, uncompounded colour, made from a single pigment. Sometimes they are called basic colours because they form the basis of all other colours, whether spectral or natural. All other colours are derived from these three colours as shown in Figure 2-2 (a).

2.1.1.2 Secondary Colours

The three secondary colours are orange, green, and purple as shown in Figure 2-2 (b). These colours are formed by mixing equal parts of red and yellow, yellow and blue, and blue and red, respectively.

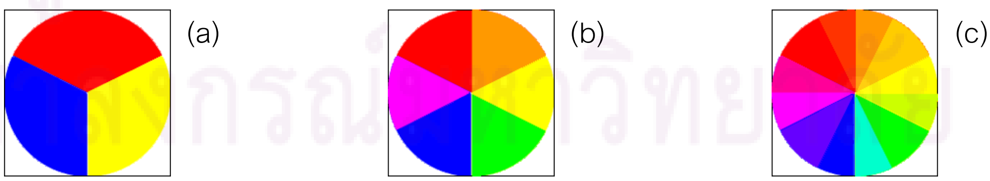


Figure 2-2 (a) Primary colours, (b) Secondary colours, (c) Tertiary colours. [14]

2.1.1.3 Tertiary Colours

The six tertiary colours are yellow-orange, red-orange, red-purple, blue-purple, blue-green, and yellow-green as shown in Figure 2-2 (c). These colours are formed by mixing equal parts of a primary and a secondary colour. That is why the hue is a two word name.

2.1.2 Colour Harmony

Colour harmony has been of enormous significance in art and design but none of the studies was acceptable either in explaining the concept of colour harmony or in providing an accurate prediction. These studies can be divided into two categories [19]: those based on the orderly arrangement or colours and those based on the interrelationship between colours. The former included those by Ostwald, Munsell, Itten, and Nemcsics. The general idea behind these studies was that colours could harmonize only when they were selected systematically from a hue circle or from a specific "path" within an ordered colour space. The latter included those by Goethe, Chevreul, Moon and Spencer, Albers, and Chuang and Ou. The general idea was that colours could harmonize only when they were complementary or analogous (similar) in ether hue, lightness, or chroma.

There is still no conclusion of the existing definitions of colour harmony but there are some similar suggestions. For example, Judd and Wyszecki [4] said "when two or more colours seen in neighbouring areas produce a pleasing effect, they are said to produce a colour harmony." Burchett [9] suggested a similar definition of colour harmony: "when two or more colours are brought together to produce a satisfying affective response, they are said to be harmonised." And Kuehni [17] took a similar view that there is no doubt that perceptions of beauty and harmony are strongly influenced by nurture and culture so that it is quite evident that there are no universal laws of harmony. So, this study adopted that given by Judd and Wyszecki for assessing harmony of colour pairs.

2.1.3 Principles of Colour Harmony

Colour harmony has been studied for a long time so there are many principles that describe how the colours work well. A harmonious colour scheme depends on the balance between all three properties of colour – hue, value, and chroma. The following illustrations and descriptions present for some common principles of harmony of hues in many art and design textbooks with reference to hue circles. [12, 17-24]

2.1.3.1 Monochromatic Colour Harmony

Monochromatic colours are usage of the single hue and a selection of tints, tones and shades depending upon how much white or black is added - in other words, using hues of the same colour that have different levels of value and/ or chroma as shown in Figure 2-3 (a). They are often the easiest on the eyes of all the colour schemes. The gentle changes in tint and shade make the colours flow into one another better.

2.1.3.2 Analogous Colour Harmony

Analogous colours are any three colours which are next to each other on the colour wheel, such as yellow-green, green, and blue-green in Figure 2-3 (b). Usually one of the three colours predominates. These colours can work very well together and create more colourful than the monochromatic colour. They are often found in nature and pleasing to the eyes.

2.1.3.3 Complementary Colour Harmony

Complementary colours are any two colours in the colour wheel which are directly opposite each other, such as red-purple and yellow-green, red and green as shown in Figure 2-3 (c). They are most often used on pieces that need to stand out because the high contrast of them creates a vibrant look especially when used at full saturation. This colour scheme must be managed well so it is not jarring and they are really bad for text.

2.1.3.4 Triadic Colour Harmony

Triadic colour schemes are made up of three colours by placing an equilateral triangle on the colour wheel such as orange, purple and green as shown in Figure 2-3 (d). They tend to be quite vibrant, even if pale or unsaturated versions of your hues are used. To use a triadic harmony successfully, the colours should be carefully balanced - let one colour dominate and use the two others for accent. Note that combining equal proportions of three triadic complementary colours produces white.

Other samples [23] told that there are nine principles methods of achieving colour harmony including five types of complementary colours (*complementary*, *split-complementary* - two colours adjacent to its complement as shown in Figure 2-3 (e), *triadic*, *tetradic* - four colours that are equidistant from one another on a colour wheel as shown in Figure 2-3 (f), and *tetradic split-complementary* colour harmony - two pairs of split-complements as shown in Figure 2-3 (g)), analogous, monochromatic, tonal - colours with similar values, or chromatic methods – colour with similar levels of chroma, or saturation.

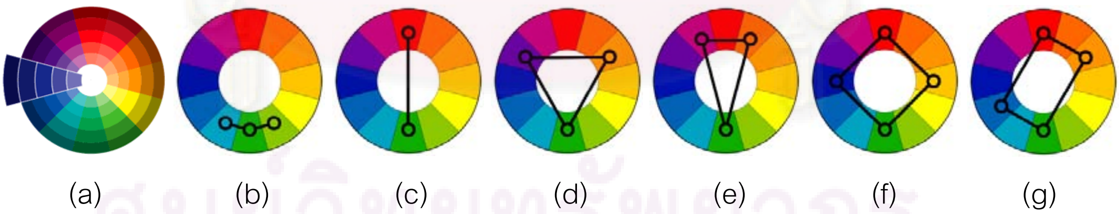


Figure 2-3 Some principles of colour harmony (a) Monochromatic (b) Analogous (c) Complementary (d) Triadic (e) Split-complementary (f) Tetradic (g) Tetradic split-complementary. [16, 18]

Beauty is in the eye of the beholder, but it is an unfortunate fact that not all colours go together. Discordant colours are colours that are farther than around 30 degrees apart on the colour wheel and are not complementary or part of a triad.

Discordant colour schemes can be very shocking and should only used to generate attention. [19]

More recently, experimental psychologists have sought to ground theories of colour harmony in the empirical study of responses to single and paired coloured samples by subjects. However, this empirical work has done little to either substantiate or replace any of the traditional theories [17]. The existing colour harmony theories can be categorised into several "principles" [25]. The following descriptions present for some common colour harmony principles.

2.1.3.5 Equal Hue

Chevreul (1839), Ostwald (1916), Munsell (1921), Moon and Spencer (1944), Nemcsics (1993), Hård and Sivik (2001) suggested that colours harmonise if they are of the same hue (see References in [25]).

2.1.3.6 Equal Chroma

Ostwald (1916), Munsell (1921), Moon and Spencer (1944), Nemcsics (1993), Hård and Sivik (2001) suggested that colours harmonise if they are of the same chroma (see References in [25]).

2.1.3.7 Complementary Hue

Goethe (1810), Chevreul (1839), Munsell (1921), Moon and Spencer (1944), Nemcsics (1993) suggested that colours harmonise if they are complementary in hue (see References in [25]).

The last hundred years have seen a divergence in view between artists and scientists on the topic of colour aesthetics, and we suggest that this trend needs to be reversed if significant progress is to be made in terms of understanding colour harmony. A similar sentiment has been expressed for art and design in general. [17]

2.1.4 CIECAM02 Colour Appearance Model

A colour appearance model (CAM) is any model that includes predictors of at least the relative colour appearance attributes of lightness, chroma, and hue. This definition was given by TC 1-34 (CIE Technical Committee 1-34 Testing Colour Appearance Models). For a model to include reasonable predictors of these attributes, it must include at least some form of a chromatic adaptation transform. [3]

CIECAM02 colour appearance model, the current CIE colour appearance model, is based on the basic structure and form of the CIECAM97s colour appearance model but it is consisted of a number of refinements and simplifications of the CIECAM97s. It provides a prediction of the colour appearance under a variety of viewing conditions, including different light sources, luminance levels, surrounds, and lightness of backgrounds and performs as well as, or better than CIECAM97s in almost all cases. It is particularly useful for achieving successful cross-media colour reproduction. It overcomes three significant drawbacks of the earlier CIECAM97s model. There is over-prediction of chroma for near neutral colours, poor prediction of saturation results, and large variation of the predicted saturation values for colours having the same chromaticity but different luminance factors. [26]

The structure of the CIECAM02 is composed of three parts: Chromatic adaptation, Dynamic response function, and Colour space. They are presented in the following sections.

2.1.4.1 Chromatic Adaptation

Chromatic adaptation [3] is a visual adaptation that is far more important and must be included in all colour appearance models. It is the largely independent sensitivity control of the three mechanisms of colour vision. This is illustrated schematically in Figure 2-4, which shows that the overall height of the three cones spectral responsivity curves can vary independently. Often it is considered to be only the independent changes in responsivity of the three types of cone photoreceptors.

However, it is very important that there are other mechanisms of colour vision that are capable of changes in sensitivity that can be considered mechanisms of chromatic adaptation. For example, consider a piece of white paper illuminated by daylight. When such a piece of paper is moved to a room with incandescent light, it still appears white despite the fact that the energy reflected from the paper has changed from predominantly blue to predominantly yellow. This appearance is called chromatic adaptation. Chromatic adaptation can be thought of as analogous to an automatic exposure control. [3]

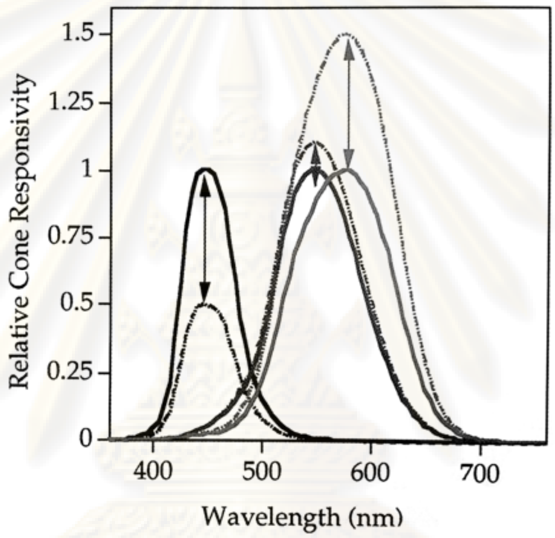


Figure 2-4 Conceptual illustration of the process of chromatic adaptation as the independent sensitivity regulation of the three cone responsivities. [3]

This adaptation is one process in a colour appearance model, known as a chromatic adaptation transform (CAT or chromatic adaptation model) [3]. A chromatic adaptation model simply provides a transformation from tristimulus values in one viewing condition to matching tristimulus values in a second set of viewing conditions. It does not include correlates of appearance attributes such as lightness, chroma, and hue. There are many models but they have differences of capable predicting corresponding colours that depend on the attributes in their equations such as von Kries Model, Nayatani *et* al. Model, Guth's Model, or Fairchild's Model. A general form of a chromatic adaptation model can be expressed as shown in Equations 2.1-2.3.

$$L_a = f(L, L_{white}, \ldots) \tag{2.1}$$

$$M_a = f(M, M_{white}, \ldots) \tag{2.2}$$

$$S_a = f(S, S_{white}, \ldots) \tag{2.3}$$

This generic chromatic adaptation model is designed to predict three cone signals, L_a, M_a, and S_a, after all of the effects of adaptation have acted upon the initial cone signals, L, M, and S. Such a model requires, as a minimum, the cone excitations for the adapting stimulus, L_{white}, M_{white}, and S_{white}. It is quite likely that an accurate model would require additional information as well. A chromatic adaptation model can be converted into a chromatic adaptation transform by combining the forward model for one set of viewing conditions with the inverse model for a second set. Often such a transform is expressed in terms of CIE tristimulus values as shown in Equation 2.4. [3]

$$XYZ_2 = f(XYZ_1, XYZ_{white1}, XYZ_{white2}, \ldots) \tag{2.4}$$

In order to accurately model the physiological mechanisms of chromatic adaptation, it is necessary to express stimuli in terms of cone excitations LMS rather than CIE tristimulus values, XYZ. Fortunately, cone excitations can be reasonably approximated by a linear transformation (3x3 matrix) of CIE tristimulus values. Thus a generic chromatic adaptation transform can be described as shown in the flow chart in Figure 2-5. [3]

In Figure 2-5, first, begin with CIE tristimulus values ($X_1Y_1Z_1$) for the first viewing condition. Second, transform them to cone excitations ($L_1M_1S_1$). Then incorporate information about the first set of viewing conditions (VC_1) using the chromatic adaptation model to predict adapted cone signals ($L_aM_aS_a$) and the last step, reverse the process for the second set of viewing conditions (VC_2) to determine the corresponding colour in terms of cone excitations ($L_2M_2S_2$) and ultimately CIE tristimulus values ($X_2Y_2Z_2$). The complete process is as follows: [3]

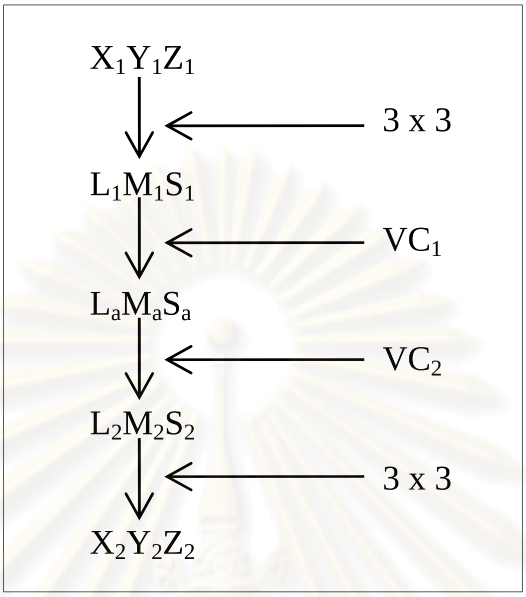


Figure 2-5 A flow chart of the application of a chromatic adaptation model to the calculation of corresponding colours. [3]

Any physiologically plausible model of chromatic adaptation must act on signals representing the cone response (or at least relative cone responses). Thus, in applications for which the use of CIE colorimetry is important, it is necessary to first transform from CIE tristimulus values (*XYZ*) to cone responses (denoted ***LMS***, ***RGB***, or ***rgb***, depending on the model). Fortunately, cone responsivities can be accurately represented using a linear transformation of CIE tristimulus values. An example of such a transformation is graphically illustrated in Figure 2-6. This transformation, or a similar one, is common to all chromatic adaptation and colour appearance models that are compatible with CIE colorimetry. [3]

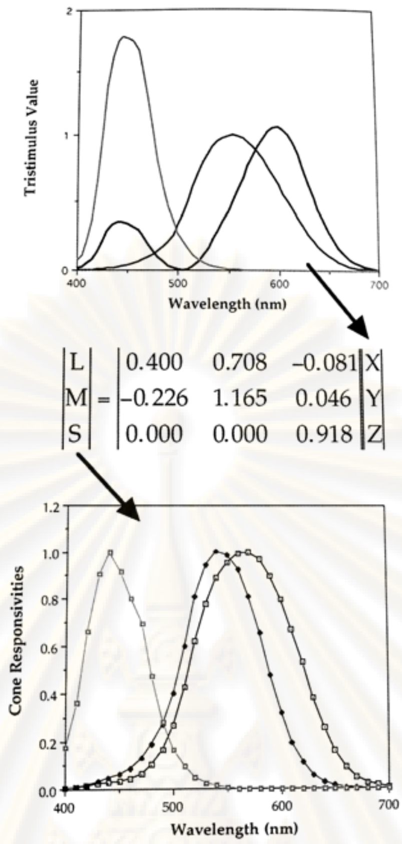


Figure 2-6 The process of transformation from XYZ tristimulus values to LMS cone responsivities using an example linear matrix multiplication. [3]

Input data for the CIECAM02 include the relative tristimulus values of the test colour stimulus in the source conditions (XYZ) and the relative tristimulus values of the source white in the source conditions ($X_{\mathrm{w}}Y_{\mathrm{w}}Z_{\mathrm{w}}$) such as the tristimulus values of D_{65} white, normalized to make Y_{w} = 100, the adapting field luminance (often taken to be 20% of the luminance a white object in the scene) L_{A}, in cd/m^2, the relative luminance of the source background in the source conditions Y_{b} (often taken to be 20% for 'average' image conditions, 8% for 'dark background') and the relative luminance of the surround (dark, dim, average). [3, 27]

The surround relative luminance is generally taken to be average for reflection prints, dim for CRT displays or televisions, and dark for projected transparencies under the assumption that these media are being viewed in their typical environments. Table 2-1 is used to set the values of c an exponential nonlinearity, N_c the chromatic induction factor, and F the maximum degree of adaption. [3]

Table 2-1 Input parameters for the CIECAM02 model. [3]

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

After calculating those of input data and viewing condition into the chromatic adaptation model, the values of responsivity of the three cone photoreceptors when viewed the stimulus that put on the background and under the illuminant are represented by the adapted R', G', and B' responses.

2.1.4.2 Dynamic Response Functions

Dynamic response functions are functions of predicting the extent of changes of responses of stimuli of different luminance factors across a wide range of luminance levels. The functions have many types such as a cube-root function for CIELAB, RLAB, a hyperbolic function for CIECAM97s, CIECAM2000, CIECAM02, or a logarithmic function for Nayatani.

The post-adaption nonlinearities are similar in form to those in CIECAM97s, but slightly modified to produce a simple power-function response over a larger dynamic range. This facilitates a simple definition of saturation later in the model. For much of the normal operating range of these functions, they are similar to simple square-root functions. These nonlinearities are given in Equations 2.5 – 2.9. [3]

$$R'_a = \frac{400(F_L R'/100)^{0.42}}{27.13 + (F_L R'/100)^{0.42}} + 0.1 \quad (2.5)$$

$$G'_a = \frac{400(F_L G'/100)^{0.42}}{27.13 + (F_L G'/100)^{0.42}} + 0.1 \quad (2.6)$$

$$B'_{a} = \frac{400(F_L B'/100)^{0.42}}{27.13+(F_L B'/100)^{0.42}} + 0.1 \quad (2.7)$$

Where luminance-level adaptation factor F_L

$$F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3} \quad (2.8)$$

$$k = 1/(5L_A + 1) \quad (2.9)$$

These values are then used to create opponent colour responses and formulate correlates of colour appearance.

2.1.4.3 Colour Space

Colour space extends tristimulus colorimetry to three-dimensional spaces with dimensions that approximately correlate with the perceived lightness, chroma, and hue of a stimulus based on a reference set of illumination conditions. It provides redness-greenness and yellowness-blueness scales (opponent responses) including achromatic signals. This is accomplished by incorporating features to account for chromatic adaptation and nonlinear visual responses. [3]

2.1.4.3.1 Lightness

An initial achromatic response A is computed by weighted summation of the nonlinear adapted cone responses modified with the brightness induction factor as illustrated in Equations 2.10-2.12. A similar quantity must also be computed for the white in order to facilitate computation of lightness and brightness. [3]

$$A = [2R'_a + G'_a + (1/20)B'_a - 0.305]\,N_{bb} \quad (2.10)$$

Where the induction factors N_{cb}, N_{bb}

$$N_{cb} = N_{bb} = 0.725(1/n)^{0.2} \quad (2.11)$$

$$n = \frac{Y_b}{Y_w} \quad (2.12)$$

Lightness J is then simply computed from the achromatic response, A, achromatic response for white A_w, the surround factor c, and the base exponent z, according to Equations 2.13 and 2.14.

$$J = 100(A/A_w)^{cz} \quad (2.13)$$

Where the base exponential nonlinearity z

$$z = 1.48 + \sqrt{n} \quad (2.14)$$

2.1.4.3.2 Chroma

A temporary quantity t, that is related to saturation and incorporates the chromatic induction factors for surround and background (N_c and N_{cb}) as well as the eccentricity adjustment e_t, is computed as the basis for chroma, colourfulness, and saturation correlates. The formula for t is given in Equation 2.15. [3]

$$t = \frac{(50000/13)N_c N_{cb} e_t \sqrt{a^2 + b^2}}{R'_a + G'_a + (21/20)B'_a} \quad (2.15)$$

CIECAM02 chroma *C*, is then computed by multiplying a slightly nonlinear form of *t* by the square root of lightness *J*, with some adjustment for background *n*, as shown in Equation 2.16. This formulation, as with most of the model, is based on empirical fitting to various colour appearances scaling data.

$$C = t^{0.9}\sqrt{J/100}(1.64 - 0.29^n)^{0.73} \quad (2.16)$$

2.1.4.3.3 Hue

Initial opponent-type responses in CIECAM02 are calculated using Equations 2.17 and 2.18. Hue angle h is calculated in CIECAM02 space using the same procedure as CIELAB. As in CIELAB, h is expressed in degree ranging from 0° to 360°, measured from the positive a axis calculated according to Equation 2.19. [3]

$$a = R'_a - 12\,G'_a/11 + B'_a/11 \quad (2.17)$$

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

$$h = \tan^{-1}(b/a) \tag{2.19}$$

Finally, given C, h and a Cartesian representation can be computed. This is shown in Equations 2.20 and 2.21 using the chroma correlate. The subscript C is used to specify the use of the chroma correlate and corresponding equations. The subscripts should be used to avoid confusion both with the preliminary Cartesian coordinates shown in Equations 2.17 and 2.18 and to specify which perceptual attribute correlate is the coordinates are based on. [3, 28]

$$a_C = C\cos(h) \tag{2.20}$$

$$b_C = C\sin(h) \tag{2.21}$$

CIECAM02 can predict all the phenomena that can be predicted by CIECAM97s. In includes correlates of all the typical appearance attributes (relative and absolute) and can be applied over a large range of luminance levels and states of chromatic adaptation. Like CIECAM97s, CIECAM02 is not applicable to situations in which there is significant rod contribution to vision or at extremely high luminance in which cone bleaching might occur. It is appropriate to think of CIECAM02 as a simpler and better version on CIECAM97s. [3]

2.1.5 Characterisation of CRT Monitor

2.1.5.1 CRT Monitor

In CRT (cathode ray tube) of a computer or video monitor, a screen is coated on the inside surface with dots of chemicals called phosphors. Each time a beam of electrons makes a pass across the screen or hits dots on the screen, it lights up phosphor dots (pixels) on the inside of the glass tube, thereby illuminating the active portions of the screen. By drawing many such lines from the top to the bottom of the screen, it creates an entire image. A colour CRT monitor uses three electron guns which activate red light-emitting, green light-emitting, and blue light-emitting phosphors. This

RGB system can create all the other colours by combining what dots are aglow. In Figure 2-7, there are three colour signals that control the three electron beams in the monitor, one for each RGB colour. Each beam only touches the dots that the signal tells it to light. All the glowing dots together make the picture that you see. The human eye blends the dots to see all the different colours. And a shadow mask blocks the path of the beams in a way that lets each beam only light its assigned colour dots. [29-30]

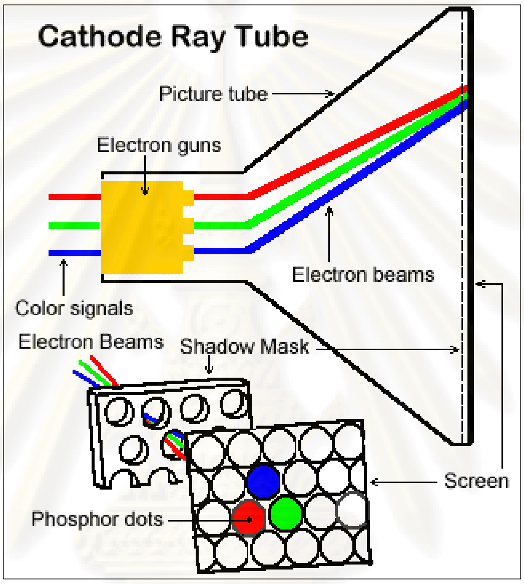


Figure 2-7 Making Colored Pictures of CRT monitor. [30]

2.1.5.2 Definitions

Device calibration refers to setting the imaging device to a known state. This might represent a certain white point, gain, and offset for a CRT. Calibration ensures that the device is producing consistent results, both from day to day and from device to device. Device calibration is usually an issue for the manufacturer, rather than the user, and the techniques depend heavily on the technology. [3]

Characterisation refers to the creation of a relationship between a device-dependent (DDC) colour space and a device-independent colour space (DIC) as illustrated in Figure 2-8, i.e. the CIE system of colour measurement. It may be defined as a mathematical models based on a set of equations or a definition of a discrete number of points which constitute a look-up table.

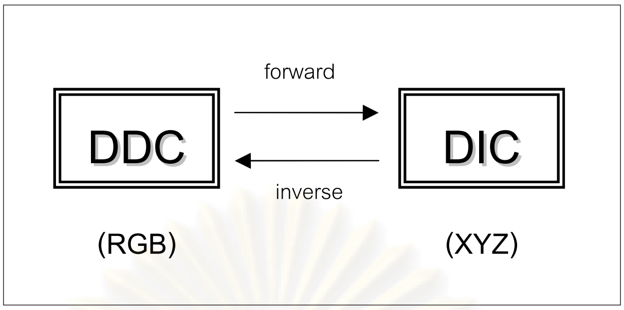


Figure 2-8 Relationship between a device-dependent (DDC) colour space and a device-independent colour space (DIC).

However, device calibration can be completed with absolutely no information about the relationship between device coordinates and the colorimetric coordinates of the input or output image. Colorimetric characterisation of the device is required to obtain this information. [3]

Flare is light that affects the colour appearance of CRT monitor. It is usually taken place when viewed the CRT monitor in dim surroundings under ambient light, not in a dark room. According to CIE 122-1996, the viewing flare can be separated into an external flare and an internal flare. The external flare is defined as the reflection of the ambient illumination on the CRT surface and the internal flare is caused by the internal reflection in the CRT glass, when the phosphor around the area detected by the eyes or the measurement instruments has some amount of emission. [31]

2.1.5.3 Processes in Characterisation of CRT

CRT monitors are widely used to view images on the Internet. The colour images on the computer graphic display can be printed out or displayed on other monitors through the Internet, and colour matching between the original and the reproduction is very important. The colour management systems (CMSs) are useful for the colour matching. CMSs utilize device profiles, in which colour characteristic information is stored, and these profiles are generated by device characterization. [31]

One approach to device characterisation is a physical modeling and this model is often used for a CRT display characterisation. It involves a nonlinear transform to convert drive voltages to the corresponding RGB phosphor luminances (Equations 2.25-2.27), followed by a linear transformation to CIE XYZ tristimulus values (Equation 2.30) [3] as illustrated in Figure 2-9. In the step1, digital inputs ($d_r d_g d_b$) are given to predict the luminance in each of the channels and the luminances will be predicted the tristimulus values for the monitor in step2.

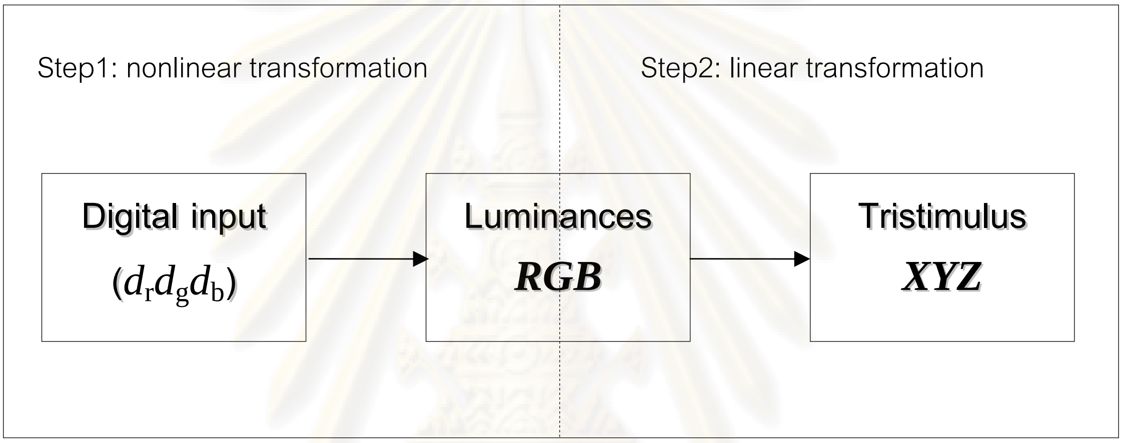


Figure 2-9 CRT display characterisation.

2.1.5.3.1 From Digital Inputs to Luminances

This section defines relationship between digital inputs $d_r d_g d_b$ where the subscripts refer to the red, green and blue channels and linearised RGB outputs. It found that the relationship is a nonlinear as shown in Figure 2-10.

The transformation can be produced by several models such as LIN-LIN2 model, LOG-LOG model, Gamma model, GOG model, GOGO model, and GGO model. For GOG model, the equation was introduced in CIE technical report 122 for characterizing computer-controlled CRT displays in 1996. [31]

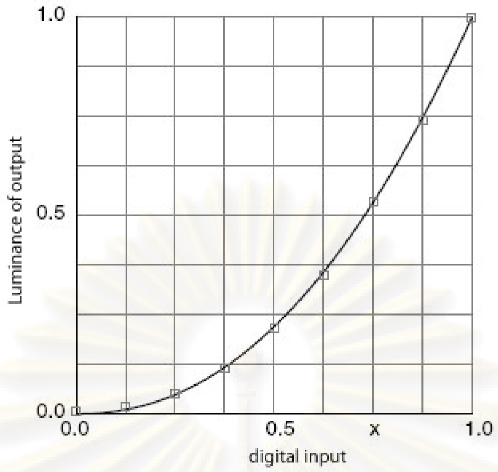


Figure 2-10 Nonlinear relationship between inputs and outputs of CRT monitors. [32]

Berns et al. [33] have derived the relationship based on historical literature and hardware common to digitally controlled CRT displays as given in Equation 2.22 for the red channel. Similar expressions can be written for the green and blue channels.

$$L_{\lambda,\mathrm{r}} = k_{\lambda,\mathrm{r}}\left[a_{\mathrm{r}}\left[(v_{\max}-v_{\min})\left(\frac{LUT_{\mathrm{r}}(d_{\mathrm{r}})}{2^N-1}\right)+v_{\min}\right]+b_{\mathrm{r}}-v_{\mathrm{C,r}}\right]^{\gamma_{\mathrm{r}}}; \quad (2.22)$$

If $v_{\mathrm{C,r}} \le a_{\mathrm{r}}\left[(v_{\max}-v_{\min})\left(\frac{LUT_{\mathrm{r}}(d_{\mathrm{r}})}{2^N-1}\right)+v_{\min}\right]+b_{\mathrm{r}}$, otherwise = 0

LUT represents the video look-up table, N is the number of bits in the digital-to-analog converter (DAC), $v_{\min}$ and $v_{\max}$ are voltages dependent on the computer video signal generator, a_{r} and b_{r} are the CRT video amplifier gain and offset, $v_{\mathrm{C,r}}$ is the cut-off voltage defining zero beam current, γ_{r} is an exponent accounting for the nonlinearity between amplified video voltages and beam currents, $k_{\lambda,\mathrm{r}}$ is a spectral constant accounting for the particular CRT phosphors and faceplate combination, and $L_{\lambda,\mathrm{r}}$ defines the spectral radiance of the red channel. Equation 2.22 is a generic equation in that it considers signal processing common to all computer-controlled CRT displays. [33]

By normalizing radiometric measurements by the maximum radiant output, so Equation 2.22 is reduced to Equation 2.23. [33]

$$L_{\lambda,\mathrm{r}} = L_{\lambda,\mathrm{r}\,\max}\left(k_{\mathrm{g,r}}\left(\frac{LUT_{\mathrm{r}}(d_{\mathrm{r}})}{2^N-1}\right)+k_{\mathrm{o,r}}\right)^{\gamma_{\mathrm{r}}}; \quad (2.23)$$

If $\left(k_{\mathrm{g,r}}\left(\frac{LUT_{\mathrm{r}}(d_{\mathrm{r}})}{2^N-1}\right)+k_{\mathrm{o,r}}\right) \geq 0$, otherwise = 0

Where constants $k_{\mathrm{g,r}}$, $k_{\mathrm{o,r}}$, and γ_{r} are referred to as the system gain, system offset, and system gamma, respectively for red channel. These three parameters will be referred to as the 'GOG' model. $L_{\lambda,\mathrm{r}\max}$ defines the maximum spectral radiance of the red channel for a given CRT set up. [33]

According to a relationship in Equation 2.24, it is useful to define a radiometric scalar, R. [33]

$$L_{\lambda,\mathrm{r}} = RL_{\lambda,\mathrm{r}_{\max}} \quad (2.24)$$

A properly set up display will, in theory, exhibit additivity between its three channels. Thus using the scalars and considering the three channels simultaneously results in Equation 2.25. Similar expressions can be written for the green and blue channels in Equations 2.26 and 2.27, respectively. [33]

$$R = \left(k_{\mathrm{g,r}}\left(\frac{LUT_{\mathrm{r}}(d_{\mathrm{r}})}{2^N-1}\right)+k_{\mathrm{o,r}}\right)^{\gamma_{\mathrm{r}}}; \quad (2.25)$$

if $\left(k_{\mathrm{g,r}}\left(\frac{LUT_{\mathrm{r}}(d_{\mathrm{r}})}{2^N-1}\right)+k_{\mathrm{o,r}}\right) \geq 0$, otherwise = 0

$$G = \left(k_{\mathrm{g,g}}\left(\frac{LUT_{\mathrm{g}}(d_{\mathrm{g}})}{2^N-1}\right)+k_{\mathrm{o,g}}\right)^{\gamma_{\mathrm{g}}}; \quad (2.26)$$

If $\left(k_{\mathrm{g,g}}\left(\frac{LUT_{\mathrm{g}}(d_{\mathrm{g}})}{2^N-1}\right)+k_{\mathrm{o,g}}\right) \geq 0$, otherwise = 0

$$B \quad = \quad \left(k_{\mathrm{g,b}}\left(\frac{LUT_{\mathrm{b}}(d_{\mathrm{b}})}{2^{N}-1}\right)+k_{\mathrm{o,b}}\right)^{\gamma_{\mathrm{b}}}; \tag{2.27}$$

$$\text{if } \left(k_{\mathrm{g,b}}\left(\frac{LUT_{\mathrm{b}}(d_{\mathrm{b}})}{2^{N}-1}\right)+k_{\mathrm{o,b}}\right) \geq 0 \text{, otherwise} = 0$$

2.1.5.3.2 From Luminances to XYZ

After going through nonlinear characteristics of the cathode ray tube, RGB phosphor will emit a light according to a given signal, which is mixed to reproduce a desired colour. According to the Grassman's law of additivity, the mixed colour of RGB channels can be calculated by mixing the tristimulus of three primaries as expressed in Equation 2.28. [31]

$$\begin{aligned} L_{\lambda,\mathrm{pixel}} &= L_{\lambda,\mathrm{r}} + L_{\lambda,\mathrm{g}} + L_{\lambda,\mathrm{b}} \\ &= RL_{\lambda,\mathrm{r_{max}}} + GL_{\lambda,\mathrm{g_{max}}} + BL_{\lambda,\mathrm{b_{max}}} \end{aligned} \tag{2.28}$$

In a matrix notation, it is represented as in Equation 2.29. [31]

$$\begin{bmatrix} L_{\lambda_1} \\ \vdots \\ \vdots \\ L_{\lambda_n} \end{bmatrix}_{\mathrm{pixel}} = \begin{bmatrix} L_{\lambda_1,\mathrm{r_{max}}} & L_{\lambda_1,\mathrm{g_{max}}} & L_{\lambda_1,\mathrm{b_{max}}} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ L_{\lambda_n,\mathrm{r_{max}}} & L_{\lambda_n,\mathrm{g_{max}}} & L_{\lambda_n,\mathrm{b_{max}}} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{2.29}$$

Because of the additive nature of the CRT display, Equation 2.29 can be replaced with a colorimetric definition shown in Equation 2.30. [33]

$$\begin{bmatrix} X_{\mathrm{pixel}} \\ Y_{\mathrm{pixel}} \\ Z_{\mathrm{pixel}} \end{bmatrix} = \begin{bmatrix} X_{\mathrm{r_{max}}} & X_{\mathrm{g_{max}}} & X_{\mathrm{b_{max}}} \\ Y_{\mathrm{r_{max}}} & Y_{\mathrm{g_{max}}} & Y_{\mathrm{b_{max}}} \\ Z_{\mathrm{r_{max}}} & Z_{\mathrm{g_{max}}} & Z_{\mathrm{b_{max}}} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{2.30}$$

If the display is viewed in a lit room resulting in ambient flare reflection off of the CRT's faceplate or as a result of measurable interreflections form neighbouring pixels, this flare must be added into the characterisation, as given in Equation 2.31. [33]

$$\begin{bmatrix} X_{\text{pixel}} \\ Y_{\text{pixel}} \\ Z_{\text{pixel}} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\substack{\text{ambient} \\ \text{flare}}} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\substack{\text{inter-} \\ \text{reflection} \\ \text{flare}}} + \begin{bmatrix} X_{r_{\max}} & X_{g_{\max}} & X_{b_{\max}} \\ Y_{r_{\max}} & Y_{g_{\max}} & Y_{b_{\max}} \\ Z_{r_{\max}} & Z_{g_{\max}} & Z_{b_{\max}} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{2.31}$$

2.2 Literature Reviews

Wright [2] studied a theory of colour psychology and colour harmony. The experiments were stringently researched with positive results and were done across six cultures, by both genders, and all age groups over eighteen years old. He could classify every colour into one of four families, within which every colour harmonises with every other colour in the same family but colours from different families do not harmonise. The colours are divided into cool and warm hues first and then they are subdivided in terms of both saturation and value to four groups. He also divided all humanity into four basic personality types and each personality type has a natural affinity with one colour family.

Burchett [9] studied about colour harmony to clarify the various attributes of colour harmony and identify the vocabulary associated with each, to determine the relative emphasis placed on each attribute, and to establish a basis for a colour harmony conceptual learning model. He collected data and analyzed from twelve books on colour which came from all areas of colour study. He divided the meaning of colour harmony into eight terms: area, association, attitude, configuration, interaction, order, similarity, tone.

Ou and Luo studied about colour harmony for two-colour combinations [34], investigated factors that affected on colour harmony for the combinations [35], and also developed a quantitative model [10]. A psychophysical experiment was carried out to study colour harmony with participation of 17 Chinese students at the University of Derby (11 males and 6 females). The colours consisted of 49 chromatic colours (7 hues: red, orange, yellow, green, cyan, blue, and purple, and 7 tones: vivid, pale, dull, dark, light-greyish, greyish, and dark-greyish) and 5 achromatic colours (white, light grey, medium grey, dark grey, and black). Then 54 colours generated the 1431 colour pairs from CIELAB colour space. Each colour pair was presented against a medium-grey background on a CRT monitor using the GOG model to transform CIE tristimulus values into RGB primaries for displaying in a darkened room. Each observer was asked to indicate how harmonious each colour pair appeared by pressing one of ten buttons represented colour harmony scores. From experimental results, many colour harmony principles were developed, i.e. equal-hue principle: the smaller the chromatic difference, the higher the colour harmony scores; high lightness principle: the larger the lightness sum, the higher the colour harmony scores; moderate lightness difference principle: both too small and too large size of lightness difference would lead to low colour harmony scores; and blue principle: the colour pairs containing bluish colour tended to harmonise. A model of colour harmony was constructed from three colour harmony factors: chromatic effect, lightness effect and hue effect, and the most dominant factor in the model is lightness effect. Their model was tested using an independent psychophysical data set accumulated by Gurura et al. and the result showed a satisfactory predictive performance.

Ou et al. [11] examined how cultures influence viewers' emotional responses and preference to single colours and to colour pairs. Therefore, 123 observers from six countries: Britain, France, Germany, Spain, Sweden and Taiwan took part to assess colour emotion and preference in a psychophysical experiment. In the experiment, 20 single colours and 190 colour pairs were used as the stimuli and four scales including warm-cool, heavy-light, active-passive and like-dislike were used to measure observers' responses. The British and Chinese observers took part in both single-colour and colour-pair sessions, but the others participated in only the session for colour pairs. The experimental results showed that for single colours there was little cultural effect on all the scales except "like-dislike" and the Spanish observers tended to prefer colour pairs with small lightness difference between constituent colours in each pair, while the others tended to prefer colour pairs with large lightness difference.

In the study by Chanay [36] on Colour Harmony, Subjective Appreciation or Ordered Construction?, a set of colour samples, with no functionality, in a neutral context devoid of all symbolic value was considered. The set under observation was composed of three colours of the same size and shape and laid so as all the samples shared a common border. Students had to divide the colour sets into two groups: the beautiful ones and the ugly ones. The result was found that some sets thought as beautiful by someone but as ugly by others and conversely. It should be noted that the difference of brightness of the samples in the beautiful sets was often low. However the colours without any link (hue, brightness, or saturation) between them, but set in a regular geometrical space, benefit from this order and if the vividness of the rhythm was powerful enough, the colours seemed to harmonise.

Sueeprasan and Sato [37] investigated the degree of colour harmony perceived by Thai observers for colour sample displayed on a CRT. A set of 66 colour pairs was generated from 12 single colours which were from 6 major colours (red, green, blue, cyan, magenta, and yellow) with two levels. Each colour pair was presented on a uniform grey background (R=G=B=127) in the centre of the monitor. Each observers was asked to rate the degree of colour harmony for each colour pair using a scale ranging from 0 (disharmonious) to 100 (most harmonious). The results obtained from male and female observers were significantly different, in which female observers tended to give higher colour harmony scores. The pearson correlation between mean visual scores of colour harmony and hue difference revealed that a combination of two colours that were not much different from each other would harmonise and the colour pairs with similar hues (low ΔH^*_{ab}) tended to have high colour harmony scores, in which colour pairs with similar hues looked more harmonious than colour pairs with complementary hues indicated by the paired t test.

Gao and Xin [38] studied about colour harmony of two colours with similar lightness and chroma by analysing two factors, that is, hue difference and single colour preference on colour harmony. The study was conducted using two kinds of basic two-colour patterns which usually are patterns seen in most of colour designs. One was two colours placed side by side (SS pattern) and the other is two colours in center-background relationship (CB pattern). Both of them were displayed on a characterised CRT monitor in a completely dark room and assessed by twenty subjects, 10 males and 10 females, ranging from 25 to 35 years old. The result of observer repeatability and agreement indicated that colour harmony was an unequivocal and stable feeling for most people. The relationships between colour harmony and hue difference were completely opposite in two kinds of pattern, that is, similar hues were considered to be harmonious in SS patterns but unharmonious in CB patterns, while the complementary colour pairs were on the contrary. Using multiple regression analysis, it was found that hue difference was the main factor on colour harmony for two kinds of patterns, while the influence of single colour preference was very small.

Mahyar et al. [39] investigated complementary colour harmony in CIELAB colour space to define the complementary relationships between hues to be able to produce a colour wheel that is specifically designed to represent them by using psychophysical experiments. Two colour patches placed side by side were displayed against a mid-grey background in the centre of the CRT in a darkened room. One of the colour patches was fixed (standard hue) and the hue of the other (test hue) could be varied by observers who were asked to vary the test hue until it was in maximal (hue) contrast to the standard hue. Twenty standard colours distributed around the hue circle at 18 degrees intervals were fixed at $L^* = 52$ and $C^* = 30$. The results were found in some ranges of the standard hue that the observers' colour selection was reasonably close to that predicted by opposite relations in CIELAB space. So it would seem to indicate that opposite relationships in CIELAB do not accurately predict complementary relationships (at least not for all hues).

Gurura and MacDonald [40] studied about gender differences in perception of saliency and colour harmony. The experiment was conducted with twelve observers (7 males and 5 females) looking into a viewing cabinet under D50 illumination. Sixteen different background colours were selected in size of A0 and the same sixteen colours were also used for the foregrounds in a square of dimensions 5x5 cm Each observer was asked to make two judgements: salient/neutral/non-salient; and harmonious/neutral/disharmonious. The results were found that male observers perceived all foreground as being relatively more salient than females except brown and purple and both genders were almost unanimous about black as background. For colour harmony, the colours blue, pink, and purple (against all backgrounds) were perceived less harmonious by female than by male observers, but the reverse was true for brown. They liked grey and (especially) white as backgrounds, and male observer also liked black and yellow.

CHAPTER III

METHODOLOGY

3.1 Apparatus

3.1.1 Spectroradiometer

Model	: Konica Minolta CS-1000A
Wavelength range	: 380-780 nm
Spectral bandwidth	: 5 nm
Wavelength resolution	: 0.9 nm / pixel
Display wavelength bandwidth	: 1 nm
Wavelength precision	: + 0.3 nm (median wavelength: 546.1 nm)
Luminance accuracy	: + 2%, + 1 digit
Chromaticity accuracy	: + 0.0015x, + 0.001y
Luminance repeatability	: + 0.1%, + 1 digit
Chromaticity xy repeatability	: + 0.0002
Polarization error	: Less than 5% (400-780 nm)

3.1.2 CRT Monitor

Model	: LACIE electron 22blue IV
CRT type	: DIAMONDTRON NF – Aperture grille
Dimensions	: 19.4 in x 19.5 in x 18.6 in (H x W x D)
Weight	: 67.2 lbs
Enclosure Colour	: Blue
Diagonal size	: 22.0 in (20.0 in viewable)
Dot pitch	: 0.24 mm
Max resolution	: 2048 x 1536 / 86.0 Hz
	: 1280 x 1024 (recommended resolution)

3.1.3 Laptop Computer

Model	: Fujitsu Lifebook s6240
System	: Microsoft Windows XP Home Edition

Version 2002 Service Pack 3

CPU : Intel® Pentium® M processor 1.73 GHz

RAM : DDR2 2 GB

3.1.4 VGA Cable both end male<>male DB 15 pins

3.1.5 Software

Simulation Program : knt_lab run on .NET Framework

Microsoft .NET Framework : Version 3.5 Service Pack 1
(required at least v2.0.50727)

Spreadsheet : Microsoft Office Excel 2003

3.2 Observers

Twenty Thai observers, including 10 males and 10 females ranging in age from 21 to 30 years old, took part in visual experiments (there were exactly 30 observers: 10 observers participated in both lightness and chroma experiments, and 20 observers participated in only lightness or chroma section). Among observers were 28 students in Photographic Science and Printing Technology, one student in Industrial Design, and one employee from Communication Company. Each observer had normal colour vision examined by Ishihara Test.

3.3 Experimentation

The objective of this research was to evaluate the degrees of colour harmony for two-colour combinations. A series of colour pairs was generated to display on a CRT monitor. Observers assessed these colour pairs and quantified the degrees of colour harmony for each pair presented. The visual results obtained from all observers were then analysed statistically.

Consequently, the experimentation of this study was divided into 3 parts. The first part was the pre-experiment which included preparation processes in which the colour stimuli as well as the CRT monitor were prepared. The second part involved experimental procedures whereby the visual experiments were carried out, and the last part was the analysis of observers' results. The detailed descriptions of each part are given in Sections 3.3.1, 3.3.2, and 3.3.3, respectively. All processes of this experimentation are shown in Figure 3-1.

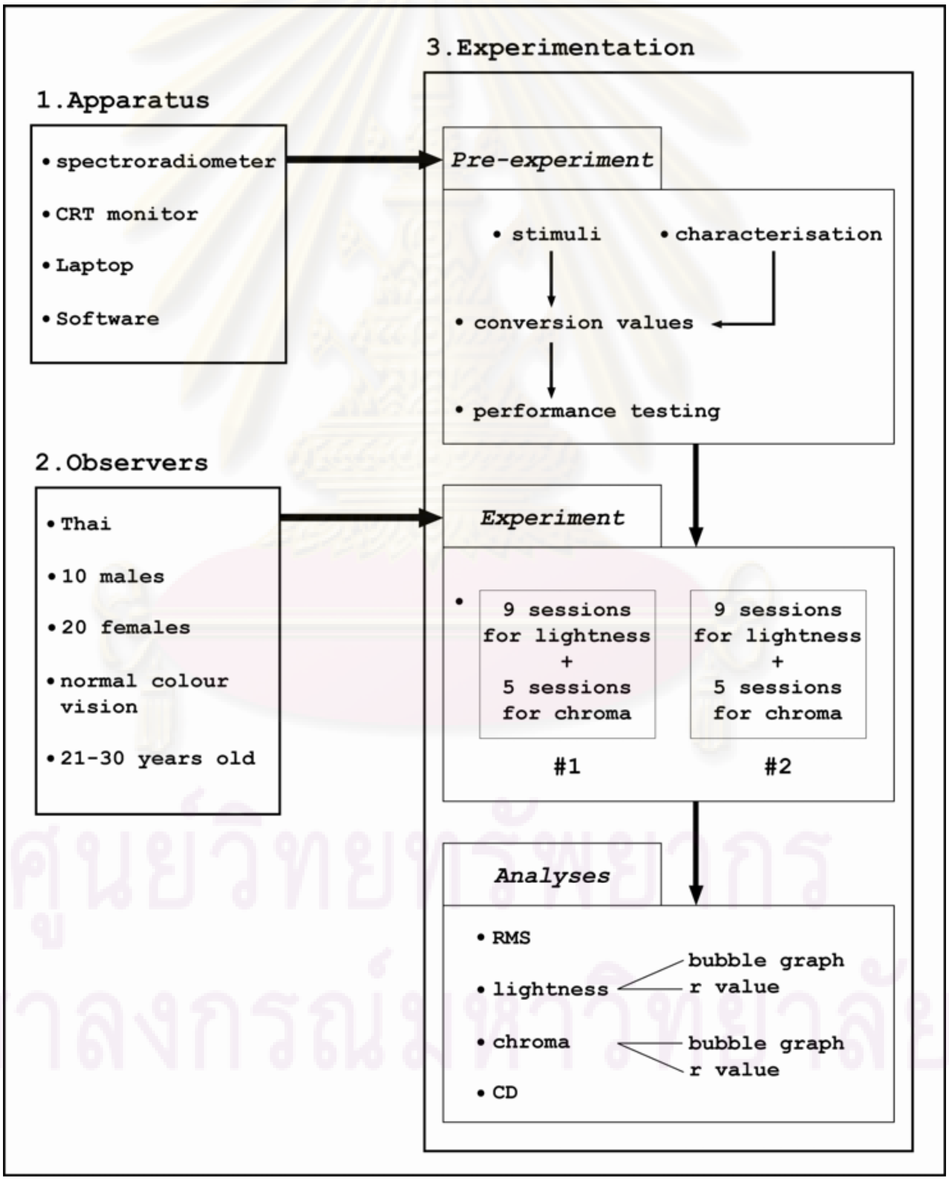


Figure 3-1 Overview of experimentation in this study.

3.3.1 Pre-Experiment

A process of experimental preparation is comprised of four parts, as illustrated in Figure 3-2. The first part was a process of stimuli preparation, in which each sample was assigned colour in terms of CIECAM02 JCh. The second part was a monitor characterisation process. The third was a transformation of JCh data to digital counts ($d_r d_g d_b$) via the monitor characterisation model found from the previous process. This process was done to ensure that colours assigned from the first process were accurately displayed on the CRT monitor under study. The accuracy of colour transformations was evaluated in the last process by means of colour differences between measurement data of displayed colours and the assigned colour data. These four processes are explained in details in Sections 3.3.1.1, 3.3.1.2, 3.3.1.3, and 3.3.1.4, respectively.

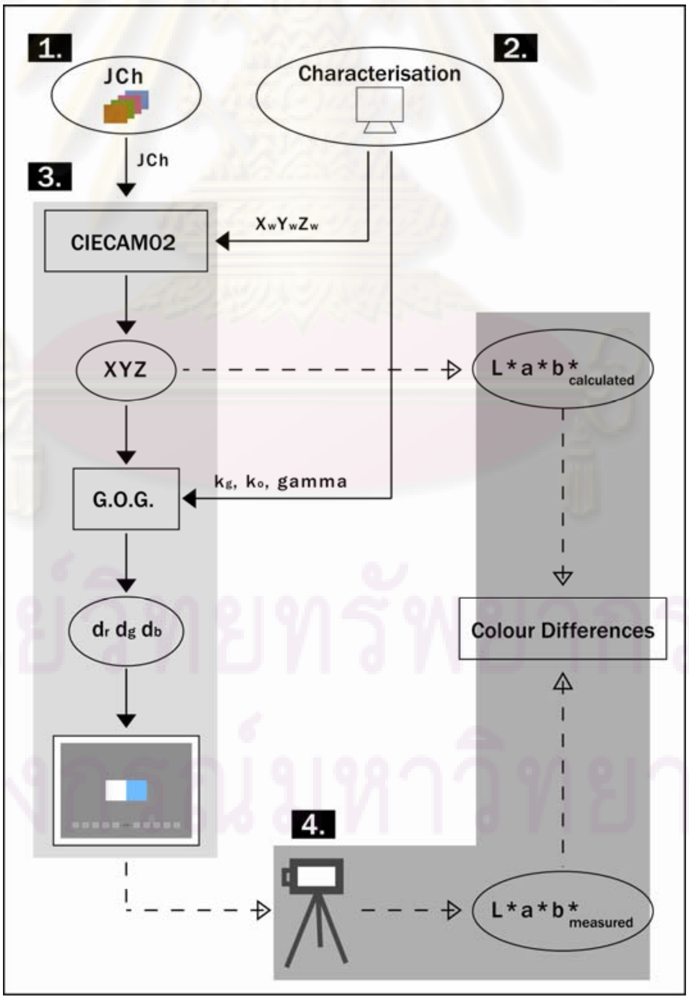


Figure 3-2 Four processes in the pre-experiment.

3.3.1.1 Design of Colour Samples

The present study aimed to investigate an impact of lightness and chroma of colour pairs on the degree of perceived colour harmony; therefore, colour samples used in this experiment were divided into two sets. Both of them had the same six primary hues which were selected systematically from CIECAM02 colour space. The six main hues consisted of red (hue angle = 0^{o}), orange (hue angle = 60^{o}), yellow (hue angle = 120^{o}), green (hue angle = 180^{o}), blue (hue angle = 240^{o}), and purple (hue angle = 300^{o}), as shown in Figure 3-3. Each colour sample was determined in terms of "JCh" (J=lightness, C=chroma, h=hue angle) CIECAM02 colorimetric values.

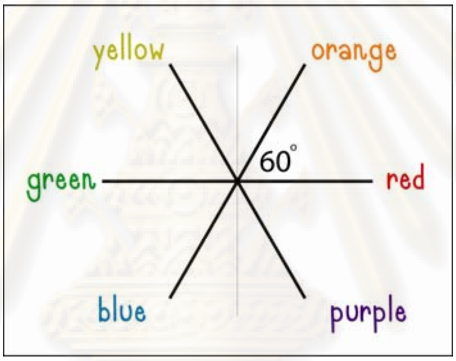


Figure 3-3 Six primary hues.

To investigate the impact of lightness attribute, all colour samples in this group had an equal chroma (C = 15) but varied in seven levels of lightness. Each hue consisted of 7 lightness levels (J): 25, 35, 45, 55, 65, 75, and 85. Thus 42 colour samples were made up and 861 colour pairs were then generated from all possible two-colour combinations. Figure 3-4 shows the 42 single colour samples: (a) the distributions of the colour samples in tomography of CIECAM02 colour space which each plane had an equal lightness and (b) the physical colour samples in RGB mode by R, O, Y, G, B, and P, represented the six primary hues and the numbers of 1 to 7 are the levels of lightness (1=low lightness: J=25 and 7=high lightness: J=85).

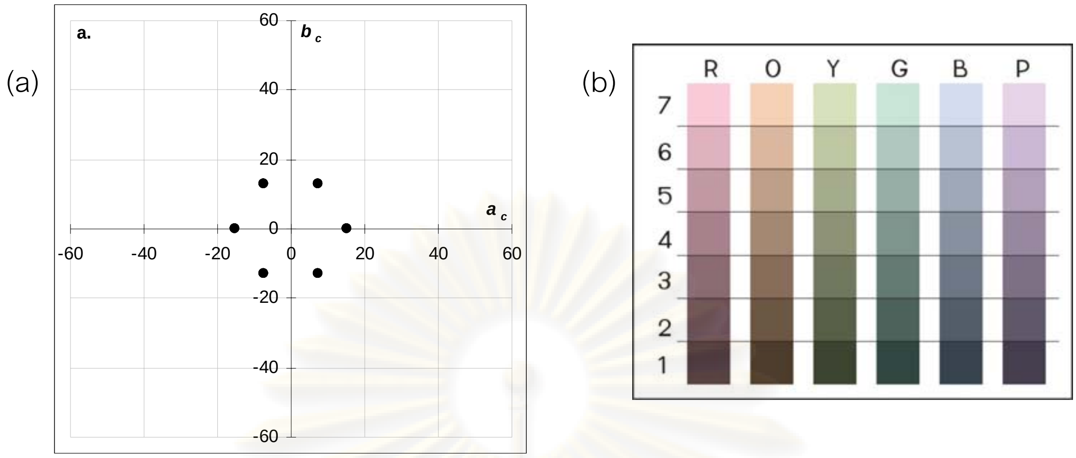


Figure 3-4 The 42 samples in the lightness group (a) CIECAM02 a_cb_c (b) RGB mode.

In the case of chroma attribute, all of colour samples in this group had an equal lightness (J = 50) but changed in the levels of chroma for 5 levels: 5, 15, 25, 35, and 45, yielding 30 chromatic colour samples (6 hues x 5 chroma levels). Three achromatic colour samples: white, grey, and black, were included. Therefore 33 single colour samples were in this group and generated a set of 528 colour pairs from all possible combinations. The distribution of these 33 colour samples in CIECAM02 colour space is shown in Figure 3-5 (a) and the RGB colour mode of these samples is also shown in Figure 3-5 (b) by R, O, Y, G, B, and P, represented the six primary hues and BK, GY, WE the three achromatic colours and the numbers of 1 to 5 are the levels of chroma (1=low chroma: C=5 and 5=high chroma: C=45).

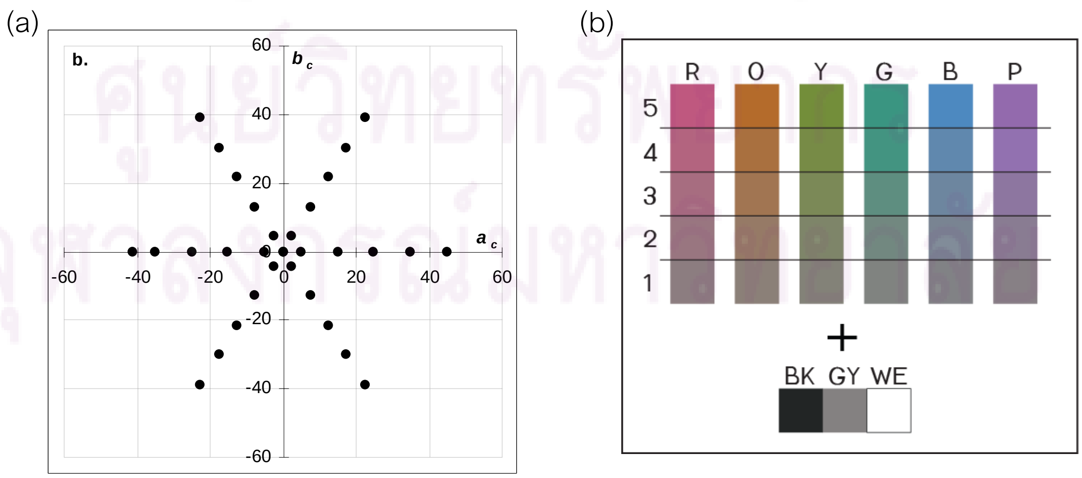


Figure 3-5 The 33 samples in the chroma group (a) CIECAM02 a_cb_c (b) RGB mode.

Each colour pair in both groups was made of two 2.25” x 2.25” single colour patches. They were presented side by side without a gap against a uniform grey background in the centre of LACIE electron 22blue IV monitor with its white point set to D65. Figure 3-6 summarises the steps in this process.

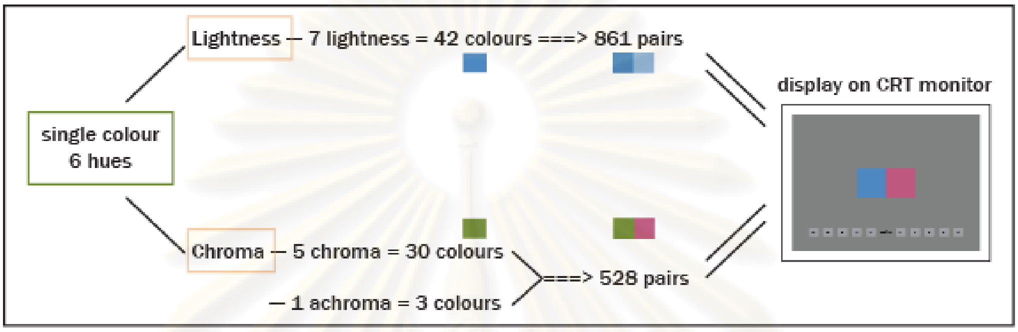


Figure 3-6 All of the steps in design of colour samples.

3.3.1.2 Monitor Characterisation

In order to accurately display the assigned colours on the CRT monitor, the monitor was characterised using the GOG model. Moreover, in order to eliminate the CRT monitor’s flare caused by circumstance in the experimental room, the monitor characterisation and the visual assessments were conducted in a darkened room. A set of 17 grey levels together with red (255-0-0), green (0-255-0) and blue (0-0-255) colour patches were presented on a uniform grey background (R=G=B=128) in the centre of monitor’s screen with its white point set to D65.

A spectroradiometer was stood in front of the CRT monitor with the distance around 90 cm and all samples were measured one by one in terms of “xyY”. The GOG model was then implement using a spreadsheet available in Microsoft Excel and the model parameters: k_g, k_o, and gamma (γ) for each channel, were solved. Figure 3-7 shows the set-up of this process.

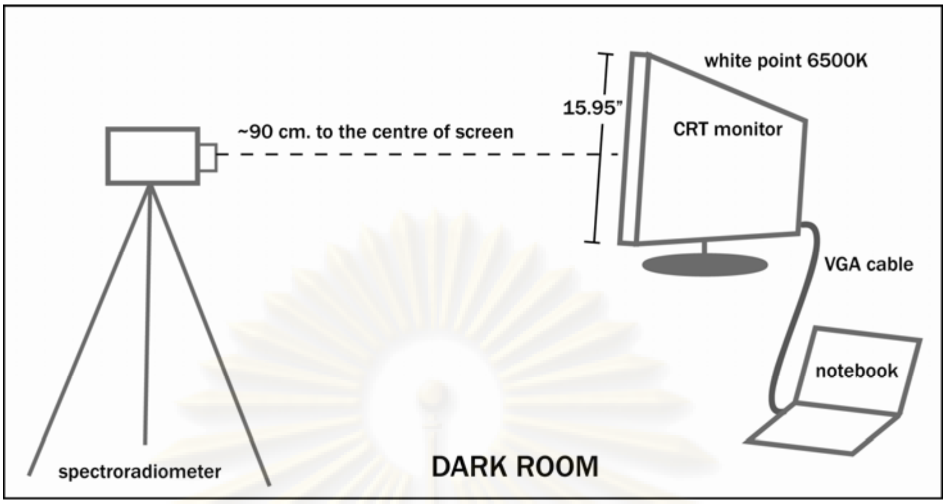


Figure 3-7 A set-up for monitor characterisation.

3.3.1.3 Conversion of Colour Values

This process was done for converting “JCh” values described in Section 3.3.1.1 to monitor’s digital counts “$d_r d_g d_b$”, so that colour samples could be correctly displayed on the CRT monitor in the dark surround. In so doing, as shown in Figure 3-2, two computational steps were required. First, the JCh values were converted to XYZ tristimulus values via CIECAM02 appearance model. This step was carried out due to the fact that CIECAM02 could predict corresponding colours under dis-similar viewing conditions. The GOG model implemented in the monitor characterisation process (Section 3.3.1.2) was then used to convert XYZ values to digital data for red, green, and blue channel. With these digital data, colour samples were able to be displayed with respect to colour appearance desired.

3.3.1.4 Performance of Monitor Characterisation

The performance of monitor characterisation determines the accuracy of displayed colours with respect to the desired colours. To evaluate the performance of the characterisation model, colour difference (ΔE) between calculated L*a*b* values (from XYZ obtained from CIECAM02, see Figure 3-2) and measured L*a*b* values (calculated from XYZ obtained from measuring displayed colours with a spectroradiometer). The small the ΔE value, the better the model’s performance. This means that displayed colours closely match to the colours initially designed for investigation.

3.3.2 Experimental Procedures

Before conducting actual visual assessments, each observer was given a definition of colour harmony. Observers were instructed to regard the term “colour harmony” as “colours that go well together and look pleasing to the eye”. Observers were also trained how to use the simulation program for displaying colour pairs and recording observers’ results. At the beginning of each experimental session, observers sat on a chair (situated in the same position of the spectroradiometer when doing colour measurements) in front of the CRT monitor with its white point set to illuminant D65, and adapted their eyes in the darkened room for 10 seconds by looking at the CRT monitor which presented a uniform grey background surrounded with 2-cm white area. Having done so, observers assessed the first colour pair presented in the centre of screen and indicated their judgements as to how harmonious that colour pair appeared.

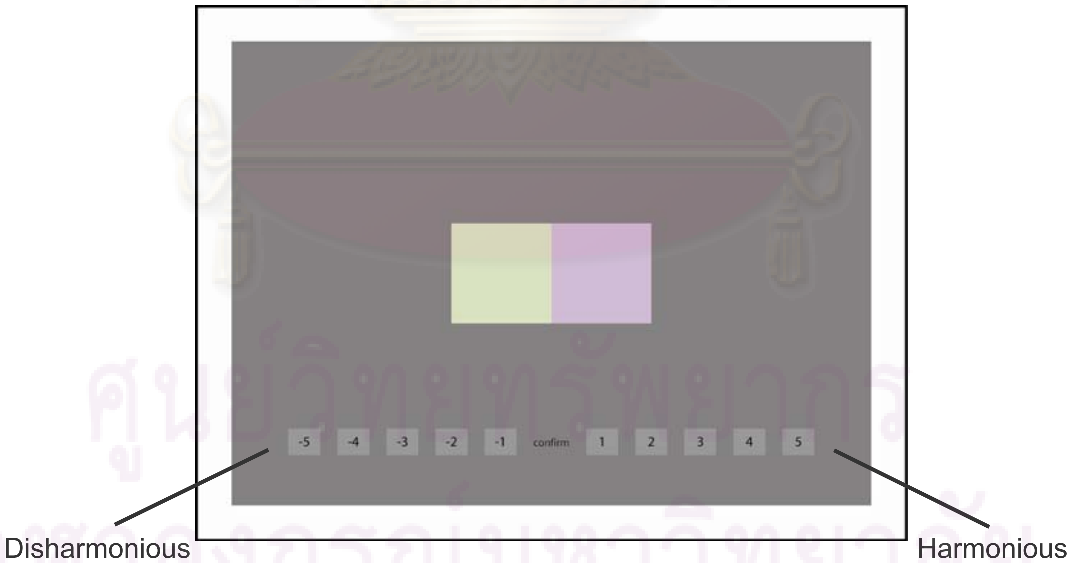


Figure 3-8 Screen layout of the experiment.

As can be seen in Figure 3-8, ten buttons were arranged in a line under the colour pair. Each button had a score value on an interval scale. These buttons were separated into 2 sides: disharmonious (on the left side of screen) and harmonious (on the right one). A set of negative numbers (-5 to -1) represented disharmonious (-5 means completely disharmonious and -1 means just disharmonious), whereas a set of positive numbers (1 to 5) represented harmonious (1 means just harmonious and 5 means completely harmonious).

After assessing the colour pair and giving visual scores by pressing on one button, the observers could change their mind and press on other number buttons. The results will be recorded and cannot be changed when observers press on a Confirm button (the middle one). Next, the observers were presented with the grey screen again for two seconds to avoid after-image effect and then the next colour pair was shown up. The observers continued running the experiment until the last colour pair was displayed and disappeared. All of the colour pairs were presented individually in a random sequence. An illustrated summary of experimental steps for screen's display is shown in Figure 3-9.

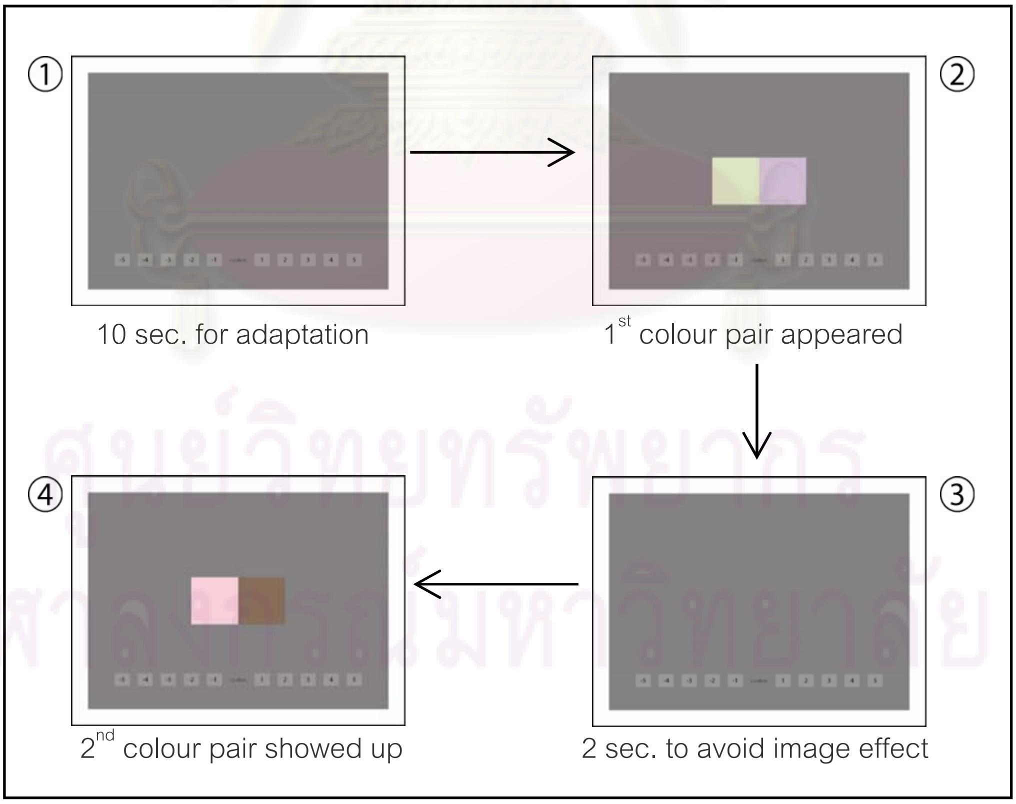


Figure 3-9 Sequence of colour pair's presentation.

For investigating the lightness factor, 861 colour pairs were randomly separated to 9 experimental sessions. Each session contained 100 colour pairs, except for the 9^{th} session that contained 61 colour pairs. To investigate the chroma factor, 528 colour pairs were also randomly divided into 5 sessions. Two sessions consisted of 105 colour pairs and the rest sessions consisted of 106 colour pairs. For each session, each observer spent approximately 15-20 minutes and they had to repeat all of the sessions two times in order to examine the consistency of the answers.

3.3.3 Analysis of the Visual Results

Twenty observers, each repeated twice, completed the visual assessments of 861 colour pairs for lightness and 528 colour pairs for chroma factor. Hence, a great number of experimental data was obtained. Methods of analysis for the visual results are given below.

1. Due to the fact that the colour samples were selected systematically according to CIECAM02, the colorimetric values of J, C and h, as are in CIECAM02, were used for analysis.

2. For each colour pair, the visual scores for each observer were averaged from the observer's first and second responses. The final visual scores representing the degree of colour harmony perceived by observers were averaged from all observers' experimental results.

3. Bubble charts provided by Microsoft Excel were employed to present the visual data with their relevant colorimetric values.

4. The root mean squared (RMS) between observers' first and second responses (intra-observer agreements), and between each individual observer's result against the panel results (averaged from all observers) (inter-observer agreements) were calculated to indicate the variation of the visual results. The RMS value is calculated by Equation 3.1 for intra-observer agreement and Equation 3.2 for inter-observer agreement.

$$RMS = \sqrt{\frac{\sum (x_i - y_i)^2}{N}} \tag{3.1}$$

$$RMS = \sqrt{\frac{\sum (x_i - \overline{x_i})^2}{N}} \tag{3.2}$$

For intra-observer agreements, x_i represents the colour harmony scores given by an observers' first response for stimulus i and y_i represents the colour harmony scores given by the same observers' second response. In the case of inter-observer agreements, x_i represents the average colour harmony scores from two responses given by an observer for stimulus i, $\overline{x_i}$ represents the mean colour harmony scores of all observers for stimulus i, and N is the number of stimuli. The mean RMS from all observers was used to represent the degree of observer agreements.

5. The measure of correct decision (CD) [10] was used to quantify the performance of the existing colour harmony principles with regard to the experimental data obtained in this study. The CD value can be calculated as follows.

$$\mathrm{CD} = \frac{\sum_i c_i}{N'} \tag{3.3}$$

In Equation 3.3, c_i represents the percentage of observers whose harmony judgements for colour pair i (in terms of the decision between "harmonious" and "disharmonious") agreed with a given colour harmony principle; N is the number of colour pairs.

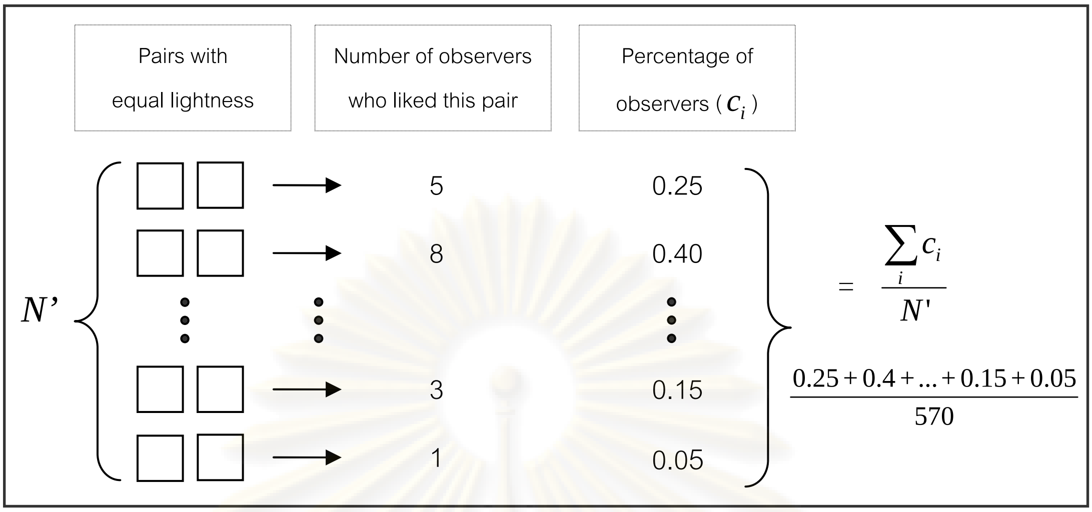


Figure 3-10 Method of measuring correct decision.

Figure 3-10 shows an example of CD calculation. Taking the principle of equal lightness as an example, colour pairs having the same lightness levels are selected. According to this principle, these colour pairs should be harmonious. Thus the numbers of observers who like these pairs are recorded, i.e. agreement between visual results and the principle under study. The CD value can then be calculated.

6. Relationships between the colour harmony scores and the two attributes (lightness and chroma) of colour pairs were analysed using Linear Correlation Coefficient (r value) [41]. The r value ranges between -1 and 1, which measures the degree to which two variables are linearly related. If there is perfect linear relationship with positive slope between the two variables, the r value will be 1; if there is positive correlation, whenever one variable has a high (low) value, so does the other. If there is a perfect linear relationship with negative slope between the two variables, the r value will be -1; if there is negative correlation, whenever one variable has a high (low) value, the other has a low (high) value. A correlation coefficient of zero means that there is no linear relationship between the variables.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Testing of the CRT Monitor

4.1.1 Variables in Pre-Experiment

In the process of experimental preparation, the CRT monitor used in the study was characterised using the GOG model. The CIECAM02 colour appearance model was implemented to convert JCh values to XYZ values. The model variables obtained from characterising the CRT monitor, as well as variables required in CIECAM02 are summarised in Table 4-1. $X_wY_wZ_w$ are reference white of the monitor. L_A is luminance of adapting field. Y_b is background factor. The surround condition parameters were those of dim surround. k_g, k_o, and γ are the system gain, offset, and gamma for each channel of the CRT monitor.

Table 4-1 The variables in the pre-experiment.

Variable	Value
X_w, Y_w, Z_w	94.02, 100.00, 105.21
L_A (cd/m^2)	20.12
Y_b	20.0
Dim surround (c, N_c, F)	0.59, 0.9, 0.9
For red ($k_{g,r}$, $k_{o,r}$, γ_r)	0.9895, 0.0105, 2.21859
For green ($k_{g,g}$, $k_{o,g}$, γ_g)	1.0325, -0.0325, 2.06923
For blue ($k_{g,b}$, $k_{o,b}$, γ_b)	1.0420, -0.0420, 2.03545

As a result of doing the experiment in the darkened room in order to avoid some effects from the CRT monitor's flare, the CIECAM02 colour appearance model was chosen to use in the conversion of colorimetric process. This is because the model can predict corresponding colours under such condition and it is the model recommended by CIE for correctly predicting corresponding colours when viewing conditions vary.

4.1.2 Monitor's Performance

There are many properties of monitor that should be tested before characterisation; however, this research tested only the temporal stability because it is important to know when the experiment should be started after turning on the monitor. The test was done by displaying white image on the screen and measuring luminance from the monitor using a spectroradiometer, and then measured it every 3 minutes until 45 minutes and every 15 minutes until 4 hours. The luminance of the monitor was stable when the time passed around 40 minutes as shown in Figure 4-1. Hence, before conducting the visual assessment the CRT monitor was turned on for 40 minutes to warm up and get to the stability state. The luminance values obtained from the test can be found in Appendix A. For the other properties, such as spatial uniformity, the test is not necessary because all of the colour pairs were displayed at the same position and they were also randomized.

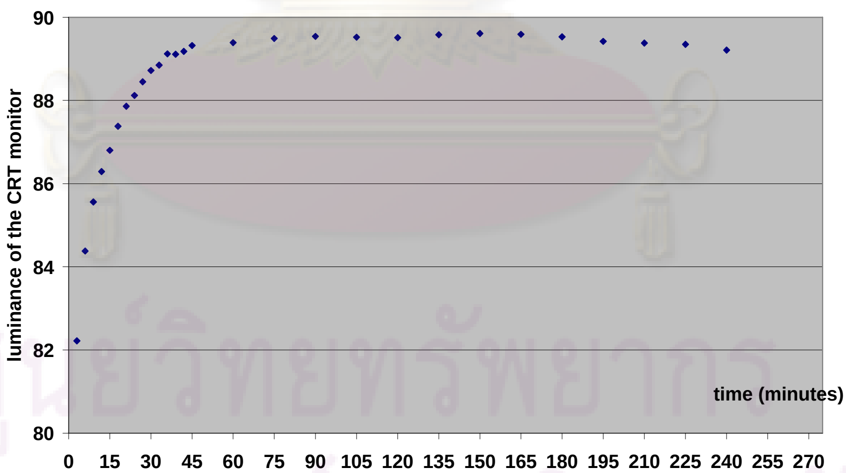


Figure 4-1 The luminance of the CRT monitor.

Regarding the colour differences testing process in Section 3.3.1.4 (the dark grey area in Figure 3-2), the mean colour difference (ΔE) between $L^*a^*b^*_{calculated}$ values (calculated XYZ via CIECAM02) and $L^*a^*b^*_{measured}$ values (measurement of displayed colours) was 1.03ΔE for lightness colour samples group (with a range of 0.12ΔE –

3.23ΔE) and 1.15ΔE in chroma group (0.62ΔE – 3.01ΔE). The results indicated that this CRT monitor had a very good performance and accuracy to display the desired colour samples.

All of the samples were selected from CIECAM02 colour space; thus, in order to display colour samples on the monitor their JCh values need to transform to XYZ first and then to d_r, d_g, and d_b. The values of d_r, d_g, and d_b for each colour sample can be found in Appendix B.

4.2 Reliability of Visual Results

Twenty observers assessed a series of colour pairs and quantify its colour harmony using an integer scale ranging from -5 to 5. The scores given by observers matched observers' feelings after seeing the colour pairs and are called colour harmony scores. The visual scores depended on colour harmony of colour pairs, personal preferences, emotion, and feeling.

The colour harmony scores averaged from 20 observers were used to represent the perceived colour harmony of each colour pair. Since the variation of observers' results could affect the averaged results, reliability of the visual data was tested by means of the root mean squared (RMS) value (see Equations 3.1 and 3.2, Section 3.3.3).

4.2.1 Intra-Observer Agreement

Each observer repeated all experiments twice and the variation between the first and second responses was examined to determine the reliability of visual results. The differences between observers' first and second responses were calculated in terms of the RMS values. Table 4-2 summarises the results for each experimental group of samples (lightness and chroma), averaged from each observer group (female and male) and from all observers. It was found that the agreements within themselves of female observer were better than the male's results for all experimental groups, showing that female observers gave more consistent responses. This could be because female observers could concentrate on the experiments and control their emotion better than male observers.

Table 4-2 Results for intra-observer agreement.

RMS	*Female*	*Male*	*All Observers*
Lightness group	2.19	2.34	2.27
Chroma group	2.03	2.25	2.14

Even though the intra-observer agreements of female observers were better than those of male observers, their results were not much different. Furthermore, the results for lightness group and chroma group were very similar, with the RMS values of approximately 2. Hence, it could be considered that all observers gave consistent results and they are reliable. Nevertheless, the method of independent t-test was employed to verify the significant difference between female and male RMS results. The hypotheses are as follows.

$$\mathrm{H}_0 \quad : \quad \mu_1 = \mu_2$$

$$\mathrm{H}_1 \quad : \quad \mu_1 \neq \mu_2$$

Where H_0 , the null hypothesis, represents that the population means are equal and H_1, the alternative hypothesis, represents that the population means are different. The null hypothesis will be accepted at the 0.05 level of significance or with the 95% confidence interval when the computed t-value is equal or lower than the critical t-value. When the null hypothesis is accepted, it means the agreement from female and male is no significant difference with the 95% confidence. If the computed t-value is upper than the critical t-value, the null hypothesis will be rejected or the alternate hypothesis will be accepted. That means there is a significant difference between the genders.

Table 4-3 A statistical analysis, using an independent t-test, for intra-observer agreements.

t-Test: Two-Sample Assuming Unequal Variances	intra-observer agreements			
	LIGHTNESS GROUP		CHROMA GROUP	
	female	*male*	*female*	*male*
Mean	2.1912	2.3419	2.0258	2.2531
Variance	0.0948	0.2963	0.0640	0.3033
Observations	10	10	10	10
Hypothesized Mean Difference	0		0	
df	14		13	
t Stat	-0.7621		-1.1859	
P(T<=t) one-tail	0.2293		0.1285	
t Critical one-tail	1.7613		1.7709	
P(T<=t) two-tail	0.4587		0.2569	
t Critical two-tail	2.1448		2.1604	

Table 4-3 shows the results of the hypothesis test. It can be seen that the t stat values (blocked values) are lower than the critical t-values (highlighted values) for both lightness and chroma groups of samples. Thus the null hypothesis is accepted, meaning that there are no significant differences between the genders in terms of agreements within themselves for both lightness and chroma attributes with the 95% confidence.

4.2.2 Inter-Observer Agreement

The inter-observer agreement demonstrates how well all the observers agree with one another. Each individual observer's data were compared with the panel results (averaged from all observers). Table 4-4 summarises the results for each experimental group of samples (lightness and chroma), averaged from each observer group (female and male) and from all observers. It was found that the agreements with all observers of female observer were better than the male's results for all experimental groups. The results for lightness group were slightly better than those of chroma group. However, overall results showed not much different between gender groups as well as experimental groups and the RMS values were approximately of 2.

Table 4-4 Results for inter-observer agreement.

RMS	*Female*	*Male*	*All Observers*
Lightness group	1.92	1.95	1.93
Chroma group	2.06	2.28	2.17

Therefore, the method of independent t-test was employed to verify the significant difference between female and male RMS results. The hypotheses are the same as in Section 4.2.1.

Table 4-5 A statistical analysis, using an independent t-test, for inter-observer agreements.

t-Test: Two-Sample Assuming Unequal Variances	inter-observer agreements			
	LIGHTNESS GROUP		CHROMA GROUP	
	female	*male*	*female*	*male*
Mean	1.9240	1.9458	2.0589	2.2839
Variance	0.1182	0.1385	0.3514	0.3730
Observations	10	10	10	10
Hypothesized Mean Difference	0		0	
df	18		18	
t Stat	-0.1359		-0.8360	
P(T<=t) one-tail	0.4467		0.2071	
t Critical one-tail	1.7341		1.7341	
P(T<=t) two-tail	0.8934		0.4141	
t Critical two-tail	2.1009		2.1009	

Table 4-5 shows the results of the hypothesis test. It can be seen that the t stat values (blocked values) are lower than the critical t-values (highlighted values) for both lightness and chroma groups of samples. Thus the null hypothesis is accepted, meaning that there are no significant differences between the genders in terms of agreements with all observers for both lightness and chroma attributes with the 95% confidence.

4.3 Results from Visual Experiments

Regarding the visual assessments, all observers were instructed to determine the scores of colour harmony for each colour pair that was presented in the size of 4.50" x 2.25" (width x height). During the assessments, they were also inquired on what ground they based their judgements on colour-harmony scores. It was found that the main reason for their decisions was colour preferences in the single colour. For example, if the observers did not like one patch of the colour pair, they tended to give a negative score for it, or if they liked the two colours of that colour pair, they inclined to give a positive score. The visual scores of each colour pair were calculated from the answers of all observers.

4.3.1 The Best and Worst Harmonious Colour Pairs

Based on 20 observers (10 females and 10 males) between the ages of 21 and 30, the average scores for all the colour pairs were calculated and were rearranged in sequence of harmonious pairs for lightness, and chroma group. The results of the top ten best and the top ten worst of the 861 colour pairs in the lightness group are shown in Table 4-6 and the result, for the chroma group (528 pairs in total) in Table 4-7. Column "#1" and "J1, C1, h1" represent the left colour patch of colour pairs and their colour values, Column "#2" and "J2, C2, h2" represent the right colour patch of colour pairs and their colour values. Column "Avg scores" is the average colour harmony scores of each colour pair.

The codes given under Column #1 and #2 could be helpful in discussing the results. There are two types of the codes: letters and numbers. The letters, the initial of the codes, consisted of "R", "O", "Y", "G", "B", "P", "BK", "GY", and "WE", meaning red, orange, yellow, green, blue, purple, black, grey, and white (the six primary hues and the three achromatic colours), respectively. The numbers followed by the letters are used to identify the 7 levels of lightness (J=25, 35, 45, 55, 65, 75, and 85), for instance, "R1" means the red with very low lightness (J=25), "B5" means the blue with pretty high lightness (J=65), "G7" means the green with very high lightness (J=85). In the case of chroma group of samples, the numbers represent the 5 levels of chroma (C=5, 15, 25, 35, and 45), for example, “Y5” means the yellow with very high chroma (C=45), “O1” means the orange with very low chroma (C=5).

Table 4-6 The top ten best and worst colour pairs for lightness group of samples.

	#1	#2	J1	C1	h1	J2	C2	h2	Avg scores
	P5	R7	65	15	300	85	15	0	2.63
	P4	P7	55	15	300	85	15	300	2.40
	P5	P7	65	15	300	85	15	300	2.35
	O1	O6	25	15	60	75	15	60	2.33
	G4	G6	55	15	180	75	15	180	2.30
	R5	P6	65	15	0	75	15	300	2.28
	P4	P6	55	15	300	75	15	300	2.23
	G6	Y7	75	15	180	85	15	120	2.18
	R4	R6	55	15	0	75	15	0	2.18
	Y4	Y6	55	15	120	75	15	120	2.15
	Y4	Y7	55	15	120	85	15	120	2.15
	O2	O7	35	15	60	85	15	60	2.15
.	.	.	.	.	.	.	.	.	.
	P1	O2	25	15	300	35	15	60	-2.35
	Y1	P2	25	15	120	35	15	300	-2.35
	Y4	B4	55	15	120	55	15	240	-2.38
	O1	P1	25	15	60	25	15	300	-2.40
	Y2	B2	35	15	120	35	15	240	-2.43
	O1	B1	25	15	60	25	15	240	-2.48
	O1	G1	25	15	60	25	15	180	-2.53
	Y1	B1	25	15	120	25	15	240	-2.65
	G1	P3	25	15	180	45	15	300	-2.78
	Y1	P1	25	15	120	25	15	300	-2.80
	R1	O1	25	15	0	25	15	60	-3.18

From the Table 4-6, the best harmonious pair was comprised of “P5” and “R7” with an average score of 2.63, and the worst harmonious pair was comprised of “R1” and “O1” with an average score of -3.18. It can be seen that the top ten best harmonious pairs contain at least one single colour in the pair with high level of lightness, mostly around the 6th (J=75) or 7th (J=85) level. On the other hand, the top ten worst pairs contain one or two colours with low lightness level, mostly the 1st (J=25) level. It should be noted that the observers thought that the colour pairs with high lightness were more harmonious than pairs with low lightness. In other words, they mostly prefered the colour pairs with high lightness to those with low lightness.

Table 4-7 The top ten best and worst colour pairs for chroma group of samples.

	#1	#2	J1	C1	h1	J2	C2	h2	Avg scores
	B5	WE	50	45	240	100	0	0	2.33
	Y5	WE	50	45	120	100	0	0	2.25
	B4	WE	50	35	240	100	0	0	2.25
	BK	WE	15	0	0	100	0	0	2.18
	R5	WE	50	45	0	100	0	0	2.18
	R5	B5	50	45	0	50	45	240	2.13
	P3	R4	50	25	300	50	35	0	2.05
	B5	BK	50	45	240	15	0	0	2.03
	R4	BK	50	35	0	15	0	0	2.00
	P4	B5	50	35	300	50	45	240	1.95
	R5	G5	50	45	0	50	41	180	1.93
	P4	WE	50	35	300	100	0	0	1.93
	R4	WE	50	35	0	100	0	0	1.93
	G4	WE	50	35	180	100	0	0	1.80
	R4	G4	50	35	0	50	35	180	1.80
	R4	B4	50	35	0	50	35	240	1.80
.	.	.	.	.	.	.	.	.	.
	G1	O4	50	5	180	50	35	60	-1.58
	P5	GY	50	45	300	50	0	0	-1.73
	P4	GY	50	35	300	50	0	0	-1.73
	Y1	P1	50	5	120	50	5	300	-1.73
	O1	B1	50	5	60	50	5	240	-1.73
	B1	B2	50	5	240	50	15	240	-1.75
	P3	GY	50	25	300	50	0	0	-1.80
	G1	GY	50	5	180	50	0	0	-1.80
	Y1	B1	50	5	120	50	5	240	-1.80
	G5	GY	50	41	180	50	0	0	-1.83
	B1	GY	50	5	240	50	0	0	-1.83
	Y1	GY	50	5	120	50	0	0	-1.88
	Y1	P5	50	5	120	50	45	300	-1.95
	R1	B1	50	5	0	50	5	240	-2.03
	P1	GY	50	5	300	50	0	0	-2.05
	G1	B1	50	5	180	50	5	240	-2.48

According to Table 4-7, the best harmonious pair consists of “B5” and “WE” with an average score of 2.33, and the worst harmonious pair consist of “G1” and “B1” with an average score of -2.48. It was found that most of the colour pairs in the top ten best were made up with either white, or black, or the colour with high chroma levels. On the other hand, most of the colour pairs in the top ten worst were made up with grey colour or the colour with low chroma levels.

It should be noted that the white colour when paired with any other colours tended to be harmonious while the grey one tended to be disharmonious. As a matter of fact, both of them are achromatic colours but having different lightness levels. This confirms the results for lightness factor showing that high lightness colour pairs tended to be harmonious.

4.3.2 The Best and Worst Harmonious Hue

In the previous section, the visual scores of all colour pairs were ordered to find the best and worst colour pairs with respect to colour harmony. In this section, the visual scores were re-calculated to determine the best and worst harmonious colours with respect to primary hue. This was done by grouping colour samples based on their primary hue such as red (See Figure 4-2), then calculating the mean visual scores when these samples were paired with other samples that have different hue. Note that for each hue in the lightness-factor group there were 7 samples with different lightness. The mean visual scores were thus calculated from the visual scores of all samples on the same hue group (7 samples with same hue) paired with any other samples. In so doing, the best and worst harmonious pairs for each hue group were found and the differences of visual scores from these two pairs were calculated to determine the contribution of that particular hue to the degree of colour harmony. If the range between the best and worst pairs is large, it could be interpreted that the primary hue in question has little contribution to the degree of colour harmony of colour pairs. Similar calculations were done for samples in the chroma-factor group. Since in this group, three achromatic colours were also included, their results were calculated in the same manner. Table 4-8 summarises the results for each hue group in the lightness and chroma groups of samples.

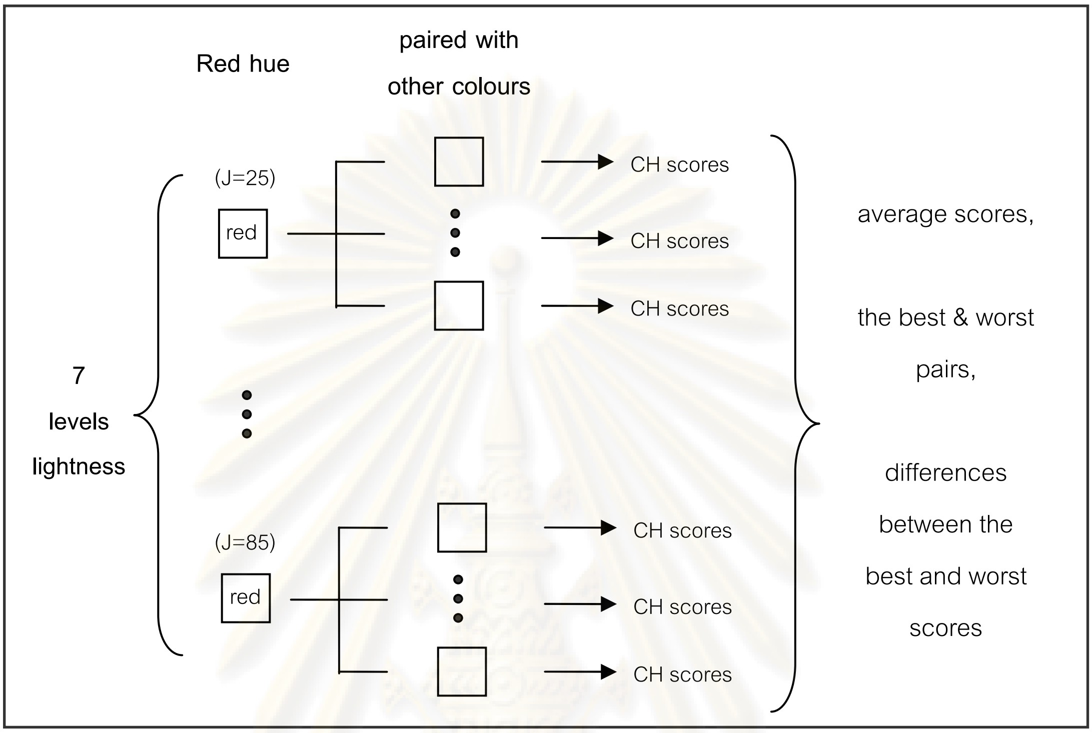


Figure 4-2 Method for finding the best and worst harmonious hue with respect to primary hue, example of red hue.

In lightness group (all samples having the same chroma but varying in lightness), red had the highest average score (-0.10) and blue had the lowest one (-0.39). In the case of chroma group, it was found that red had the highest average score (0.43) and orange had the lowest one (-0.02). As for achromatic colour, white got the highest average score (1.31), while grey got the lowest one (-1.27). When comparing the results from all groups, the results showed that white was the best harmonious colour, i.e. white always produced pleasing effect when paired with other colours, whereas grey was the worst one.

The difference between the best and the worst score of each primary hue indicates the consistency in performance of that particular hue when paired with others. The small difference shows that colour pairs containing the hue in question give not much different colour-harmony scores, revealing that the relevant hue perform consistently and the perceived colour harmony could be dependent on that hue. If the difference is large, the perceived colour harmony could be influenced by other factors.

Table 4-8 Results for the best harmonious hue. Bold figures show the best harmonious hue for each factor group. Highlighted cells show the best performance for all groups.

		Average scores	Best		Worst		Scores' difference
			pair	scores	pair	scores	
Lightness	Red	*-0.10*	R7-P5	2.63	R1-O1	-3.18	5.81
	Orange	-0.38	O1-O6	2.33	O1-R1	-3.18	5.51
	Yellow	-0.38	Y7-G6	2.18	Y1-P1	-2.80	4.98
	Green	-0.25	G4-G6	2.30	G1-P3	-2.78	5.08
	Blue	-0.39	B5-B7	1.88	B1-Y1	-2.65	4.53
	Purple	-0.11	P5-R7	2.63	P1-Y1	-2.80	5.43
Chroma	Red	*0.43*	R5-B5	2.13	R1-B1	-2.03	4.16
	Orange	-0.02	O5-G4	1.18	O1-B1	-1.73	2.91
	Yellow	0.06	Y5-R4	1.75	Y1-P5	-1.95	3.70
	Green	0.12	G5-B4	1.95	G1-B1	-2.48	4.43
	Blue	0.08	B5-R5	2.13	B1-G1	-2.48	4.61
	Purple	0.10	P3-R4	2.05	P5-Y1	-1.95	4.00
Achromatic	Black	0.49	BK-B5	2.03	BK-Y1	-0.98	3.01
	Grey	-1.27	GY-R4	-0.28	GY-P1	-2.05	1.77
	White	*1.31*	WE-B5	2.33	WE-G1	-0.33	2.66

As can be seen in Table 4-8, grey has the smallest difference between the best and the worst scores (1.77), and its average scores is -1.27, meaning it produces disharmonious colour pairs. This results thus showed that grey was the worst harmonious colour; when paired with other colours, it was likely to produce disharmonious colour pairs. On the other hand, white, having the highest average score, was the second best in terms of scores' consistency. This reveals that white was the most harmonious colour. It was likely to give pleasing effect when paired with other colours. Considering the primary hue, it was found that red gave the best average scores for both lightness and chroma group. However, its performance was inconsistent, suggesting that there were other factors influencing the perceived colour harmony. Hence, it is worth noting that the best pairs for each hue contained samples with high lightness or chroma level.

4.3.3 Investigation of Lightness Factor

4.3.3.1 Bubble Chart Analysis for Lightness Group

The relationship between colour harmony scores and lightness could be explained with bubble chart as shown in Figures 4-3 (a) to (g). From the figures, the charts are divided into three parts according to lightness levels of red primary hue: (a) and (b) a results of the low lightness levels; (c), (d) and (e) the middle lightness levels; and (f) and (g) the high lightness levels. Only the results for red colours are presented here because similar patterns were also found for the other colours and their bubble charts can be found in Appendix C.

From the charts, the bubbles show the locations of the colour pairs in CIECAM02 colour space. There are four bubble types in the charts: (1) white bubbles with a thick line represent the locations of the red colours in seven lightness levels; (2) white bubbles with a dashed line represent the corresponding locations of each red colour shown at different lightness sections; (3) white bubbles with a fine line represent the colour pairs that had negative values (disharmonious); (4) grey bubbles represent the colour pairs that had positive values (harmonious). For Types (3) and (4), the size of the bubbles indicate the colour harmony scores for colour pairs generated from one level of red colours and the other colour samples that were divided into three different lightness sections.

From Figure 4-3 (a), it can be seen that the red colour with low lightness when paired with other colours having low lightness gave negative visual scores (white bubbles). When paired with the same hue (red) with low lightness, it gave positive score (grey bubble). This means that any colour pairs generated by the red colour with low lightness and the other with low lightness tended to be disharmonious, but harmonious if paired with the red hue. Note that in the other two lightness sections, a few grey bubbles are presented near the corresponding locations of the red with low lightness. It suggests that the red colour pairs could be harmonious if another single colour had a higher lightness level but similar hue and chroma, for example, orange, purple.

For the colour pairs generated from the red with middle lightness levels and the other colours at the same lightness, there were both the grey bubbles and the white bubbles with fine line. The orange and the purple were almost presented by the grey bubbles and the others were presented by the white bubbles. That means the red with middle lightness level will be harmonious when paired with the others had similar hues at the same level. They could be more harmonious when they paired with higher lightness colours, as shown in Figure 4-3 (c). The more lightness the others were, the more harmonious the pairs were.

According to Figure 4-3 (g), the red colour with high lightness located in the high lightness section has only the grey bubbles at the same lightness level. This means that any colour samples generated from the red of high lightness and the other colours with high lightness tended to have a positive value for the colour harmony scores. These colour pairs were harmonious to the observers. For the other two lightness sections, the grey bubbles were mostly presented near the corresponding locations of the red with high lightness and a few white bubbles with fine line were presented only in the opposite hues. It suggests that colour pairs with high lightness red could be harmonious with any lightness levels if the other single colour was not the opposite hue like green and yellow.

All in all, the colour pairs generated from two high lightness colours tend to be harmonious; on the other hand, two of low lightness colours tend to be disharmonious. In other words, both of single colours should not be low lightness levels. Colour pairs generated from similar hue tend to be harmonious regardless of their lightness level. These patterns were also found for the others hue (see Appendix C).

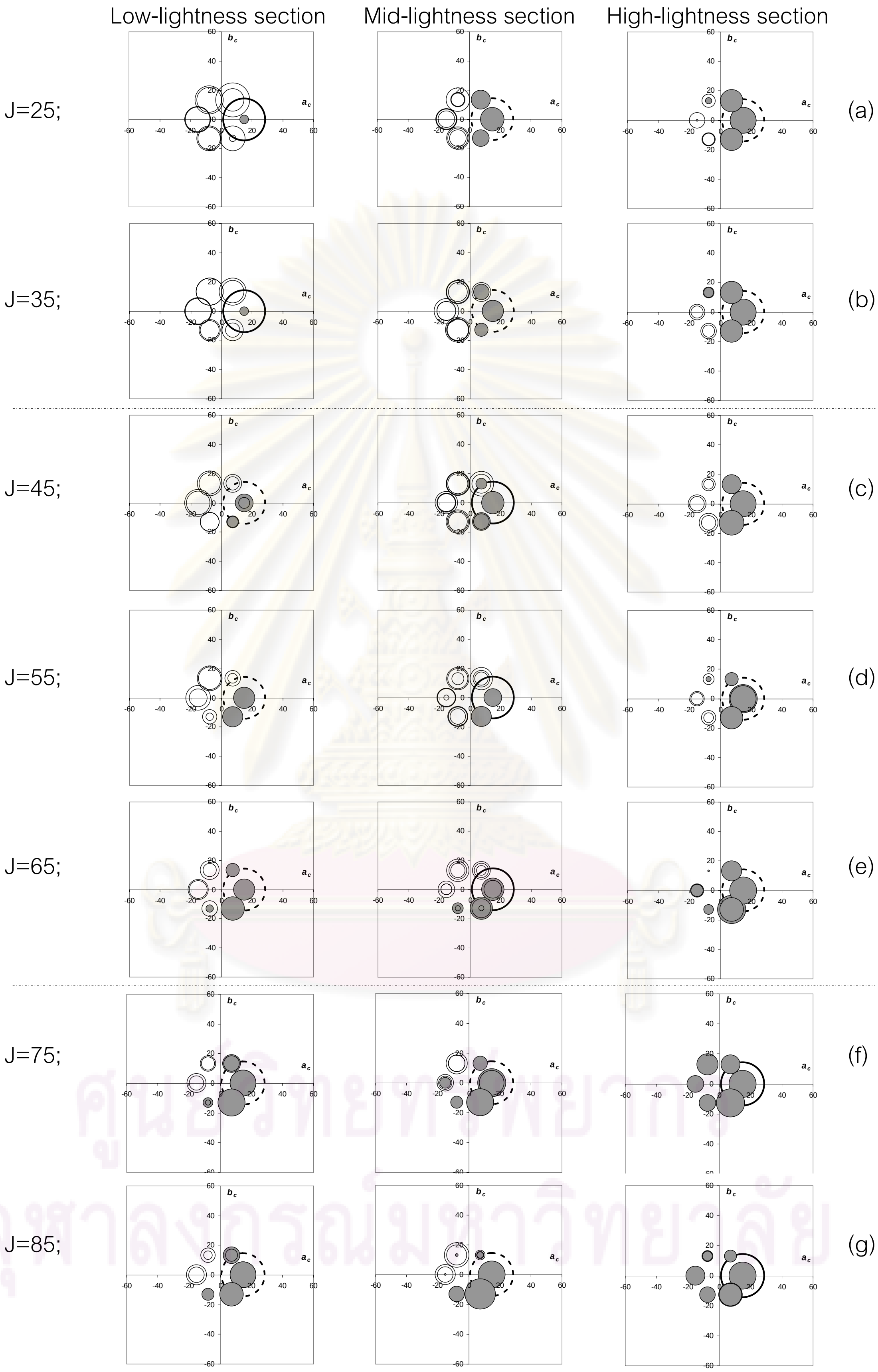


Figure 4-3 Bubble charts for colour pairs generated from Red with one of the 7 lightness levels and one of the other colours separated into three sections according to their lightness levels.

4.3.3.2 Relationships between lightness and colour harmony

To analyse the relationships between lightness and colour harmony, the method of Pearson Correlation Coefficient (r-value) was used. All of the two-colour combinations in lightness group were separated into two patterns: colour pairs that were combined with same hue and colour pairs that were combined with different hue. Each pattern was analysed for each colour, one by one. The relationships between colour harmony scores and sum of lightness and the relationship between colour harmony scores and difference of lightness for each colour pair were investigated. The lightness sum (Jsum), and lightness difference (Jdiff) were calculated for each colour pair and their relationships with colour harmony scores were investigated. The results in terms of r values are given in Table 4-9.

Table 4-9 r values of colour pairs with same hue and different hue in lightness group.

Lightness				
hue	*same hue*		*diff hue*	
	Jsum	Jdiff	Jsum	Jdiff
red	0.72	0.56	0.58	0.26
orange	0.25	0.66	0.63	0.40
yellow	0.45	0.57	0.54	0.31
green	0.63	0.36	0.59	0.27
blue	0.13	0.14	0.54	0.39
purple	0.49	0.55	0.55	0.29

Overall results showed that colour pairs combined with the same hue had moderate positive relationship (r value ~0.5-0.7) with colour harmony for both Jsum and Jdiff, in exceptions of blue for Jsum (0.13) and Jdiff (0.14), and orange for Jsum (0.25). The results suggest that when two colours with the same hue combined and produce high lightness sum, or at least one of two has high lightness, the colour pairs tend to be harmonious. These results agree with the findings from bubble chart analysis in the previous section. The results also suggest some hue effect as orange and blue did not follow the same pattern.

Moreover, red and green colour pairs had high r values in Jsum (0.72 and 0.63, respectively) and moderate r values in Jdiff (0.56 and 0.36, respectively). It means that these colour pairs should be generated from colours with similar lightness with the levels high enough to yield high lightness sum. For the orange, the pairs had low r value in Jsum but high r value in Jdiff; this implies that the orange colour pairs should be combined with high and low levels of lightness in order to harmonise. Figure 4-4 shows the relationship between the colour harmony scores and lightness sum of red colour pairs and Figure 4-5 shows the relationship between the colour harmony scores and lightness difference of orange colour pairs, as both of them have strong positive relationships.

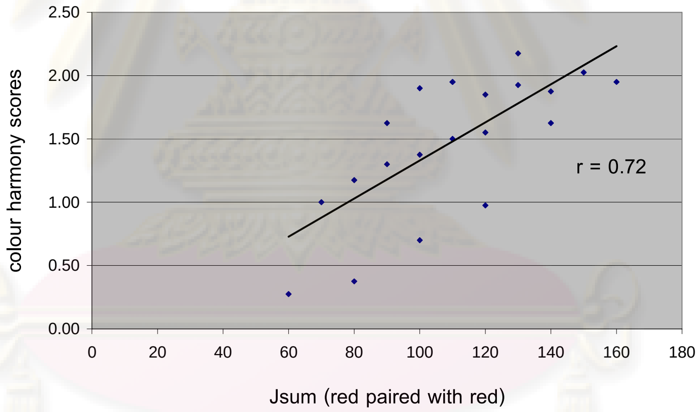


Figure 4-4 Relationship between colour harmony scores and lightness sum of red pairs.

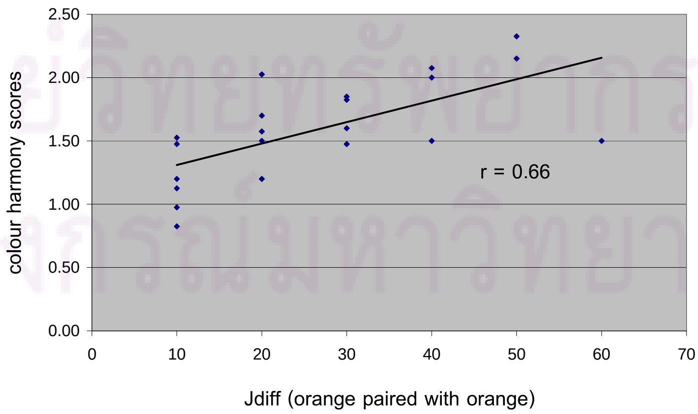
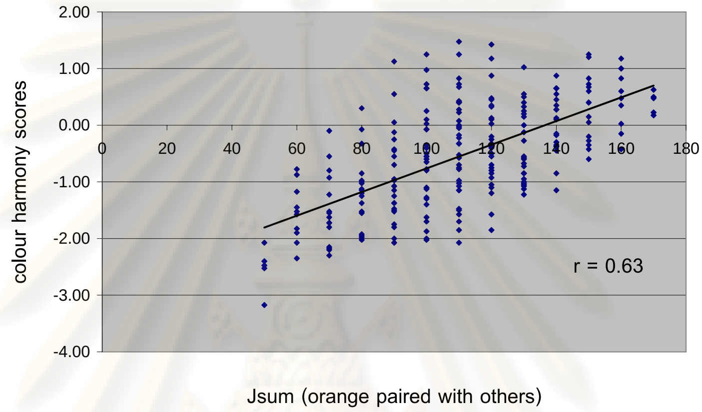


Figure 4-5 Relationship between colour harmony scores and lightness difference of orange colour pairs.

In the case of colour pairs with different hues, moderate positive values (0.5-0.6) were found in Jsum and low values (0.2-0.4) in Jdiff. It means that the colour pairs will harmonise when they are combined with colours having similar lightness with high or middle levels. Figures 4-6 (a) and (b) show the relationships between colour harmony scores and lightness sum of pairs containing either orange or green colour. They are the two relationships with the highest r values of all the findings.

(a)



(b)

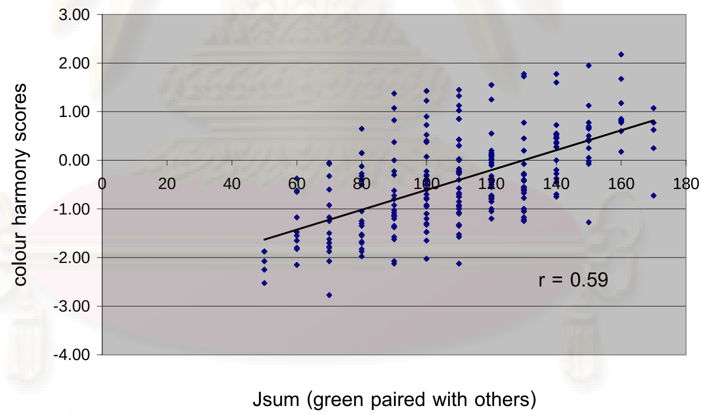


Figure 4-6 Relationships between colour harmony scores and lightness sum in (a) orange paired with others and (b) green paired with others.

4.3.4 Investigation of Chroma Factor

4.3.4.1 Bubble Chart Analysis for Chroma Group

The relationship between colour harmony scores and chroma could be analysed by bubble chart as shown in Figures 4-7 (a) to (e). Details of the bubble chart are the same as in the previous section (4.3.3.1) but there are only three bubble types excluding Type (2) white bubbles with a dashed line because all of the bubbles here have the same lightness level. The higher the chroma level was, the higher the harmony score was.

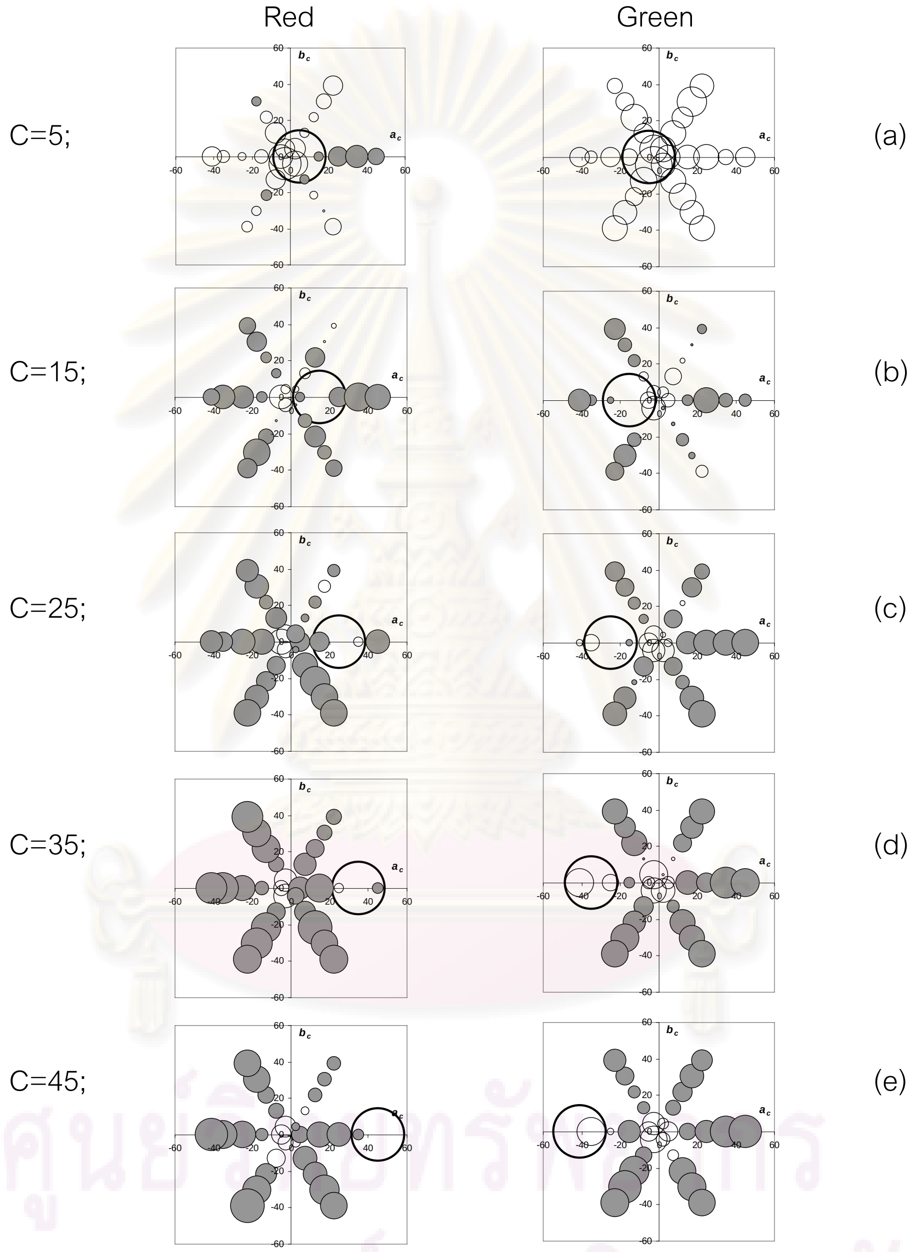


Figure 4-7 Bubble charts for colour pairs generated from Red / Green and one of the other colours varying in chroma levels.

From Red in Figure 4-7 (a), it was found that many white bubbles occurred for the other hues and the grey bubbles were only present in the red for all different chroma levels. This shows that any colour pairs generated from the red with low chroma and the same hue with any chroma tend to be harmonious. Moreover, as the chroma levels of red are higher, many grey bubbles are present in all regions as seen in Figures 4-7 (b) to (e) and the size of the bubbles tend to be bigger. It should be noted that any colour pairs tend to be more harmonious when they are made up from the middle, or high chroma red and a sample with any hues and chroma.

For Green in Figure 4-7 (a); it was found that there was no grey bubble showed in this chart, so all colour pairs were disharmonious. This meant that any colour pairs made up from the green with low chroma would be disharmonious to observers. However, the grey bubbles would be more present if one colour of any pairs generated from the higher chroma green as seen in Figures 4-7 (b) to (e). It should be noted that any colour pairs tend to be harmonious when they are made up from the middle or high chroma green.

Even though the results showed that the higher the chroma level, the more harmonious the colour pairs seemed to appear. It was also found that in some hues when the chroma levels were higher, the size of the grey bubbles became smaller (see the bubble sizes of Figure 4.7 (e) in comparison with those in Figure 4.7 (d) for orange and yellow). Some pairs generated from samples having the same hue and similar chroma (C=25, C=35) always gave negative scores of colour harmonious (white bubbles). It could be that these colours looked so much alike that observers could not distinguish between them and thought that the pairs had only one colour.

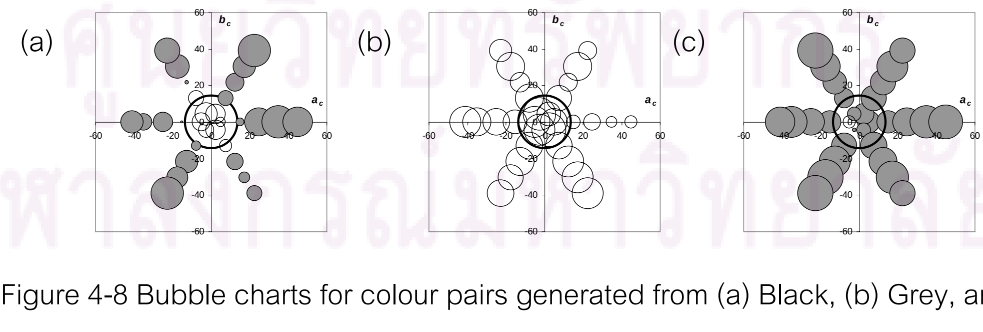


Figure 4-8 Bubble charts for colour pairs generated from (a) Black, (b) Grey, and (c) White and one of the other colours.

Figure 4-8 shows the results for colour pairs generated from one of achromatic colours (white, grey, and black) and one of the other chromatic colours. It was found that the pairs of black colour could be either harmonious or disharmonious. The pairs were harmonious when combined black with middle or high chroma colours and they were disharmonious when combined black with low chroma or nearly neutral colours, as seen in Figure 4-8 (a).

All of the colour pairs that were generated from white colour had positive colour harmony scores, so there are only grey bubbles (see Figure 4-8 (c)). This suggests that any colour samples paired with white would be harmonious or beautiful pairs. On the other hand, all of the colour pairs generated from the grey colour had negative colour harmony scores, as only white bubbles can be seen in Figure 4-8 (b). This suggests that any colour samples paired with grey would be disharmonious or unattractive pairs.

It should be noted that the grey sample had the colorimetric value, rgb = 132 127 127; while the grey background of the screen had rgb = 128 128 128. So, they were so similar that observers could not distinguish between them and thought that the pairs with grey colour were not beautiful or harmonious.

4.3.4.2 Relationships between Chroma and Colour Harmony

The method of Pearson Correlation Coefficient was employed to analyse the relationship between chroma and colour harmony. The analysis was done in the same way as was the lightness analysis in Section 4.3.3.2, i.e. colour pairs were separated into two patterns: samples paired with same hue, and with different hue. The relationships between chroma sum (Csum), and chroma difference (Cdiff), and colour harmony scores were evaluated.

Table 4-10 r values of colour pairs with same hue and different hue in chroma group.

Chroma				
hue	*same hue*		*diff hue*	
	Csum	Cdiff	Csum	Cdiff
red	0.02	0.46	0.71	-0.33
orange	-0.19	0.50	0.65	-0.24
yellow	0.16	0.60	0.76	-0.33
green	-0.10	0.27	0.78	-0.36
blue	0.74	0.00	0.79	-0.32
purple	0.16	0.40	0.67	-0.37

Table 4-10 shows the results of r values, indicating the relationships between chroma and colour harmony. It was found that colour pairs with same hue tended to harmonise when two colours in a given pair had different chroma levels. This tendency can be observed in yellow pairs (r value = 0.60), as shown in Figure 4-9. However, blue pairs will tend to be more harmonious when chroma sum in the pair increases but their chroma levels should not be different, as shown in Figure 4-10.

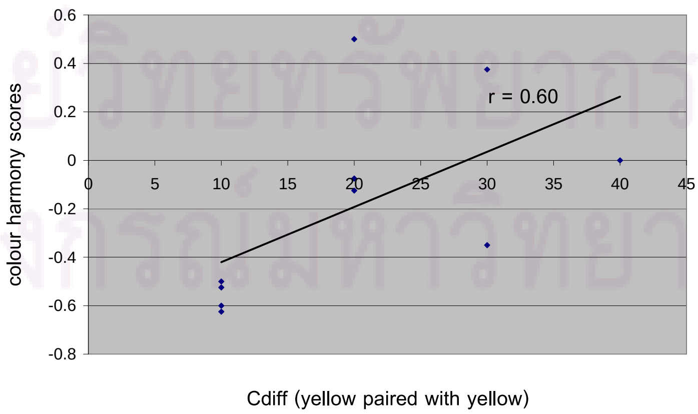


Figure 4-9 Relationship between the colour harmony scores and chroma difference of yellow colour pairs.

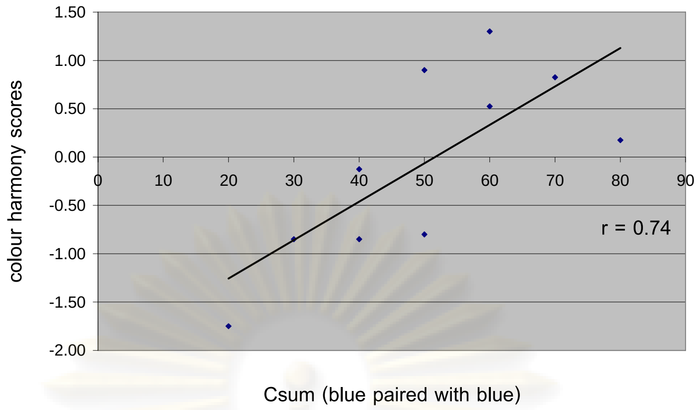


Figure 4-10 Relationship between colour harmony scores and chroma sum of blue pairs.

In the case of pairs with different hues, high positive values were found in Csum (0.6-0.8), and low negative values in Cdiff (-0.4 to -0.2). It means that colour pairs with different hue will be more harmonious if both colours have equal, high chroma levels. Figures 4-11 (a) and (b) show the relationships between colour harmony scores and chroma sum of pairs containing either blue or green colour.

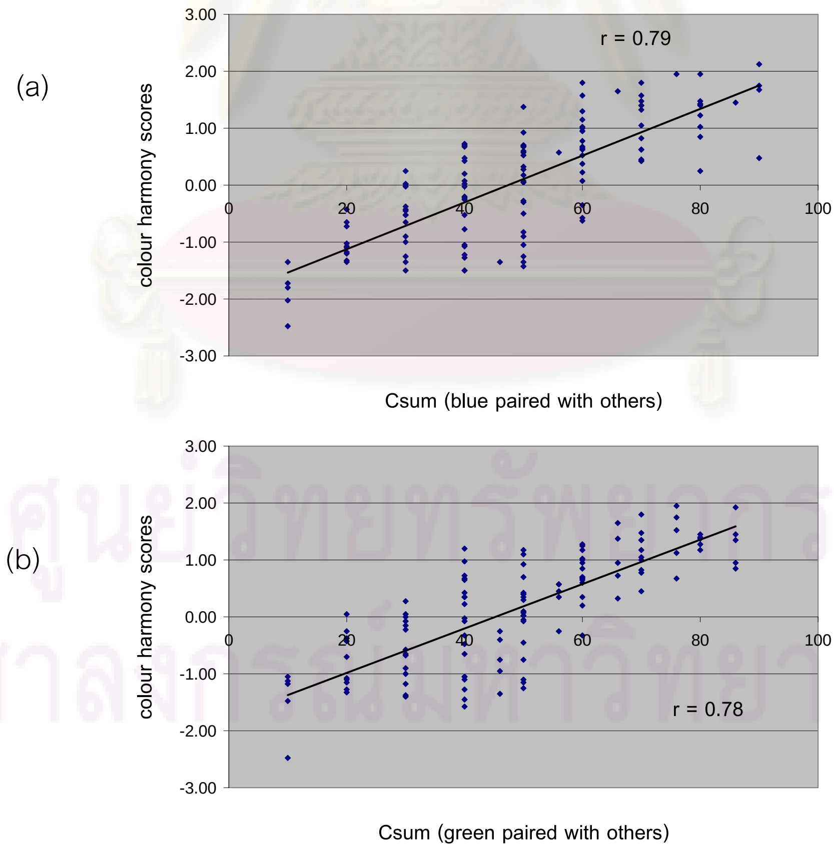


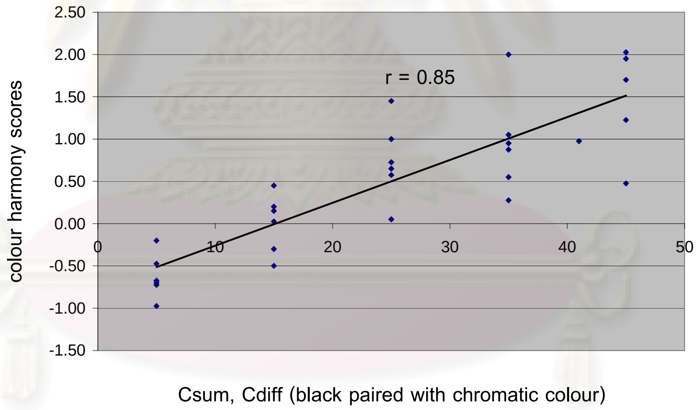
Figure 4-11 Relationships between colour harmony scores and chroma sum in (a) blue paired with others and (b) green paired with others.

Table 4-11 r values of colour pairs with chromatic and achromatic colour.

Chromatic – Achromatic Colours (Csum, Cdiff)	
black	0.85
grey	0.27
white	0.82

Three achromatic colours (black, grey and white) were also included in the chroma group of samples. Therefore, relationships between colour pairs containing one of the three achromatic colours and colour harmony scores were analysed. The results of r value are given in Table 4-11. The black and white colour had high r values (0.85 and 0.82, respectively), implying that the colour pairs will tend to harmonise when one colour in the pair is black or white, as shown in Figures 4-12 (a) and (b). It also suggests that the other colour in the pair should have high chroma.

(a)



(b)

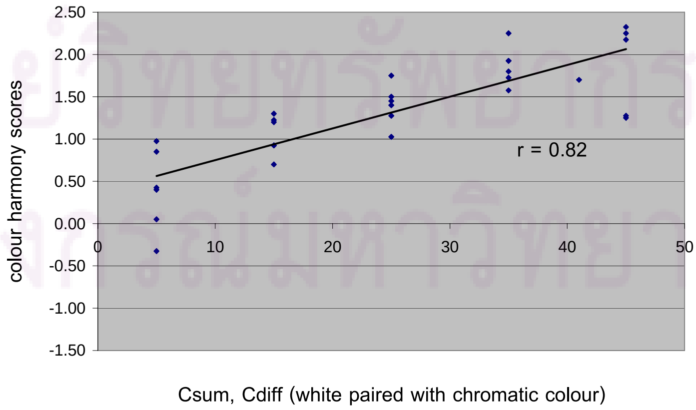


Figure 4-12 Relationships between colour harmony scores and chroma sum in (a) black paired with chromatic colours and (b) white paired with chromatic colours.

4.4 Comparison with Existing Colour Harmony Principles

Some of well-known colour harmony principles were tested using the experimental data obtained in this study. Five principles: complementary hue, equal hue, equal lightness, equal chroma, and equal tone, were included. Based on these principles, colours can harmonise if they are complementary in hue (complementary hue), they share the same hue (equal hue), the same lightness (equal lightness), the same chroma (equal chroma), or the same lightness and chroma (equal tone). In this study, colour pairs for the complementary hue principle were red-green, orange-blue, and yellow-purple (see Figure 3-2).

Table 4-12 Test results of existing colour harmony principles in terms of CD values.

CD value	Complementary hue	Equal hue	Equal lightness	Equal chroma	Equal tone
Ou and Luo	0.53	0.61	0.40	0.56	0.53
Present data	0.37	0.66	0.45	0.45	0.38
Number of pairs in this test	237	204	570	934	175

The CD values range from 0 to 1: a value of 0 indicates that all of the observers disagree with the principle and a value of 1 indicates that all of the observers agree with this principle. The test results were shown in Table 4-12. Among five principles, the equal hue had the highest CD value. It means that the equal hue can mostly create the colour pairs to be harmonious (0.61 and 0.66). In the Ou and Luo's data [10], the equal lightness had the lowest CD values (0.40); however, in this study, the complementary hue and the equal tone had the lowest CD values (0.37 and 0.38, respectively). This means that colour pairs combined with complementary hue or equal tone will be harmonious lowest. This also suggests that the opposite principle, perhaps called uncomplementary hue and unequal tone, would have CD values of 0.63 (1-0.37) and 0.62 (1-0.38). As a result, the two colour combinations will harmonise when they are combined with colours that are equal hue, uncomplementary hue, or unequal tone.

CHAPTER V
CONCLUSIONS

5.1 Conclusions

This research aimed at investigating the effects of lightness and chroma on colour harmony of colour pairs that were displayed on the CRT monitor. Normal colour vision observers assessed the colour pairs one at a time and rated their perceived colour harmony from -5 (the most disharmonious) to 5 (the most harmonious). The visual results were analysed to define relationships between colour harmony scores and lightness, and chroma attributes.

Twenty Thai observers (10 males and 10 females) ranging in age from 21 to 30 years old took part in the visual assessments. The experimental samples were divided into two groups according to factors under investigation. There were 861 colour pairs for lightness group and 528 colour pairs for chroma group. These colours were systematically selected from the CIECAM02 colour space.

In this study, observers were given a definition of colour harmony as two-colour combinations that possess aesthetic and look pleasing to the eye. By this definition, colour harmony perceived by observers could then be dependent on individual colour preference. Each observer repeated the same experiments two times. The reliability of visual scores of colour harmony was evaluated in terms of intra-observer agreement and inter-observer agreement using RMS values. The results showed that observers' first and second responses agreed well with one another with RMS values of approximately 2. The performance of female and male observers was insignificantly different. The results of inter-observer agreement suggested that the visual data could be considered reliable.

Six major hues: red, orange, yellow, green, blue and purple, were tested in this study. Regarding the best and the worst scores for major hue, it was found that red colour with high lightness or high chroma paired with other colours was the best chromatic colour giving the highest colour harmony scores for the lightness group and the chroma group. In addition to chromatic colours, three achromatic colours, i.e. black, grey and white, were included in the chroma group. White colour was the most harmonious achromatic colour when paired with other colours; on the other hand, grey colour was the most disharmonious achromatic colour when paired with other colours.

Overall results showed that both lightness and chroma attributes had impacts on perceived colour harmony of colour pairs. Colour pairs with either high lightness or high chroma levels tend to be harmonious. For example, colour pairs consisted of two high lightness colours would be more harmonious than the pairs consisted of two low lightness colours. In addition, it was found that the best top ten colour pairs of lightness group and chroma group were the colour pairs that consisted of the colours with high lightness level or the colours with high chroma level. On the one hand, colour pairs with low lightness level, or low chroma level tend to be disharmonious. It was found that the worst ten colour pairs of lightness group and chroma group were the colour pairs that consisted of the colours with low lightness level or the colours with low chroma level.

As a result, an easy way to select colours for best combinations regarding colour harmony is to use colours with high lightness or high chroma levels. However, there should not be much difference between lightness or chroma levels of the two colours in the colour pair. In addition, the use of low lighness or low chroma levels together should be avoided, as these colour pairs tend to generate poor colour harmony.

5.2 Suggestions

This study investigated lightness and chroma attributes as factors influencing the degree of colour harmony. The visual assessments were conducted for two sample groups designed to investigate lightness and chroma factors individually. This was done by constraining other factors and varying only the factor under investigation. However, there are other factors that have an impact on the degree of colour harmony of colour pairs. These factors could be hue, hue difference, colour preference, colour difference, number observers, culture, observers' experience, and so on. Consequently, future study could focus on the other factors. In addition, observers may be informed the usage of colour pairs they assess and make judgements accordingly. The colour harmony data collected from this study are useful as the colour harmony database of Thai observers for applications in industrial design, industrial art, fashion and beauty, etc.

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Appendices

Appendix A

The CRT monitor's luminance

Table A-1 : The luminances of the CRT monitor by measuring white image every 3 minutes in 45 minutes and every 15 minutes until 4 hours.

	Time	Y	x	y
1	1:03 PM	82.22	0.3115	0.3335
2	1:06 PM	84.38	0.3116	0.3321
3	1:09 PM	85.56	0.3121	0.3332
4	1:12 PM	86.29	0.3121	0.3330
5	1:15 PM	86.80	0.3117	0.3325
6	1:18 PM	87.38	0.3112	0.3326
7	1:21 PM	87.86	0.3118	0.3327
8	1:24 PM	88.12	0.3117	0.3320
9	1:27 PM	88.45	0.3112	0.3323
10	1:30 PM	88.72	0.3116	0.3324
11	1:33 PM	88.85	0.3122	0.3320
12	1:36 PM	89.12	0.3117	0.3324
13	1:39 PM	89.11	0.3113	0.3315
14	1:42 PM	89.18	0.3118	0.3318
15	1:45 PM	89.32	0.3116	0.3319
16	2:00 PM	89.39	0.3114	0.3314
17	2:15 PM	89.49	0.3115	0.3323
18	2:30 PM	89.54	0.3121	0.3318
19	2:45 PM	89.52	0.3122	0.3315
20	3:00 PM	89.51	0.3122	0.3312
21	3:15 PM	89.58	0.3117	0.3307
22	3:30 PM	89.61	0.3112	0.3314
23	3:45 PM	89.59	0.3111	0.3315
24	4:00 PM	89.53	0.3115	0.3320
25	4:15 PM	89.42	0.3110	0.3318
26	4:30 PM	89.38	0.3116	0.3312
27	4:45 PM	89.35	0.3114	0.3314
28	5:00 PM	89.21	0.3114	0.3316

Appendix B

Colorimetric values of the colour samples

Table B-1 : Colorimetric values of the colour samples in lightness group.

#	Hue	J	C	h	r	g	b		#	Hue	J	C	h	r	g	b	
1	R	25	15	0	80	57	64		22	G	55	15	180	125	148	140	
2	O	25	15	60	78	60	44		23	B	55	15	240	133	143	157	
3	Y	25	15	120	60	68	47		24	P	55	15	300	151	135	159	
4	G	25	15	180	48	71	65		25	R	65	15	0	194	153	164	
5	B	25	15	240	55	67	78		26	O	65	15	60	191	159	135	
6	P	25	15	300	69	61	78		27	Y	65	15	120	165	171	139	
7	R	35	15	0	110	81	89		28	G	65	15	180	150	174	165	
8	O	35	15	60	107	85	67		29	B	65	15	240	158	168	184	
9	Y	35	15	120	87	94	70		30	P	65	15	300	177	160	185	
10	G	35	15	180	75	97	90		31	R	75	15	0	221	178	190	
11	B	35	15	240	82	93	104		32	O	75	15	60	218	183	158	
12	P	35	15	300	97	86	105		33	Y	75	15	120	190	197	162	
13	R	45	15	0	138	105	114		34	G	75	15	180	175	200	190	
14	O	45	15	60	136	109	89		35	B	75	15	240	184	194	210	
15	Y	45	15	120	113	120	93		36	P	75	15	300	203	184	212	
16	G	45	15	180	100	122	115		37	R	85	15	0	249	202	215	
17	B	45	15	240	107	118	131		38	O	85	15	60	245	208	181	
18	P	45	15	300	124	110	132		39	Y	85	15	120	216	222	186	
19	R	55	15	0	166	129	139		40	G	85	15	180	200	226	216	
20	O	55	15	60	163	134	112		41	B	85	15	240	209	219	237	
21	Y	55	15	120	139	145	115		42	P	85	15	300	230	210	239	

Table B-2 : Colorimetric values of the colour samples in chroma group.

#	Hue	J	C	h	r	g	b		#	Hue	J	C	h	r	g	b	
1	R	50	5	0	139	124	127		19	R	50	35	0	178	99	126	
2	O	50	5	60	138	126	119		20	O	50	35	60	170	112	63	
3	Y	50	5	120	131	129	120		21	Y	50	35	120	118	138	70	
4	G	50	5	180	127	130	127		22	G	50	35	180	67	147	128	
5	B	50	5	240	129	128	132		23	B	50	35	240	96	135	173	
6	P	50	5	300	134	126	132		24	P	50	35	300	146	113	176	
7	R	50	15	0	152	117	127		25	R	50	45	0	189	88	126	
8	O	50	15	60	150	122	101		26	O	50	44	60	179	107	44	
9	Y	50	15	120	126	133	104		27	Y	50	45	120	115	141	50	
10	G	50	15	180	113	135	127		28	G	50	37	180	60	148	128	
11	B	50	15	240	120	130	144		29	B	50	45	240	79	137	190	
12	P	50	15	300	137	123	145		30	P	50	45	300	152	105	195	
13	R	50	25	0	166	108	127		31	BK	15	0	0	35	38	38	
14	O	50	25	60	161	117	82		32	GY	50	0	0	132	127	127	
15	Y	50	25	120	122	136	87		33	WE	100	0	0	255	254	254	
16	G	50	25	180	94	141	127										
17	B	50	25	240	109	133	158										
18	P	50	25	300	142	118	160										

Appendix C

Bubble chart of colour pairs generated from each colour.

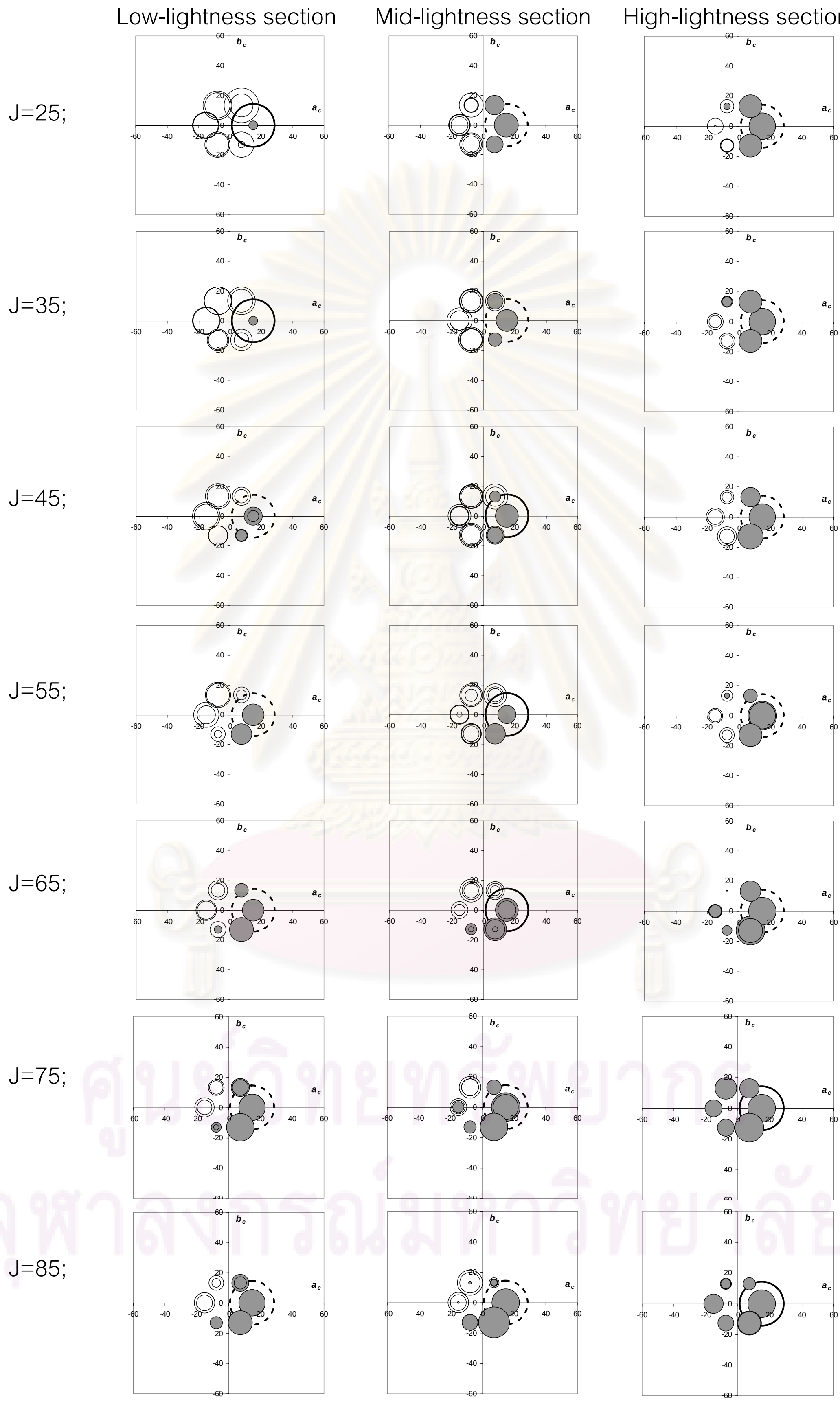

Figure C-1 Bubble charts for colour pairs generated from Red with one of the 7 lightness levels and one of the other colours separated into three sections according to their lightness levels.

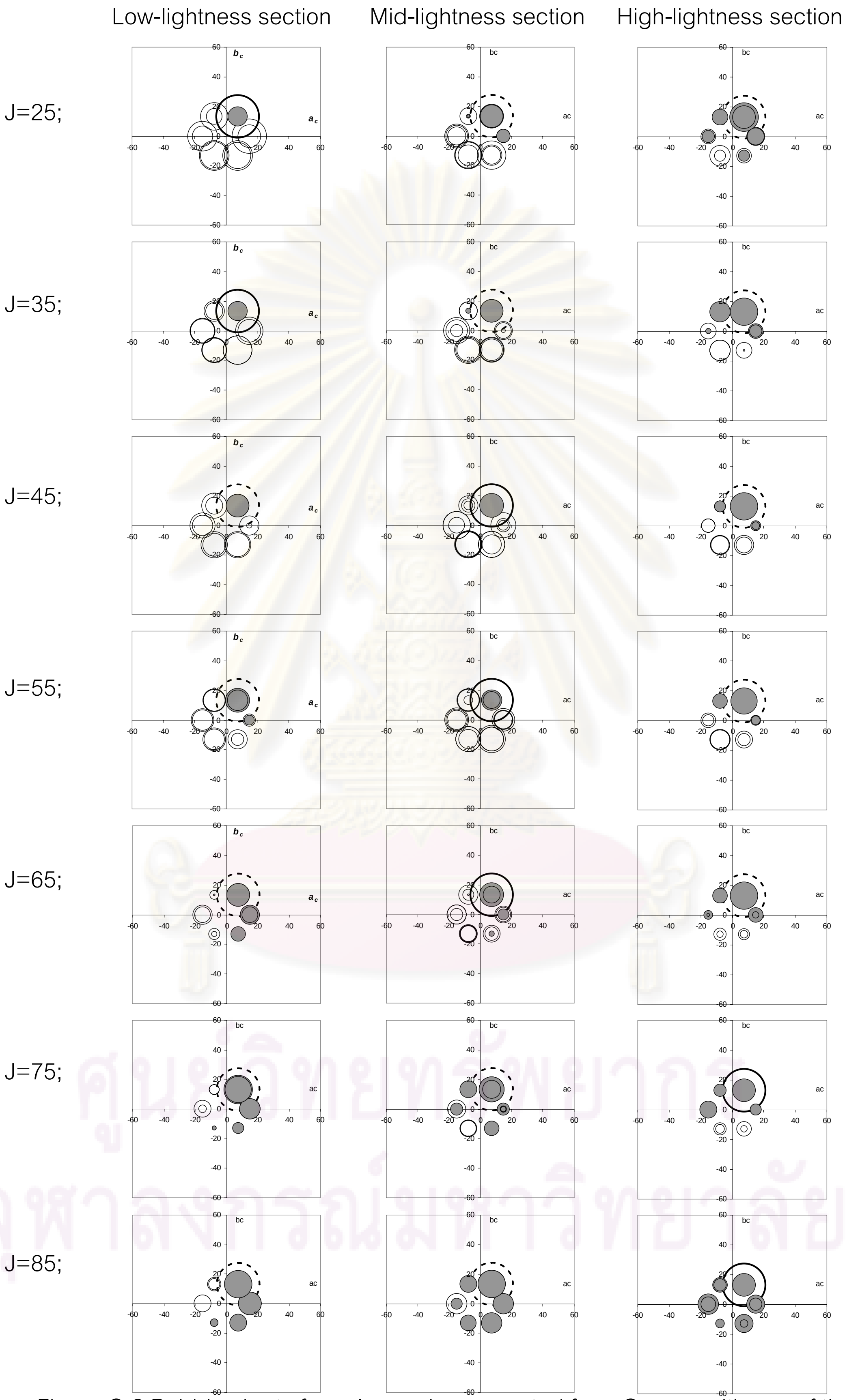

Figure C-2 Bubble charts for colour pairs generated from Orange with one of the 7 lightness levels and one of the other colours separated into three sections according to their lightness levels.

Low-lightness section | Mid-lightness section | High-lightness section

J=25;

J=35;

J=45;

J=55;

J=65;

J=75;

J=85;

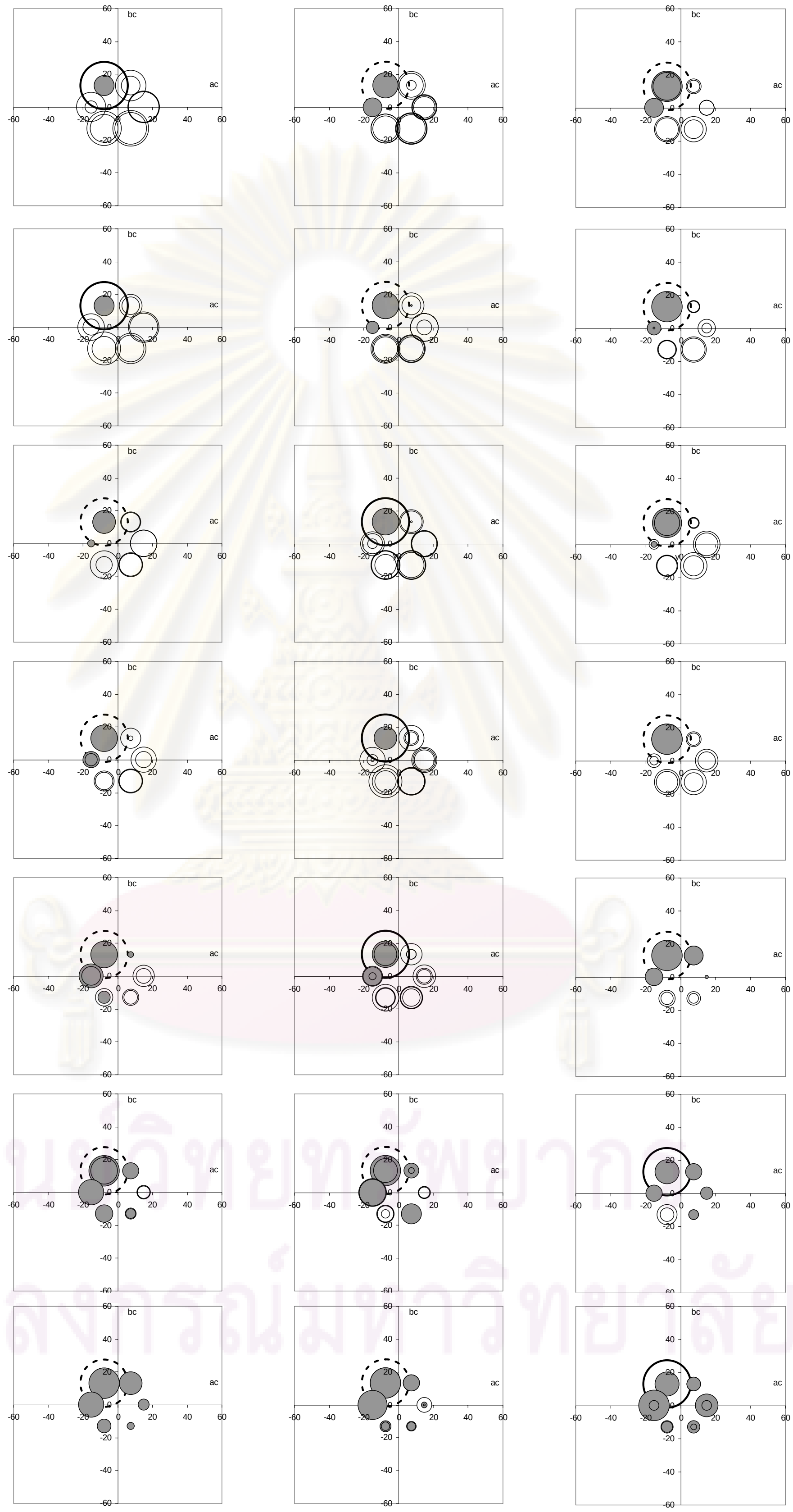

Figure C-3 Bubble charts for colour pairs generated from Yellow with one of the 7 lightness levels and one of the other colours separated into three sections according to their lightness levels.

Low-lightness section | Mid-lightness section | High-lightness section

J=25;

J=35;

J=45;

J=55;

J=65;

J=75;

J=85;

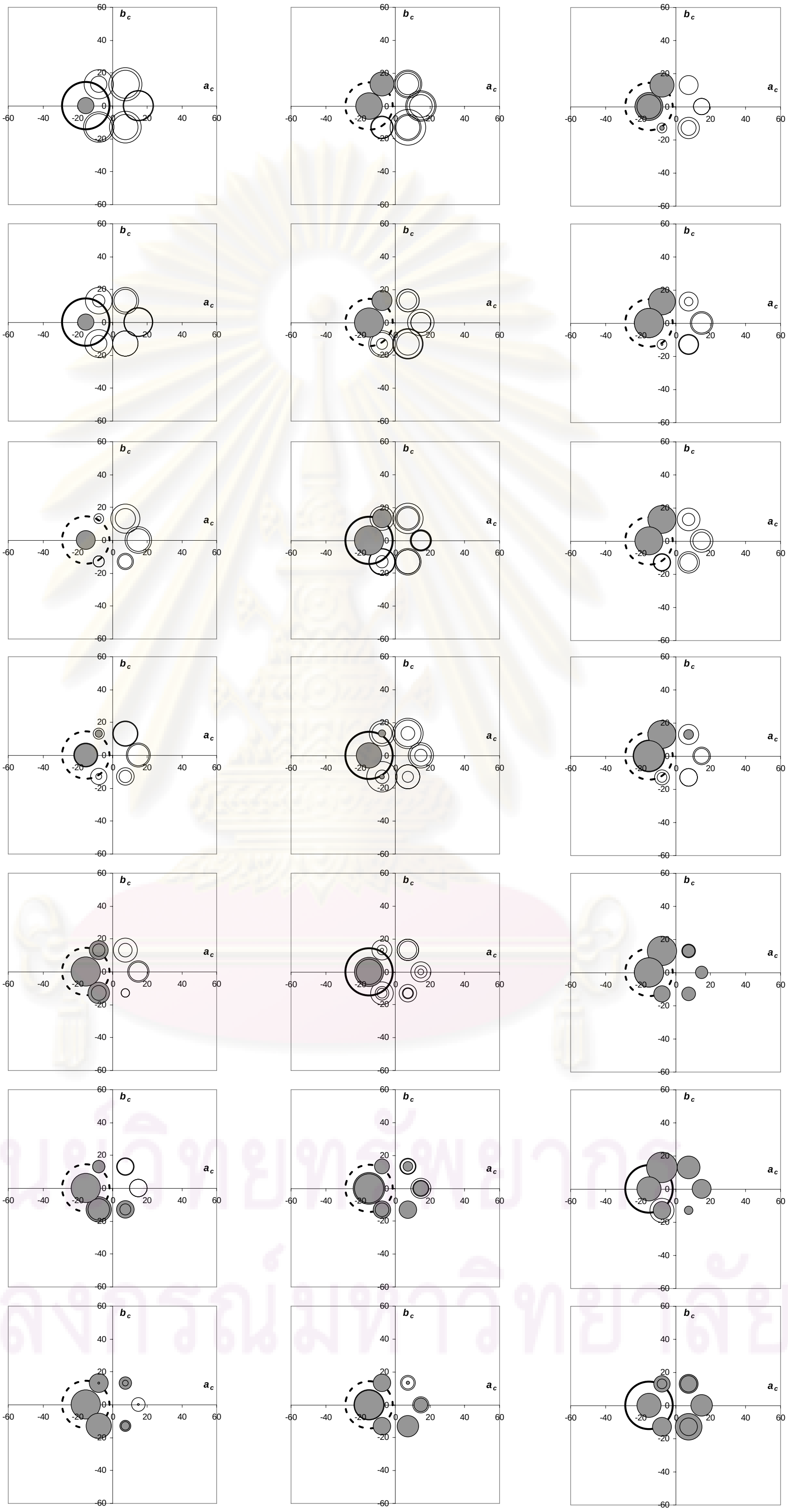

Figure C-4 Bubble charts for colour pairs generated from Green with one of the 7 lightness levels and one of the other colours separated into three sections according to their lightness levels.

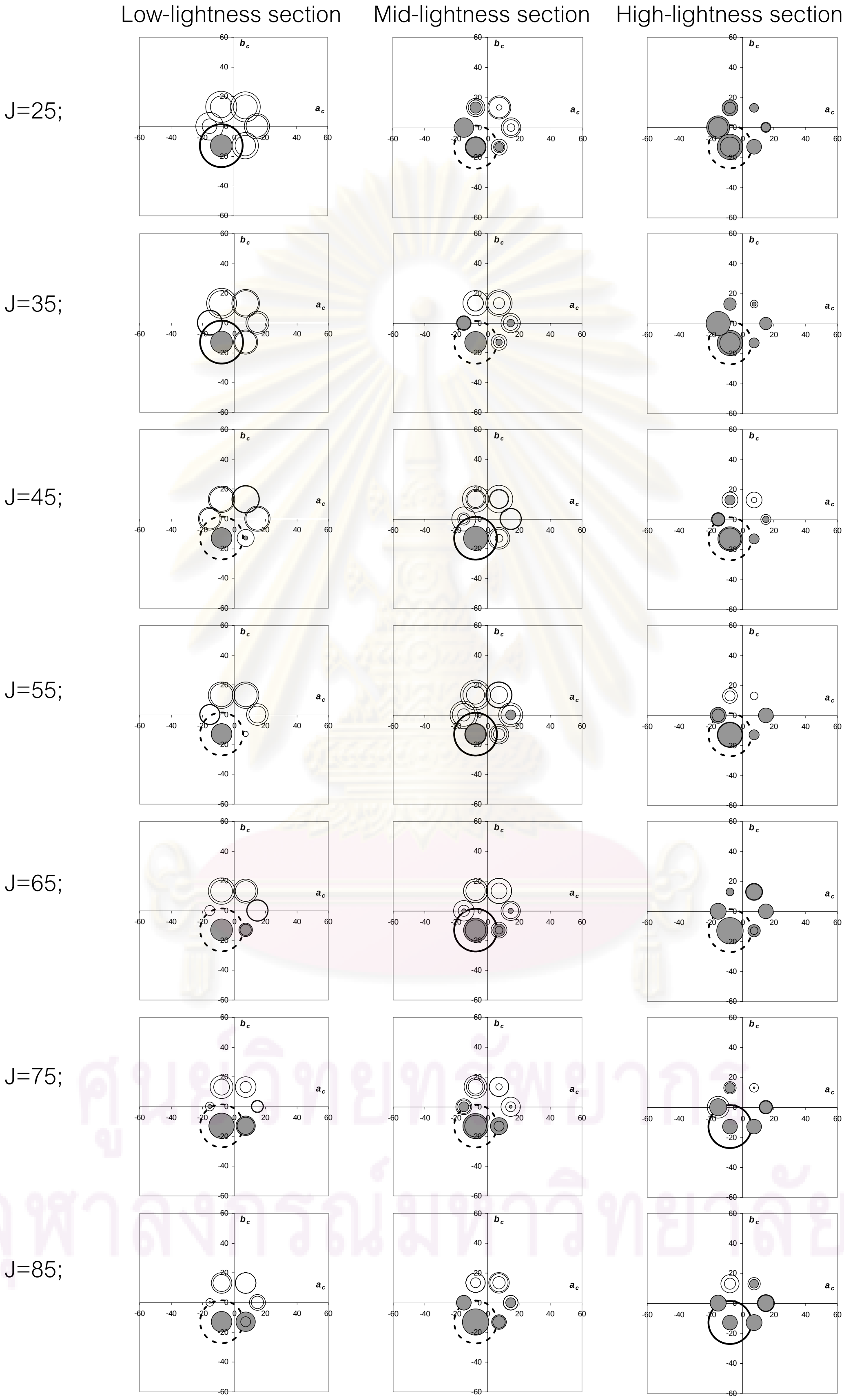

Figure C-5 Bubble charts for colour pairs generated from Blue with one of the 7 lightness levels and one of the other colours separated into three sections according to their lightness levels.

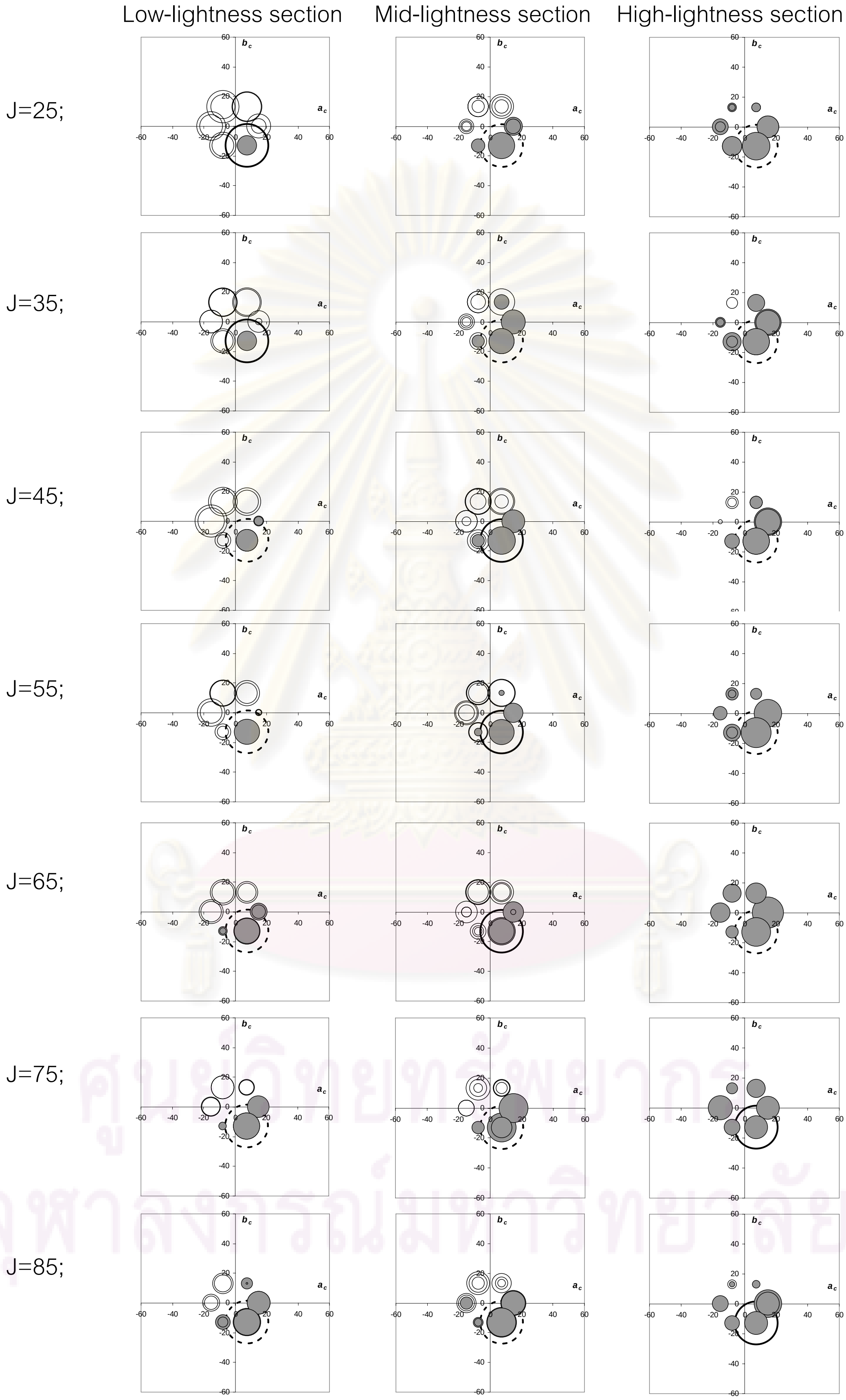

Figure C-6 Bubble charts for colour pairs generated from Purple with one of the 7 lightness levels and one of the other colours separated into three sections according to their lightness levels.

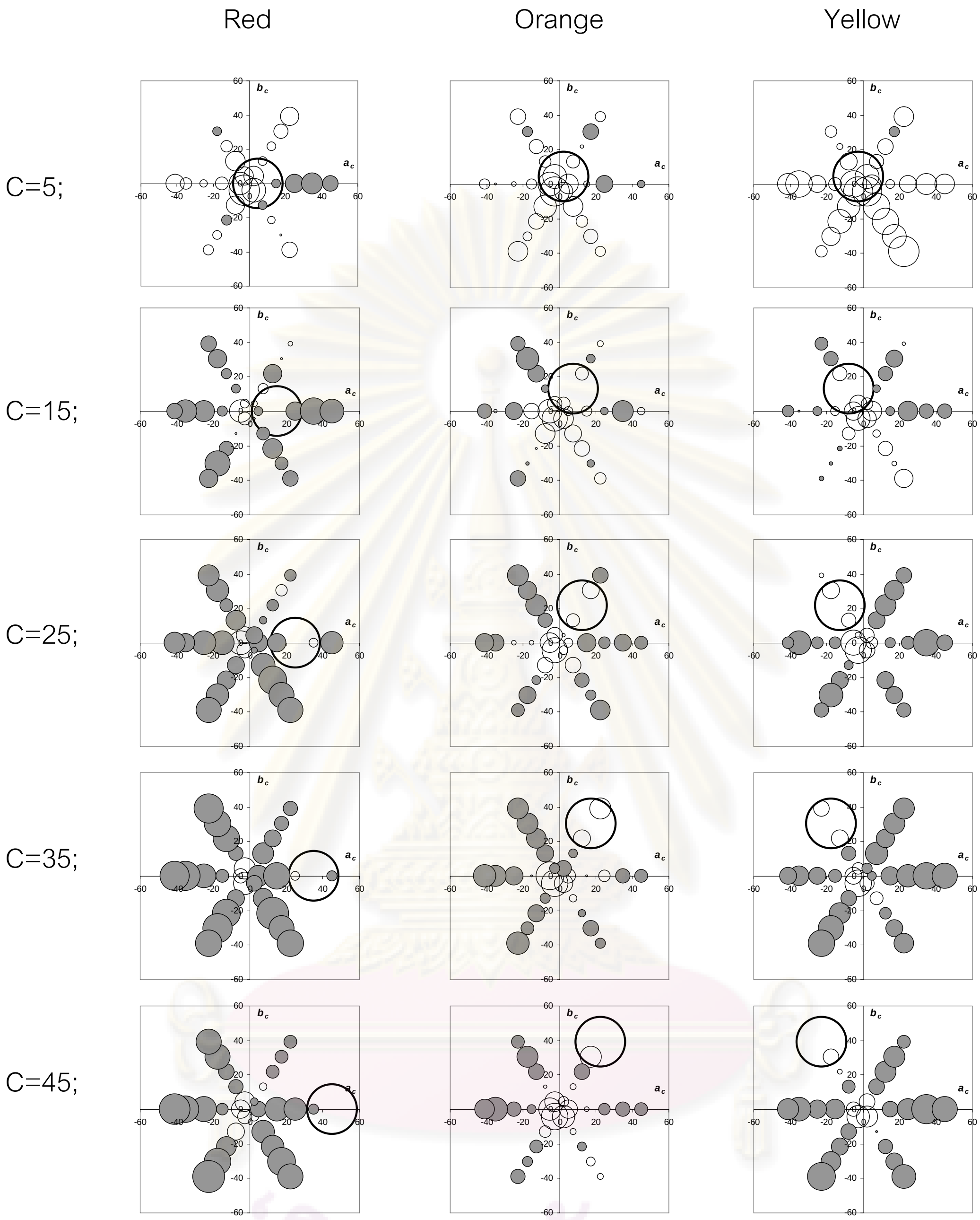

Figure C-7 Bubble charts for colour pairs generated from Red, Orange, or Yellow and one of the other colours varying in chroma levels.

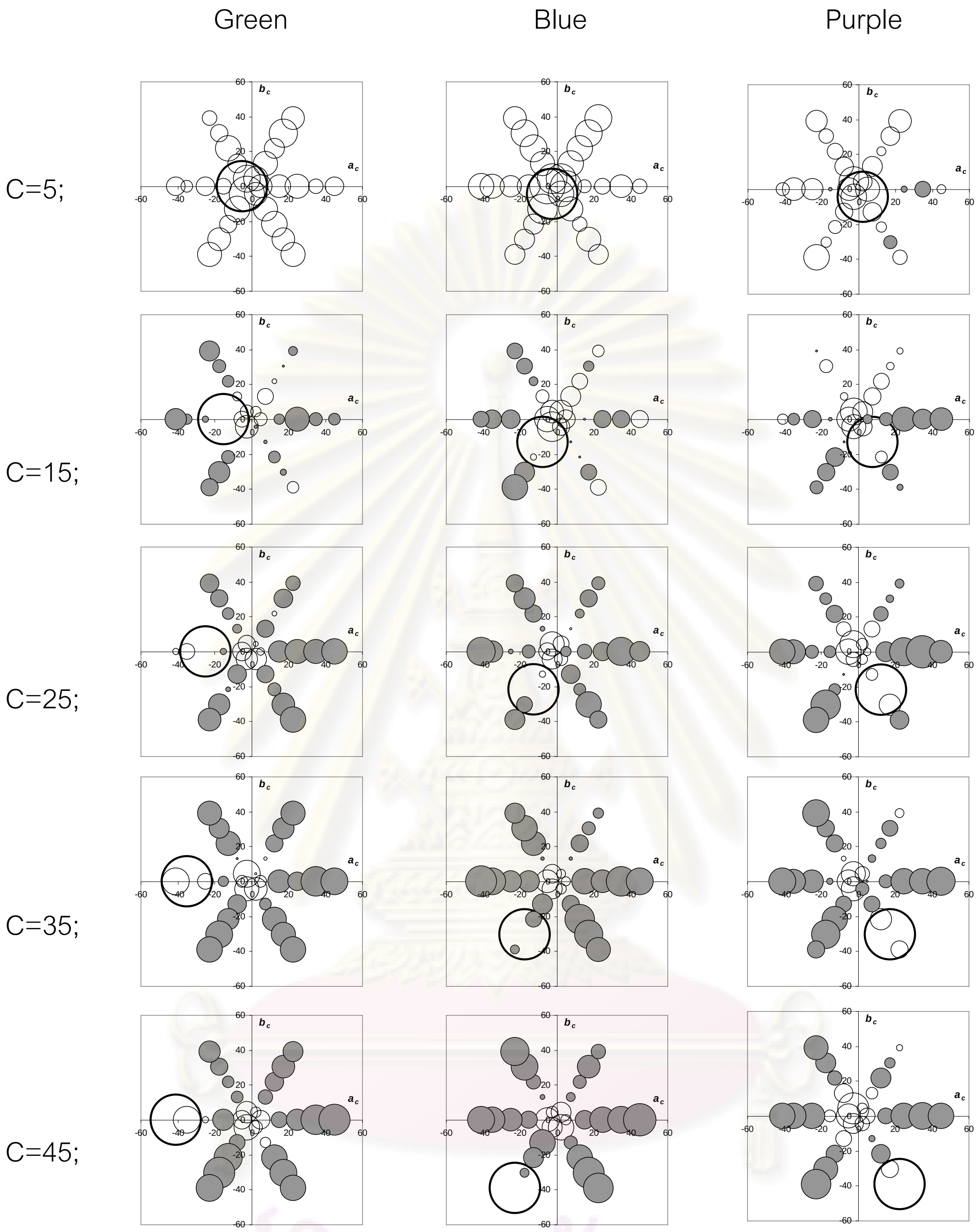

Figure C-8 Bubble charts for colour pairs generated from Green, Blue, or Purple and one of the other colours varying in chroma levels.

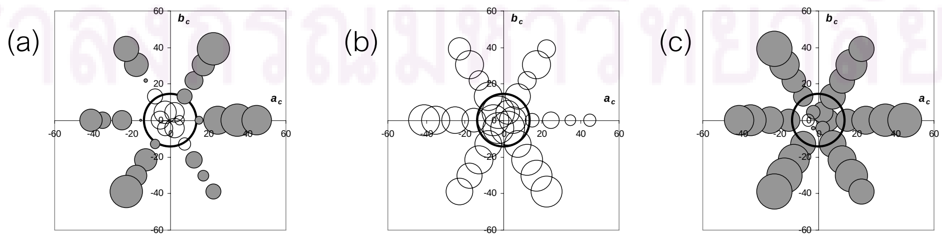

Figure C-9 Bubble charts for colour pairs generated from (a) Black, (b) Grey, and (c) White and one of the other colours.

Appendix D

Relationships between colour harmony scores and J_{sum}, $J_{diff,}$ C_{sum}, C_{diff}.

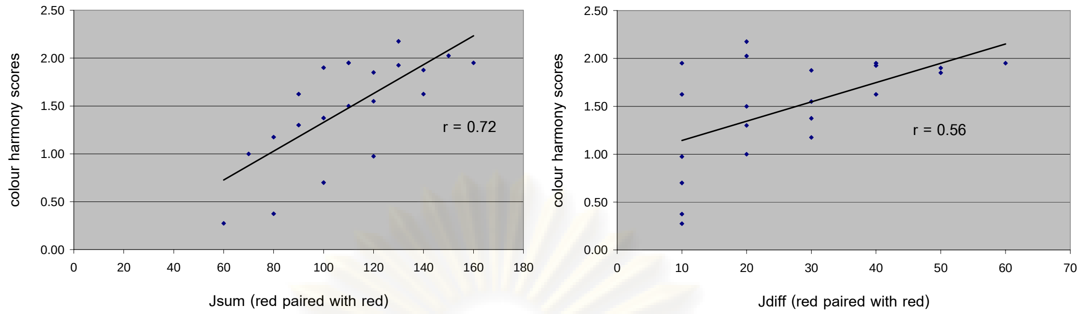

Figure D-1 Relationships between colour harmony scores and lightness of red-red pairs (left) lightness sum and (right) lightness difference.

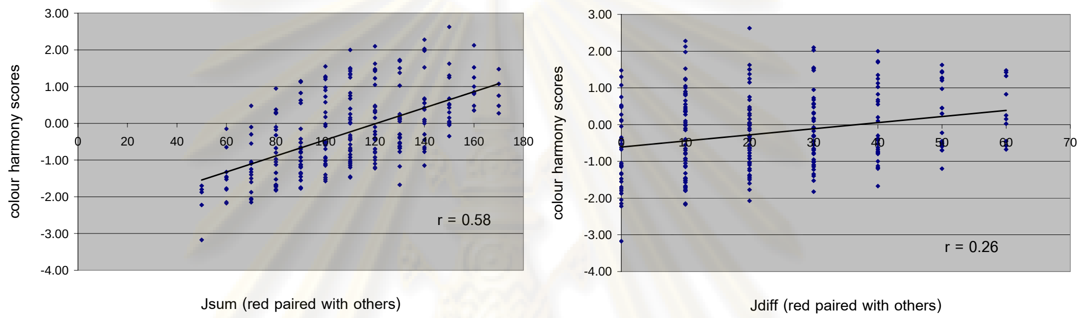

Figure D-2 Relationships between colour harmony scores and lightness of red-others pairs (left) lightness sum and (right) lightness difference.

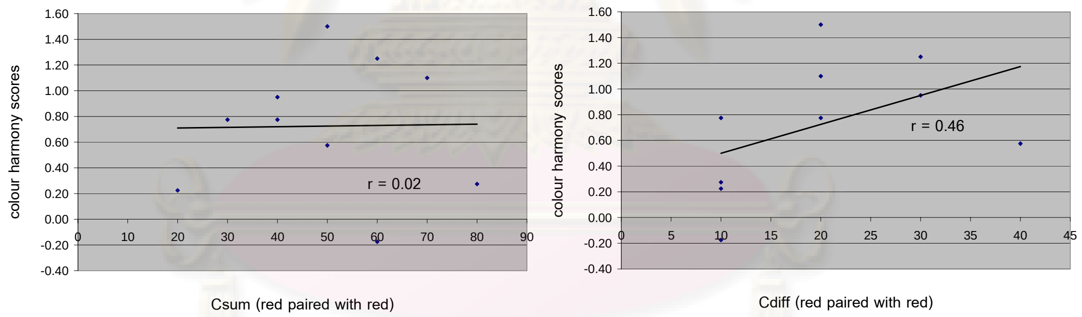

Figure D-3 Relationships between colour harmony scores and chroma of red-red pairs (left) chroma sum and (right) chroma difference.

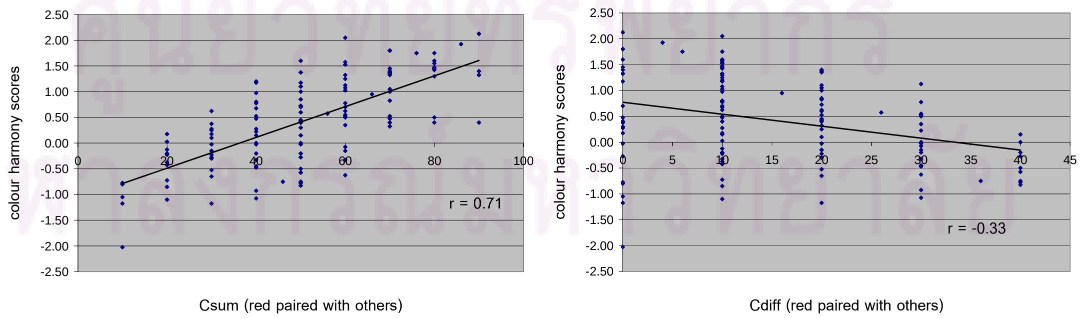

Figure D-4 Relationships between colour harmony scores and chroma of red-others pairs (left) chroma sum and (right) chroma difference.

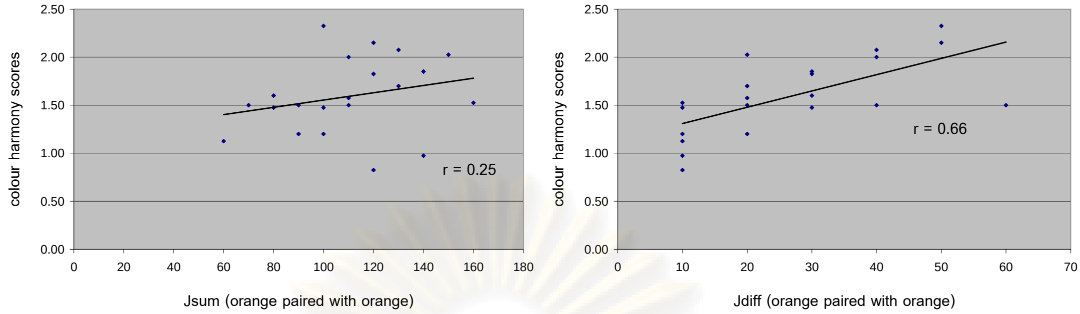

Figure D-5 Relationships between colour harmony scores and lightness of orange-orange pairs (left) lightness sum and (right) lightness difference.

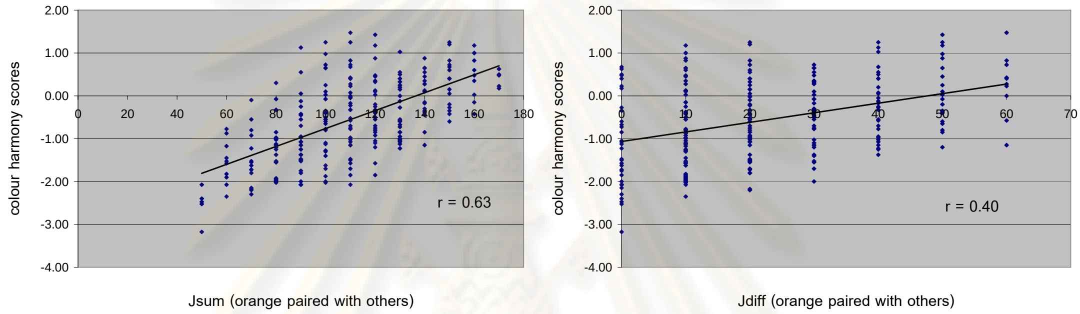

Figure D-6 Relationships between colour harmony scores and lightness of orange-others pairs (left) lightness sum and (right) lightness difference.

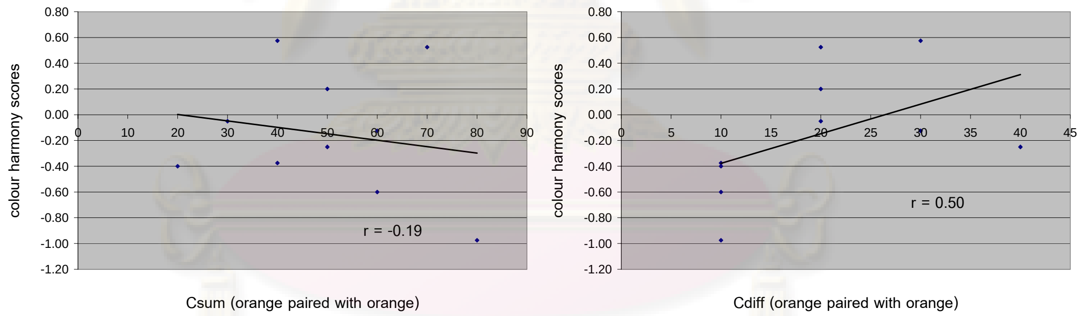

Figure D-7 Relationships between colour harmony scores and chroma of orange-orange pairs (left) chroma sum and (right) chroma difference.

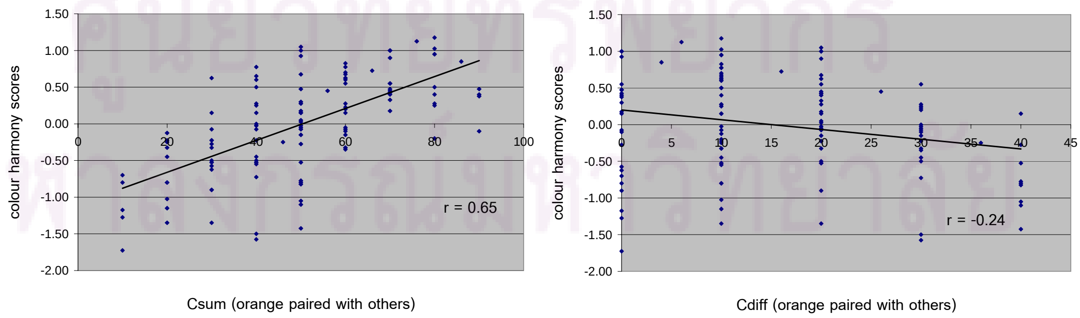

Figure D-8 Relationships between colour harmony scores and chroma of orange-others pairs (left) chroma sum and (right) chroma difference.

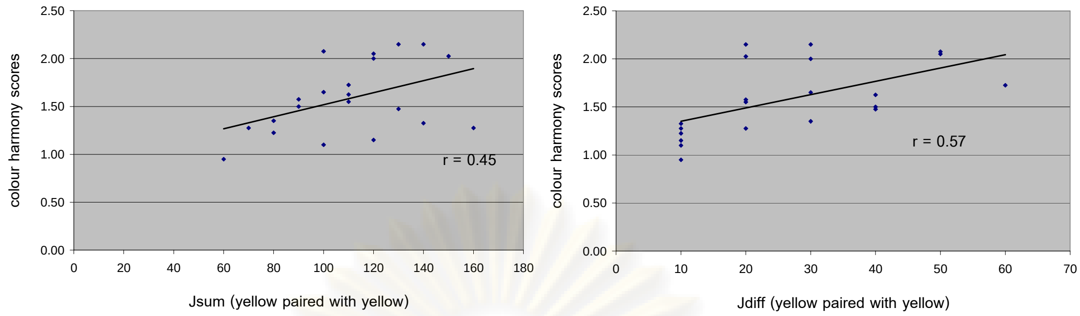

Figure D-9 Relationships between colour harmony scores and lightness of yellow-yellow pairs (left) lightness sum and (right) lightness difference.

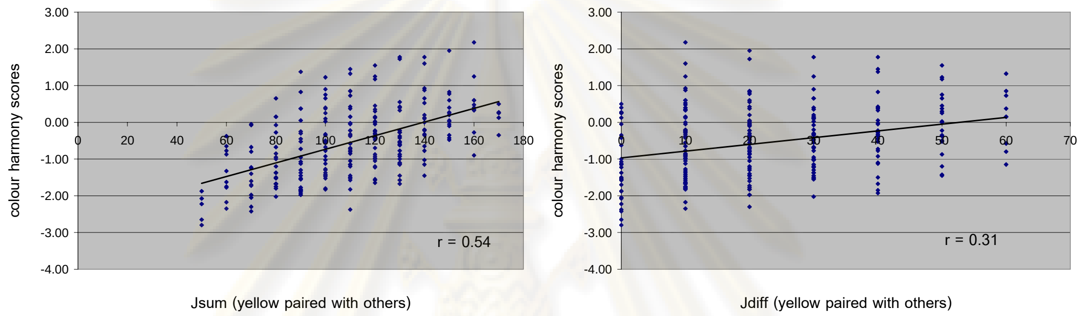

Figure D-10 Relationships between colour harmony scores and lightness of yellow-others pairs (left) lightness sum and (right) lightness difference.

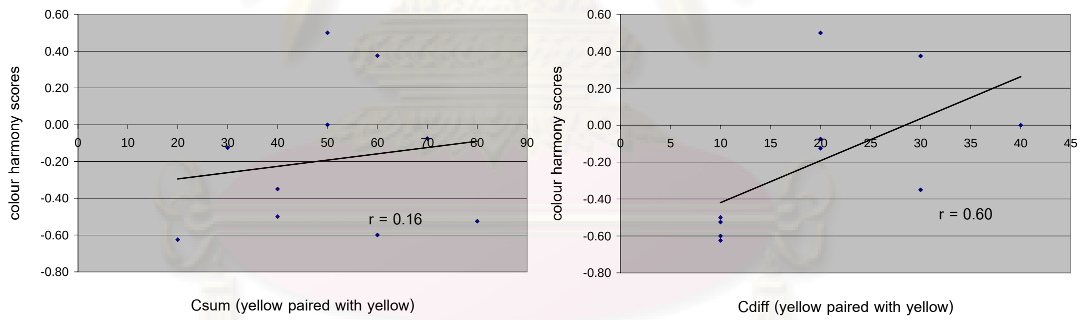

Figure D-11 Relationships between colour harmony scores and chroma of yellow-yellow pairs (left) chroma sum and (right) chroma difference.

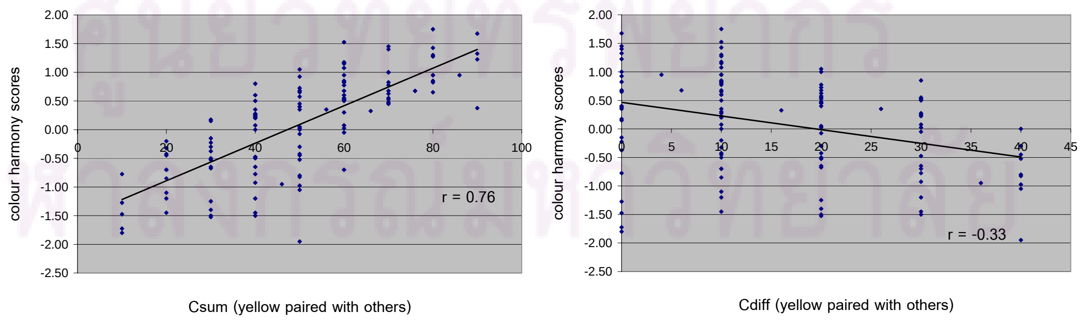

Figure D-12 Relationships between colour harmony scores and chroma of yellow-others pairs (left) chroma sum and (right) chroma difference.

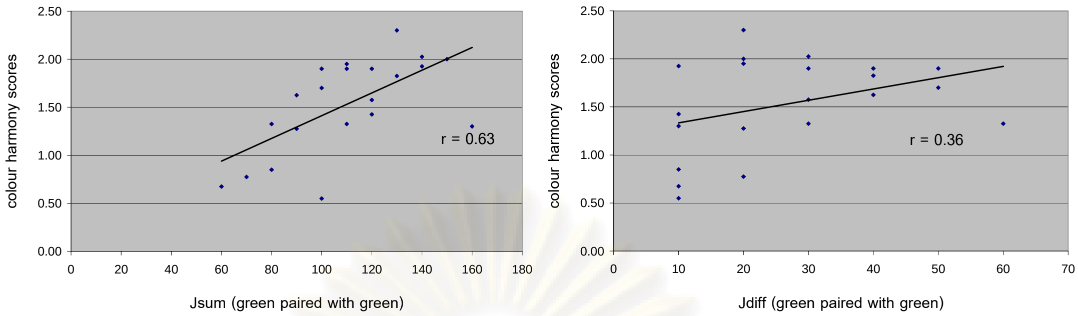

Figure D-13 Relationships between colour harmony scores and lightness of green-green pairs (left) lightness sum and (right) lightness difference.

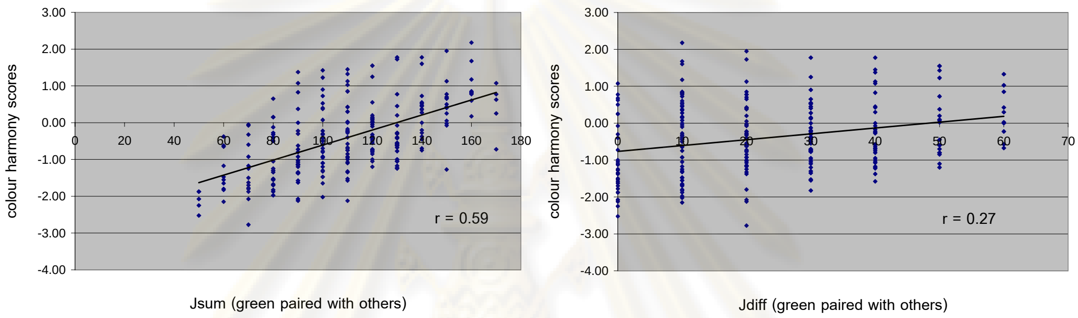

Figure D-14 Relationships between colour harmony scores and lightness of green-others pairs (left) lightness sum and (right) lightness difference.

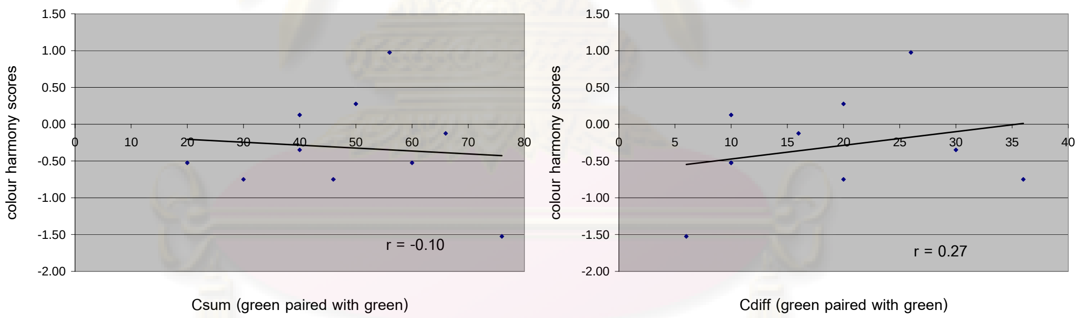

Figure D-15 Relationships between colour harmony scores and chroma of green-green pairs (left) chroma sum and (right) chroma difference.

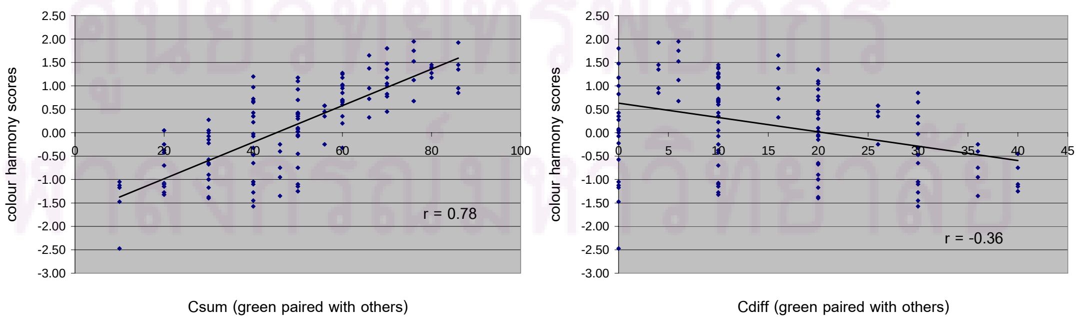

Figure D-16 Relationships between colour harmony scores and chroma of green-others pairs (left) chroma sum and (right) chroma difference.

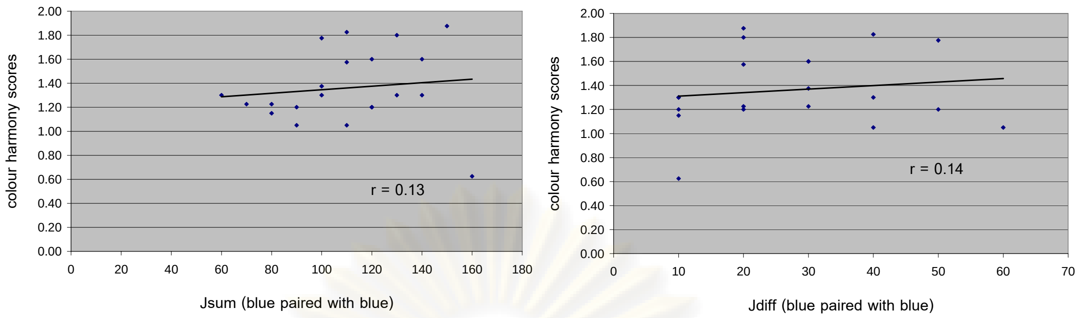

Figure D-17 Relationships between colour harmony scores and lightness of blue-blue pairs (left) lightness sum and (right) lightness difference.

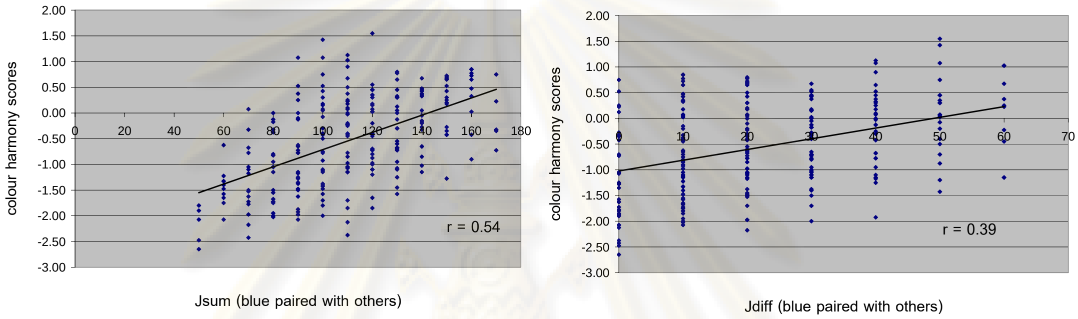

Figure D-18 Relationships between colour harmony scores and lightness of blue-others pairs (left) lightness sum and (right) lightness difference.

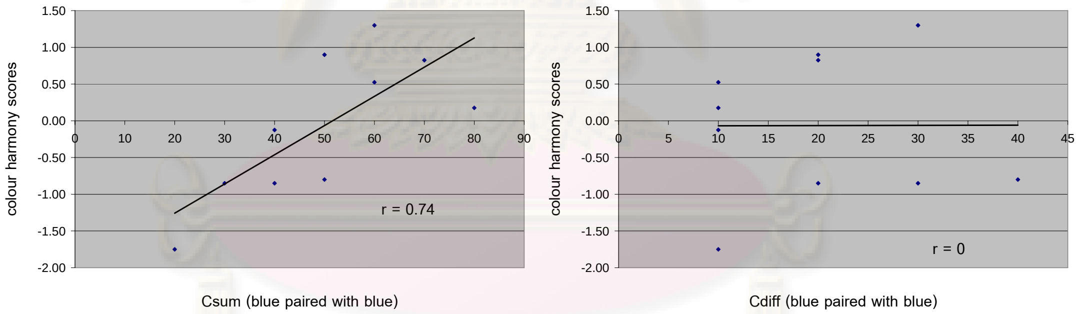

Figure D-19 Relationships between colour harmony scores and chroma of blue-blue pairs (left) chroma sum and (right) chroma difference.

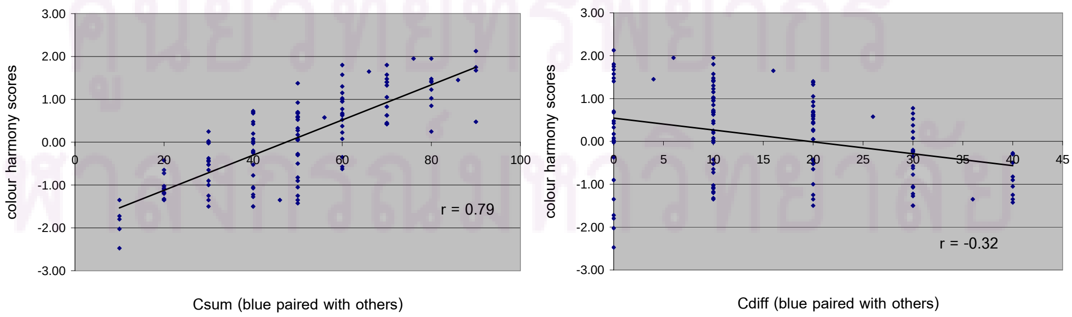

Figure D-20 Relationships between colour harmony scores and chroma of blue-others pairs (left) chroma sum and (right) chroma difference.

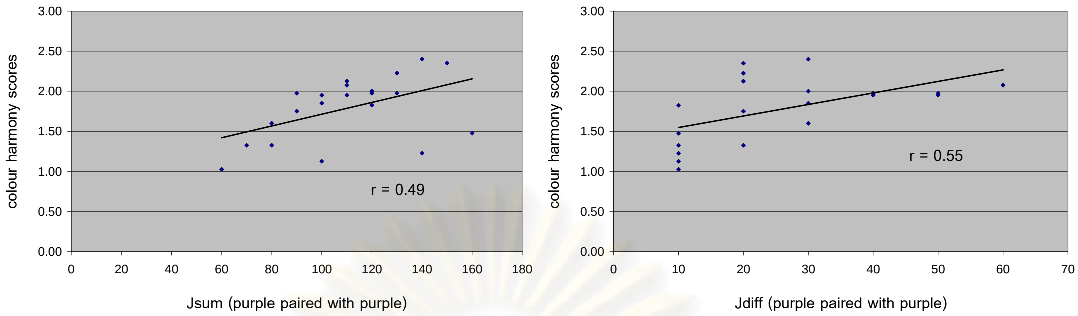

Figure D-21 Relationships between colour harmony scores and lightness of purple-purple pairs (left) lightness sum and (right) lightness difference.

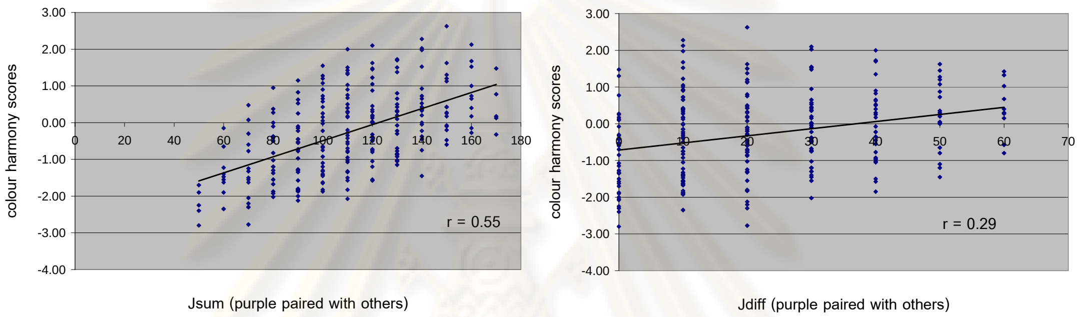

Figure D-22 Relationships between colour harmony scores and lightness of purple-others pairs (left) lightness sum and (right) lightness difference.

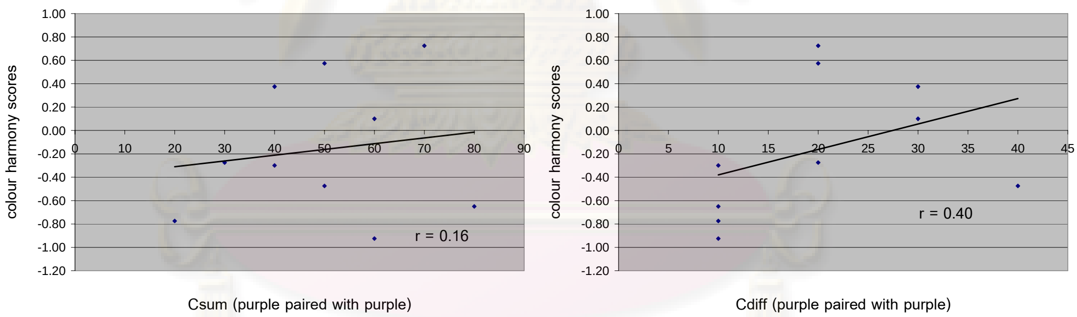

Figure D-23 Relationships between colour harmony scores and chroma of purple-purple pairs (left) chroma sum and (right) chroma difference.

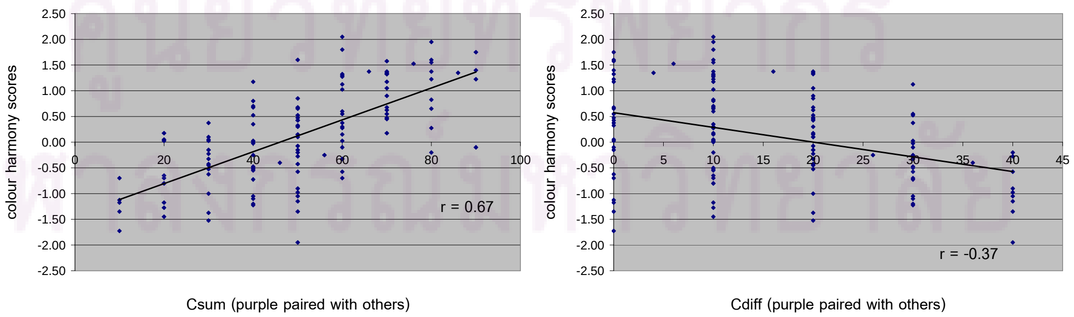

Figure D-24 Relationships between colour harmony scores and chroma of purple-others pairs (left) chroma sum and (right) chroma difference.

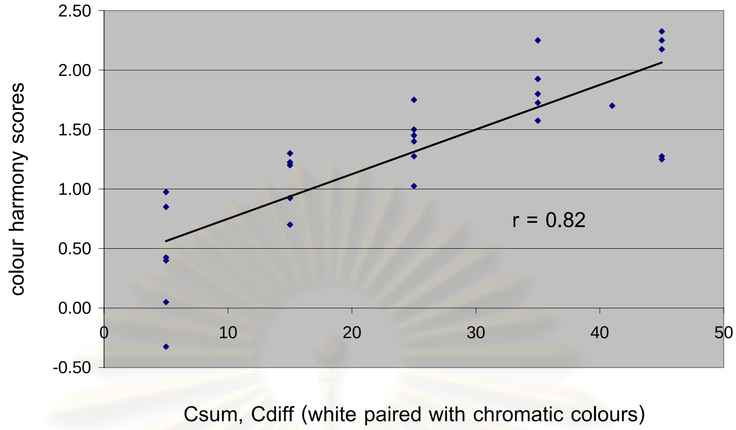

Figure D-25 Relationships between colour harmony scores and chroma of white-chromatic colour pairs.

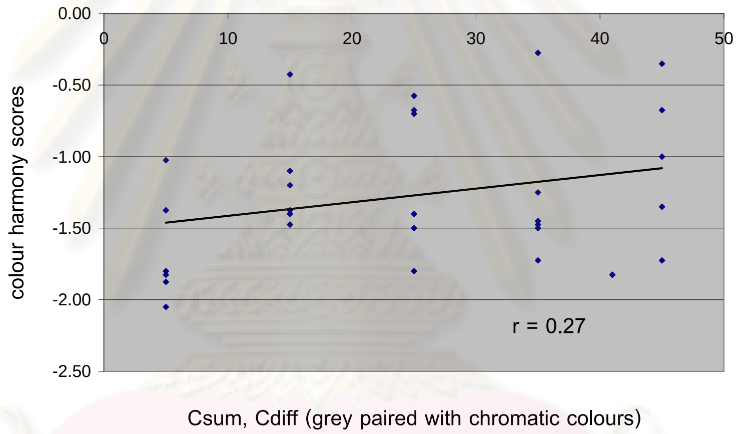

Figure D-26 Relationships between colour harmony scores and chroma of grey-chromatic colour pairs.

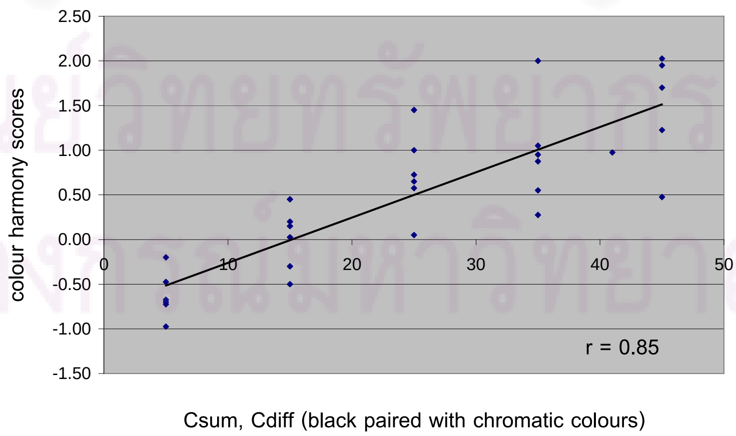

Figure D-27 Relationships between colour harmony scores and chroma of black-chromatic colour pairs.

VITA

Miss Parnsiri Ngammaneewat was born on December 14, 1979 in Bangkok, Thailand. She received a Bachelor's Degree of Engineering in Computer Engineering from the Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang in 2002 and she has been a graduate student in Imaging Technology Program, Department of Photographic Science and Printing Technology, Faculty of Science, Chulalongkorn University since 2007.