ระบบการรับรู้สีสำหรับสีปฐมภูมิในการพิมพ์

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COLOUR PERCEPTION SYSTEM FOR PRIMARY COLOURS IN PRINTING

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A Dissertation Submitted in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy Program in Imaging Technology

Department of Imaging and Printing Technology

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Thesis Title	COLOUR PERCEPTION SYSTEM FOR PRIMARY COLOURS IN PRINTING
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ระบบสีสำหรับการพิมพ์ที่ใช้กันอยู่ในปัจจุบันนั้น กำหนดคำเรียกสีโดยใช้ค่าร้อยละพื้นที่เม็ดสกรีนของแม่สีหลักแต่ละสี ได้แก่ สีน้ำเงินเขียว สีม่วงแดง สีเหลือง และสีดำ ซึ่งไม่สอดคล้องกับระบบการวัดสีที่ได้จากการผสมสีแบบบวกด้วยแม่สี สีแดง สีเขียว และสีน้ำเงิน ดังนั้นระบบสีบนหลักการของการรับรู้สีของสิ่งพิมพ์ จะให้ความสัมพันธ์ระหว่างระบบการวัดค่าสีกับระบบการพิมพ์ที่ดีกว่า งานวิจัยนี้จึงเสนอ ความเข้มสี (colour strength) ซึ่งเป็นลักษณะการรับรู้สี มาใช้ในการเชื่อมโยงกันระหว่างระบบการวัดสีกับระบบการพิมพ์ โดยมีวัตถุประสงค์เพื่อกำหนดระบบสีบนหลักการของระบบการรับรู้สีสำหรับสีปฐมภูมิในการพิมพ์ จากผลการทดลองสามารถกำหนดความสัมพันธ์ระหว่างร้อยละพื้นที่เม็ดสกรีนของสีปฐมภูมิในการพิมพ์กับความเข้มสี ตัวอย่างสีในการทดลองพิมพ์ด้วยระบบออฟเซต ค่าความเข้มสีของตัวอย่างสีเทาอ้างอิงได้จากวิธีการประมาณค่าตัวเลขของผู้สังเกต สำหรับค่าความเข้มสีของสีปฐมภูมิ ได้แก่ สีน้ำเงินเขียว สีม่วงแดง และสีเหลือง ได้จากการจับคู่ตัวอย่างสีของสีปฐมภูมิกับตัวอย่างสีเทาอ้างอิงที่มีความเข้มสีเท่ากัน ผลที่ได้นำมาสร้างสมการโพลิโนเมียลกำลังสองเพื่อการคำนวณค่าความเข้มสีจากค่าร้อยละพื้นที่เม็ดสกรีน และการคำนวณค่าร้อยละพื้นที่เม็ดสกรีนจากค่าความเข้มสีของสีน้ำเงินเขียว สีม่วงแดง สีเหลือง และสีดำ นำค่าความเข้มสีจากสมการนี้และค่าสีในระบบสี CIEL*a*b* มาสร้างแบบจำลองความเข้มสี ระบบสีที่เสนอขึ้นในงานวิจัยนี้ใช้ค่าสีในระบบสี CIEL*a*b* เป็นข้อมูลในการทำนายค่าความเข้มสี และใช้ค่าความเข้มสีเพื่อทำนายค่าร้อยละพื้นที่เม็ดสกรีนของสีปฐมภูมิ ทดสอบประสิทธิภาพในการทำนายของระบบสีด้วยสีทุติยภูมิ ซึ่งประกอบด้วยสีแดง สีเขียว และสีน้ำเงิน พบว่า ความผิดพลาดในการทำนายความเข้มสีสำหรับ สีแดง สีเขียว และสีน้ำเงิน คิดเป็นร้อยละ 15.92, 14.07 และ 43.10 ตามลำดับ และความผิดพลาดในการทำนายร้อยละพื้นที่เม็ดสกรีนสำหรับ สีแดง สีเขียว และสีน้ำเงิน คิดเป็นร้อยละ 6.28 (ค่าเฉลี่ยความผิดพลาดของสีเหลืองและสีม่วงแดง) 3.90 (สีเหลืองและสีน้ำเงินเขียว) และ 3.28 (สีน้ำเงินเขียวและสีม่วงแดง) ตามลำดับ เมื่อพิจารณาจากผลความแตกต่างระหว่างผู้สังเกต พบว่า มีความแตกต่างกันร้อยละ 20 จึงถือได้ว่า ระบบสีที่เสนอในงานวิจัยนี้ให้ค่าการทำนายที่ดี

ภาควิชา วิทยาศาสตร์ทางภาพถ่ายและเทคโนโลยีทางการพิมพ์

สาขาวิชา เทคโนโลยีทางภาพ

ปีการศึกษา 2556

ลายมือชื่อนิสิต ....

ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม ....

5173885623 : MAJOR IMAGING TECHNOLOGY
KEYWORDS: COLOUR-ORDER SYSTEM / COLOUR STRENGTH / PRIMARY COLOURS

SURAWIT NANTAKARAT: COLOUR PERCEPTION SYSTEM FOR PRIMARY COLOURS IN PRINTING. ADVISOR: ASST. PROF. SUCHITRA SUEEPRASAN, Ph.D., CO-ADVISOR: PROF. TETSUYA SATO, Ph.D., 129 pp.

The current colour system for printing specifies colours using percentages of dot areas of each primary colour, i.e. cyan, magenta, yellow and black. However, this system does not conform with the colour measurement system that relates to additive colour-mixing with red, green and blue as primaries. Thus, a colour system based on colour perception of prints will provide better correlation between the colour measurement system and the printing system. This study proposed colour strength as the colour perception parameter used to connect these two systems. The aim of this study was to devise a colour system based on colour perception for primary colours in printing. The relationships between the dot area percentages of primary colours and colour strength were obtained through a series of experiments. The colour samples were printed with the offset printing system. The colour strength values of the grey samples in the reference scale were quantified by the magnitude estimation method. For the primary colour samples (C, M, and Y), the colour strength values were obtained from matching the samples to the reference scale. The second-order polynomial equations for computing the colour strength value from the dot area percentage of C, M, Y, and K and vice versa were derived. The colour strength values obtained from these equations and CIEL*a*b* values were used to derive the colour strength model. The colour system proposed in this study used CIEL*a*b* values as the input data to predict the colour strength values, then from the colour strength values to predict the dot area percentages of primary colours. The performance of the system was tested with secondary colour samples (RGB). It was found that the percentages of colour strength prediction errors for red, green and blue were 15.92, 14.07 and 43.10, respectively. The percentages of %dot area prediction errors for red, green and blue were 6.28 (average errors of Y and M), 3.90 (Y and C) and 3.28 (C and M), respectively. Since the agreements between observers' visual data of colour strength were approximately 20% errors, the proposed colour system was considered to give good predictions.

Department: Imaging and Printing Technology
Field of Study: Imaging Technology
Academic Year: 2013

Student's Signature ....

Advisor's Signature ....

Co-Advisor's Signature ....

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CHAPTER 1

INTRODUCTION

1.1 Background and rationale

A colour-order system is a system that specifies colours by words or symbols for communication. It contains a number of colour samples arranged in a systematic way. Colour samples bearing the same words or symbols will have the same colour appearance [1]. Given the colour notations, ones could communicate and has the mutual understanding between them. With the physical samples, a colour-order system is practically useful for making comparisons between reproductions of colours. Thus, it is widely used in various industries such as design and architecture. There are several colour-order systems in use; among them are Munsell, DIN6164 and NCS. These systems specify colours by hue, chroma and brightness, which are colour perception attributes. However, these systems do not correspond to the subtractive colour-mixing system in a printing process, which generates colours by overprinting halftone dots of cyan, magenta, yellow and black in appropriate proportions [2]. The current colour system for printing thus specifies colours using percentages of dot areas that each primary colour is printed. The percentages start from zero (no screen dot) to 100 (solid), for example, a red sample could be specified by 80% of magenta and 70% of yellow. However, this red sample may not have the same appearance when reproduced with different printing materials, e.g. ink and/or substrate, and settings such as printing speed and impression [3]. Hence, the specification of colour by percentages of dot areas must be used with care for communication or reference.

There are a number of factors that affect colour appearance of prints, one of which is the angle of screen dots. The change of screen angle affects the perception of colour depth [4]. Furthermore, the brightness of colour tends to increase gradually when the chroma of colour increases [5]. In Brozovic et al. study [6], the correlation between subjective and objective artwork reproductions using different printing technologies was investigated. It was found that the best quality of colour lightness was produced with conventional offset printing and an AM screen.

The specification of colour based on colorimetry is helpful in the process of quality control in printing. The colorimetry system such as CIEL*a*b* specifies colour by numbers based on the measurements of physical properties of colour perception components. Thus, this system can quantify the differences between printed reproductions. Colour samples with the same CIEL*a*b* values will have the same colour appearance. However, the values in the CIEL*a*b* colour system do not correlate well with the printing system, as it is derived from the human visual system, which is the additive colour-mixing system. Thus, the colour perception terms in CIEL*a*b* do not conform to the colour specified by the percentages of dot area in printing. Hence, there should be the specification of colour perception to connect between CIEL*a*b* and the percentage of dot area. The present study aimed to derive the colour system for printing based on colour perception. To achieve this goal, it is important to understand how colour is perceived.

Colour perception has three components: light source, object and observer [7]. Colour is a sensation stimulated in the observer’s eyes by the wavelengths of light produced by the light source and transformed by the object. The affecting factors of colour perception in the concepts of colour observed by the human eye are colour psychology, colour physiology and physical colour [8]. In the view of colour mixing, colour results from the trichromatic structure of the human retina – the mixing of colour signals of red, green and blue – while cyan, magenta and yellow are used in the way of colour classification systems in printing technology [2].

For object colours with the same luminance factor, their perceived brightness or lightness values are sometimes very different between achromatic and chromatic colours. This phenomenon is called the B/L (brightness/luminance) ratio or the L/Y (lightness/luminance factor) ratio effect. Sometimes, both effects are called the Helmholtz–Kohlrausch (H–K) effect [9]. The H-K effect was the basic theory for defining the colour perception in this study. H-K effect is a human eye behavioural effect with colour lighting. This effect refers to the human eye phenomenon that colour light appears brighter to an observer than white light of the same luminance. It is the influence of colour purity on the perceived brightness of a colour object [10]. Nayatani [11] studied the H-K effect that was related to the chromatic strengths of spectral colours. An estimate of the chromatic strengths of spectral colours was given by using the colour-matching functions and their combinations. The chromatic strengths of spectral colours were considered the cause of the H-K effect. Kaleigh et al. [12] tried to converse complex images and video to the appearance of greys by the H-K effect, to predict differences between achromatic and chromatic colours. The change of the H-K effect for varying hues was compared to luminance based on lightness, nearly equal lightness was predicted for all colours, as they were mapped to the same grey scale value.

The term chromatic strength is similar to colour depth used in textile for indicating the intensity of dyes. However, colour depth is not compatible with the printing process. This is because colour depth refers to the intensity of dyes with the adding of colourant (concentration application method) [13]. In the printing process, the intensity of inks on the substrate is derived from the proportions of the dot area of the ink to the non-printing area of the substrate [2]. When two or more printing colours overlapped, the separate colours were mixed within the combining of colour dots by subtractive mixing [14]. Therefore, the appearance of the intensity between dye and ink was not the same phenomenon. Hence, this study used the term colour strength to describe the colour perception that relates to the intensity of ink on the substrate in the printing process.

1.2 Objectives

1) To establish relationships between the dot area percentage of prints and colour perception.

2) To devise a colour system for primary colours that is based on colour perception for printing.

1.3 Scope of the research

The colour system for primary colours proposed in this study was derived based on the four-colour process printing (CMYK). The colour samples were produced with the conventional offset printing and an AM screen, according to the reproduction process control set forth by ISO 12647-2. The relationships between percentages of dot area of primary colours (CMY) and colour strength were analysed, as well as the relationships between CIEL*a*b* and colour strength, in order to derive a system of colour perception incorporating the percentage of dot area, colour strength and colour measurement. The performance of the proposed colour system was investigated using secondary colour samples (RGB).

1.4 Experimental process

To derive the colour system for primary colours in printing based on colour perception, a series of experiments were conducted. Figure 1-1 summarises the process of this research. This study divided the process into 6 experiments. First, the reference scale of perceived colour strength was established in Experiment I. Experiment II used this scale to determine the colour strength values. The colour strength of primary colour samples was quantified from the dot area percentages in Experiment III. Experiment IV investigated the relationship between colour strength and lightness. The colour system incorporating the dot area percentages of primary colours, colour strength and colour measurement values (CIEL*a*b*) was derived in Experiment V. Finally, the performance of the proposed colour system was tested using secondary colour samples (Experiment VI). A brief explanation of each experiment is given below.

In Experiment I, the colour samples were produced according to the Graphic technology-Process control for the production of half-tone colour separations, proof and production prints-Part 1 (ISO 12647-1) [15]. The visual assessments were conducted to find the perceptual scale of colour strength. Observers looked at the grey scale and rearranged the grey patches to construct the new scale with distinguishable colour strength between different steps. The resultant scale was used as the reference scale of colour strength.

In Experiment II, the perceived colour strength was quantified by means of the magnitude estimation method. In the visual assessments, observers evaluated the value of colour strength for each grey patch in the reference scale. The relationship between the colour strength value and the dot area percentages of black ink was determined, and the equation for converting %dot area of black to colour strength values was derived.

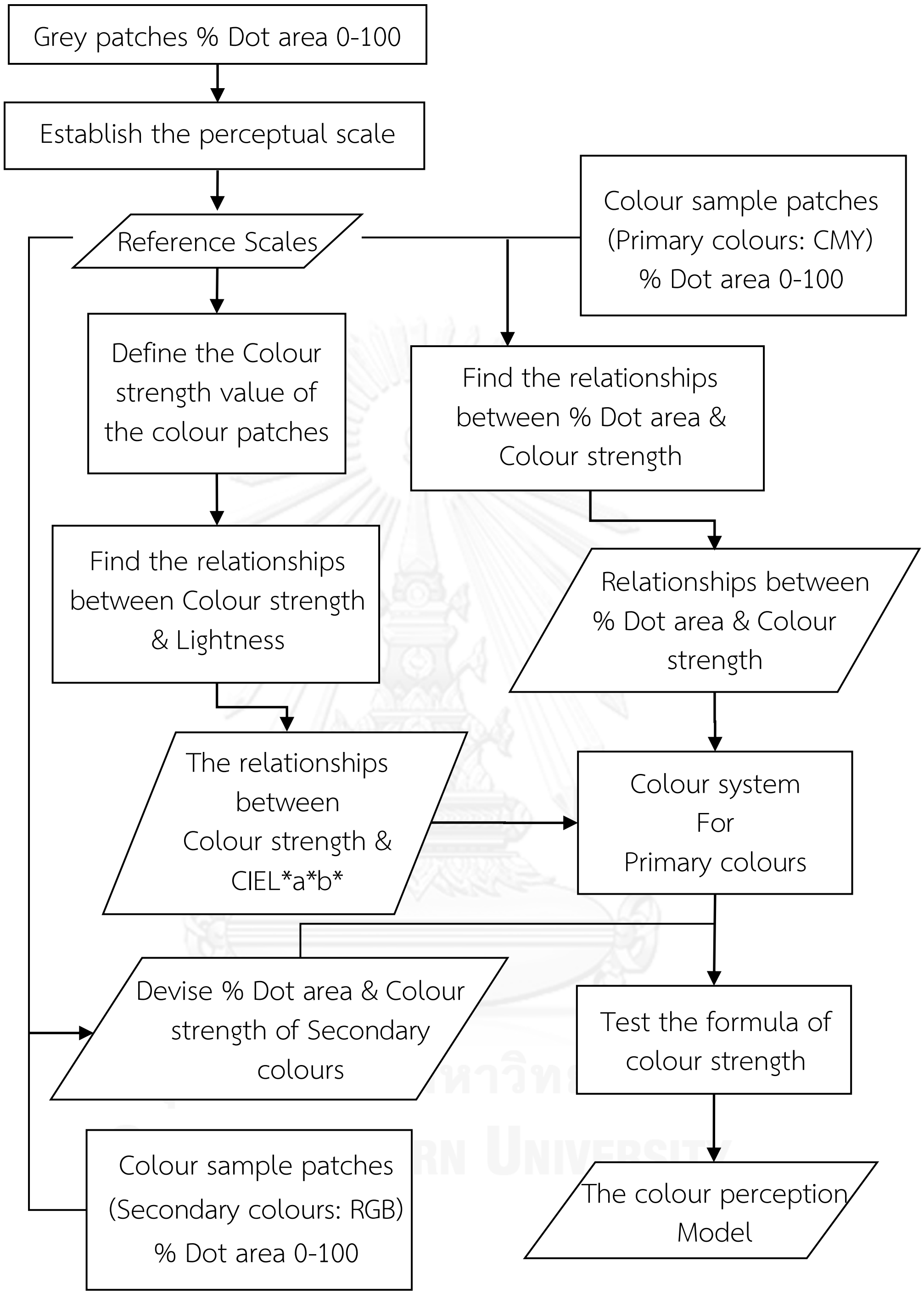


Figure 1-1 A flow chart of the experimental process.

In Experiment III, the colour strength values of primary colour samples (CMY) were quantified by finding the colour-strength-matching grey patch from the reference scale and converting the %dot area of that patch to the colour strength value using the equation obtained in Experiment II. The relationships between percentages of dot area of prints and colour strength were found, the equations for converting %dot area of primary colours to colour strength values were derived.

In Experiment IV, the relationships between colour strength and lightness were examined. The colour patches were measured in terms of XYZ values and the CIEL*a*b* colour values were calculated. The dot area percentages of black ink were plotted against the colour strength values, and the lightness values. The results showed that colour strength increased with the dot area percentages, but lightness decreased with the dot area percentages.

In Experiment V, the relationships between dot area percentages and CIEL*a*b* colour values were established, and a colour strength model was derived. The colour strength model predicted the colour strength values from the given CIEL*a*b* values. Based on this model and the results of Experiments I-IV, the colour system for primary colours was derived. The colour system requires CIEL*a*b* values as input data and returns the corresponding colour strength values and the dot area percentages of primary colours.

In Experiment VI, the performance of the proposed colour system was analysed using the secondary colour samples (RGB). The colour strength values of the colour samples were quantified in the same way as Experiment III, and the results were considered as the visual colour-strength data. The visual colour strength values were compared with the values predicted from the colour strength model. The performance in predicting the dot area percentages was analysed by comparing the %dot area of CMY combined to generate RGB with the %dot area predicted by the equations in the colour system.

1.5 Outline of the thesis

Chapter 1 gives an introduction to the thesis. Chapter 2 consists of an overview of the theoretical consideration and literature review relevant to this research. Chapter 3 describes the experimental procedure, including materials, apparatuses and observers. Chapter 4 presents the results and discussions of Experiments I-IV, where the relationships between colour strength and dot area percentage were established. Chapter 5 presents the results and discussions of Experiments V-VI, where the colour system for primary colours in printing was proposed and tested. Finally, conclusions and some suggestions are given in Chapter 6.

CHAPTER 2

THEORETICAL CONSIDERATIONS AND LITERATURE REVIEWS

2.1 Theoretical considerations

In this thesis, the relationships between the percentage of dot area and colour perception are investigated for deriving the colour perception system for primary colours in printing. The importance theories are the colour perception with its three components: light source, object and observer; concepts of the colour observed by human eyes: colour psychology, colour physiology and physical colour; colour mixing theory, including the trichromatic structure of the human retina, the relationship of the primary colours and secondary colours; printing technology and Helmhotz-Kohlrausch effect.

2.1.1 Elements of colour perception

The concept captures our colour perception when colour illusions are perceived such as colour lights, successive contrast and others that do not seem to originate in the objects themselves. Colour is something that arises in the eye or the brain of the observer. The phenomenon of colour is an event that occurs among three basic factors: light source, object and observer (Figure 2-1). Colour is a sensation evoked in the observer by the wavelengths of light produced by the light source and modified by the object. Colour is a subjective term which changes according to each person’s view. The observers’ perception of colour will be different for different observers [7].

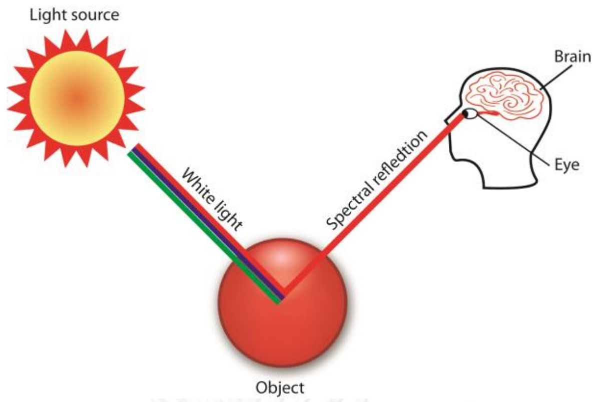


Figure 2-1 The phenomenon of colour perception.

2.1.1.1 Light sources

The first factor in the colour phenomenon is light. Sunlight makes the full range of energy levels (wavelengths), and the visible spectrum, which is the part of this spectrum that stimulates our eyes, is a small wavelength from 400 nm to 700 nm. The different wavelengths are associated with the colours they evoke, from the red, orange, yellow, green, blues, indigo and violet. A light source is just something that emits large quantities of photons in the visible spectrum. The spectral curves of the light energy emitted by the light source at each wavelength are shown in Figure 2-2 [7].

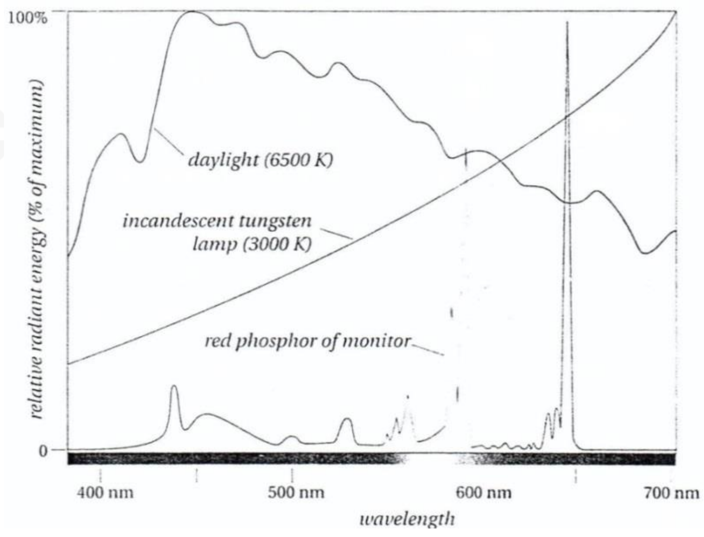


Figure 2-2 The spectral curves of three light sources [7].

2.1.1.2 The object

The second factor in the colour phenomenon is object. The way an object interacts with light plays a large role in determining the nature of the colour event. An object's surface interacts with light to affect the light's colour. Light strikes the object, travels some way onto the surface and then reflexes. During the light's interaction with this surface, the object absorbs some wavelengths and reflects others, so the spectral of the reflected light is not the same as that of the incoming light. The degree to which an object reflects some wavelengths and absorbs others is called its spectral reflectance. Reflectance then is an invariant property of the object that shows in Figure 2-3 (a) [7].

A transmissive object affects wavelengths in the same way as the reflective object, except that the transmissive object must be at least partially translucence so that the light can pass all the way through it. However, it too alters the wavelength of the light by absorbing some wavelengths and allowing others to pass through. The surface of a reflective object or the substance in a transmissive object can affect the wavelengths that strike it in many specific ways that shows in Figure 2-3 (b).

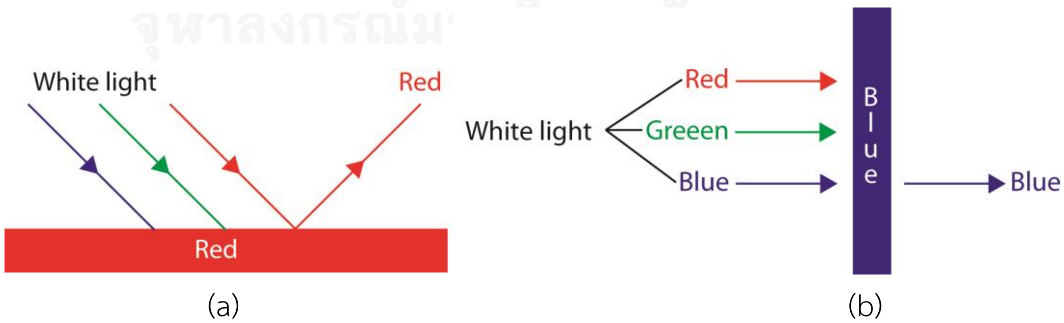


Figure 2-3 (a) The reflective object and (b) transmissive object.

2.1.1.3 The observer

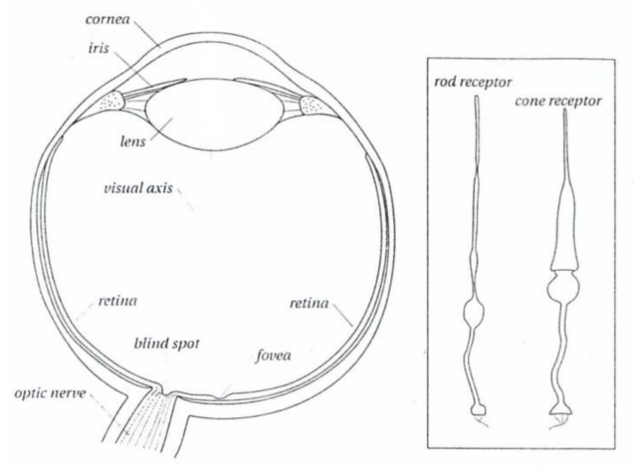
The third factor in the colour phenomenon is observer. Our visual system is complex. It starts with the structures of the eye. Contrary to general belief, the main task of focusing light into an image at the back of the eye is handled not by the lens, but by the cornea, the curved front layer of the eye. The lens adjusts to make focus, and the retina is a complex layer of nerve cells lining the back of the eye. In the retina, the nerve cells that respond to light are called photoreceptors that shows in Figure 2-4 (a). Receptors come in two types, called rods and cones because of their shapes, as shown in Figure 2-4 (b) [7].

1) Rod cells

Rods contribute vision in low light conditions, such as night vision. They are sensitive in low levels of light and are largely blinded by daylight conditions. Human has more rod cells (around 120 million rods) than cone cells (around 6 million cones) throughout of the retina.

2) Cone cells

Cones are more in the fovea at the center of retina and response in bright light conditions. This center area, where human has the highest density of photoreceptors, also contributes the best acuity. There are three types of cones. One responds primarily to the long wavelength of light and has little response in the middle or short wavelengths. Another responds primarily to the middle wavelengths, and the third responds to the short wavelengths. Many people call these the red cones, green cones and blue cones, respectively, because of the colours we normally associate with these three regions of the spectrum, but it is less misleading to refer to them as the long, medium and short-wavelength cones (or L, M and S), respectively.



(a) (b)

Figure 2-4 (a) The human eye and (b) two type of receptor [7].

2.1.2 Affecting factors of colour perception

Colour vision is an aspect of general vision that is an important capability of human, helping them to interact in a meaningful way with the environment. In human, colour is mediated by complex mechanisms in the eye and the brain. The vision for perception system results in our ability to contemplate and compare objects for recognition and planning actions, involving both form and colour. The substance of our visual memories, including objects and their colours, is available in consciousness. So, colour can be considered by three concepts of the colour that observed by human eye [8].

2.1.2.1 Colour psychology

Colour psychology is the emotion stimulated in the brain by light and colour. If a wavelength is characterized as red, it is red because this is what the person has been taught. The meaning of red can be different for two different people. Consequently, due to the effect this wavelength has on a person, differences are observed in the colour senses of different people.

2.1.2.2 Colour physiology

Physiological effects are produced on the human eye by different wavelengths. The eye being a very good optical observer can also sense an area of the spectrum. Although the eye is highly sensitive to the colours red, blue and green, it responds the greatest to the yellowish green area that has a wavelength of 556 nm.

2.1.2.3 Physical colour

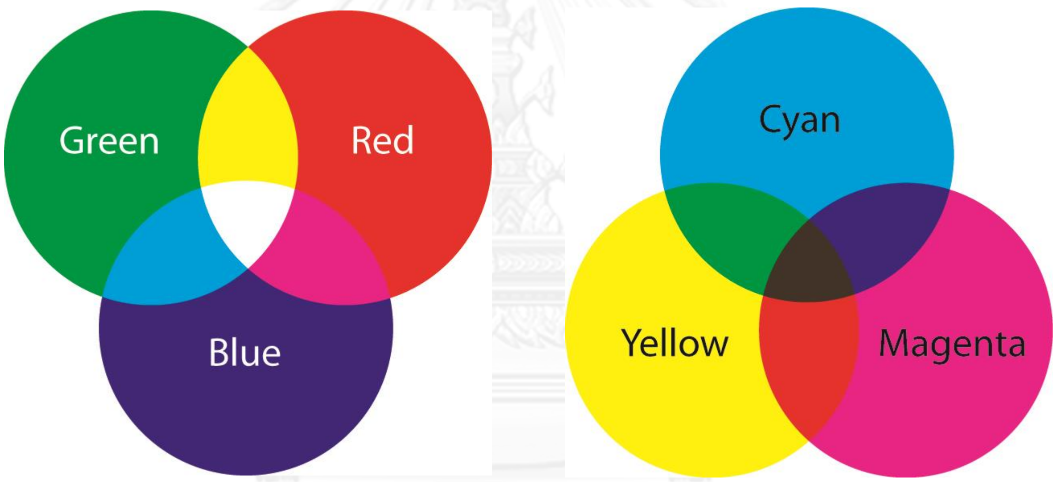
The colour is physically defined by numbers according to the wavelength and intensity of light. By means of measurement appliances, it can be defined mathematically. This colour is also important in terms of Spectrophotographic methods and measurements.

2.1.3 Colour mixing theory

The colour theory in the field of reproduction technology is used in the way of colour classification systems, which must be aligned with the colour perception of the eye of the human observer. Both additive and subtractive colour mixing processes occur in modern colour reproduction technology. The building up of luminosity by means of the individual colours involved is known as additive colour mixture. With subtractive colour mixing, on the other hand, luminosity is suppressed by the addition of individual colour. The classification method of additive or subtractive colour mixing systems is frequently assumed, as a result of the colorfulness of its individual components, but solely as a result of the light-increasing or light-reducing effect of the mixing processes [2].

2.1.3.1 Additive colour mixing

The additive colour mixing is defined as a colour stimulus of which the radiant power in any wavelength interval, small or large, in any part of the spectrum, is equal to the sum of the powers in the same interval of the components of the mixture that are assumed to be optically incoherent. An important characteristic of the additive system is that the object itself is a light emitter. Red, green and blue are additive primaries. The mixture of two additive primaries produces a subtractive primary. This phenomenon can be illustrated in the spectra; the mixture of red and green is yellow, the mixture of green and blue is cyan, and the mixture of red and blue is magenta, which shows Figure 2-5 (a). The mixture of all three additive primaries produces a spectrum, giving a white colour. A good example of additive colour mixing is colour television.



(a) (b)

Figure 2-5 (a) The additive colour mixing and (b) the subtractive colour mixing.

2.1.3.2 Subtractive colour mixing

Subtractive colour mixing of the subtractive primaries is defined as colour stimuli for which the radiant powers in the spectra are selectively absorbed by an object so that the remaining spectral radiant power is reflected or transmitted, then received by observers or measuring devices. The object itself is not a light emitter, but a light absorber. Cyan, magenta and yellow are subtractive primaries, the complement of the additive system. The mixing of two subtractive primaries creates an additive primary; the mixture of cyan and magenta is blue, the mixture of magenta and yellow is red and the mixture of cyan and yellow is green. When all three subtractive primaries are mixed, all components of the incident light are given a black colour, as shown in Figure 2-5 (b). A good example of subtractive colour mixing is colour printing on paper [16].

2.1.4 Printing technology

Printing is a reproduction process in which printing ink is applied to a printing substrate in order to transmit information; images, graphics and text, in a repeatable form using an image-carrying medium; a printing plate. The type of image-carrying medium employed depends on the printing technology used. Printing technologies with a master (image-carrying medium) are also referred to as conventional printing technologies. The printing plate is the image-carrying medium for all the procedures. Image is generated on the printing substrate by the partial surface transfer of ink. All images are denoted by image elements (transferred ink) and non-image elements (no ink).

2.1.4.1 Screen dots

To enable continuous colour tone values to be reproduced in print, such as from photographic originals, the original has to be broken up into extremely small dots (screen dots) that vary in size (percentage of dot area) or are at various distances from each other. This process is called “screening”. The main function of screening is to generate halftone values, which are intended to simulate the continuous tonal gradation, ending with the conversion of gray images into binary images (black and white). Such screening is necessary because most printing technologies operate on a binary system and can therefore only perform one of two actions, namely to transfer ink (in an evenly distributed layer) or not to transfer ink.

In the process of reproduction, two types of screen dot for colour separation in conventional printing are:

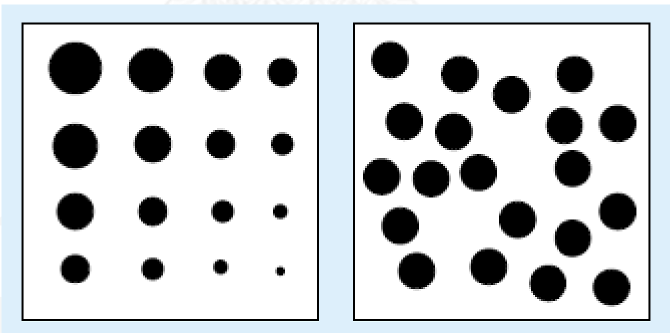
1) Amplitude modulation (AM) screen

Amplitude modulation screen is unevenly distributed screen dots that vary in size, as illustrated in Figure 2-6 (a).

2) Frequency modulation (FM) screen

Frequency modulation screen is evenly distributed screen dots that vary in spacing and equal dots in size and shape, as illustrated in Figure 2-6 (b).

The observer receives the impression of a continuous of tone from the halftone screen that has the suitable resolution; for example, when a 60 lines/cm (150 lpi) screen structure has been used [2].



(a) (b)

Figure 2-6 (a) The amplitude modulation (AM) and (b) the frequency modulation (FM) screen [2].

2.1.4.2 Offset printing

In this study, offset printing technology was used to reproduce colour samples. This is because Brozovic's study showed that the best quality of lightness reproduction was achieved by conventional offset printing with AM screen [6].

Offset printing is the major lithographic technology. It is an indirect lithographic technology, in which the ink is first transferred from the printing plate onto a flexible intermediate carrier (blanket) and then onto the substrate. The principle of offset printing is shown in Figure 2-7. To achieve an ink-repellent effect on the printing plate, the printing plate is applied with dampening solution (water with additives). The dampening solution is applied to the plate in a very fine film by dampening rollers. The non-image areas of the plate are water-receptive, and the image areas of the plate are the ink-accepting surfaces, which are unreceptive to water. The film of dampening solution prevents the transfer of ink when the printing plate receives ink. Then printing plate carries ink to transfer onto the substrate [2].

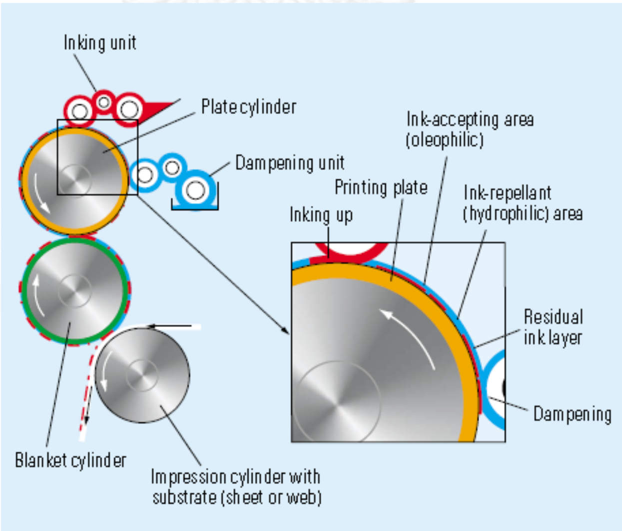


Figure 2-7 The principle of offset printing technology [2].

2.1.5 The CIE colour system

CIE (Commission International de I'Eclairage or International Commission on Illumination) is an organization that determines to describe physical and physiological effects of colours. CIE developed the standards of the colorimetric to be concerned with the relative spectral distributions of the three elements of color perception. The CIE system developed on the human colour perception process that a stimulus is provided by the proper combination of a light source, an object and an observer.

2.1.5.1 CIE standard sources and illuminants

The CIE has established a number of spectral power distributions as CIE illuminants for colorimetric. These distributions are based on statistical representations of measured light source:

1) CIE illuminant A

The CIE standard illuminant A represents the light emitted from an incandescent light bulb and has a black-body distribution with a correlated colour temperature of approximately 2856 K.

2) CIE illuminant B

CIE Illuminant B is represented as a direct sunlight. It is the light with a correlated colour temperature of about 4874 K.

3) CIE illuminant C

An illuminant C is the spectral power distribution of illuminant A as modified by Davis-Gibson filter. It represents a daylight simulator with a correlated colour temperature of about 6774 K.

4) CIE illuminant D

Illuminant D has four types; D50, D55, D65 and D75, these represent daylight with correlated colour temperatures of about 5000 K, 5500 K, 6500 K and 7500 K respectively [10].

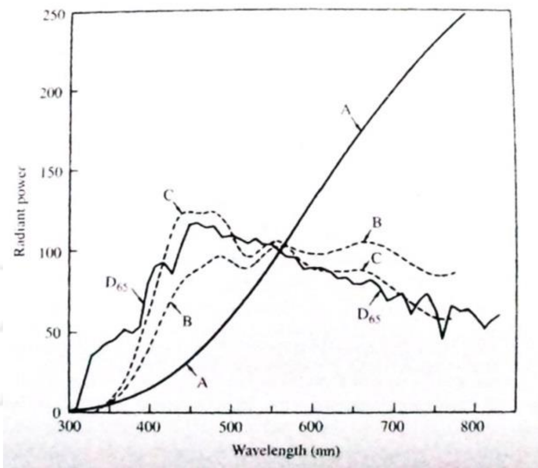


Figure 2-8 Spectral distribution of CIE illuminants A, B, C and D_{65} [10].

2.1.5.2 CIE standard observers

In 1931, CIE introduced the 1931 XYZ colour system by establishing reference stimuli [X], [Y] and [Z] in such a manner that the colour matching function from the colour matching experiments at a viewing angle of 2 degrees was defined. It is called "2° 1931 CIE standard observer" the colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ of the system are given. The viewing angle of 2 degrees on the colour matching experiments were conducted with such a narrow viewing angle to cover the region in the retina (Fovea) having the highest visual acuity.

In 1964, the other colour matching function that is based on colour matching experiments with a visual field of 10 degrees was defined. It is called "10° 1964 CIE standard observer". These are applicable to different viewing angles with respect to the observer's eye. It is recommended when the viewing angle is at 4° or greater. The colour matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$ and $\bar{z}_{10}(\lambda)$ of the new system are shown in Figure 2-9 [10].

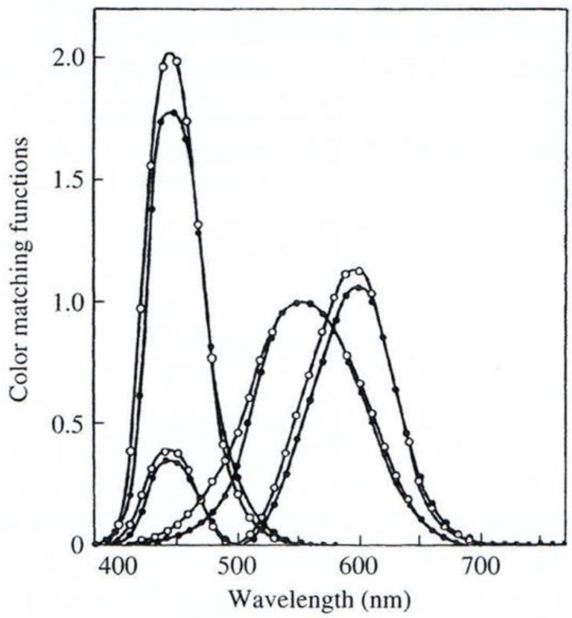


Figure 2-9 Colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ system (filled circles) and $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$ and $\bar{z}_{10}(\lambda)$ system (open circles) [10].

2.1.5.3 CIE XYZ Tristimulus values

The tristimulus values X, Y and Z are colour values in the CIE system, in which a colour stimulus is calculated from the CIE standard observer functions, taking into account the type of illumination and reflectance of the sample. At each wavelength $\bar{x}$, $\bar{y}$ and $\bar{z}$ are multiplied by the spectral energy emitted by the light source. Then that value is multiplied by the reflectance of the sample at each wavelength from 380 to 780 nanometers. The values for the entire wavelength are then summed. So, the colour stimulus can be specified into the number, as shown in Equation 2.1-2.4 [10]:

$$X = k \int_{380}^{780} S(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \tag{2.1}$$

$$Y = k \int_{380}^{780} S(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \tag{2.2}$$

$$Z = k \int_{380}^{780} S(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda \tag{2.3}$$

$$k = \frac{100}{\int_{380}^{780} S(\lambda)\bar{y}(\lambda)d\lambda} \tag{2.4}$$

Where S(λ) is the relative spectral power distribution of the illuminant

R(λ) is the spectral reflectance of specimen

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the colour matching functions

$d\lambda$ is the wavelength from 380-780 nanometer

k is the normalizing constant.

*2.1.5.4 CIE L*a*b* colour space*

The L*a*b* colour space was established by CIE in 1976 as a uniform colour space. This colour space is expressed by the following three-dimensional orthogonal coordinates: L* is lightness that has the value from 0 (black) to 100 (white) in the axis perpendicular to the plane a* and b*, a* is the correlate of redness or greenness and b* is the correlate of yellowness or blueness. The L*, a* and b* are defined as:

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16 \tag{2.5}$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right] \tag{2.6}$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right] \tag{2.7}$$

Where $\frac{X}{X_n}$, $\frac{Y}{Y_n}$ and $\frac{Z}{Z_n}$ are higher than 0.008856

X, Y and Z are the tristimulus values of the object

X_n, Y_n and Z_n are the tristimulus values of the reference white.

*2.1.5.5 CIE Colour-Difference on CIE L*a*b* colour space*

Colour-Difference (ΔE^*_{ab}) in the L*a*b* colour space expresses the difference of colours between a reference and a sample. Colour difference between two samples is defined by their difference in lightness (ΔL*), redness or greenness (Δa*) and yellowness or blueness (Δb*), as follows:

$$\Delta E^*_{ab} = \sqrt{(L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2} \quad (2.8)$$

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (2.9)$$

Where $L^*_1 a^*_1 b^*_1$ are the CIE L*a*b* colour values of the sample.

$L^*_2 a^*_2 b^*_2$ are the CIE L*a*b* colour values of the reference.

ΔL^* Δa^* Δb^* are the coordinate colour difference between the sample and reference colour.

2.1.6 Quantitative Analysis

Quantitative data are the data derived from measurements and calculations and collected in the form of numbers. The data or numbers derived from the measurement are an integer or a decimal number used for quantitative analysis. The analyses used in this study are as follows.

2.1.6.1 Average

The average analysis simply computes the arithmetic mean or average of a numeric variable. The mean or average of a set of values is the sum of the values divided by the number of the values, as given in Equation 2.10 [17].

$$\bar{x} = \frac{\sum x}{N} \quad (2.10)$$

Where $\bar{x}$ is the average value.

$\sum x$ are sum of all data.

N is the total number of data.

2.1.6.2 Median

The median is used instead of the mean when the data is not normally distributed. To find the median, the data are first sorted into an ascending or descending order. The median value is the middle value of the data set containing an odd number of values, or the average of the two middle values of a data set with an even number of values, as given in Equations 2.11 and 2.12 [17].

If the data set contains an odd number of values, the median value is in the middle position (Equation 2.11):

$$\text{Position} = \frac{N+1}{2} \tag{2.11}$$

If the data set contains an even number of values, the median value is the average of the two values in the middle position (Equation 2.12):

$$\text{Position} = \frac{N}{2} \text{ and } \frac{N}{2}+1 \tag{2.12}$$

Where N is the number of values.

2.1.6.3 Standard deviation

Standard deviation is the measurement of the distribution of the mean value of the data set or the difference between each value and the mean value. If the value of each data differs largely from the mean value, it means that the data set is highly distributed. The standard deviation can be calculated by Equation 2.13 [17]:

$$\text{S.D.} = \sqrt{\frac{\sum_{i=1}^{N}(X_i-\bar{X})^2}{N}} \tag{2.13}$$

Where X is each value of the data.

$\bar{X}$ is the mean value.

N is the number of values.

2.1.6.4 Root mean square

Root mean square (RMS), referred to as the quadratic mean, is a measure of statistical quantities of the data that are constantly changing. This method can calculate any value or any function that has various data. The root mean square is the square root of the average of the sum square value of the data (Equation 2.14) [17]:

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^{N} {X_i}^2}{N}} \tag{2.14}$$

Where X is the value in each of the data

N is the number of values.

2.1.6.5 Coefficient of variation

Coefficient of variation is the proportion value of standard deviation when compared to the average value of the data. Coefficient of variation is used to compare the variance of the data set (Equation 2.15) [17]:

$$\text{CV} = \frac{SD}{\bar{X}} \times 100 \tag{2.15}$$

Where SD is the standard deviation.

$\bar{X}$ is the mean value.

2.1.6.6 Coefficient of determination

Coefficient of determination (R^2) is the variation between the variables x and y or correlation coefficient square that is used to estimate the equations that are suitable to be used. The range of acceptable value is close to 1. The calculation is given in Equation 2.16 [19]:

$$\gamma^2 = \left(\frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n\sum x^2 - (\sum x)^2}.\sqrt{n\sum y^2 - (\sum y)^2}}\right)^2 \tag{2.16}$$

Where γ is correlation coefficient between the variables x and y n is number of samples.

x is the variable x or independent variable.

y is the variable y or dependent variable.

2.1.7 Polynomial function

A polynomial function is a function such as a constant (non-zero), a linear, a quadratic, a cubic, and a quartic polynomial of degree 0, 1, 2, 3, and 4, respectively. A polynomial of degree n is a function in the form given below [18]:

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_2 x^2 + a_1 x + a_0 \tag{2.17}$$

Where $f(x)$ is a polynomial function.

a is the coefficient of the polynomial.

n is the highest power of x or its degree.

x is the value of the x-axis or independent variable.

2.1.8 Least square method (LSM)

Least square method (LSM) is the estimation function technique. This method estimates the parameters or function by reducing the equations in a linear equation for easy calculation. The least square method estimates the parameters that have lowest errors to be used in the equation, as given by Equation 2.18 [19].

$$\mathrm{L} = \sum_{i=1}^{n} \varepsilon_i^2 \text{ or } \sum_{i=1}^{n} (\bar{x} - x_i)^2 \tag{2.18}$$

Where L is the response received from the estimates or sum of square error (epsilon: **ε**) or sum of the difference between the values.

$\bar{X}$ is the average value.

X is value in each of the data.

2.1.9 Helmholtz-Kohlrausch effect

The Helmholtz-Kohlrausch (H-K) effect is a human eye behavioral effect with coloured lighting. This effect describes the human eye phenomenon in which coloured light appears brighter than white light of the same luminance. It is the influence of colour purity on the perceived brightness of a colour object. The H-K effect led to the development of colour-appearance models that help to describe the brightness/luminance discrepancies. The measure that corresponds best to the sensation of brightness is luminance. Thus, light having the same luminance might be expected to have the same brightness, irrespective of colour. If the luminance of a red and a blue light are the same, for example, the brightness of the red light is expected to appear the same as that of the blue light. However, in fact, the brightness is not the same. Therefore, if a white light is used as the reference light and a red light as the test light, the red light appears brighter than the white light when the luminance is the same for both. That is the ratio of brightness to luminance (B/L) which is found to vary in every colour. When comparing between the concept of H-K effect and the appearance of the object colour in printing, they are highly associated. H-K effect is a human eye behavioural effect with colour lighting. This effect refers to the human eye phenomenon that colour light appears brighter to an observer than white light of the same luminance. It is the influence of colour purity on the perceived brightness of an object colour. In printing, colour patches represent the change of the tone by the percentage of dot area of the screen dots, so that colour appearance is derived from the area of ink and the area of paper white in the unit. In printing, there are three primary colours; cyan, magenta and yellow. Although, the three primary colours have the same percentage of dot area (comparable to the same brightness of the non-print area), they do not have the same lightness and chroma [10]. This means that the H-K effect has an influence on the perception of colour prints.

2.2 Literature Reviews

The current colour system for printing specifies colours using percentages of dot areas that each primary colour is printed. This system is not related to how colour is perceived by the human eye. The present study aimed to derive the colour system for printing based on colour perception. There have been a number of researches relating to this study. A review of the previous studies is given as follows.

Munsell colour system, built in 1907 by Albert Henry Munsell, is a widely-known colour order system. The system is constructed with 3 scales: hue, value and chroma. In the system, there are five primary colours in the hue scale: yellow, red, purple, blue and green. Munsell called the lightness scale as the value scale based on the experimental data and called the third attribute “chroma”. The Munsell colour system is perceptually uniform [1]. In 1940s, the Optical Society of America (OSA) investigated the spacing of colours of the Munsell book of colour and defined many new colours. This system was called Munsell Renotation.

Sturges and Whitfield [20] extended the study of locating basic colours in the OSA space. They used the Munsell system to define the location of the eleven basic surface colours within Munsell space using the monolexemic colour naming technique. The results revealed that the Munsell system offers a well-balanced and full range of surface colours conveniently arranged according to Hue, Value, and Chroma, with all regions well defined and easy to visualize.

In the eighteenth century, the colour prints were reproduced based on trichromatic colour mixing: yellow, red and blue [21]. Since the nineteenth century, the primary colours for printing has been changed to cyan (C), magenta (M), and yellow (Y); the printing primaries are then called CMY. Black is also added to the process, so the four-colour process system (CMYK) has become accepted today [1-3]. Hermann Hoffmann, a German printer, made colour samples with 3 printing ink primaries and arranged them according to hue, lightness and greyness [1]. After that, Robert Steinheil, a French printer, produced 13,300 colour samples with three ink primaries printed on different paper and with different ink sequences [1]. Later, Harald Küppers developed a colour-order system that related to the human visual system. This colour-order system is a rhombohedric colour order system, whose colour samples are produced with a printing process [1]. Küppers believed that spectral colours could not be explained by additive colour mixing of colour light. He believed that colours were explained by spectral signals on human's retina, where three different types of cone cells separate the signals. Nevertheless, Küppers's colour system does not correspond to colour perception.

Brozovic et al. [6], studied the colour perception of the object colours that reproduced by the printing technology. They investigated any correlation between subjective and objective artwork reproduction assessment when the reproductions were generated using different printing technologies. The colour reproductions of three oil paintings were painted on canvas. They were characterized by dominant hues: blue, red and yellow. The reproductions of three oil paintings were printed using different techniques and evaluated with respect to their original paintings. The reproductions on two printing techniques were conventional and digital offset printing. The conventional prints were reproduced with amplitude modulation (AM) screen and frequency modulation (FM) screen. And the digital offset prints were reproduced with AM screen. Observers conducted the visual assessments in an experimental booth illuminated with the fluorescent lamp. The judgments of visual evaluation were given to all reproductions. They found that the best quality of colour lightness was produced with conventional offset printing and an AM screen.

For luminous surfaces with the same luminance or object colours with the same luminance factor, their perceived brightness or lightness values are sometimes very different between achromatic and chromatic colours. The phenomenon is called the B/L (brightness/luminance) ratio or the L/Y (lightness/luminance factor) ratio effect. Sometimes, this effect is called the Helmholtz–Kohlrausch (H–K) effect [9]. Nayatani [11] studied the H-K effect that was related to the chromatic strengths of spectral colours. An estimate of the chromatic strengths of spectral colours is given by using the colour-matching functions and their combinations. The chromatic strengths of spectral colours are considered the cause of the Helmholtz-Kohlrausch effect. The estimate of the chromatic strength corresponds to chromaticness per unit luminance at each spectral colour on the basis of 2 degree colour-matching functions. From the result, the contributions of chromatic responses to the chromatic strength $CS(\lambda)$ may be different between those of red, green, yellow and blue in the opponent-colours theory. The chromatic strength $CS(\lambda)$ is estimated satisfactorily well from the Evans zero-greyness function $G_0(\lambda)$. The derived chromatic-strength function is very similar to the Helmholtz–Kohlrausch effect and the zero-grayness function for spectral colours.

Pridmore [22] studied the effects of luminance, wavelength and purity on the colour attributes. A colour stimulus was characterized by three psychophysical dimensions (luminance, dominant wavelength, and purity), whose corresponding colour attributes were lightness, hue, and chroma/colorfulness. The 3 x 3 matrix was given to nine basic effects of the psychophysical dimensions on the colour attributes. This study reviewed the common effect of the luminance and wavelength on lightness, which had been reported by experimental data in general agreement. In the case of luminance effect, the lightness of the sample increased not linearly when the luminance of surround increased. The non-linear relation was found for the perception of lightness. When the surround luminance increased, the lightness of the sample increased. When the rate of lightness changed, the light colours appeared lighter, and the dark colours appeared darker, but not linearly. For the effect of wavelength on lightness, this effect was the same as Helmholtz-Kohlrausch effect or the Brightness/Luminance (B/L) ratio. In the experiments, the reference samples were compared to the test samples whose luminance and purity were constant. The lightness of object colours varied widely with wavelength. The result showed that the perceived lightness inversely related to the perceived chroma.

Kaleigh et al. [12] tried to convert complex images and video to the greyscale appearance by the H-K effect for predicting differences between achromatic differences and chromatic differences. The CIEL*a*b* colour space was used in their study, in which the lightness was chosen for the grey values, and chroma for predicting the effect of strength according to colorfulness. The H-K effect for varying hues was predicted by comparing a chromatic stimulus with the same luminance as a white reference stimulus when the chromatic stimulus appeared brighter than the reference. This means that by comparing all sample colours to the same grey value, blue appeared lighter than the duller yellow, as predicted by the H-K effect.

Kulube and Hawkyard [14] investigated the way to predicting the colour of trichromatic prints by the Maxwell equation. In the experiment, the colour appearance from the dot overlapping of cyan, magenta, yellow and black inks was simulated by spinning discs and measured the colour value using a spectrophotometer. This study determined the partitive colour mixing that is the mixing of colour lights (additive mixing). This colour mixing involved light reflected from separate colour surfaces that were merged by the visual system of the observer. The luminance of the mixture equalled to the average luminance of all the colour patches. The predicting equation was used to calculate the colour mixing from the tristimulus values (CIE chromaticity coordinates and Y tristimulus values were measured by spectrophotometer) of the mixing colour. The fractional area of the two (C+M), (C+Y) and (Y+M) or three (CMY) or four (CMYK) colours were compared in terms of ΔE^*_{ab} to tristimulus values of the measured colours mixed from Maxwell spinning disc. This study showed the revolution equation from Maxwell that could predict the colour mixing in prints.

CHAPTER 3

METHODOLOGY

The goal of this study was to find the relationships between percentages of dot area of prints and colour perception and to devise a colour system for primary colours based on these relationships. To achieve this goal, a series of experiments were conducted. Firstly, a grey scale was printed and used to find a perceptual scale (Experiment I). From the perceptual scale that was taken as a reference scale, the values of colour strength, a colour perceptual attribute proposed in this study, were determined (Experiment II). The relationships between percentages of dot area of primary colours and colour strength were established in Experiment III. In Experiment IV, the relationship between colour strength and lightness was investigated. Based on the results from Experiments I-IV, Experiment V devised a colour system for printing, which involved a model to convert CIEL*a*b* of primary colour patches to colour strength and from colour strength to dot area percentages of primary colours (CMYK). Finally, the accuracy of the model was tested using secondary colours (RGB) in Experiment VI. This chapter describes materials, apparatus, observers, and procedures used in the experiments.

3.1 Materials

The materials used to make the printed colour patches of primary colours, secondary colours, and black colour are described in this section.

3.1.1 Paper

All colour patches were printed on 130 g/m^2 (GSM), gloss-coated, wood-free paper that had the CIEL*a*b* coordinates, gloss, ISO brightness and tolerances of paper according to the definition given in ISO 12647-2:2004, as shown in Table 3-1 [23].

Table 3-1 The CIEL*a*b* coordinates, gloss, ISO brightness and tolerances of papers.

Characteristic	L*	a*	b*	Delta E*$_{ab}$	Gloss	ISO Brightness
ISO 12647-2[1]	95.00	0.00	-2.00		65.00	89.00
130 GSM gloss-coated, Wood-free paper	95.20	0.28	-1.73	0.44	68.00	88.93
	95.44	0.29	-1.66	0.63	66.40	88.80
	95.58	0.28	-1.78	0.68	67.60	88.66
	95.53	0.33	-1.82	0.65	67.80	88.46
	95.51	0.33	-1.67	0.69	67.90	88.88
	95.52	0.31	-1.78	0.64	67.50	88.80
	95.55	0.31	-1.79	0.67	68.70	88.72
	95.61	0.31	-1.84	0.70	67.80	88.91
	95.57	0.39	-1.88	0.70	67.90	88.79
Average	95.50	0.31	-1.77	0.63	67.73	88.77
Tolerance[1]	± 3	± 2	± 2	-	± 5	-

[1] This is the CIEL*a*b* coordinates and tolerance value of paper type 1 from Table 1 in ISO 12647-2:2004 [23].

3.1.2 Ink

The process ink (CMYK) of offset printing used in this study had the CIEL*a*b* coordinates and tolerances of process ink according to the definition given in ISO 12647-2:2004, as shown in Table 3-2 [23].

Table 3-2 The CIEL*a*b* coordinates and tolerances of process ink.

CIEL*a*b* Coordinates		L*	a*	b*	Delta E*$_{ab}$	Deviation tolerance[2]
C	reference[1]	54.00	-36.00	-49.00	4.58	5
	OK print	56.25	-34.05	-52.35		
M	reference[1]	46.00	72.00	-5.00	3.23	5
	OK print	46.56	73.99	-3.21		
Y	reference[1]	88.00	-6.00	90.00	3.09	5
	OK print	90.66	-7.14	90.68		
K	reference[1]	16.00	0.00	0.00	3.69	5
	OK print	14.17	2.78	1.39		

[1] This table shows the CIEL*a*b* coordinate of paper type 1 in ISO 12647-2:2004 [23].
[2] Deviation tolerance is the OK print that is derived from the permissible difference between a production run and the reference value [15].

3.2 Apparatus

The instruments and machines that used to make and measure the printed colour patches are given in this section. The colour patches were printed with offset printing with amplitude modulation screen (AM screen).

3.2.1 Adobe Illustrator CS

Vector image application software was used to generate the original of the colour patches of primary colours, secondary colours and black colour.

3.2.2 Platesetter

Platesetter is a plate-making machine; Heidelberg Suprasetter 105H that was computer-to-plate technology for making offset plates was used in all four process colours (CMYK) with the resolution of 2400x2400 pixel per inches (ppi).

3.2.3 Printing machine

Printing machine used in this study was the A2-plus size (765 x 580 mm) four colours Ryobi 750G offset press with process ink (cyan, magenta, yellow and black ink).

3.2.4 Measuring instrument

The measurements of printed colour patches were done with two purposes: first, to control the printing process and second to measure the tristimulus values X, Y and Z.

3.2.4.1 X-rite spectrodensitometer 500 series was used for the reproduction control (to measure dot gain, density and CIEL*a*b* of prints). According to ISO 12647-2:2004, the measurements were done with 45/0 geometry, illuminant D50, 2° standard observer and black backing [21].

3.2.4.2 Techkon SpectroDens Advance was used to measure the tristimulus values X, Y and Z. According to ISO 12647-2:2004, the measurements were done with 0/45 geometry, illuminant D50, 2° standard observer and black backing [23].

3.2.5 Viewing cabinet

The viewing cabinet used in this study followed the standard set forth by ISO 3664:2000 [24]. The light source located at the top of the cabinet was Philip TLD 950 made in Holland (D50 simulators). The interior of the cabinet was neutral matt. Table 3-3 shows the measurement results of the viewing conditions in the cabinet, compared to those of the standard.

Table 3-3 Viewing condition in the viewing cabinet base on ISO 3664:2000.

Viewing condition in the cabinet		
Description	Standard	Result
CIE Illuminant D50	5000 K	4906.00
Illuminance/luminance	2000 lx, +/- 500 lx (P1), 500 lx, +/- 125 lx (P2)	1680.00
Colour rendering index	> 90	98.00
Metamerism index	Visual: C or better 0.5-1.0 (should be B)	0.14 (A)
Chromaticity coordinates of D50	x, y = 0.3478, 0.3595	0.3481, 0.3567
	u', v' = 0.2102, 0.4889	0.2115, 0.4876
Illumination uniformity	For surfaces up to 1 m x 1 m >/= 0.75	0.83
	For surfaces greater than 1 m x 1 m >/= 0.60	0.67
Surround Luminous reflectance	< 60% (neutral and matt)	21.95
Background Luminous reflectance	< 60% (neutral and matt)	18.83

3.3 Observers

In the 6 experiments conducted in this study, Experiments I, II, III and VI required observers to assess colour patches, so as to obtain visual data. The number of observers and their performance were varied in each experiment.

3.3.1 Experiment I

In this experiment, the observers' task was to rearrange the grey colour patches to form the perceptual scale of colour strength, whereby each step was observable different. Fifteen observers (7 males and 8 females) participated in this experiment. They came from three groups of people in printing technology, including experts, workers and students. The experiment was considered not difficult for the observers, and each observer repeated the experiment twice. To investigate the performance of the observers, the coefficient of variance (%CV) was calculated from the results of the first and second assessment of each observer (within observer agreement) and the mean result from all observers against each observer result (between observer agreement). For perfect agreement, %CV should be zero. The results are given in Table 3-4.

Table 3-4 Performance of observers in Experiment I.

%CV	Maximum	Average	Minimum
Within observer agreement	7	3	2
Between observer agreement	45	10	0

3.3.2 Experiment II

In this experiment, the magnitude estimation method was employed to obtain the colour strength values. The perceptual scale of distinguishable colour strength levels found in Experiment I was taken as a reference scale of colour strength. The observers' task was to assign the colour strength value for the grey patches in the scale. Since the method of magnitude estimation is considered a difficult task, the large number of observers are required to compensate for low precision of the results. 71 Observers (32 males and 39 females) participated in the experiment. They were students in printing technology division. Each observer did the experiment twice. Their performance (within observer agreement and between observer agreement) was investigated with a CV measure, and the results are given in Table 3-5.

Table 3-5 Performance of observers in Experiment II.

%CV	Maximum	Average	Minimum
Within observer agreement	41	12	2
Between observer agreement	64	27	7

3.3.3 Experiments III and VI

The matching of primary and secondary colour patches to the grey patches in the reference scale was done in Experiments III and VI, respectively. These experiments were conducted to determine the colour strength values for each patch of primary and secondary colours, in order to find the relationships between dot area percentages and colour strength. Although the observers' task was not difficult, it was not as easy as Experiment I. Therefore, more numbers of observers were used. Thirty observers (15 males and 15 females) was comprised of 4 experts, 18 students and 8 workers. Their performance is shown in Table 3-6.

Table 3-6 Performance of observers in Experiments III and VI.

%CV		Maximum	Average	Minimum
C	Within observer agreement	32	9	2
	Between observer agreement	46	25	17
M	Within observer agreement	29	8	2
	Between observer agreement	49	24	15
Y	Within observer agreement	20	7	2
	Between observer agreement	45	22	15
R	Within observer agreement	23	6	2
	Between observer agreement	36	20	10
G	Within observer agreement	12	5	2
	Between observer agreement	40	20	12
B	Within observer agreement	16	5	2
	Between observer agreement	43	20	12

3.4 Procedures

This section describes the detail of each experiment, including the preparation of printed colour samples.

3.4.1 Preparing the colour samples

Printed colour patches were used to establish the relationships between dot area percentages and colour strength, and colour strength and colour measurement values. Figure 3-1 shows the process of making printed colour samples of primary, secondary and black colours. The detail is explained as follows.

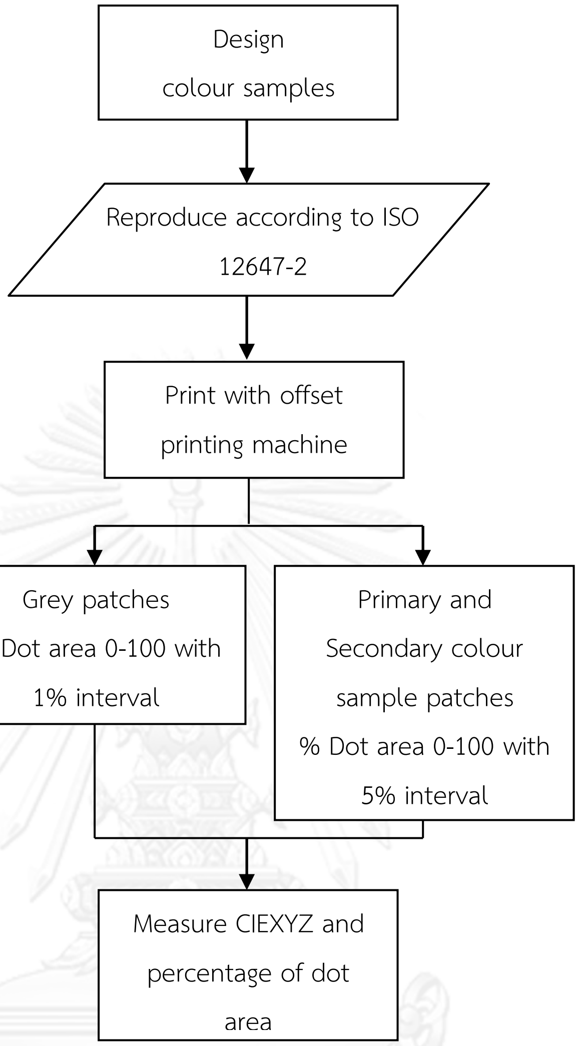


Figure 3-1 A process of preparing the colour samples.

3.4.1.1 Designing and reproducing the colour samples

Colour samples were created using a vector image application program (Adobe Illustrator CS). Each sample was a 3-cm square. For primary colour patches, each sample was filled with either one of the primary colours (cyan, magenta and yellow) with varying percentages of dot area from 0-100 with 5 percent intervals. For secondary colour patches (red, green and blue), each sample was filled with 2 relevant primaries with equal percentages of dot area, for example, one red sample was filled with 5% dot area of magenta and yellow. The percentages of dot area for each primary to generate secondary colours varied from 0-100 with 5 percent intervals. Figure 3-2 illustrates the colour samples of primary and secondary colours. For grey patches, each sample was filled with black with varying percentages of dot area from 0-100 with 1 percent intervals, as shown in Figure 3-3.

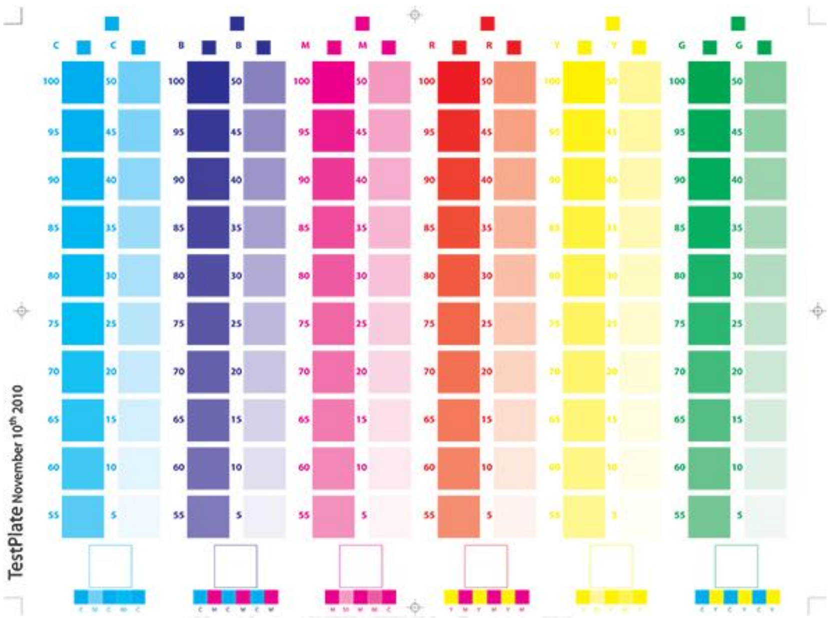


Figure 3-2 Primary and secondary colour samples.

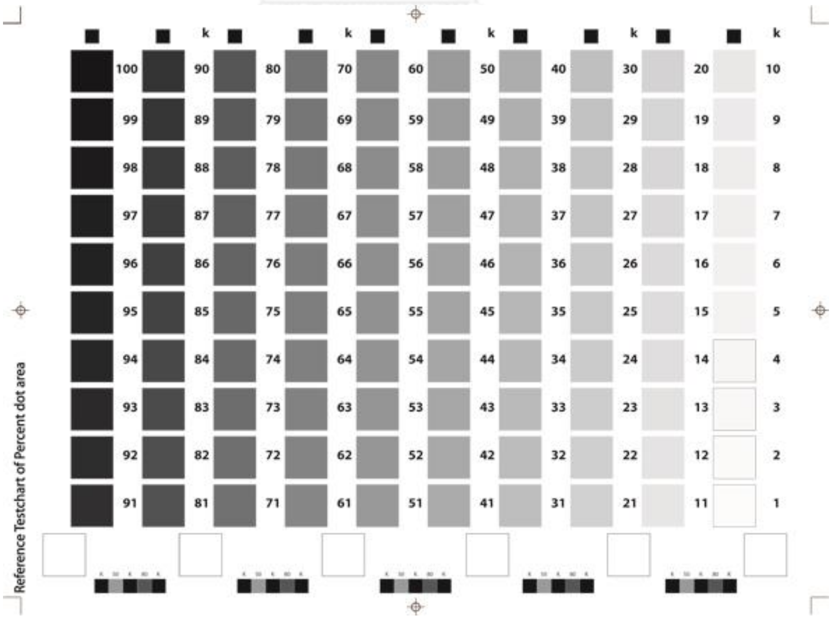


Figure 3-3 Grey colour samples.

3.4.1.2 Printing the colour samples

Reproduction of colour samples was generated with offset printing under controlled settings according to the Graphic technology-Process control for the production of half-tone colour separations, proof and production prints-Parts 2 (ISO 12647-2) [23]. These colour samples were first reproduced on offset printing plates using a platesetter. The reproduction of colour samples was then printed onto 130-g/m^2 coated paper in a size of 24”x35”. Ink sequence for printing was cyan, magenta, yellow, and black, respectively. The colour samples were produced with conventional offset printing and an amplitude modulation (AM) screen. The settings of half-tone screen are as follows.

1) screen type : Amplitude modulation (AM) screen

2) dot shape : Round

3) screen ruling : 150 lines per inch

4) screen angle : cyan = 15°

magenta = 45°

yellow = 0°

black = 75°

Tonal value increase of the tone reproduction at the middle tone was lower than 8%, as shown in Figure 3-4. The data can be found in Appendix A.

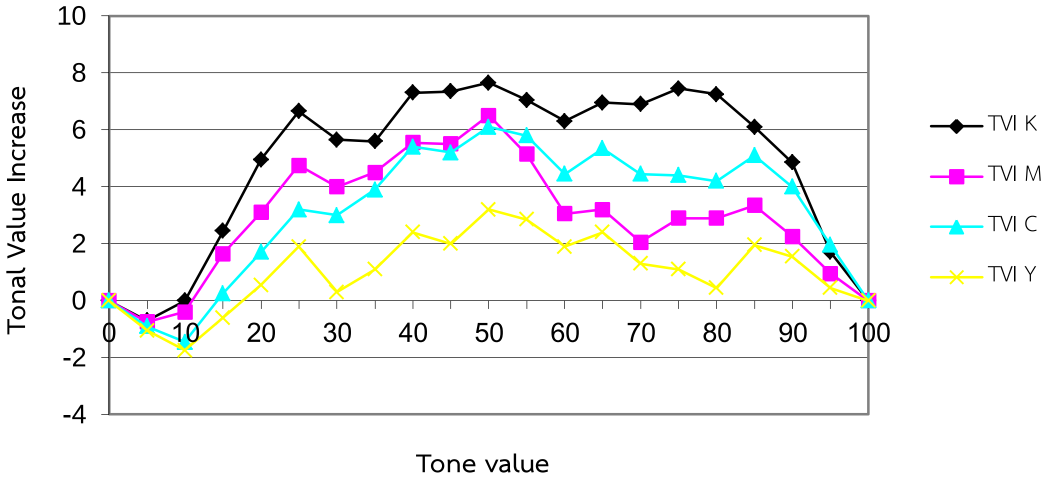


Figure 3-4 Tonal value increase of printed primaries (CMYK).

3.4.1.3 Measurement of colour samples

Each colour patch of printed samples was measured in terms of tristimulus X, Y, and Z values. The CIEL*a*b* values were then calculated with the colour of paper taken as the reference white. CIEXYZ, CIEL*a*b*, and percentages of dot area can be found in Appendix A.

3.4.1.4 Making the colour patches

Each colour patch was cut out from the printed samples, and codes were given to each cut-out colour chip having different percentage of dot area. The code can be seen in Appendix B. Each colour patch was covered with a 5-cm square neutral grey that was made as a frame, in which the centre was an open 3-cm square, showing the colour area of the colour sample.

3.4.2 Experiment I

ISO 12647 is the standard for reproduction control in printing technology. In its process control, CIEL*a*b* is used, as it is the colour measurement system relating to colour perception. However, it is not the system used to communicate in the printing process by printers. They use density and percentages of dot area. One drawback of using such system is that it does not correlate well with the CIEL*a*b* system. For example, when the percentage of dot area of a print increases, its chroma (C^*_{ab}) increases with decreasing lightness (L*). For this reason, a better connection between the system of communication in printing (percentage of dot area) and the system of colour measurement (CIEL*a*b*) is needed. This study aimed to find a sensation term that can connect between CIEL*a*b* and dot area percentage. Colour strength was proposed. It is the term related to colour perception describing the intensity of colour. In printing, inks impress on the substrate, so colour strength of the prints appears from the proportion of the area of inks to the area of substrate, i.e. the dot area percentage. Thus, colour strength increases when the percentage of dot area increases.

To establish the relationships between percentage of dot area and colour strength, a reference scale of colour strength is needed. A grey scale generated from black ink with varying percentage of dot area was used in this study because it covers the range of colour strength of all other colours. This is because black is void of colour; thus, its intensity will be the highest when printed with 100 percentage of dot area (solid). In addition, the reference scale must also be a perceptual scale of colour strength. In other words, the steps in the scale must be observable different from their adjoining steps.

Experiment I aimed at finding the perceptual scale of colour strength, to be used as the reference scale. The grey scale derived from the percentages of dot area from 0 to 100 with 1% intervals was used in the experiment, in order to find the reference scale that each step was distinguished in terms of colour strength.

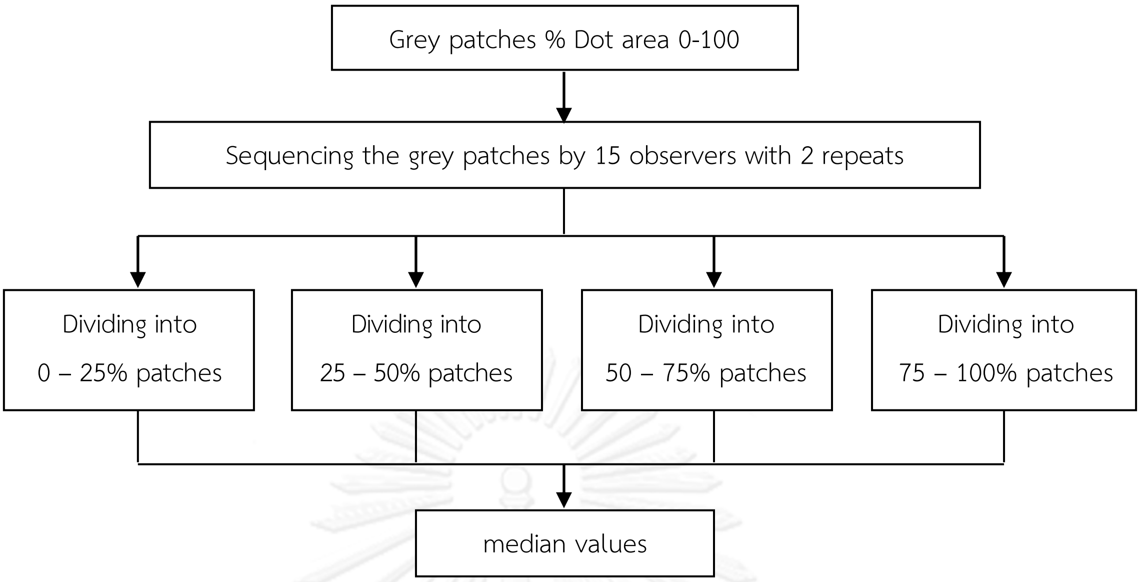


Figure 3-5 Diagram of Experiment I.

3.4.2.1 Visual assessment

Figure 3-5 shows the process of Experiment I. The goal was to find the number of steps in the grey scale from black (100% dot area) to white (0% dot area, or no print) that are distinguishable. The experimental steps are as follows:

1) Before starting the visual assessments, observers were asked to look at the interior of the viewing cabinet illuminated with D50 for 1 minute for adaptation. The grey scale was placed at the bottom of the cabinet, and the viewing angle was approximated 45° to the grey scale with a distance around 43 cm from observers.

2) Observers arranged a series of grey patches varying in percentages of dot area from 0–100% in such a way that the patches form a perceptual scale of colour strength. The experiments were divided into 4 sessions for each observer. Each session had 25 patches (either 0–25%, or 25–50%, or 50–75%, or 75–100% patches) to be arranged. This was done based on the observations from the first few trials of the experiments. When the experiments were divided into 2

sessions (50 patches for each session, i.e. 0-50% and 50-100%), the observers took 60 minutes to finish the whole arrangement, which was considered too long.

3) Observers were asked to arrange the grey patches in an increasing order of colour strength. They could group the grey patches that were not distinguished into the same step.

4) Each observer repeated the same experiments twice.

3.4.2.2 Analysis

From 100 steps of dot area percentages in the grey scale, the number of steps that could be distinguishable was analysed, as well as the representative patches of each step.

1) From the observers' results, the grey patches that were not correctly arranged in terms of increasing order of dot area percentages were grouped into the same step. For example, if the arrangement of grey patches that one observer thought to be in the increasing order of colour strength was in the sequence of percentage of dot area of 5, 7, 8, 6, and 9, the resultant number of distinguishable steps for this observer was 3, instead of 5. This was because the patches of percentage of dot area of 7, 8 and 6 were in the wrong sequence, so they were grouped to be in the same step.

2) After correcting the sequence of patches for all observers, the perceptual scales for each observer were found. The scales were varied from one observer to another. To derive the reference scale, the number of distinguishable steps was based on the highest number of steps found.

3) The representative patches for each step in the reference scale were obtained from the median values of the observers' results in that particular step.

3.4.3 Experiment II

The reference scale obtained from Experiment I was the perceptual scale of colour strength. However, the value of colour strength was not yet specified, as the dot area percentages of grey patches were not correlated with colour perception. Thus, the colour strength values in the reference scale were determined in Experiment II. In this experiment, the method of magnitude estimation was employed.

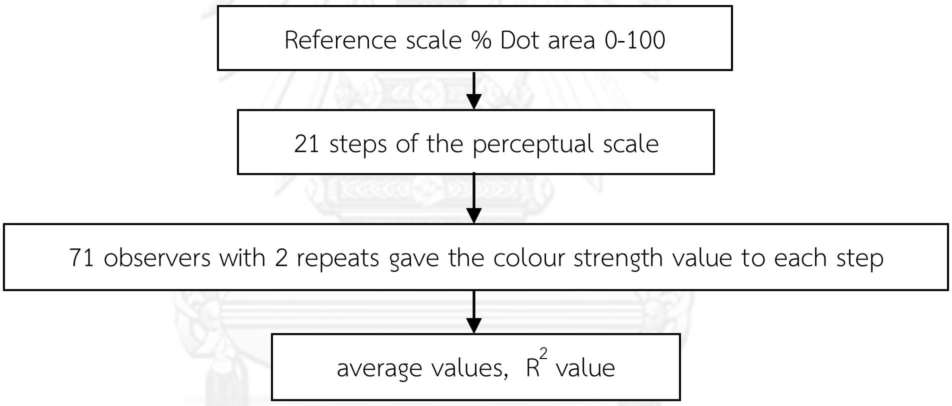


Figure 3-6 Diagram of Experiment II.

3.4.3.1 Visual assessment

The reference scale obtained from Experiment I had 70 steps of distinguishable colour strength. In order to conduct the experiments using the magnitude estimation method, the grey patches in the reference scale were sampled very 3 steps. This was done to reduce the number of steps from 70 to 21 steps, so the experiments would not be too difficult and too long for observers. Figure 3-6 shows the procedure of Experiment II. The experimental steps are as follows:

1) Before starting the visual assessments, observers were asked to look at the interior of the viewing cabinet illuminated with D50 for 1 minute for adaptation. The viewing angle was at approximated 45° to the grey scale placed on the bottom of the cabinet with the distance around 43 cm from observer, as shown in Figure 3-7.

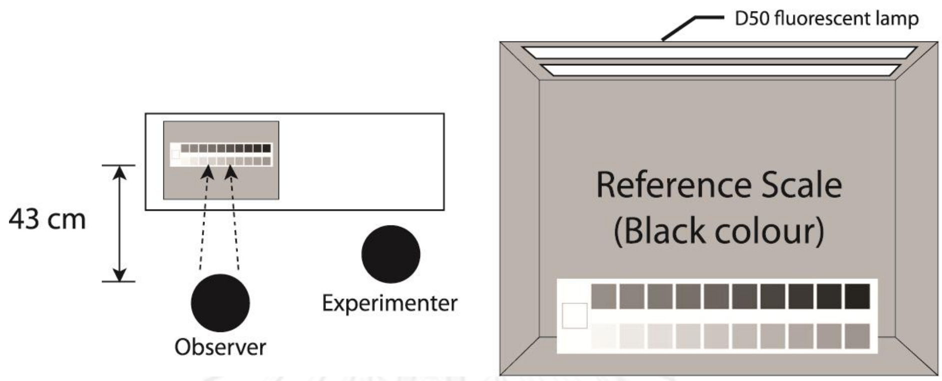


Figure 3-7 Viewing configuration.

2) The grey patches of 0% and 100% dot area were used as anchor patches. They were given the colour strength values of 0 and 100, respectively.

3) Observers' task was to estimate the colour strength value of the other grey patches in the 21 steps of the reference scale. In so doing, they were given one of the grey patches randomly and compared its colour strength to the anchor patches. They then gave the estimated values of colour strength for that patch. This was done for all 21 steps in the reference scale.

4) Each observer repeated the same experiments twice.

3.4.3.2 Analysis

The observers' results of the values of colour strength from the magnitude estimation method were calculated all 71 observers to obtain the colour strength values for each of the 21 steps in the reference scale. Having done so, the relationship between percentage of dot area and colour strength was determined in order to estimate the other colour strength values of the other patches in the reference scale. The procedure of data analysis is given below.

1) The colour strength values for each of the 21 patches used in the visual experiments were averaged from all observers' results.

2) The colour strength values were plotted against dot area percentages, in order to find the relationship between them. The dot area percentages were in the x-axis, and the colour strength values were in the y-axis.

3) The relationship was determined by the curve fitting method, using the function Add Trend line in Excel. The coefficient of determination (R^2) was used as a measure of goodness of fit of the curve fitting functions.

4) The function that gave the best fit to the data points was selected to define an equation for calculating colour strength values from known dot area percentages of black ink.

3.4.4 Experiment III

In this experiment, the colour strength values for other primary colour in printing (i.e. cyan, magenta and yellow – C, M, and Y) were determined. The reference scale obtained from Experiment I and the equation for calculating colour strength obtained from Experiment II were used as a tool to obtain colour strength values in this experiment. The relationships between percentages of dot area of primary colours (CMY) and colour strength were then defined. The procedure of Experiment III is shown Figure 3-8.

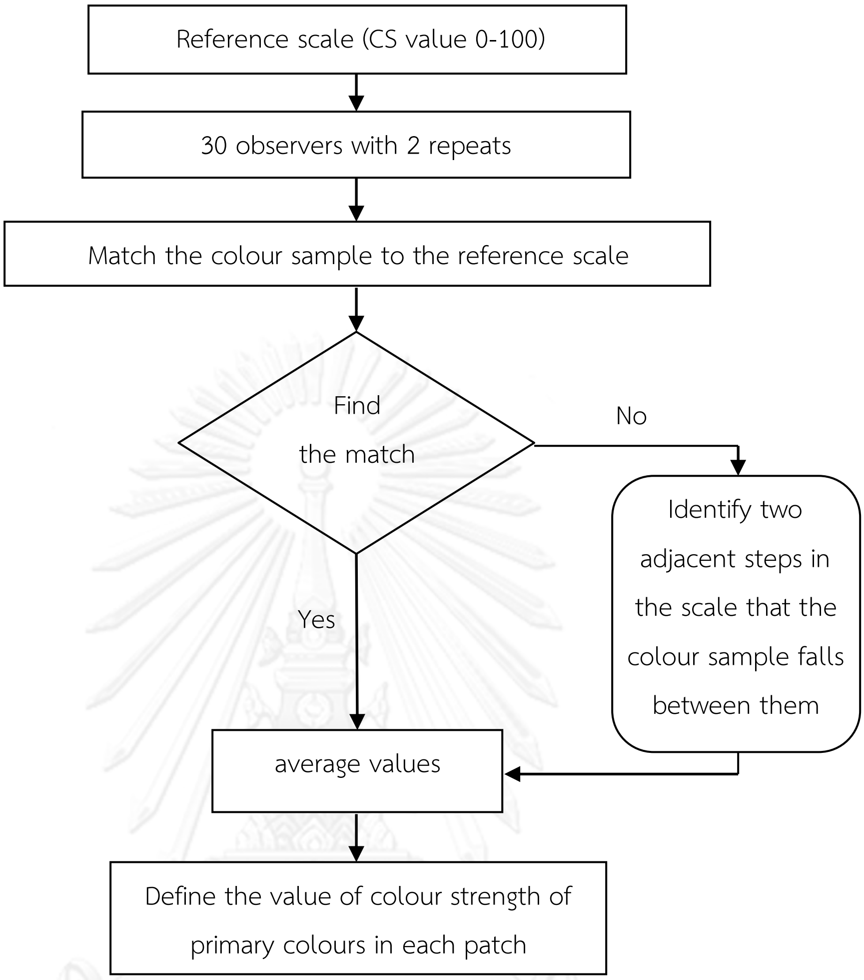


Figure 3-8 Diagram of Experiment III.

3.4.4.1 Visual assessment

The reference scale, containing 70 steps of distinguishable colour strength of grey patches that varied in percentage of dot area of black ink, was used to locate a colour strength match of the C, M, and Y patches. The C, M, and Y patches were varied in percentage of dot area of the relevant ink from 0-100 with 5% intervals. The experimental steps are as follows:

1) Observer adapted to the viewing condition in the viewing cabinet by looking at its interior for 1 minute. The reference scale was placed at the

bottom of the cabinet with the viewing angle of approximated 45° and the distance of 43 cm to the observers (Figure 3-7).

2) In the visual assessment, observers' task was to compare a given colour patch, for example, 20% dot area of cyan, to the reference scale and identify the step in the reference scale with which the given patch matched in terms of colour strength. In case of finding no exact match, the two adjacent steps were identified.

3) The assessments were done for all C, M, and Y patches in a random order. Each observer repeated the experiments twice.

3.4.4.2 Analysis

The grey patches in the reference scale that matched in colour strength with the C, M, and Y patches were found. The data analysis was done to determine colour strength values for each of the C, M, and Y patches. After that, the relationships between percentage of dot area of C, M, and Y and colour strength were established.

1) For each of the C, M, and Y patches, the dot area percentage of black of the matching grey patches was averaged from all observers' results.

2) The colour strength values of C, M and Y patches were calculated from the equation obtained in Experiment II using the matching percentage of dot area of black.

3) The percentage of dot area of C, M, and Y were plotted against the colour strength values. The dot area percentages were in the x-axis, and the colour strength values were in the y-axis.

4) The relationship was determined by the curve fitting method, using the function Add Trend line in Excel. The coefficient of determination (R^2) was used as a measure of goodness of fit of the curve fitting functions.

5) The functions that gave the best fit to the data points was selected to define the equations for calculating colour strength values from known dot area percentages of cyan, magenta and yellow inks.

3.4.5 Experiment IV

The aim of this experiment was to investigate the correlation between colour specification and colour strength. The colour system for printing that this study aimed to establish had the connections between colour specification (CIEL*a*b*), colour perception (colour strength), and colour mixing (percentage of dot area of primaries in printing). In the previous experiments, the relationships between percentage of dot area and colour strength were established. In this experiment, the correlation between lightness (L*) and colour strength was investigated. Figure 3-9 summarises the experimental procedure in this experiment, and the details are given below.

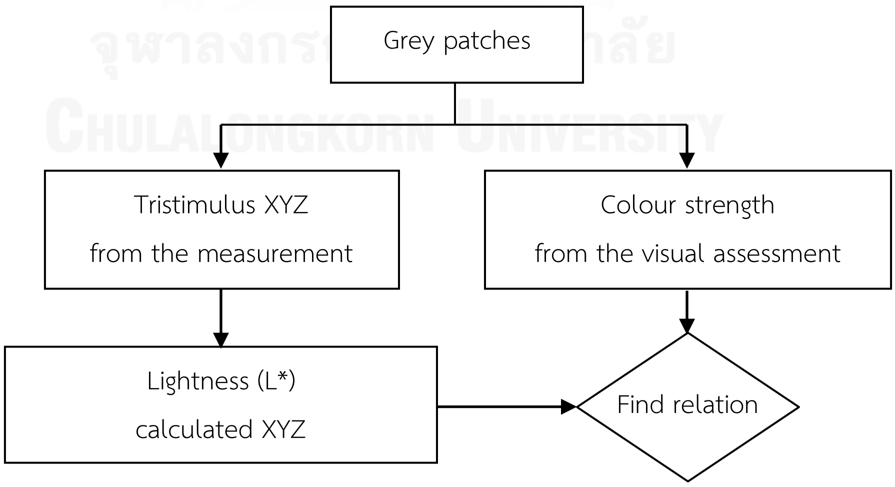


Figure 3-9 Diagram of Experiment IV.

1) The grey patches in the reference scale of perceived colour strength were sampled every 3 steps. The resultant grey scale had the grey patches from 0% to 100% dot area of black ink.

2) Each patch was measured in terms of XYZ values. The lightness values (L*) were then calculated using XYZ of the 0% patch (no print, thus, the paper white) as the reference white.

3) The dot area percentages were plotted against the colour strength values obtained from the observers' results of Experiment I, and the lightness values.

4) The colour strength values were plotted against the lightness values.

3.4.6 Experiment V

This experiment aimed to devise a colour model for printing based on colour perception. In the proposed model, CIEL*a*b* values were connected with the percentage of dot area of process colours (CMYK) via colour strength. The CIEL*a*b* values were obtained from the measurements of printed colour patches. The colour strength values were obtained from visual data in Experiments II and III. The dot area percentages of primaries were the original values before printing. The model has two steps of calculations. The first step is to convert CIEL*a*b* to colour strength values. The second step is to convert the colour strength values to the percentage of dot area of primaries. Figure 3-10 summarises the experimental procedure to develop such model.

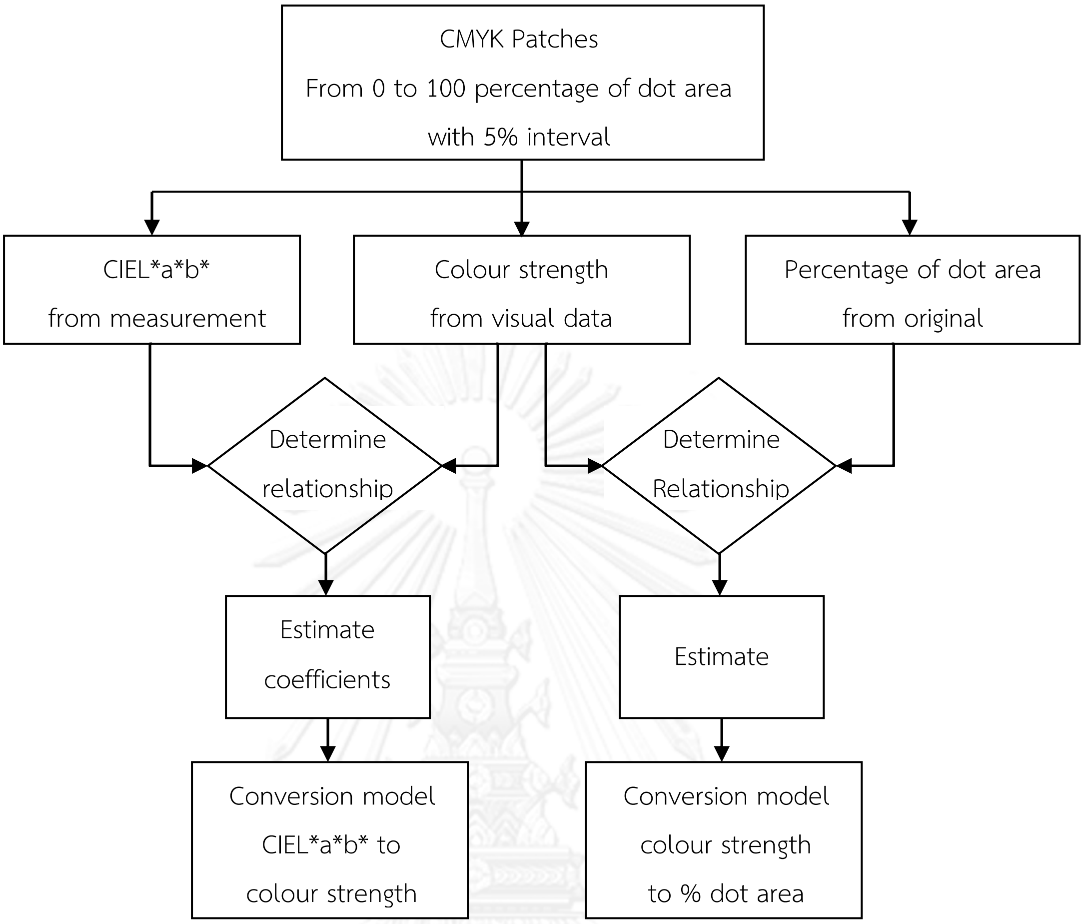


Figure 3-10 Diagram of Experiment V.

3.4.6.1 Devising a colour strength model

The colour strength model is a conversion model for converting CIEL*a*b* values to colour strength values. To devise the model, the following steps were carried out.

1) Calculate CIEL*a*b* values of process colour patches (CMYK) from XYZ values using the paper white as the reference white.

2) Plot the CIEL*a*b* values of all process colour patches having different percentages of dot area from 0-100 with their corresponding colour strength also varying from 0-100.

3) The plot will form 4 lines of process colours, indicating the changes in colours due to the change of percentage of dot area, and the change in colour strength. From this plot, the relationship between CIEL*a*b* and colour strength can be determined, and a generic equation with CIEL*a*b* as variables is proposed.

4) Compose a series of equations based on the generic equation proposed. These equations have the same unknown coefficients, with different CIEL*a*b* and colour strength values (calculated from the equations in Experiments II and III, using percentage of dot area).

5) Optimise the equation coefficients to yield the best predictions of colour strength values using the least square method (LSM). The function Solver in Excel was utilised to do the optimisation.

6) Replace the coefficients in the generic equation, to generate the colour strength model.

3.4.6.2 Analysis

The accuracy of the colour strength model was investigated by comparing the colour strength values obtained from this model with the values obtained in Experiments II and III. The investigations were done for the primary colours (CMYK) with percentage of dot area varied from 0-100 with 5% intervals. The following steps were carried out.

1) Calculate the colour strength values from the equations obtained in Experiments II and III, using percentage of dot area. These data represented the visual colour strength.

2) Calculate the colour strength values from the colour strength model, using CIEL*a*b*.

3) Calculate the root mean square to investigate the differences between the model's predictions and the visual results of colour strength.

4) Calculate the percentage of error by:

$$\%error = \frac{\sqrt{(s_1 - s_2)^2}}{s_1} * 100 \qquad (3.1)$$

Where %error is the percentage of differences in colour strength between the predicted colour strength and the visual colour strength.

S_1 is the visual colour strength.

S_2 is the predicted colour strength.

3.4.6.3 Deriving equations to convert colour strength to percentage of dot area of CMYK

To complete the colour system for printing, the next step is to convert the colour strength value to percentage of dot area of CMYK. To derive the equations in this step, the data of the primary colour patches (CMYK) from 0-100% with 5% intervals were used. The following procedure was carried out.

1) Calculate the colour strength values from percentage of dot area of one primary using the equation obtained in Experiments II (for black) and III (for cyan, magenta, and yellow).

2) Plot the colour strength values (x-axis) against percentage of dot area (y-axis).

3) Use the function Add Trend line in Excel to find the best fits to the data points, with the use of the coefficient of determination (R^2) as an indicator of goodness of fit.

4) Derive the equation for converting the colour strength values to percentage of dot area of the relevant primary.

5) Repeat all steps with the remaining primaries.

3.4.7 Experiment VI

In the last experiment, the accuracy of the model derived from Experiment V was tested using secondary colours. The secondary colour patches (RGB) were printed with the equal percentages of two primary colours. For example, one blue patch was printed with 5% dot area of cyan and magenta, the percentages were varied from 0 to 100 with 5% intervals. Test of colour strength predictions is described in Section 3.4.7.1. The performance of predicting percentage of dot area was also tested and is described in Section 3.4.7.2.

3.4.7.1 Testing the predictions of colour strength

To investigate the accuracy of colour strength predictions, the visual colour strength data of secondary colour patches were needed. The reference scale obtained in Experiment I was used. It was the grey scale containing 70 steps of distinguishable colour strength. Thirty observers participated in the visual experiments. The process of acquiring the visual data and testing the models' performance is given below. Figure 3-11 illustrates a summary of this process.

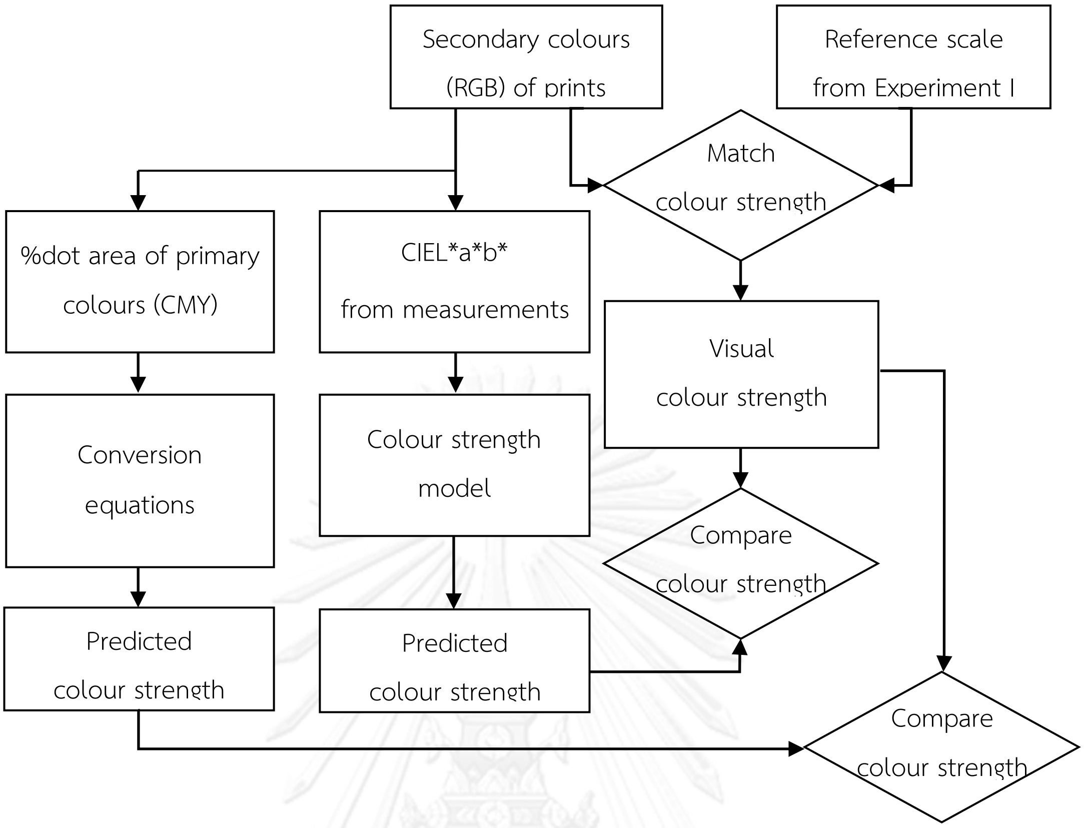


Figure 3-11 Test of the colour strength model in Experiment VI.

1) Observers were given one secondary colour patch at a time to compare its colour strength with the reference scale. Their task was to identify the grey patch that matched in colour strength with the given patch. The procedure of this visual experiment was the same as that in Experiment III.

2) The median values were calculated from the results of all observers for percentage of dot area of black that matched each of the secondary colour patches.

3) Calculate the visual colour strength of secondary colours by the equation obtained in Experiment II.

4) To investigate the accuracy of the colour strength model, measure CIEL*a*b* of the RGB colour patches and use the colour strength model to

calculate colour strength values. Then, compare the predicted values with the visual values using the root mean square and the percentage of error.

5) To investigate the accuracy of conversion equations, use the percentage of dot area of primary colours to calculate the colour strength values via the equations in Experiment III. Then, compare the predicted values with the visual values using the root mean square and the percentage of error.

3.4.7.2 Testing the predictions of %dot area of primaries

In the proposed colour system for printing, the colour strength values can be converted to %dot area of primary colours. In this section, the performance of the model for predicting %dot area of primaries for the secondary colour patches was tested. The process of testing is summarised in Figure 3-12. The detailed procedure is given below.

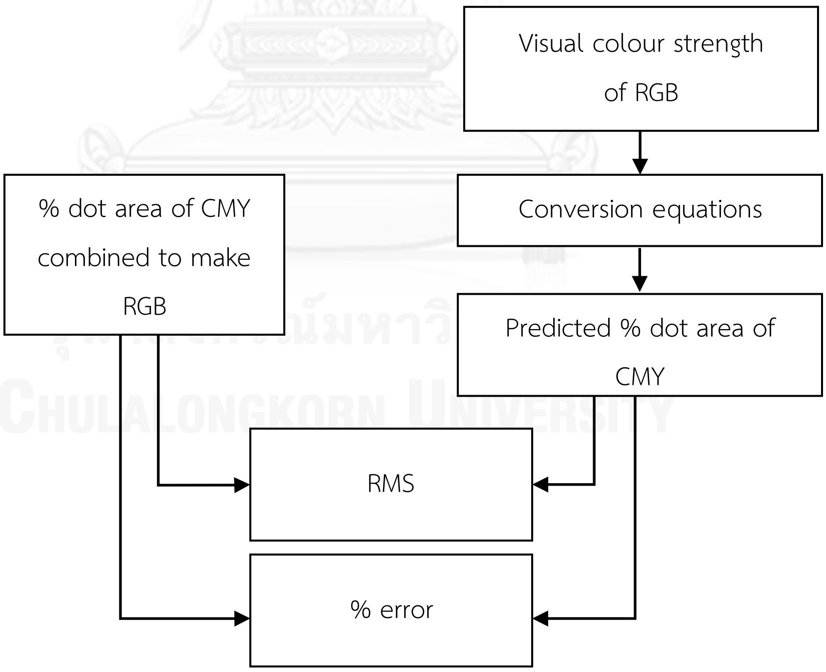


Figure 3-12 Test of percentage of dot area predictions in Experiment VI.

1) The colour strength of secondary colours was derived from the visual assessments.

2) The percentages of dot area of primary colours were calculated by the equations obtained in Experiment V.

3) The root mean square and the percentage of error were used to investigate the differences between the predicted percentages of dot area of primary colours and the original percentage of dot area.

CHAPTER 4

RELATIONSHIPS BETWEEN %DOT AREA OF PRINTS AND COLOUR PERCEPTION

To devise the colour perception -system for printing, the relationships between percentages of dot area and colour perception needed to be established. This study employed colour strength as the colour perception of prints and derived the equations of colour strength–%dot area conversion. To do so, 4 experiments were conducted. This chapter discusses each of the 4 experiments. Detailed descriptions of the experimental procedures were given in Chapter 3.

4.1 Experiment I: Defining the reference scale

4.1.1 Introduction

This experiment aimed at finding the perceptual scale of distinguishable colour strength to be used as the reference scale. In this study, colour strength was defined as the intensity of colour with an inverse proportion of lightness. The colour strength is high when the ink covers more areas of prints, but the lightness is low when more areas of the paper are covered. However, the colour strength of prints with different percentages of dot area may not be observed due to the perceptibility tolerances. Thus, this experiment was conducted to find the reference scale of colour strength, in which each step was distinguishable from its adjoining steps. The grey scale was used in the experiment because the range of colour strength of achromatic colours is wider than chromatic colours. Black is non-selective colour, so it has the lowest lightness and the highest colour strength.

4.1.2 Procedure

The grey scale of prints varying in %dot area of black from 0-100 with 1% intervals was assessed by the panel of 15 observers twice. The observers arranged the grey patches to generate the scale of distinguishable colour strength. This scale was used as the reference scale to evaluate the colour strength in the other experiments.

4.1.3 Results

The colour samples were printed onto 130-g/m^2 coated paper in a size of 24"x35". Ink sequence for printing was cyan, magenta, yellow, and black, respectively. The reference scale was made with black ink. The results form the visual assessments were analysed to determine the number of distinguishable steps in the reference scale, as well as the %dot area of black for each step. In the visual experiments, the original grey scale had 100 patches.

In the first few trials, the experiments were divided into 2 sessions for each observer, so that the observers had 50 patches (either 0–50% or 50–100% patches) to arrange in each session. It was found that on average it took observers 60 minutes to finish the whole arrangement, which was considered to be too long. Moreover, the observer repeatability was quite poor. To solve this problem, the grey scale was divided into 4 sessions for each observer, so that the observers had 25 patches (either 0–25% or 25–50% or 50–75% or 75–100% patches) to arrange in each session. The results showed that the observers took 45 minutes to finish, and the repeatability was much better.

From the observers' results, the number of distinguishable steps was determined. Seventy distinguishable steps were found from the grey scale of 100 steps varied in %dot area. The median values of the observers' results were used to represent %dot area of black in each step. The results are given in Table 4-1.

Table 4-1 The %dot area of black for each step in the reference scale.

The perceptual scale													
step	% dot area	Step	% dot area	step	% dot area	step	% dot area	step	% dot area	step	% dot area	step	% dot area
1	1	11	17	21	32	31	49	41	64	51	77	61	91
2	3	12	18	22	34	32	50	42	65	52	79	62	92
3	5	13	19	23	35	33	51	43	66	53	81	63	93
4	6	14	21	24	36	34	53	44	67	54	82	64	94
5	7	15	23	25	39	35	56	45	68	55	83	65	95
6	9	16	24	26	40	36	57	46	69	56	84	66	96
7	10	17	26	27	41	37	59	47	70	57	86	67	97
8	12	18	27	28	43	38	61	48	71	58	87	68	98
9	13	19	29	29	44	39	62	49	74	59	88	69	99
10	15	20	31	30	46	40	63	50	76	60	90	70	100

4.1.4 Discussion

From 100 grey patches in the original scale, observers could differentiate the colour strength only 70 steps. This is because of the characteristic of the offset printing process. Due to the structure of the printing unit, screen dots from the blanket cylinder are transferred to the substrate by the pressure of the impression cylinder [2]. This results in dot gain. Dot gains do not increase with linear proportion from 0-100%. Some parts of 0-100% dot area have higher dot gains than the others. Thus the actual percentages of dot area of prints are very close and are hard to differentiate in some parts. For this reason, observers colour not differentiate between two grey patches with close percentages of dot area.

The agreement of observers' results was investigated using %CV. It indicated the reliability of the visual data. The larger the %CV, the poorer the agreement. For example, the %CV of 20 means the differences between the observers' data by 20%, or 20% error. The mean CV for observer repeatability was found to be 3%, indicating the good agreement between observers' first and second results. The agreement between observers' results was 10% error, showing the good agreement and the reliability of the data.

4.2 Experiment II: Quantifying colour strength

4.2.1 Introduction

This experiment aimed at finding the value of colour strength by the magnitude estimation method. The reference scale found in Experiment I consisted of grey patches with varying percentages of dot area of black. However, the dot area percentages do not correspond to the perception of colour strength. The colour strength is the perceptual attribute that relates to the coverage area of ink on the paper. Thus, the colour strength value is useful for connecting between the percentage of dot area and CIEL*a*b* for communication in the printing process. The change of %dot area results in the change of colour strength of prints. With the colour strength values, the quantitative analysis of the relationship between %dot area and colour strength could be performed. The equation derived from this relationship was used to specify the colour strength value of other colours when the grey patch of the matching colour strength was known.

4.2.2 Procedure

The reference scale found in Experiment I were sampled every 3 steps to reduce the number of steps from 70 to 21 steps, so that the visual assessments would not take too much time, and the observer could evaluate the colour strength value more easily. The grey patches at 0% and 100% dot area of black were taken as the references to the colour strength values of 0 (minimum) and 100 (maximum), respectively. The observers evaluated the colour strength of the grey patches in between these references. The grey patches given to the observers were in random order.

4.2.3 Results

The colour strength values were averaged from all observers' results for each step, and the results are given in Table 4-2. The dot area percentages of black and their colour strength values are plotted in Figure 4-1.

Table 4-2 The values of colour strength of grey patches.

% dot area	0	6	10	17	21	27	32	39	43	50	56
Colour strength value	0.00	4.2	7.9	12.2	16.0	20.5	24.8	29.2	34.5	38.9	44.1
% dot area	62	65	69	74	81	84	90	93	98	100	
Colour strength value	49.1	54.1	57.0	64.2	70.0	75.2	81.2	87.1	93.7	100	

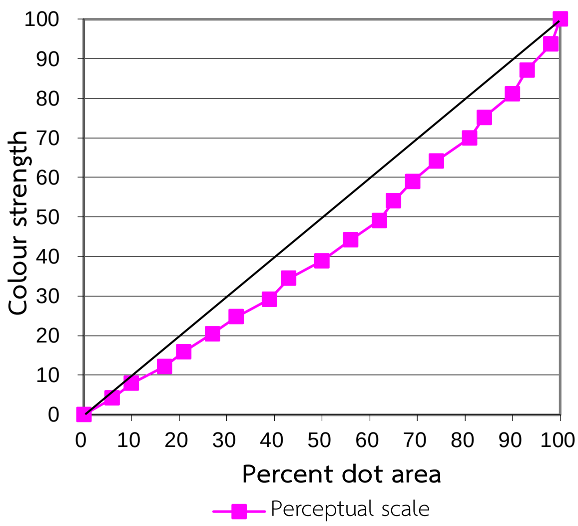


Figure 4-1 Relationship between %dot area of black and colour strength.

From Figure 4-1, the square dot line represents the relationship between the perceptual attribute of colour strength and the physical data of %dot area of prints. It was found that the two data sets were in positive correlation: the colour strength increased with the dot area percentages. In addition, the straight line represents the equal values of %dot area and colour strength. It can be seen that the visual results were lower than this line with unequal proportions, suggesting that the perception of colour strength was non-linear to the dot area percentages. This finding also confirmed that the %dot area do not correspond to the colour perception of prints.

The curve fitting method was employed to determine the function that best fit the data points. The equation of converting %dot area of black ink to the colour strength values was derived based on the best-fitted function found. Figure 4-2 shows the fitting of the second-order polynomial function to the visual results.

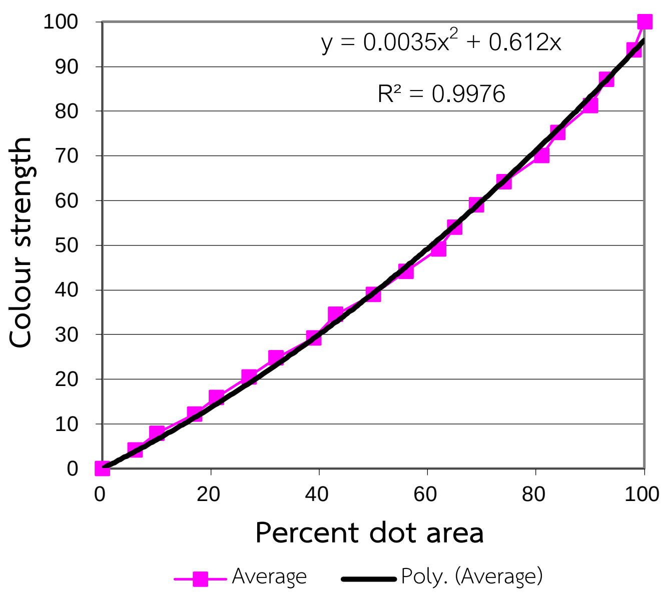


Figure 4-2 The polynomial trend line of colour strength scale of black ink with starting point at zero.

The polynomial trend line in Figure 4-2 had the starting point at zero. The best-fitted function to the visual data was the second-order polynomial function with the coefficient of determination (R^2) of 0.9976. The equation of conversion from %dot area of black to colour strength values of the reference scale was derived and can be found in Equation 4.1.

$$S_K = 0.0035(\%K)^2 + 0.612(\%K) \tag{4.1}$$

Where S_K is colour strength of print, and K is percentage of dot area of black ink.

4.2.4 Discussion

On average, the observers took 15 minutes to finish the quantification of 21 grey patches. 71 observers did the experiments twice. The mean CV for the agreement between observers' first and second results was found to be 12%, and 27% for between each observer's results against the panel results. Due to the nature of the magnitude estimation method, the experiments were difficult for the observers. Thus, the observer errors found in this experiment were acceptable.

From Figure 4-1, when considering in the percent dot area lower than 30, it can be seen that the observers differentiated the value of colour strength lower than high %dot area (over 30). In other words, the observers perceived the changing of colour strength in the dark zone better than the lighter zone. This suggests that the perception of colour strength of observers is more sensitive in the shadow area of prints than the highlight area. The non-linear system of colour strength perception found in this study agrees with the finding in the study by Pridmore [22], where the non-linear relation was found for the perception of lightness. When the surround luminance increased, the lightness of the sample increased. When the rate of lightness changed, the light colours appeared lighter, and the dark colours appeared darker, but not linearly.

Equation 4.1 was derived from the trend line in Figure 4-2. The trend line had the coefficient of determination (R^2) of 0.9976, which was nearly 1. This means that this polynomial function had good curve fitting and was good for predicting the colour strength value of the reference scale.

4.3 Experiment III: Determining colour strength of CMY

4.3.1 Introduction

This experiment aimed at finding the relationships between %dot area of primary colours (CMY) and colour strength. The colour strength values of primary colour patches were determined by matching with the reference scale. The dot area percentages of black of the matching grey patches to the colour patches in terms of colour strength were used to calculate the colour strength values of the relevant colour patches, using Equation 4.1 found in Experiment II. The quantitative analyses of the relationships between %dot area of CMY and colour strength could be carried out. The equations for calculating the colour strength values from %dot area of CMY were then derived. These equations could be used to estimate the colour strength values from the known %dot area of primary colours.

4.3.2 Procedure

Observers were given the primary colour patch to find the match of colour strength in the reference scale. The %dot area of black of that particular grey patch was input in Equation 4.1 to calculate the colour strength value. The calculation result was the colour strength value of the given colour patch because it had the same colour strength as the grey patch. This process was completed for all patches in the primary colour scale (varied in %dot area of C, M, or Y from 0-100 with 5% intervals).

The sequence of primary colour patches given to each observer was random, and each observer repeats the same experiments twice.

4.3.3 Results

The percentages of dot area of black obtained from all observers were averaged to represent the matching grey patches for each of the primary colour patches. The colour strength values for cyan (S_{KC}), magenta (S_{KM}), and yellow (S_{KY}) were calculated. The results are shown in Table 4-3. Figure 4-3 shows the plots between %dot area of primary colours and the colour strength values obtained from Equation 4.1.

Table 4-3 The results of %dot area of black and the colour strength values for primary colours.

Percent dot area of primary colours	0	5	10	15	20	25	30	35	40	45	50
K_C	1	7	12	17	21	26	30	33	37	42	47
S_{KC}	1	4	8	11	14	18	22	24	27	32	36
K_M	1	7	12	16	21	26	31	35	40	44	49
S_{KM}	1	4	8	11	14	18	22	26	30	34	38
K_Y	1	6	11	16	21	26	31	35	40	44	50
S_{KY}	1	4	7	11	14	18	22	26	30	34	39

Percent dot area of primary colours	55	60	65	70	75	80	85	90	95	100	
K_C	50	54	58	63	65	70	74	79	83	87	
S_{KC}	39	43	47	52	55	60	64	70	75	80	
K_M	54	58	63	66	70	75	79	83	87	91	
S_{KM}	43	47	52	56	60	66	70	75	80	85	
K_Y	54	58	63	67	70	75	79	82	86	89	
S_{KY}	43	47	52	57	60	66	70	74	79	82	

From Table 4-3, K_C, K_M, and K_Y represent the %dot area of black ink (grey scale) that matched to the given primary colours of cyan, magenta, and yellow, respectively. Some patches with different primary colours had the same colour strength because they matched to the same grey patches. For example, the colour patches of cyan, magenta, and yellow of 20% dot area matched to the same grey patch of 21% dot area of black, so they all had the colour strength value of 14.

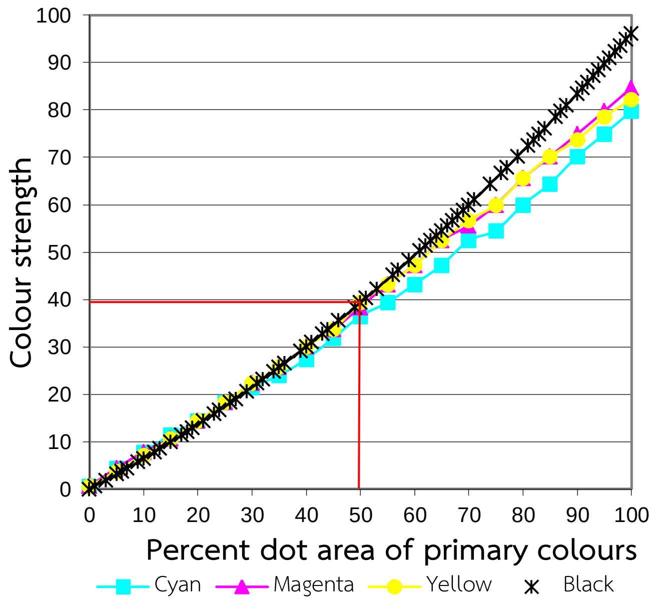


Figure 4-3 The relationships between %dot area and colour strength of primary colours.

In Figure 4-3, the horizontal and vertical straight lines that cross the curve lines of primary colours show the reference point for colour strength comparisons. At 50% dot area of each primary, the perception of colour strength was not the same for different primary colours. The colour strength values of each primary colour at 50% dot area were: C=36%, M=38% and Y=39%. This suggested that to generate the same colour strength, the dot area percentage of cyan should be higher than the other primary colours.

The plots in Figure 4-3 are separated for each primary colour for analyses of %dot area and colour strength relationships. The plots for cyan, magenta, and yellow, together with the curve fitting functions are shown in Figures 4.4, 4.5, and 4.6, respectively.

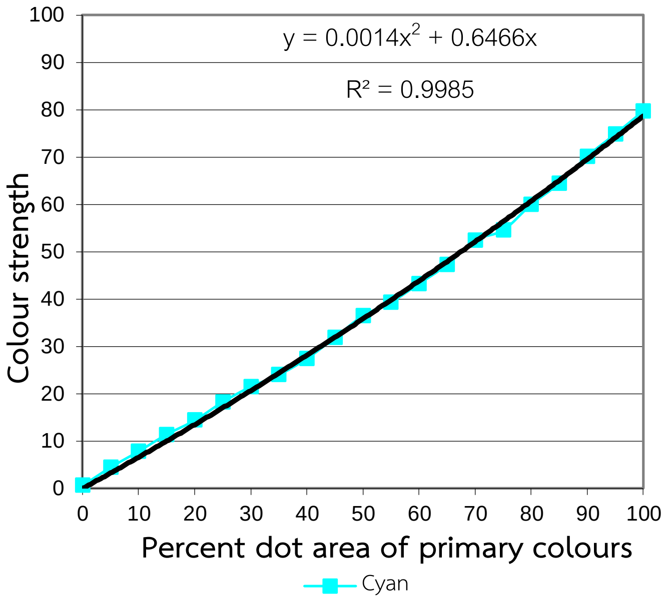


Figure 4-4 The polynomial trend line of colour strength scale of cyan with starting point at zero.

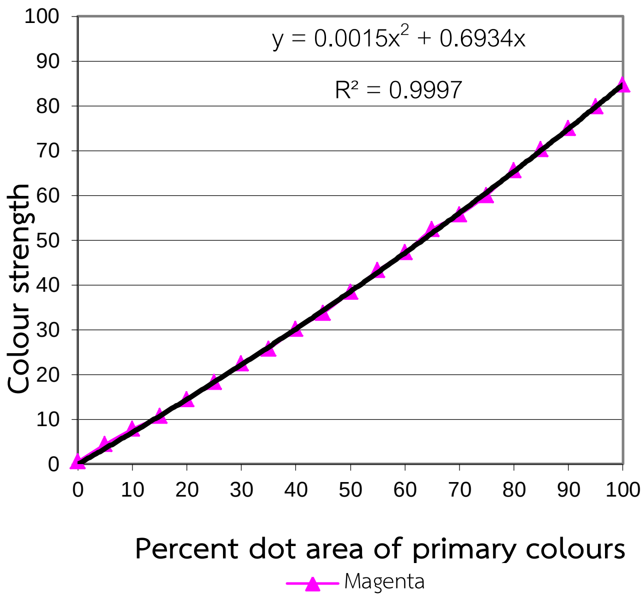


Figure 4-5 The polynomial trend line of colour strength scale of magenta with starting point at zero.

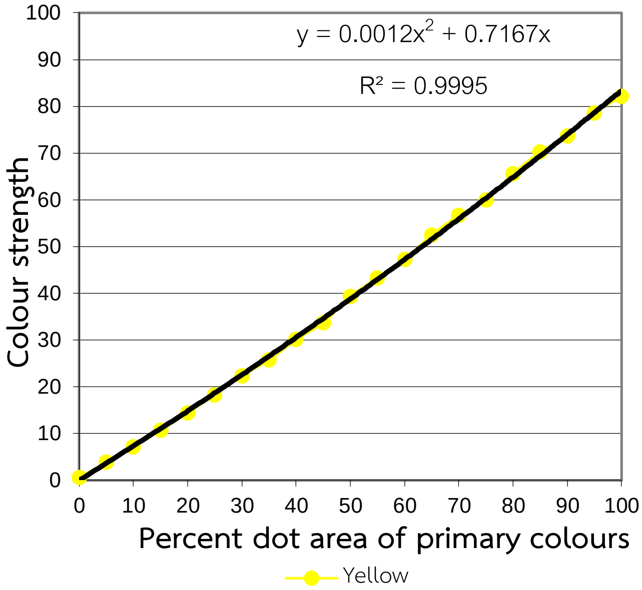


Figure 4-6 The polynomial trend line of colour strength scale of yellow with starting point at zero.

From Figures 4-4 to 4-6, the relationships between the perceptual attribute of colour strength and %dot area of primary colours were determined. Using the curve fitting method, the best-fitted function was found. The second-order polynomial function was the best function to fit the visual data for all primary colours. The values of coefficient of determination (R^2) used to indicate the goodness of fit were 0.9985, 0.9997, and 0.9995, for cyan, magenta, and yellow, respectively. The equations were derived to convert %dot area of cyan, magenta, and yellow to the corresponding colour strength, as given in Equations 4.2, 4.3, and 4.4, respectively.

$$S_C = 0.0014(\%C)^2 + 0.6466(\%C) \tag{4.2}$$

$$S_M = 0.0015(\%M)^2 + 0.6934(\%M) \tag{4.3}$$

$$S_Y = 0.0012(\%Y)^2 + 0.7167(\%Y) \tag{4.4}$$

Where S_C, S_M, and S_Y are the colour strength values of cyan, magenta, and yellow colour, respectively. C, M, and Y are the percentages of dot area of cyan, magenta, and yellow colour, respectively.

4.3.4 Discussion

This experiment investigated the relationships between %dot area of prints and their colour perception. The colour samples were printed with AM (Amplitude Modulation) screen and offset printing process. AM screening was selected in this study, based on results found in Brozovic et al's study [6]. They found that the best quality of colour lightness was produced with conventional offset printing and an AM screen. Figure 4-3 shows that the yellow scale provided the colour strength closer to the grey scale than any other primary colours. This finding conformed to the study by Kaleigh [12], where mapping two different colours to the same grey value for predicting the H-K effect showed that blue appeared lighter than the duller yellow.

From Figure 4-3, it can be seen that the cyan scale had the lowest colour strength. At 100% dot area of primary colours (solid area), cyan also gave the lowest colour strength. To validate the visual results, the coefficient of variance (CV) was employed to indicate the agreement between different observers and the agreement between two responses from the same observer (see Table 3-6). The study by Vaughn [25] also used %CV to indicate the inter-assay variability and intra-assay variability. It was found that the agreements of results within individual observers were always better than the agreements between different observers.

Equations 4.2 to 4.4 were derived from the trend line in Figures 4-4 to 4-6. The values of coefficient of determination (R^2) indicating the goodness of fit for the results of cyan, magenta and yellow were 0.9985, 0.9997 and 0.9995, respectively. The values were close to 1, indicating the good fit. This means that this polynomial function was good for predicting the colour strength value of cyan, magenta and yellow colour, respectively.

4.4 Experiment IV: Correlation of Colour strength and lightness

4.4.1 Introduction

Before establishing the colour system, the relationship between colour strength and lightness was investigated. This was done to understand the correlation between the perception of colour strength and the measurement value of lightness. In the previous study, lightness was one of the colour attributes that affected hue and chroma [26]. So, in this experiment, the effect of lightness on the perception of colour strength in printing was analysed.

4.4.2 Procedure

The lightness values of grey patches (black ink) were calculated from XYZ values using the 0% dot area (paper white) as the reference white, i.e the lightness value (L*) of 100, The colour strength values of the relevant grey patches were the visual results obtained in Experiment II. The lightness, colour strength, and dot area percentage of the grey patches were plotted for analyses of correlation.

4.4.3 Results

The results of visual colour strength and the measured L* for the grey patches with different %dot area of black are given in Table 4-4. The plots between these values are shown in Figure 4-7.

Table 4-4 The values of colour strength and lightness (L*) of grey patches (%dot area of black).

% dot area	0	6	10	17	21	27	32	39	43	50	56
Colour strength value	0.0	4.2	7.9	12.2	15.9	20.5	24.8	29.2	34.5	38.9	44.1
Lightness	100	98.1	95.7	93.0	89.8	87.0	83.5	82.5	78.0	74.5	72.9
Inverse L*	0.0	1.9	4.3	7.0	10.3	13.0	16.5	17.5	22.0	25.5	27.1
% dot area	62	65	69	74	81	84	90	93	98	100	
Colour strength value	49.1	54.1	59.0	64.2	70.0	75.2	81.2	87.1	93.7	100	
Lightness	68.2	65.7	62.2	58.0	52.8	47.2	43.4	37.4	31.0	21.2	
Inverse L*	31.8	34.3	37.8	42.0	47.2	52.8	56.6	62.6	69.0	78.8	

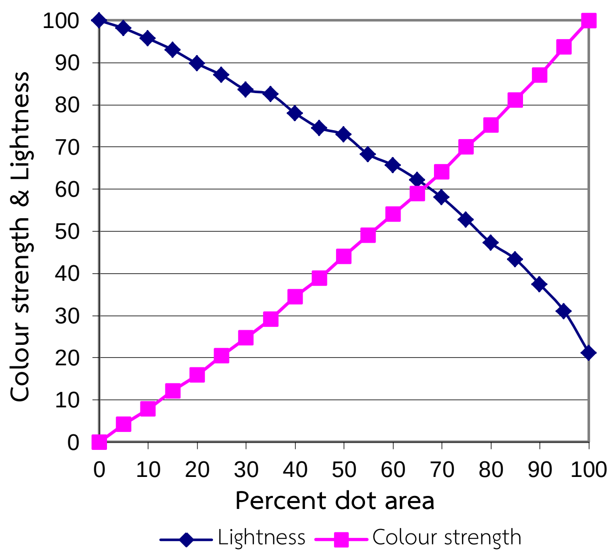


Figure 4-7 The relationships between colour strength, lightness, and %dot area of black ink.

Figure 4-7 shows the relationships between %dot area of black and colour strength (square dot line), and lightness (diamond shape dot line). The %dot area was in positive correlation with the colour strength, but in negative correlation with lightness. This means that when %dot area increases, the colour strength increases, while the lightness decreases.

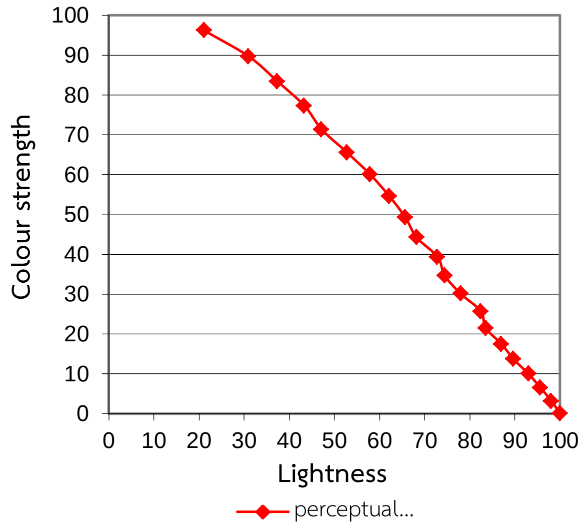


Figure 4-8 The relationships between colour strength and lightness of black ink.

Figure 4-8 shows the relationship between colour strength and lightness of prints with different %dot area of black. The negative correlation was found, meaning that when the colour strength increases, the lightness decreases.

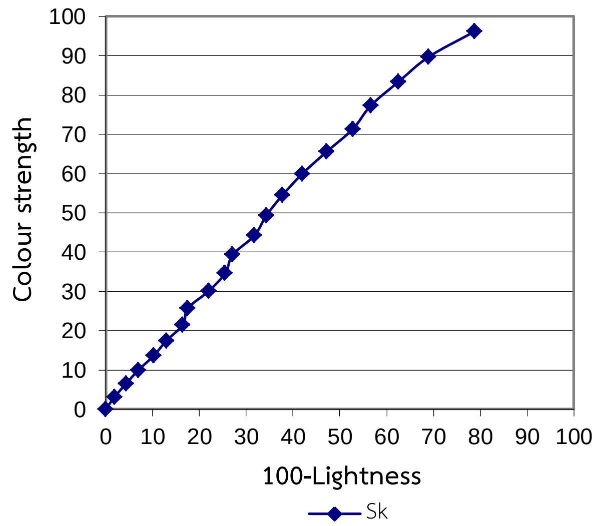


Figure 4-9 The relationships between colour strength and inverse lightness of black ink.

Figure 4-9 shows the relationship between colour strength and inverse lightness (100-L*). The positive correlation was found, meaning that with the inverse lightness, the colour strength increases.

4.4.4 Discussion

From Figure 4-7, the results showed that the colour strength and lightness values were correlated with %dot area of black in the different way. When %dot area of black ink increased, lightness decreased while colour strength increased. However, the cross of lightness and colour strength was found at 68% dot area of black. This revealed that at this point the colour strength and lightness were of the same value. Because the grey patch (black ink) was achromatic colour, the perception of colour strength was actually given for lightness. In the study by Nayatani [27] on attributes of achromatic and chromatic object-colour perception, the lightness of an achromatic colour sample had a correspondence to its whiteness-blackness perception.

The result in Figure 4-8 showed the negative relation between colour strength and lightness: colour strength increased with decreasing lightness. This finding conformed to the study of "predicting the colour of trichromatic prints" by Kulube and Hawkyard [14]. They found the method to predict the colour resulting from the overlap of trichromatic dots of cyan, magenta and yellow on printing surfaces. Their study showed the chromaticities x, y and luminance, Y of the dye that was printed on the printing surface. When the percentage of concentrations (intensity) of the dye increased, Y (Luminance for the surface colour represented by the Y tristimulus value) decreased.

From Figures 4-7 and 4-8, the results showed that when %dot area of prints and colour strength increased, lightness decreased. The negative relation of the lightness value was problematic for deriving the colour system model of good predictions. Consequently, the lightness value was inverted by subtracting 100 with the lightness value (100-L*). The inverse lightness values were obtained, and the positive relation to the colour strength values could be established, as shown in Figure 4-9. The relation was used to derive the colour strength model in the following experiment.

CHAPTER 5

A COLOUR SYSTEM FOR PRIMARY COLOURS IN PRINTING BASED ON COLOUR PERCEPTION

The study proposed the colour system for printing, where the system incorporates the colour measurement (CIEL*a*b*), colour perception (colour strength) and the communication system in printing (%dot area of CMYK). This chapter explains how the colour system is derived (Experiment V) and the performance of the model embedded in the system (Experiment VI). Detailed descriptions of each experiment were given in Chapter 3.

5.1 Experiment V: Devising a colour system for primary colours

5.1.1 Introduction

The proposed colour system for primary colour in printing connects the system of colour measurement and colour communication in printing with the perception of colour strength. The colour measurement values employed were the values in the CIEL*a*b* colour system because it is the system used for the reproduction control set forth by ISO 12647-2:2004 [23]. In printing, the percentage of dot area of primary colours is used for communication, as it is corresponding to how the prints are reproduced. As for the perceptual attribute, this study employed the perception of colour strength. This is because the colour strength is related to the intensity of ink, which is defined by the proportion of area covered by ink on the substrate. There are two models embedded in the colour system: the colour strength model and the %dot area conversion model. The colour strength model converts CIEL*a*b* values to the colour strength values, while the %dot area model converts the colour strength values to %dot area of primary colours.

5.1.2 Procedure

The data used for devising the colour system were obtained from the series of colour samples with different %dot area of C, M, Y, and K from 0-100 with 5% intervals. The colour strength values for the colour samples were calculated from %dot area of the relevant primaries via Equations 4.1-4.4. The colour strength model was then derived from the colour strength values and the CIEL*a*b* values. The model to predict %dot area was derived from the visual colour strength data (through Equation 4.1) and the %dot area of prints.

5.1.3 Results

Table 5-1 shows the results of the colour strength values and CIEL*a*b* values for each step of the scale of primary colours.

Table 5-1 The results of colour strength and CIEL*a*b* values for the primary colour scales.

Percent dot area	S_K	S_C	S_M	S_Y	L^*_K	L^*_C	L^*_M	L^*_Y
0	0.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00
5	3.15	3.27	3.50	3.61	98.12	98.51	97.37	99.94
10	6.47	6.61	7.08	7.29	95.69	97.17	95.12	99.45
15	9.97	10.01	10.74	11.02	93.03	95.96	93.03	99.36
20	13.64	13.49	14.47	14.81	89.75	94.31	90.90	99.02
25	17.49	17.04	18.27	18.67	87.02	92.99	88.87	98.76
30	21.51	20.66	22.15	22.58	83.53	91.28	86.39	98.44
35	25.71	24.35	26.11	26.55	82.46	89.81	83.87	98.27
40	30.08	28.10	30.14	30.59	78.02	88.20	81.67	97.82
45	34.63	31.93	34.24	34.68	74.50	86.53	79.53	97.77
50	39.35	35.83	38.42	38.84	72.87	84.70	76.79	97.37
55	44.25	39.80	42.67	43.05	68.23	84.36	75.78	97.45
60	49.32	43.84	47.00	47.32	65.70	82.90	73.13	96.94
65	54.57	47.94	51.41	51.66	62.20	80.95	70.59	96.75
70	59.99	52.12	55.89	56.05	57.99	79.26	68.22	96.39

Table 5-1 (continued)

Percent dot area	S_K	S_C	S_M	S_Y	L^*_K	L^*_C	L^*_M	L^*_Y
75	65.59	56.37	60.44	60.50	52.79	77.34	65.82	96.34
80	71.36	60.69	65.07	65.02	47.21	75.20	63.16	96.05
85	77.31	65.08	69.78	69.59	43.38	73.67	60.69	95.61
90	83.43	69.53	74.56	74.22	37.41	72.08	58.62	95.46
95	89.73	74.06	79.41	78.92	31.00	70.55	55.97	95.16
100	96.20	78.66	84.34	83.67	21.18	68.99	54.41	95.03
Percent dot area	a^*_K	a^*_C	a^*_M	a^*_Y	b^*_K	b^*_C	b^*_M	b^*_Y
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.11	-1.54	3.43	-0.55	0.22	-1.93	-1.04	3.27
10	0.08	-2.89	6.52	-0.94	0.18	-3.82	-1.76	6.17
15	0.08	-4.32	9.00	-1.32	0.12	-5.68	-2.18	9.23
20	0.02	-5.98	11.75	-1.70	0.07	-7.86	-2.59	12.72
25	0.02	-7.26	14.80	-2.12	0.00	-9.55	-3.22	16.21
30	-0.22	-9.18	18.24	-2.52	-0.13	-11.92	-3.74	20.02
35	0.02	-10.51	21.99	-2.79	0.03	-13.72	-4.37	23.19
40	0.00	-12.17	25.11	-3.19	0.19	-15.80	-4.80	27.25
45	0.08	-13.99	28.24	-3.46	-0.04	-18.06	-5.16	31.09
50	0.06	-16.06	32.50	-3.78	0.13	-20.55	-5.60	35.69
55	0.01	-16.42	34.62	-4.06	0.10	-20.88	-6.20	36.33
60	0.08	-18.32	38.69	-4.55	0.27	-23.13	-6.62	41.96
65	0.11	-20.55	42.71	-4.87	0.33	-25.68	-6.95	46.57
70	0.13	-22.76	47.07	-5.16	0.41	-28.02	-7.24	51.36
75	0.19	-25.05	51.34	-5.30	0.49	-30.41	-7.46	55.72
80	0.30	-27.45	55.99	-5.67	0.76	-33.17	-7.66	61.36
85	0.53	-29.66	61.13	-5.87	1.42	-35.28	-7.80	67.16
90	0.62	-31.70	65.19	-6.08	1.77	-37.29	-7.76	74.22
95	0.98	-33.92	70.11	-6.27	2.61	-42.09	-7.17	80.65
100	1.49	-35.74	73.41	-6.29	4.02	-41.79	-6.82	85.63

From Table 5-1, S, and L*, a*, b* represent the colour strength value and the CIEL*a*b* values, respectively. The subscripts K, C, M and Y represent the primary colours: black, cyan, magenta and yellow, respectively..

The CIEL*a*b* values of the primary colour samples were plotted. The results are illustrated in Figure 5-1 as the 3D plot, Figures 5-2 and 5-3 as the projection onto a*-L* and b*-L* planes, respectively. All plots show the lines of each individual primary, namely the primary colour scales in this study. This is because colour changes due to the change of %dot area of primaries. All primaries have the same starting point at CIEL*a*b* values of zeros, corresponding to 0% dot area of prints. The lightness gradually decreases when %dot area of primaries increases. Since colour strength varies with %dot area of primaries, these plots show the relationships between CIEL*a*b* and colour strength.

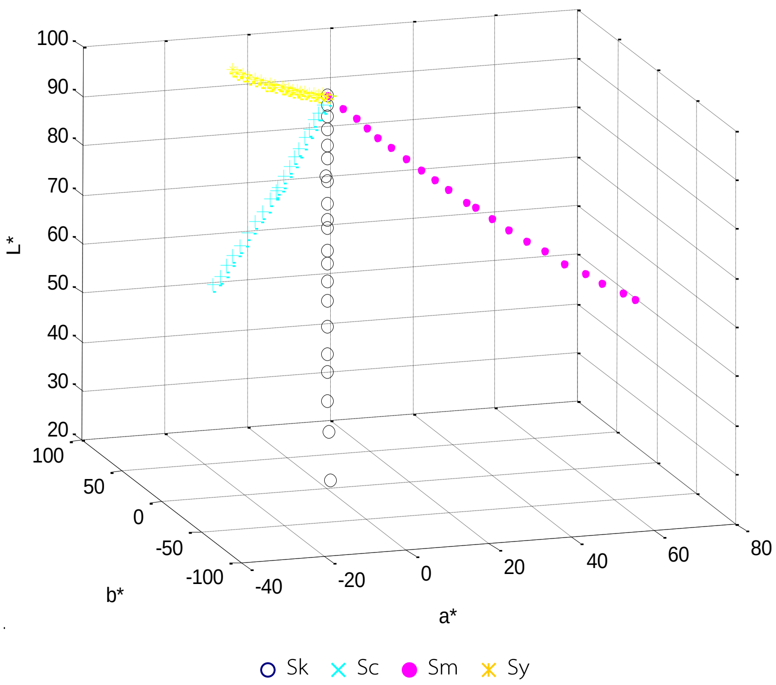


Figure 5-1 3D plot of CIEL*a*b* of the primary colour scale.

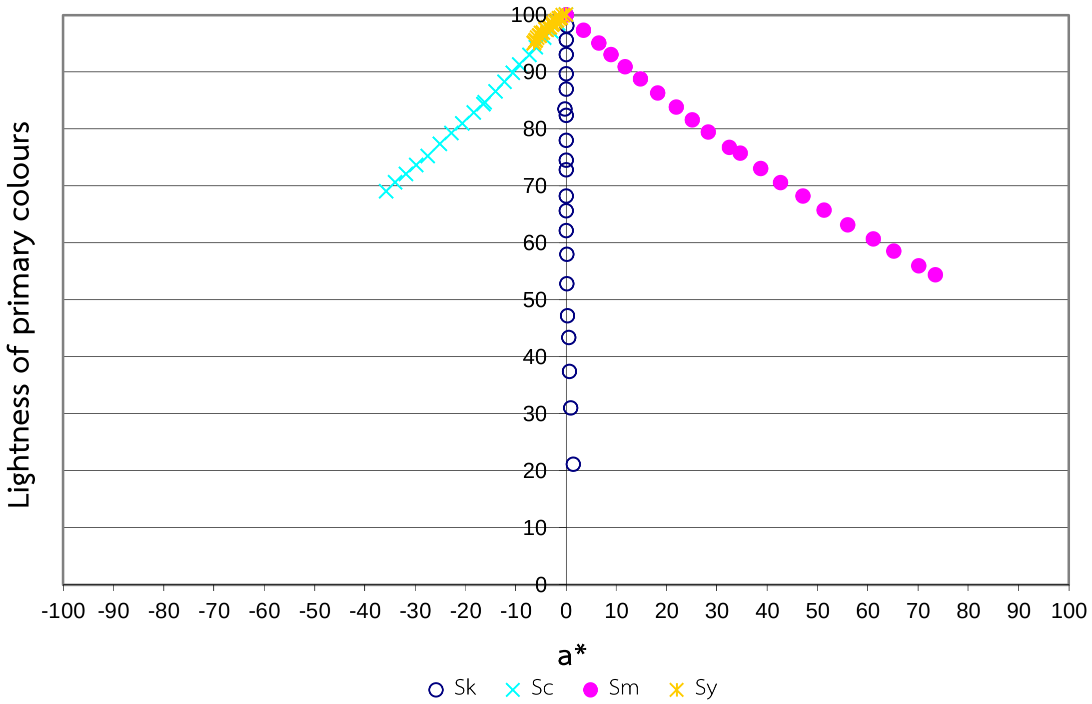


Figure 5-2 2D plot between a* and L* of the primary colour scale.

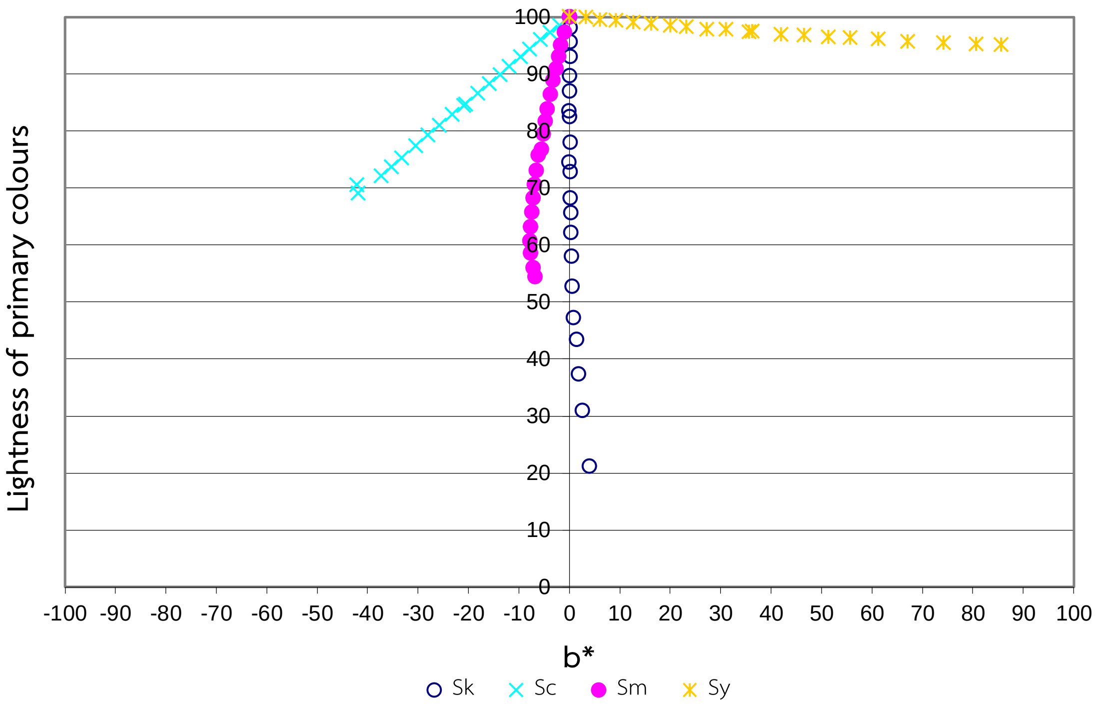


Figure 5-3 2D plot of b* and L* of the primary colour scale.

5.1.4 Discussion

From the plots in Figures 5-1 to 5-3, the length of primary colour scales was different, suggesting that the colour strength depended on hue. The black scale had the longest line, showing that the range of colour strength of black covered the ranges of all other colours. The primary colour scale pointed to the different directions. It was found that when %dot area of prints increased, the lightness decreased, while the chroma increased. This relationship thus described the perception of colour strength. The colour strength is perceived as the intensity of colour (chroma) in inverse proportion to lightness. The results also showed that the change of colour strength was not the same for different hues. This result was also found in the Nayatani's study [28], where yellow hue had the chroma scale larger than the other hues for constant Munsell chroma.

The positions of colours on the primary colour scales that have the same colour strength were different in terms of lightness and chroma. This means that all three attributes (lightness, chroma and hue) had an effect on colour strength. When connecting the positions of matching colour strength on the different scales together, the connection roughly formed an ellipsoid. Hence, the relationship between CIEL*a*b* and colour strength should be in a form of ellipsoid function, as given below.

$$S_i = \sqrt{K_{L*}(100 - L*_i)^2 + K_{a*}(a*_i)^2 + K_{b*}(b*_i)^2} \tag{5.1}$$

Where S_i is the predictor for colour strength value of the primary colour in printing and K_{L*}, K_{a*} and K_{b*} are the model coefficients of lightness, a* and b*, respectively. $100 - L*_i$ is the inverse lightness value, $a*_i$ is the value indicated a position between red and green, and $b*_i$ is the value indicated a position between yellow and blue.

Using the data in Table 5-1 to substitute the variables in Equation 5.1, the series of the unknown model coefficients were formed. The model coefficients K_{L*}, K_{a*} and K_{b*} can be estimated by the least square method (LMS), as given in Equation 5.2.

$$L = \sum_{i=1}^{n} \varepsilon_i^2 \text{ or } \sum_{i=1}^{n} (S_i - (K_{L*}(100 - L*_i)^2 + K_{a*}(a*_i)^2 + K_{b*}(b*_i)^2)^{\frac{1}{2}})^2 \quad (5.2)$$

Where L is the response received from the estimates or sum of square error (epsilon: **ε**) or sum of the difference between the colour strength value (S_i) and the estimated values from L*a*b* values, together with the model coefficients.

Using an iterative method for optimising the model coefficients, the equation was solved, and the model coefficients are given in Table 5-2.

Table 5-2 The model coefficients in Equation 5.1.

coefficient of the relation of CIEL*a*b*	K_{L*}	K_{a*}	K_{b*}
For black colour and primary colours	1.83	0.64	1.16

By applying the model coefficients in Table 5-2 to Equation 5.1, the colour strength model was established. The colour strength model is given in Equation 5.3.

$$S_i = \sqrt{1.83(100 - L*_i)^2 + 0.64(a*_i)^2 + 1.16(b*_i)^2} \quad (5.3).$$

To investigate the accuracy of the model, the colour strength values calculated by Equation 5.3 were compared with the colour strength values calculated by Equations 4.1-4.4. Since the colour strength values obtained from Equations 4.1-4.4 were the original values to estimate the model coefficients in Equation 5.3, the differences from these values indicated the model's performance. Table 5-3 shows the results of the predicted values by Equation 5.3 (the colour strength model) in comparison with the original values. The root mean square (RMS) and the percentage of error were used to indicate the accuracy of the predictions. The RMS value was found to be 4.84, 5.57, 1.76, and 3.57, and %error of 12.62, 13.32, 5.03 and 4.27, for K, C, M, and Y, respectively.

Table 5-3 The comparisons between visual colour strength values and the values calculated by Equation 5.3.

Colour strength value							
Black and primary colours in printing				by Equation 5.3			
S_K	S_C	S_M	S_Y	S_K	S_C	S_M	S_Y
0	0	0	0	0	0	0	0
4	4	4	4	3	3	5	4
8	8	8	7	6	6	9	7
12	11	11	11	9	9	12	10
16	14	14	14	14	12	16	14
20	18	18	18	18	15	19	18
25	22	22	22	22	19	24	22
29	24	26	26	24	22	28	25
34	27	30	30	30	25	32	30
39	32	34	34	35	29	36	34
44	36	38	39	37	33	41	39
49	39	43	43	43	34	43	39
54	43	47	47	46	37	48	46
59	47	52	52	51	41	53	51
64	52	56	57	57	45	58	56
70	55	60	60	64	49	62	60
75	60	66	66	71	54	67	67
81	64	70	70	77	57	73	73
87	70	75	74	85	61	77	80
94	75	80	79	93	66	82	87
100	80	85	82	107	68	85	93
RMS				4.84	5.57	1.76	3.56
% error				12.62	13.32	5.03	4.27

It was found that the prediction for cyan was the poorest, with an average error of 13.32%. However, the agreement of the visual data between observers (Table 3-6) was around 20% error, which is higher than the prediction error by the colour strength model. The means that the performance of the model was acceptable.

The colour strength values calculated from Equations 4.1 to 4.4 were compared to the observers' data (visual colour strength). The RMS values of K, C, M and Y were around 3.66, 0.89, 0.46, and 0.59, respectively, and the %error were 10.03, 4.33, 2.10 and 1.62, respectively.

The next step of devising the colour system is to derive the equations for converting the colour strength to %dot area of primaries. The visual colour strength data were plotted against the %dot area of primary colours, and the result is shown in Figure 5-4.

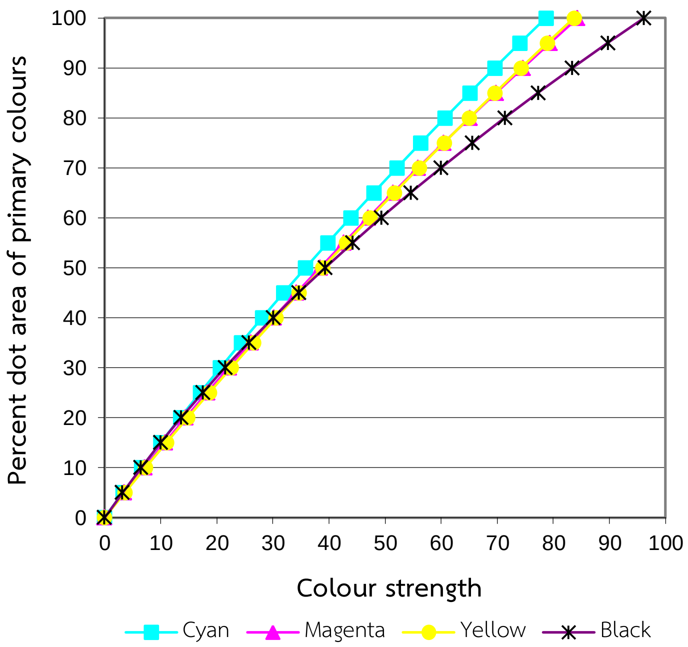


Figure 5-4 Relationships between %dot area and colour strength.

From Figure 5-4, the colour strength was plotted in the x-axis, and the %dot area in the y-axis. The relationships between the %dot area of CMYK and colour strength were best in the form of the second-order polynomials, with the coefficient of determination (R^2) of 1 for CMY, 0.9993 for K. The equations representing these relationships are given in Equations 5.4-5.7. The trend lines of these plots can be found in APPENDIX D.

$$\%C = -0.003(S_C)^2 + 1.5041(S_C) \quad (5.4)$$

$$\%M = -0.0026(S_M)^2 + 1.4027(S_M) \quad (5.5)$$

$$\%Y = -0.0021(S_Y)^2 + 1.3706(S_Y) \quad (5.6)$$

$$\%K = -0.0044(S_K)^2 + 1.4447(S_K) \quad (5.7)$$

Where %C, %M, %Y, and %K are percentage of dot area of cyan, magenta, yellow, and black, respectively. S_C, S_M, S_Y, and S_K are colour strength of cyan, magenta, yellow, and black, respectively.

5.2 Experiment VI: Testing the colour system for secondary colours

5.2.1 Introduction

This experiment aimed at testing the colour system derived from the previous experiment. The test samples were secondary samples (R, G, and B) that were printed with the equal percentages of two relevant primaries. The performance of the colour strength model (Equation 5.3) was first tested. The predictions for the colour strength values of red, green and blue samples were calculated using CIEL*a*b* values. Finally, the method to apply the %dot area equations (Equations 5.4-5.6) for determining %dot area of CMY was presented.

5.2.2 Procedure

To investigate the accuracy of the model predictions, the visual colour strength of secondary colour samples were required. The secondary colour samples were compared to find the colour strength match in the reference scale of black ink. The %dot area of the matching patches was used to obtain the visual colour strength data. The predicted colour strength data by the colour strength were compared with the visual data.

5.2.3 Results

Table 5-4 shows the results of %dot area of the matching grey patches in terms of colour strength to the secondary colour patches and their visual colour strength values.

Table 5-4 The visual results of %dot area of black and the relevant colour strength of secondary colours.

Percent dot area of secondary colours	0	5	10	15	20	25	30	35	40	45	50
K_R	1	6	12	17	22	28	32	37	42	47	53
S_{KR}	1	4	8	11	15	20	23	27	32	36	42
K_G	1	7	12	17	22	27	32	36	41	46	50
S_{KG}	1	4	8	11	15	19	23	27	31	36	39
K_B	1	6	11	17	21	27	31	36	41	46	51
S_{KB}	1	4	5	11	14	19	22	27	31	36	40
Percent dot area of secondary colours	55	60	65	70	75	80	85	90	95	100	
K_R	58	62	67	71	74	80	83	87	90	94	
S_{KR}	47	51	57	61	64	71	75	80	83	88	
K_G	55	59	63	67	71	74	78	83	87	91	
S_{KG}	44	48	52	57	61	64	69	75	80	85	
K_B	57	60	66	70	74	78	82	87	90	93	
S_{KB}	46	49	56	60	64	69	74	80	83	87	

From Table 5-4, K_R, K_G, and K_B represent the %dot area of black ink (grey scale) that matched in terms of colour strength to the given secondary colours of red, green, and blue, respectively. S_{KR}, S_{KG}, and S_{KB} are the visual colour strength values (from Equation 4.1) of red, green and blue samples, respectively. The colour patches of secondary colours that matched to the same grey patches had the same colour strength. For example, the colour patches of red, green and blue of 15% dot area of relevant primary colours matched to the same grey patch of 17% dot area of black, so they had the same colour strength value of 11. The secondary colour samples were measured in terms of XYZ values, and the CIEL*a*b* values were calculated, using the paper white as the reference white. Thus, at 0% dot area of ink (no print), the L*=100, and a*=b*=0. The CIEL*a*b* values of the secondary colour samples, together with the visual colour strength data (calculated from Equation 4.1), are given in Table 5-5.

Table 5-5 The visual colour strength and CIEL*a*b* values of secondary colour samples.

Percent dot area	S_{KR}	S_{KG}	S_{KB}	L^*_R	L^*_G	L^*_B
0	0.00	0.00	0.00	100	100	100
5	3.80	4.46	3.80	97.34	97.94	95.81
10	7.85	7.85	5.12	94.61	96.26	92.00
15	11.42	11.42	11.42	92.63	94.47	88.61
20	15.16	15.16	14.40	90.02	92.79	85.32
25	19.88	19.08	19.08	87.41	91.01	81.78
30	23.17	23.17	22.34	84.41	88.78	77.38
35	27.44	26.57	26.57	81.89	87.32	74.11
40	31.88	30.98	30.98	79.07	85.11	70.63
45	36.50	35.56	35.56	76.89	83.04	66.47
50	42.27	39.35	40.32	73.67	80.78	63.09
55	47.27	44.25	46.26	73.90	80.08	62.13
60	51.40	48.29	49.32	71.42	77.81	58.54

Table 5-5 (continued)

Percent dot area	S_{KR}	S_{KG}	S_{KB}	L^*_R	L^*_G	L^*_B
65	56.72	52.45	55.64	69.00	76.21	54.57
70	61.10	56.72	59.99	66.99	74.19	51.67
75	64.45	61.10	64.45	64.07	71.85	48.08
80	71.36	64.45	69.03	61.52	69.79	44.38
85	74.91	69.03	73.72	58.99	67.51	40.41
90	79.74	74.91	79.74	56.70	65.27	37.66
95	83.43	79.74	83.43	54.62	63.02	34.93
100	88.45	84.68	87.19	53.22	60.82	32.83
Percent dot area	a^*_R	a^*_G	a^*_B	b^*_R	b^*_G	b^*_B
0	0.00	0.00	0.00	0.00	0.00	0.00
5	2.85	-2.14	1.60	2.47	1.48	-3.55
10	5.43	-3.84	2.94	5.03	2.69	-6.16
15	7.41	-5.63	3.93	7.20	3.60	-8.48
20	10.20	-7.41	5.19	9.49	4.94	-10.63
25	13.01	-9.32	6.16	11.93	5.97	-13.19
30	16.35	-11.56	8.29	14.50	7.48	-15.71
35	19.42	-13.33	9.19	16.63	8.65	-17.97
40	22.96	-15.63	10.48	19.03	10.14	-19.99
45	26.13	-18.41	11.22	21.45	11.29	-23.04
50	30.41	-20.97	11.98	23.83	12.82	-25.14
55	30.96	-23.39	15.48	25.08	13.21	-24.09
60	34.79	-26.47	17.40	27.78	15.00	-26.32
65	38.88	-28.35	18.79	30.39	15.03	-28.79
70	41.54	-31.66	20.06	32.86	18.90	-30.43
75	47.22	-35.47	21.77	34.90	20.72	-32.26
80	51.51	-39.53	24.20	36.94	22.61	-34.34
85	56.75	-43.86	26.81	39.18	25.72	-36.75
90	60.97	-48.04	27.39	40.77	27.53	-38.61
95	65.81	-52.90	28.53	41.57	30.06	-40.12
100	68.58	-57.42	27.89	41.54	30.97	-41.40

The subscripts R, G, B in Table 5-5 represent the colour samples: red, green, blue, respectively. The subscript K of the colour strength value represents the colour strength values derived from the visual experiments.

5.2.4 Discussion

Table 5-4 shows the results of visual experiments, in which the colour strength values of secondary colour samples were determined. The matching %dot area of black was averaged from all observers' results. The mean CV indicating the agreement between observers' results was around 20% for colours (Table 3-6).

Table 5-6 The comparisons between the visual colour strength values and the values predicted by Equation 5.3 for red, green and blue samples.

Colour strength value					
Secondary colour in printing			By equation 5.3		
S_{KR}	S_{KG}	S_{KB}	S_R	S_G	S_B
0	0	0	0	0	0
4	4	4	5	4	7
8	8	5	10	7	13
11	11	11	14	10	18
15	15	14	19	13	23
20	19	19	24	16	29
23	23	22	29	19	36
27	27	27	34	22	41
32	31	31	39	26	46
36	36	36	44	30	52
42	39	40	50	34	58
47	44	46	51	36	59
51	48	49	56	40	64
57	52	56	62	43	70
61	57	60	66	48	75
64	61	64	72	52	80
71	64	69	77	57	86

Table 5-6 (continued)

Colour strength value					
Secondary colour in printing			By equation 5.3		
75	69	74	83	63	92
80	75	80	88	67	96
83	80	83	92	73	101
88	85	87	95	78	104
RMS			5.94	6.08	13.91
% error			15.92	14.07	43.10

The CIEL*a*b* values in Table 5-5 were put into Equation 5.3 (the colour strength model) to obtain the colour strength values of secondary colours. The results are given in Table 5-6. The RMS value and the %error were calculated to determine the differences between the visual colour strength values and the predicted values. The RMS values were found to be 5.94, 6.08, and 13.91, and %error were 15.92, 14.07, and 43.10, for red, green, and blue samples, respectively.

In the process of reproducing the secondary colours in printing, the secondary colour is derived from the overlapping of two primary colours. For example, red is derived from the combination of magenta and yellow with appropriate proportion. The reproduction of prints by trichromatic primaries was investigated in the previous study by Kulube [14]. In addition, the colour strength of secondary colours is obtained from the combination of colour strength of two primary colours. Therefore, in order to accurately predict the colour strength of secondary colours, the ratio of colour strength of two primaries must be accounted for. Because the visual colour strength data obtained from Experiment III were not in the same range for different primaries, the proportion of colour strength should be taken into account. Nayatani [11] studied the chromatic strength (the estimate of the chromatic strength corresponding to chromaticness per unit luminance at each spectral colour) and found that it differed in each colour. The visual colour strength data from Experiment III showed that cyan had the lowest colour strength, So, the ratios of colour strength were derived from dividing the colour strength of the primary colours by the colour strength value of cyan. This was done for every step in the primary colour scale. The results are given in Table 5-7.

Table 5-7 The ratios of colour strength of primary colours in printing (C, M, and Y).

Percent dot area	Ratio			Percent dot area	Ratio		
	R_C	R_M	R_Y		R_C	R_M	R_Y
0	0.00	0.00	0.00	55	1.00	1.07	1.08
5	1.00	1.07	1.11	60	1.00	1.07	1.08
10	1.00	1.07	1.10	65	1.00	1.07	1.08
15	1.00	1.07	1.10	70	1.00	1.07	1.08
20	1.00	1.07	1.10	75	1.00	1.07	1.07
25	1.00	1.07	1.10	80	1.00	1.07	1.07
30	1.00	1.07	1.09	85	1.00	1.07	1.07
35	1.00	1.07	1.09	90	1.00	1.07	1.07
40	1.00	1.07	1.09	95	1.00	1.07	1.07
45	1.00	1.07	1.09	100	1.00	1.07	1.06
50	1.00	1.07	1.08				
average					1.00	1.07	1.08

From the known %dot area of two primaries combined to produce the secondary colours, the colour strength of the two primaries can be calculated by Equations 4.2-4.4. The colour strength of the secondary can then be determined by the combination of the colour strength of the two primaries. However, the simple addition must be modified to incorporate the different range of colour strength (ratio) and the proportion of %dot area (weight) of the two primaries. The average ratio of primary colours (R_C, R_M, and R_Y) was derived and used to compensate for the different ranges of colour strength.

The modify equation for finding the colour strength value of secondary colours is given in Equation 5.8.

$$S_i = R_1(S_1)W_1 + R_2(S_2)W_2 \tag{5.8}$$

Where S_i is the colour strength value of secondary colour,

S_1 and S_2 are the colour strength value of two relevant primary colours, W_1 and W_2 are weight of the proportion of %dot area of primary colours,which can be calculated by

$W_1 = A_1/(A_1+A_2)$ and $W_2 = A_2/(A_1+A_2)$, where A is %dot area,

and R_1 and R_2 are the ratio of the primary colours mixed in the secondary colour in printing. R_C=1.00, R_M=1.07, R_Y=1.08

The results of colour strength calculated by Equation 5.8 for red, green and blue are given in Table 5-8.

Table 5-8 The comparisons between the visual colour strength and the values calculated by Equation 5.8 for secondary colours.

Colour strength value					
Secondary colour in printing			By equation 5.8		
S_{KR}	S_{KG}	S_{KB}	S_R	S_G	S_B
0	0	0	0	0	0
4	4	4	4	4	4
8	8	5	8	7	7
11	11	11	12	11	11
15	15	14	16	15	14
20	19	19	20	19	18

Table 5-8 (continued)

Colour strength value					
Secondary colour in printing			Secondary colour in printing		
23	23	22	24	23	22
27	27	27	28	27	26
32	31	31	33	31	30
36	36	36	37	35	34
42	39	40	42	39	38
47	44	46	46	43	43
51	48	49	51	47	47
57	52	56	55	52	51
61	57	60	60	56	56
64	61	64	65	61	61
71	64	69	70	65	65
75	69	74	75	70	70
80	75	80	80	75	75
83	80	83	85	80	80
88	85	87	90	85	84
RMS			0.90	0.63	2.73
% error			1.73	2.59	6.06

The modify equation (Equation 5.8) with the ratio of colour strength value and the proportion (weight) of primary colours was used to find the colour strength value of secondary colours (Table 5-8). Comparing the colour strength value from the Equation 5.8 and from the visual assessments, the root mean square values of secondary colours (R, G, and B) were found to be around 0.90, 0.63, and 2.73, respectively, and %error were 1.73, 2.59, and 6.06, respectively.

Lastly, the accuracy of predictions for Equations 5.4 to 5.6 was investigated. The visual colour strength data of the secondary colours (R, G, and B) in printing were used to calculate %dot area of primaries. Since the secondary colours in printing were generated from the mixing of the two primary colours, the %dot area of secondary colours must be separated into two parts for primary colours mixed in it.

Equations 5.4-5.6 were derived to find the colour strength of primary colours. In order to use with secondary colours, 2 equations for primaries mixed in the secondary colours are required. For example, when finding the %dot area of primaries for blue colour (B), the colour strength of cyan (C) and magenta (M) are required to calculate the %dot area of C and M. Equations 5.4 and 5.5 are used for finding the percent dot area of cyan and magenta, respectively. However, the colour strength value of blue (S_B) was used instead of the colour strength value of cyan and magenta.

$$C = -0.0030(S_B)^2 + 1.5041(S_B) \quad \text{from equation 5.4}$$

and

$$M = -0.0026(S_B)^2 + 1.4027(S_B) \text{ from equation 5.5}$$

For example, the colour strength value of blue (S_B) of %dot area of blue at 100 (Table 5-8) equals 84.45. This value is applied to both 5.4 and 5.5 equations, as shown below.

$$C = -0.0030(84.45)^2 + 1.5041(84.45) \quad \text{from equation 5.4}$$

and

$$M = -0.0026(84.45)^2 + 1.4027(84.45) \quad \text{from equation 5.5}$$

From the calculation, the %dot area of cyan and magenta for %dot area of blue at 100% were 106 and 100, respectively. Using the method, the %dot area of primaries mixed in the secondary colours were found. From the results of secondary colours (R, G, and B), the root mean square values of red (Y and M) equalled 3.95

and 3.87, green (Y and C) equalled 0.46 and 4.04, and blue (C and M) equalled 3.73 and 0.22, respectively. The %error of primary colours that was calculated from colour strength value of secondary colours (R (Y and M), G (Y and C) and B (C and M)) were 5.92 (Y) and 6.63 (M), 0.81 (Y) and 6.98 (C), and 5.97 (C) and 0.58 (M), respectively.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS

This study aimed to devise the colour system for primary colours in printing, where CIEL*a*b* values were converted to colour strength values, and the colour strength values were converted to %dot area of primary colours. A series of experiments were conducted to achieve this goal. They are summarised as follows.

6.1 Conclusions

In this study, the colour samples were printed onto 130-g/m^2 coated paper with AM (Amplitude Modulation) screen and offset printing process. Ink sequence for printing was cyan, magenta, yellow, and black, respectively. First, the reference scale (grey scale) was established. The observers were asked to arrange a series of grey patches varying in percentage of dot area from 0–100% in such a way that the patches form a perceptual scale of colour strength. The reference scale was divided into 4 sessions for each observer, so that the observers had 25 patches (either 0–25% or 25– 50% or 50–75% or 75–100% patches) to arrange in each session. There were 70 distinguishable steps of colour strength in the reference scale (perceptual scale). The %dot area of each step was derived from the median values from the observers' results.

21 steps from 70 steps with 3 steps intervals were chosen to establish the values of colour strength by the magnitude estimation method. Observers were students in the printing technology division. The observers were asked to evaluate a given grey patch to compare to the minimum colour strength value (colour strength chip at 0%) and maximum colour strength value (colour strength chip at 100%) and identify the value to the gray chip in terms of colour strength. The values of colour

strength were derived from the average values of the observers' results. The agreement between observers had %CV below 27% and 12% for within observer agreement, suggesting good reliability of the results.

The relationship between the percentage of dot area of grey patches and values of colour strength was positive: colour strength increased when the percentage of dot area increased with non-linearity. The observers perceived the changing of colour strength in the range of dark zone better than lighter zone. The relationship was best described by the second order polynomial (R^2=0.9976).

The 70 steps of the perceptual scale (reference scale) were used to compare colour strength to the colour sample patches. The colour strength values were derived from the matching patches in the reference scale. The relationships between the %dot area of primary colours and colour strength were best described by the second order polynomial with R^2 of 0.9985, 0.9997, and 0.9995 for cyan, magenta, and yellow, respectively.

The relationships between lightness and colour strength were estimated. The relationships between the percentage of dot area of black and colour strength were positive, but lightness was negative: when %dot area of ink increased, colour strength increased with decreasing lightness.

The relationships between colour strength and CIEL*a*b* were investigated. The ranges of colour strength were different for different colours. The chroma increased when the lightness decreased and the colour strength increased. But the change was not constant for different hues. This means that all three attributes (lightness, chroma and hue) had an effect on colour strength.

The colour strength model was devised from the measured value based on CIEL*a*b*. The model coefficients relating to L*, a* and b* values were optimized by the least square method. The percentages of error of models' predictions were 4.57, 10.46, 7.01 and 4.57 for black, cyan, magenta and yellow, respectively.

The equations for finding the percentage of dot area from the colour strength were defined. The relationships were best described by the second order polynomial, with R^2 of 1 for primary colours and 0.9993 for black.

The colour system devised in this study was tested with secondary colour samples. The predictions of the colour strength model (from input CIEL*a*b* to predict colour strength) had %error of 15.92, 14.07, and 43.10 for red, green, and blue, respectively.

The colour strength of secondary colours was obtained from the combination of colour strength of two primary colours. Therefore, the ratio of colour strength must be used to calculate the colour strength of the secondary in the equation. The ratio of colour strength was derived from dividing the colour strength of the other primary colours by colour strength of cyan colour. Thus, simple addition was modified to incorporate the ratio of colour strength and the proportion (weight) of two primary colours. The predictions of this equation had %error of 1.73, 2.59, and 6.06 for red, green, and blue, respectively

To predict %dot area of primary colours from the colour strength values of secondary colours, the colour strength of secondary colours was applied to both equations of two primary colours that were mixed to make the secondary colours. The %error of predictions were 5.92 (Y) and 6.63 (M) for red, 0.81 (Y) and 6.98 (C) for green, and 5.97 (C) and 0.58 (M) for blue.

The results of the colour perception system for primary colours in printing were summarised as follows:

1) In the reference scale of black ink, there were 70 steps of distinguishable colour strength.

2) The perception of colour strength was non-linear: colour strength was better perceived in the dark zone than the lighter zone.

3) The perception of colour strength was not the same for different primary colours. Cyan had the lowest colour strength, suggesting that to produce the same colour strength as the other colours, cyan requires higher %dot area than other primaries.

4) The relationships between %dot area of primary colours and colour strength were in the second-order polynomial form. The equations are given below.

$$S_K = 0.0035(\%K)^2 + 0.612(\%K) \quad (4.1)$$

$$S_C = 0.0014(\%C)^2 + 0.6466(\%C) \quad (4.2)$$

$$S_M = 0.0015(\%M)^2 + 0.6934(\%M) \quad (4.3)$$

$$S_Y = 0.0012(\%Y)^2 + 0.7167(\%Y) \quad (4.4)$$

S represents colour strength. The subscripts C, M, Y and K represent primary colours: cyan, magenta, yellow, and black, respectively.

%C, %M, %Y and %K are %dot area of cyan, magenta, yellow, and black, respectively.

When the colour strength values resulted from the calculations are greater than 100, the values of 100 are used instead.

5) The %dot area was in positive correlation with the colour strength, but in negative correlation with lightness: when %dot area increases, the colour strength increases with decreasing lightness.

6) The colour strength means the colour appearance of object colors that is related to chroma and lightness regardless of hue. The colour strength is perceived as the intensity of colour (chroma) in inverse proportion to lightness. The change of colour strength is not the same for different hues.

7) The relationships between CIEL*a*b* and colour strength were used to derive the colour strength model. The colour strength model is defined as:

$$S_i = \sqrt{1.83(100 - L^*_i)^2 + 0.64(a^*_i)^2 + 1.16(b^*_i)^2} \quad (5.3)$$

In the case of getting the resultant colour strength value of over 100, the result is set to 100.

8) The equations for converting the colour strength to %dot area of primary colours were derived and given as:

$$\%C = -0.003(S_C)^2 + 1.5041(S_C) \quad (5.4)$$

$$\%M = -0.0026(S_M)^2 + 1.4027(S_M) \quad (5.5)$$

$$\%Y = -0.0021(S_Y)^2 + 1.3706(S_Y) \quad (5.6)$$

$$\%K = -0.0044(S_K)^2 + 1.4447(S_K) \quad (5.7)$$

In the case that the dot area percentages calculated from the above equations are over 100, the percentages of 100 are reported.

9) The colour strength of secondary colours can be calculated from the colour strength of the two primaries that are mixed to make the secondary colour by the following equation.

$$S_i = R_i (S_1) W_1 + R_i (S_2) W_2 \quad (5.8)$$

S_i is the colour strength value of secondary colour,

S_1 and S_2 are the colour strength value of two relevant primary colours,

W_1 and W_2 are weight of the proportion of %dot area of primary colours, which can be calculated by

$W_1 = A_1/(A_1+A_2)$ and $W_2 = A_2/(A_1+A_2)$, where A is %dot area,

R_1 and R_2 are the ratio of the primary colours mixed in the secondary colour: R_C=1.00, R_M=1.07, R_Y=1.08

If the colour strength value of over 100 is found, the value of 100 is used instead.

10) To calculate %dot area of two mixing primary colours from the colour strength of secondary colour, Equations 4.2-4.4 are applied. The colour strength of the given secondary colour is applied to two equations of the relevant primaries to the results of %dot area for the primary colours.

6.2 Suggestions

This study established the relationships between percentages of dot area and colour perception for devising the colour system for primary colours that is based on colour perception system for printing. The relationships between percentages of dot area and colour strength in printing are useful for the future work. The colour system for primary colours derived from this study corresponds to the subtractive colour-mixing system in printing process and is useful for communication in design and printing process. Although the model derived in this study is suitable for finding the colour strength value and the percentage of dot area of primary colours and secondary colours in printing, it should be tested with other colours that are combined from the primary colours in different proportions. For approving the performance of this colour system, more colour samples can be included to estimate the model coefficients and investigate the means of predicting the other colours that are mixed from the primary colours. Consequently, the future work could include the tertiary colours and/or otherr colours in different proportion of primary colours to find the colour strength by the model proposed in this study.

The colour strength and dot area percentages are not supposed to be over 100, but the results calculated from the equations derived in this study were sometimes more than 100. These results were found with samples with low lightness. Thus, future work could take this matter into account and derive a set of equations to compensate low lightness samples. In addition, the effects of viewing conditions on the colour perception system for primary colours in printing must be investigated.

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APPENDICES

APPENDIX A: TONAL VALUE OF PRINTED AND TONAL VALUE INCREASE OF PERCENTAGE OF DOT AREA OF CYAN, MAGENTA, YELLOW AND BLACK, COLORIMETRIC VALUES ON TRISTIMULUS XYZ AND CIEL*a*b* COLOUR SPACE

Table A-1 Tonal value of printed and tonal value increase of percentage of dot area of Cyan, Magenta, Yellow, and Black.

Tone value	Cyan		Magenta		Yellow		Black	
	Print	TVI[1]	Print	TVI[1]	Print	TVI[1]	Print	TVI[1]
0	0	0	0	0	0	0	0	0
5	4	-1	4	-1	4	-1	4	-1
10	10	-1	11	0	9	-2	11	0
15	15	0	17	2	14	-1	17	2
20	22	2	23	3	21	1	25	5
25	28	3	30	5	27	2	32	7
30	34	3	35	4	31	0	37	6
35	39	4	40	5	36	1	41	6
40	45	5	46	6	42	2	47	7
45	51	5	52	6	48	2	53	7
50	55	6	56	7	52	3	57	8
55	62	6	61	5	59	3	63	7
60	65	4	64	3	63	2	67	6
65	70	5	68	3	67	2	72	7
70	74	4	72	2	71	1	77	7
75	79	4	78	3	76	1	82	7
80	84	4	83	3	80	0	87	7
85	89	5	87	3	86	2	90	6
90	93	4	91	2	91	2	94	5
95	97	2	96	1	95	0	97	2
100	100	0	100	0	100	0	100	0

[1] TVI: Tonal value increase

Table A-2 The tristimulus XYZ value and CIEL*a*b* coordinates of cyan colour samples.

Colour	Cyan					
Percent dot area	X	Y	Z	L*[1]	a*[1]	b*[1]
0	87.08	90.29	76.74	100.00	0.00	0.00
5	82.98	86.85	76.00	98.51	-1.54	-1.93
10	79.44	83.85	75.54	97.17	-2.89	-3.82
15	76.21	81.18	75.27	95.96	-4.32	-5.68
20	72.10	77.65	74.52	94.31	-5.98	-7.86
25	68.93	74.89	73.86	92.99	-7.26	-9.55
30	64.86	71.42	73.21	91.28	-9.18	-11.92
35	61.63	68.53	72.40	89.81	-10.51	-13.72
40	58.13	65.45	71.63	88.20	-12.17	-15.80
45	54.60	62.35	70.95	86.53	-13.99	-18.06
50	50.87	59.06	70.21	84.70	-16.06	-20.55
55	50.22	58.48	69.95	84.36	-16.42	-20.88
60	47.30	55.95	69.65	82.90	-18.32	-23.13
65	43.70	52.71	68.78	80.95	-20.55	-25.68
70	40.64	50.00	68.17	79.26	-22.76	-28.02
75	37.41	47.04	67.20	77.34	-25.05	-30.41
80	34.06	43.88	66.23	75.20	-27.45	-33.17
85	31.65	41.70	65.67	73.67	-29.66	-35.28
90	29.35	39.53	64.92	72.08	-31.70	-37.29
95	27.17	37.50	67.17	70.55	-33.92	-42.09
100	25.17	35.51	64.07	68.99	-35.74	-41.79

[1]Calculate CIEL*a*b* by tristimulus XYZ of paper white (87.08, 90.29 and 76.74 respectively).

Table A-3 The tristimulus XYZ value and CIEL*a*b* coordinates of magenta colour samples.

Colour	Magenta					
Percent dot area	X	Y	Z	L*[1]	a*[1]	b*[1]
0	87.64	90.86	77.23	100.00	0.00	0.00
5	83.55	84.82	73.25	97.37	3.43	-1.04
10	80.22	79.86	69.77	95.12	6.52	-1.76
15	77.03	75.44	66.38	93.03	9.00	-2.18
20	73.98	71.12	63.04	90.90	11.75	-2.59
25	71.32	67.13	60.16	88.87	14.80	-3.22
30	68.06	62.49	56.56	86.39	18.24	-3.74
35	64.94	57.98	53.13	83.87	21.99	-4.37
40	62.25	54.24	50.16	81.67	25.11	-4.80
45	59.73	50.75	47.32	79.53	28.24	-5.16
50	56.71	46.51	43.83	76.79	32.50	-5.60
55	55.84	45.01	42.93	75.78	34.62	-6.20
60	53.01	41.21	39.75	73.13	38.69	-6.62
65	50.45	37.79	36.82	70.59	42.71	-6.95
70	48.35	34.77	34.2	68.22	47.07	-7.24
75	46.23	31.88	31.63	65.82	51.34	-7.46
80	43.93	28.87	28.91	63.16	55.99	-7.66
85	42.14	26.26	26.51	60.69	61.13	-7.80
90	40.59	24.19	24.51	58.62	65.19	-7.76
95	38.57	21.7	21.83	55.97	70.11	-7.17
100	37.54	20.32	20.35	54.41	73.41	-6.82

[1]Calculate CIEL*a*b* by tristimulus XYZ of paper white (87.64, 90.86 and 77.23 respectively).

Table A-4 The tristimulus XYZ value and CIEL*a*b* coordinates of yellow colour samples.

Colour	Yellow					
Percent dot area	X	Y	Z	L*[1]	a*[1]	b*[1]
0	87.27	90.49	76.99	100.00	0.00	0.00
5	86.84	90.34	73.15	99.94	-0.55	3.27
10	85.54	89.2	69.05	99.45	-0.94	6.17
15	85.16	89.01	65.67	99.36	-1.32	9.23
20	84.21	88.22	61.52	99.02	-1.70	12.72
25	83.43	87.63	57.69	98.76	-2.12	16.21
30	82.52	86.89	53.63	98.44	-2.52	20.02
35	82.02	86.51	50.55	98.27	-2.79	23.19
40	80.85	85.49	46.45	97.82	-3.19	27.25
45	80.6	85.37	43.28	97.77	-3.46	31.09
50	79.6	84.48	39.26	97.37	-3.78	35.69
55	79.63	84.66	38.89	97.45	-4.06	36.33
60	78.31	83.52	34.31	96.94	-4.55	41.96
65	77.76	83.1	31.09	96.75	-4.87	46.57
70	76.87	82.31	27.8	96.39	-5.16	51.36
75	76.7	82.2	25.28	96.34	-5.30	55.72
80	75.92	81.56	22.05	96.05	-5.67	61.36
85	74.92	80.6	18.92	95.61	-5.87	67.16
90	74.51	80.27	15.79	95.46	-6.08	74.22
95	73.81	79.62	13.16	95.16	-6.27	80.65
100	73.56	79.36	11.4	95.03	-6.29	85.63

[1]Calculate CIEL*a*b* by tristimulus XYZ of paper white (87.27, 90.49 and 76.99 respectively).

Table A-5 The tristimulus XYZ value and CIEL*a*b* coordinates of black colour samples.

Colour	Black					
Percent dot area	X	Y	Z	L*[1]	a*[1]	b*[1]
0	87.71	91.09	77.43	100.00	0.00	0.00
5	83.58	86.74	73.49	98.12	0.11	0.22
10	78.34	81.32	68.93	95.69	0.08	0.18
15	72.86	75.63	64.17	93.03	0.08	0.12
20	66.46	69.01	58.59	89.75	0.02	0.07
25	61.45	63.81	54.24	87.02	0.02	0.00
30	55.32	57.54	49.02	83.53	-0.22	-0.13
35	53.64	55.70	47.32	82.46	0.02	0.03
40	46.70	48.50	41.08	78.02	0.00	0.19
45	41.67	43.25	36.79	74.50	0.08	-0.04
50	39.46	40.96	34.73	72.87	0.06	0.13
55	33.58	34.87	29.58	68.23	0.01	0.10
60	30.67	31.83	26.90	65.70	0.08	0.27
65	26.90	27.91	23.55	62.20	0.11	0.33
70	22.79	23.64	19.90	57.99	0.13	0.41
75	18.33	19.00	15.95	52.79	0.19	0.49
80	14.24	14.74	12.27	47.21	0.30	0.76
85	11.84	12.22	9.96	43.38	0.53	1.42
90	8.63	8.89	7.13	37.41	0.62	1.77
95	5.92	6.06	4.67	31.00	0.98	2.61
100	2.97	3.00	2.10	21.18	1.49	4.02

[1]Calculate CIEL*a*b* by tristimulus XYZ of paper white (87.71, 91.09 and 77.43 respectively).

Table A-6 The tristimulus XYZ value and CIEL*a*b* coordinates of red colour samples.

Colour	Red					
Percent dot area	X	Y	Z	L*[1]	a*[1]	b*[1]
0	87.23	90.45	76.95	100.00	0.00	0.00
5	82.8	84.37	69.09	97.34	2.85	2.47
10	78.24	78.42	61.57	94.61	5.43	5.03
15	75.1	74.29	56.19	92.63	7.41	7.20
20	71.15	69.05	50.06	90.02	10.20	9.49
25	67.37	64.08	44.29	87.41	13.01	11.93
30	63.24	58.67	38.39	84.41	16.35	14.50
35	59.99	54.35	33.87	81.89	19.42	16.63
40	56.56	49.8	29.26	79.07	22.96	19.03
45	54.15	46.45	25.67	76.89	26.13	21.45
50	50.57	41.78	21.51	73.67	30.41	23.83
55	51.13	42.1	21.09	73.90	30.96	25.08
60	48.67	38.72	17.88	71.42	34.79	27.78
65	46.45	35.59	15.08	69.00	38.88	30.39
70	44.41	33.12	12.88	66.99	41.54	32.86
75	42.15	29.75	10.56	64.07	47.22	34.90
80	40.02	26.99	8.7	61.52	51.51	36.94
85	38.29	24.44	7.04	58.99	56.75	39.18
90	36.61	22.27	5.82	56.70	60.97	40.77
95	35.41	20.41	4.96	54.62	65.81	41.57
100	34.48	19.22	4.53	53.22	68.58	41.54

[1]Calculate CIEL*a*b* by tristimulus XYZ of paper white (87.23, 90.45 and 76.95 respectively).

Table A-7 The tristimulus XYZ value and CIEL*a*b* coordinates of green colour samples.

Colour	Green					
Percent dot area	X	Y	Z	L*[1]	a*[1]	b*[1]
0	88.57	91.82	78.07	100.00	0.00	0.00
5	82.84	87.01	72.32	97.94	-2.14	1.48
10	78.39	83.23	67.86	96.26	-3.84	2.69
15	73.82	79.31	63.68	94.47	-5.63	3.60
20	69.65	75.74	59.44	92.79	-7.41	4.94
25	65.4	72.08	55.53	91.01	-9.32	5.97
30	60.4	67.68	50.69	88.78	-11.56	7.48
35	57.14	64.89	47.52	87.32	-13.33	8.65
40	52.57	60.81	43.2	85.11	-15.63	10.14
45	48.3	57.15	39.58	83.04	-18.41	11.29
50	44.06	53.32	35.67	80.78	-20.97	12.82
55	42.27	52.17	34.57	80.08	-23.39	13.21
60	38.23	48.56	30.83	77.81	-26.47	15.00
65	35.63	46.12	29.11	76.21	-28.35	15.03
70	32.26	43.15	24.87	74.19	-31.66	18.90
75	28.64	39.88	21.81	71.85	-35.47	20.72
80	25.52	37.14	19.2	69.79	-39.53	22.61
85	22.38	34.26	16.14	67.51	-43.86	25.72
90	19.57	31.58	13.93	65.27	-48.04	27.53
95	16.87	29.02	11.68	63.02	-52.90	30.06
100	14.53	26.67	10.2	60.82	-57.42	30.97

[1]Calculate CIEL*a*b* by tristimulus XYZ of paper white (88.57, 91.82 and 78.07 respectively).

Table A-8 The tristimulus XYZ value and CIEL*a*b* coordinates of blue colour samples.

Colour	Blue					
Percent dot area	X	Y	Z	L*[1]	a*[1]	b*[1]
0	86.74	89.93	76.47	100.00	0.00	0.00
5	78.46	80.54	72.34	95.81	1.60	-3.55
10	71.34	72.58	68.05	92.00	2.94	-6.16
15	65.3	65.96	64.38	88.61	3.93	-8.48
20	59.88	59.92	60.83	85.32	5.19	-10.63
25	54.27	53.87	57.42	81.78	6.16	-13.19
30	48.1	46.91	52.74	77.38	8.29	-15.71
35	43.61	42.15	49.77	74.11	9.19	-17.97
40	39.26	37.46	46.43	70.63	10.48	-19.99
45	34.22	32.32	43.12	66.47	11.22	-23.04
50	30.49	28.5	40.26	63.09	11.98	-25.14
55	30.33	27.48	38.28	62.13	15.48	-24.09
60	26.96	23.86	35.48	58.54	17.40	-26.32
65	23.38	20.25	32.56	54.57	18.79	-28.79
70	21.02	17.85	30.42	51.67	20.06	-30.43
75	18.36	15.16	27.8	48.08	21.77	-32.26
80	15.97	12.68	25.36	44.38	24.20	-34.34
85	13.65	10.34	23	40.41	26.81	-36.75
90	12.01	8.9	21.55	37.66	27.39	-38.61
95	10.59	7.61	20.01	34.93	28.53	-40.12
100	9.4	6.71	18.94	32.83	27.89	-41.40

[1]Calculate CIEL*a*b* by tristimulus XYZ of paper white (86.74, 89.93 and 76.47 respectively).

APPENDIX B: CODES OF PRIMARY AND SECONDARY COLOURS AND BLACK COLOUR PATCHES

Table B-1 Codes of primary and secondary colour patches.

Percent dot area	C	M	Y	R	G	B
0	C1	M1	Y1	R1	G1	B1
5	C2	M2	Y2	R2	G2	B2
10	C3	M3	Y3	R3	G3	B3
15	C4	M4	Y4	R4	G4	B4
20	C5	M5	Y5	R5	G5	B5
25	C6	M6	Y6	R6	G6	B6
30	C7	M7	Y7	R7	G7	B7
35	C8	M8	Y8	R8	G8	B8
40	C9	M9	Y9	R9	G9	B9
45	C10	M10	Y10	R10	G10	B10
50	C11	M11	Y11	R11	G11	B11
55	C12	M12	Y12	R12	G12	B12
60	C13	M13	Y13	R13	G13	B13
65	C14	M14	Y14	R14	G14	B14
70	C15	M15	Y15	R15	G15	B15
75	C16	M16	Y16	R16	G16	B16
80	C17	M17	Y17	R17	G17	B17
85	C18	M18	Y18	R18	G18	B18
90	C19	M19	Y19	R19	G19	B19
95	C20	M20	Y20	R20	G20	B20
100	C21	M21	Y21	R21	G21	B21

Table B-2 Codes of black colour patches.

Percent dot area	K	Percent dot area	K	Percent dot area	K	Percent dot area	K
0	K0	26	K26	52	K52	78	K78
1	K1	27	K27	53	K53	79	K79
2	K2	28	K28	54	K54	80	K80
3	K3	29	K29	55	K55	81	K81
4	K4	30	K30	56	K56	82	K82
5	K5	31	K31	57	K57	83	K83
6	K6	32	K32	58	K58	84	K84
7	K7	33	K33	59	K59	85	K85
8	K8	34	K34	60	K60	86	K86
9	K9	35	K35	61	K61	87	K87
10	K10	36	K36	62	K62	88	K88
11	K11	37	K37	63	K63	89	K89
12	K12	38	K38	64	K64	90	K90
13	K13	39	K39	65	K65	91	K91
14	K14	40	K40	66	K66	92	K92
15	K15	41	K41	67	K67	93	K93
16	K16	42	K42	68	K68	94	K94
17	K17	43	K43	69	K69	95	K95
18	K18	44	K44	70	K70	96	K96
19	K19	45	K45	71	K71	97	K97
20	K20	46	K46	72	K72	98	K98
21	K21	47	K47	73	K73	99	K99
22	K22	48	K48	74	K74	100	K100
23	K23	49	K49	75	K75		
24	K24	50	K50	76	K76		
25	K25	51	K51	77	K77		

APPENDIX C: COLOUR STRENGTH VALUE OF BLACK COLOUR AND PRIMARY COLOUR IN PRINTING (K, C, M AND Y) CALCULATED FROM THE EQUATION 4.1-4.4, PERCENTAGE OF DOT AREA OF PRIMARY COLOURS FROM COLOUR STRENGTH OF PRIMARY COLOURS IN PRINTING, PERCENTAGE OF DOT AREA OF PRIMARY COLOURS FROM COLOUR STRENGTH OF SECONDARY COLOURS IN PRINTING

Table C-1 The colour strength value of black colour and primary colour in printing (K, C, M and Y) calculated from the equation 4.1-4.4.

Colour strength value							
Black and primary colours in printing				by equation 4.1-4.4			
S_K	S_C	S_M	S_Y	S_K	S_C	S_M	S_Y
0	0	0	0	0	0	0	0
4	4	4	4	3	3	4	4
8	8	8	7	6	7	7	7
12	11	11	11	10	10	11	11
16	14	14	14	14	13	14	15
20	18	18	18	17	17	18	19
25	22	22	22	22	21	22	23
29	24	26	26	26	24	26	27
34	27	30	30	30	28	30	31
39	32	34	34	35	32	34	35
44	36	38	39	39	36	38	39
49	39	43	43	44	40	43	43
54	43	47	47	49	44	47	47
59	47	52	52	55	48	51	52
64	52	56	57	60	52	56	56
70	55	60	60	66	56	60	61
75	60	66	66	71	61	65	65
81	64	70	70	77	65	70	70
87	70	75	74	83	70	75	74
94	75	80	79	90	74	79	79
100	80	85	82	96	79	84	84
RMS				3.66	0.89	0.46	0.59
% error				10.03	4.33	2.10	1.62

Table C-2 The percentage of dot area of primary colours and black colour from colour strength value calculated by the equation 5.4 to 5.7.

Percent dot area	Percent dot area of primary colours from colour strength of primary colours by equation 5.4 to 5.7			
	S_C	S_M	S_Y	S_K
0	0	0	0	0
5	5	5	5	5
10	10	10	10	9
15	15	15	15	14
20	20	20	20	19
25	25	25	25	24
30	30	30	30	29
35	35	35	35	34
40	40	40	40	39
45	45	45	45	45
50	50	50	50	50
55	55	55	55	55
60	60	60	60	61
65	65	65	65	66
70	70	70	70	71
75	75	75	75	76
80	80	80	80	81
85	85	85	85	85
90	90	90	90	90
95	95	95	95	94
100	100	100	100	98
RMS	0.40	0.41	0.35	0.82
%error	0.57	0.58	0.39	2.44

Table C-3 The percentage of dot area of primary colours from colour strength value of secondary colours in printing (R (Y and M), G (Y and C) and B (C and M)) calculated by the equation 5.4 to 5.6.

Percent dot area	Percent dot area of primary colours from colour strength of secondary colours by equation 5.4 to 5.6					
	Yellow of S_R	Magenta of S_R	Yellow of S_G	Cyan of S_G	Cyan of S_B	Magenta of S_B
0	0	0	0	0	0	0
5	5	5	5	5	5	5
10	10	11	10	11	11	10
15	16	16	15	16	16	15
20	21	21	20	22	21	20
25	26	27	25	27	27	25
30	32	32	30	32	32	30
35	37	38	35	38	37	35
40	42	43	40	43	43	40
45	48	48	45	49	48	45
50	53	54	50	54	53	50
55	59	59	55	59	59	55
60	64	64	60	65	64	60
65	69	70	65	70	69	65
70	75	75	71	75	75	70
75	80	80	76	80	80	75
80	86	85	81	86	85	80
85	91	90	86	91	90	85
90	96	96	91	96	96	90
95	101	101	96	101	101	95
100	107	105	101	106	106	100
RMS	3.95	3.87	0.46	4.04	3.73	0.22
%error	5.92	6.63	0.81	6.98	5.97	0.58

APPENDIX D: FIGURE OF THE POLYNOMIAL FUNCTION OF COLOUR STRENGTH SCALE OF BLACK COLOUR AND PRIMARY COLOURS

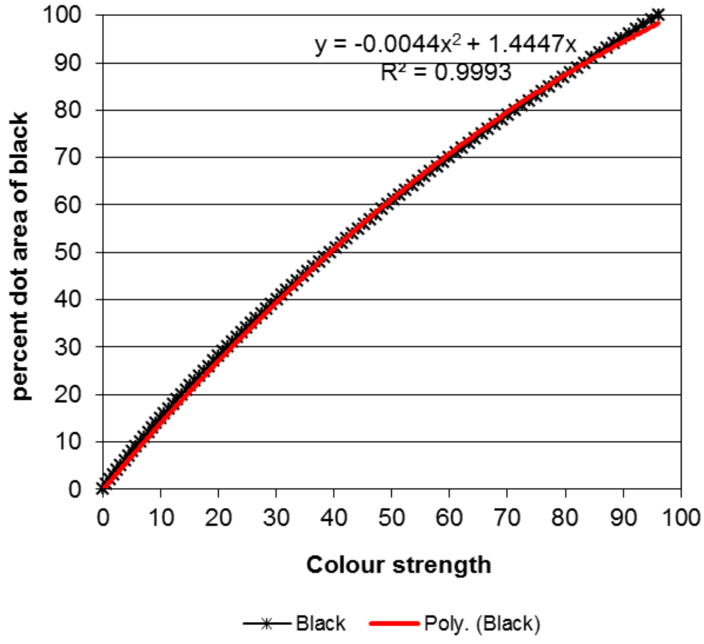

Figure D-1 The polynomial trend line of colour strength scale of black with starting point at zero.

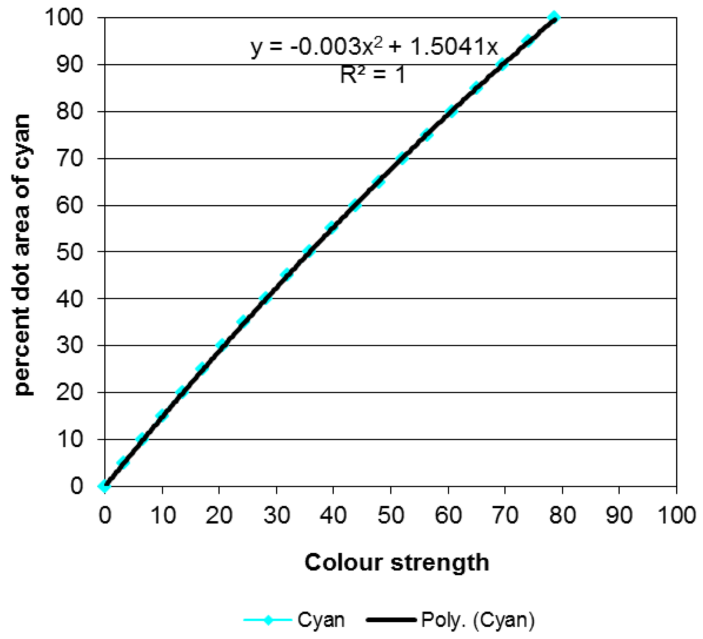

Figure D-2 The polynomial trend line of colour strength scale of cyan with starting point at zero.

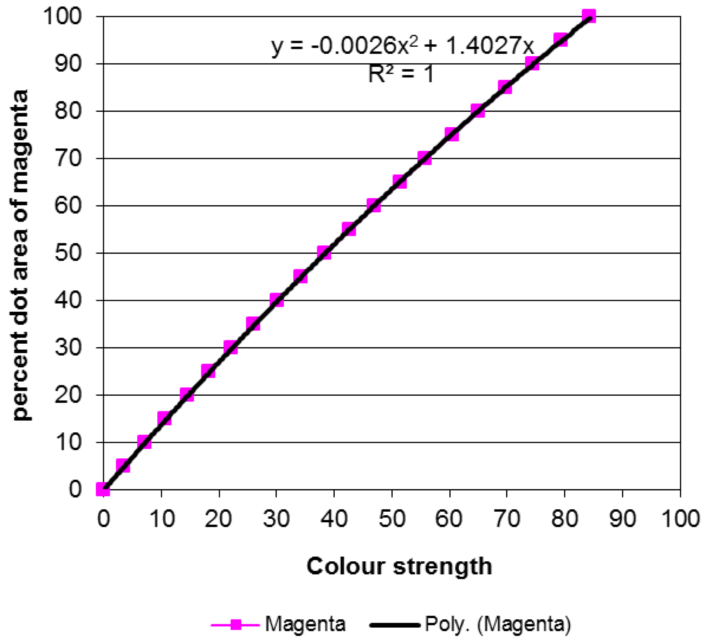

Figure D-3 The polynomial trend line of colour strength scale of magenta with starting point at zero.

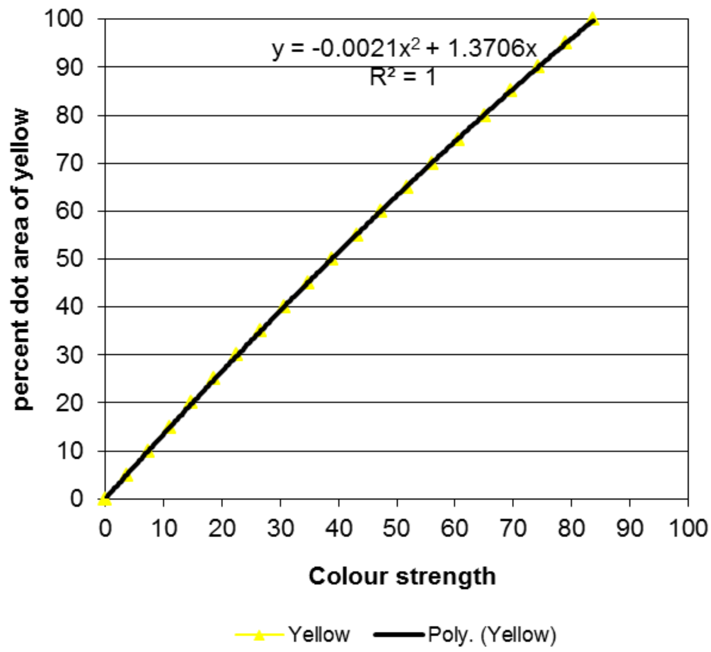

Figure D-4 The polynomial trend line of colour strength scale of yellow with starting point at zero.

VITA

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