# COLOR APPEARANCE OF COLOR CHIPS
# IN THE ENVIRONMENT LIT WITH LED LAMPS

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## ABSTRACT

The aim of this study stemmed from the prevailing use of LED lighting systems in today's world. Recognizing the impact of this technology on color perception is essential, and this motivated the detailed exploration within the study. A total of one hundred participants were invited to evaluate 26 unique color chips under six colored LEDs illuminations - Red, Yellow, Green, Cyan, Blue, and Magenta, each with two different saturation levels. A white light (D65) was utilized as the reference illuminations along with a white fluorescence light. The elementary color naming method was employed for evaluations within a controlled experimental room.

One of the key outcomes of this study was the introduction of a perceptual color constancy index. This index demonstrated a more rapid decrease under green, cyan, and yellow illumination when the saturation of the illumination increased. The RMSE for color appearance under white fluorescence and white LEDs light was found to be 0.11. It was observed that LEDs exhibited a higher chromaticness than fluorescence lights. Additionally, in less vivid illumination conditions, the color appearance of the color chips was observed to shift in four different hue directions, consistent with the opponent color theory. For the more vivid illumination conditions, there were at least two distinct hue shift directions. These shifts appeared to correlate with the complementary color of color density to the color illumination.

The results of this study can serve as a foundation for future research, especially towards improving color prediction models, given the significant presence of LED lighting in modern settings.



**Keywords:** color appearance, color constancy, LEDs, elementary color naming

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Phubet Chitapanya

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# CHAPTER 1
# INTRODUCTION

## 1.1 Background and Statement of the Problems

The rapid adoption of LEDs, or light-emitting diodes, in various industries and homes has driven a surge in research to understand their impact on human color perception. LEDs have seen their market share increase from 1% in 2010 to 48% in 2021 (IEA, 2022), offering several benefits, including energy savings of 85% compared to traditional bulbs (U.S. Department of Energy, 2008). Unlike traditional light sources, which only offer a color range from cool white to warm white, LEDs can generate a variety of colors through the control of intensity and combination of light through the diodes.

Color appearance is a crucial aspect of how humans perceive and interpret the world around them, influenced by the spectral characteristics of light sources and the nature of the objects being illuminated. With LEDs now being the predominant light source in various applications, the color appearance of objects under LED illumination has become an important topic of study.

Although the International Commission on Illumination (CIE) has established two standards, ISO 3664:2009 and ASTM D1729-2016, for D50 daylight viewing conditions and D65 as the primary daylight view condition, respectively, there is no official LED lighting standard, particularly for the printing industry in the context of color reproduction. Consequently, studying color appearance under various LED illuminations is essential for understanding how lighting conditions impact color perception and for developing more effective lighting systems that enhance the visual experience in diverse environments, including the printing industry.

In the context of color perception, color constancy plays an important role. It is the ability of humans to perceive color similarly under different colored lights, such as a white T-shirt appearing white regardless of the surrounding illumination (Lucassen & Walraven, 1996). The color constancy index (Arend & Reeves, 1986) is a quantitative measure of color constancy. Different methods have been used to study color constancy, including color matching (Arend L. E., Reeves, Schirillo, & Goldstein, 1991; Bauml, 1999; Brainard, Brunt, & Speigle, 1997) and achromatic settings (Brainard, 1998; Kraft & Brainard, 1999; Rajendran & Webster, 2020), and have been found to be effective in quantifying the shift in observed and physical colors.

Color naming is a straightforward way to identify the color of an object. It involves categorizing colors based on basic color naming (Berlin & Kay, 1969), which is a commonly used task in color research (Olkkonen, Witzel, Hansen, & Gegenfurtner, 2009; Olkkonen, Witzel, Hansen, & Gegenfurtner, 2010). Compared to the color matching method, the advantage of color naming is that it allows researchers to study a larger number of color chips. However, one limitation of this method is that it restricts the subject's response to only 11 color names, which may require a compromise answer in certain situations.

The study utilized the elementary color naming method (Hering, 1964; Ikeda & Phuangsuwan, 2019; Tangkijviwat, Rattanakasamsuk, & Shinoda, 2009), which is similar to hue scaling (Okajima, Robertson, & Fielder, 2002; Schultz, Doerschner, & Maloney, 2006), to examine color constancy under different colored illuminations and to assess the perception of color scales. The authors studied color constancy in a real room, considering the three-dimensional aspect as a factor that can improve the color constancy index (Hedrich, Bloj, & Ruppertsberg, 2009). The two-room technique (Phuangsuwan & Ikeda, 2017) was employed to study the color appearance of objects without adaptation to colored illumination, which is referred to as the physical color of the color chips. The use of the elementary color naming method provides an absolute judgment as a quantitative unit, enabling the exploration of color appearance in the perceptual color space.

## 1.2 Purpose of the Study

1.2.1 To explore the appearance of color chips under a variety of LED illuminations.

1.2.2 To calculate the color constancy index under LED illumination.

## 1.3 Scope of the Study

The study of the color appearance of 26 color chips under 13 different light conditions of RGB-LED illumination was conducted using 100 subjects with normal color vision. The subjects were trained in the use of elementary color naming before the experiment. The light conditions included one white light (D65) as the standard and 6 hues with two saturation levels, including a vivid illumination that represented the maximum capacity of the lighting used in the experiment, In addition, a fluorescent and LED which had a correlated color temperature as standard white light as D50 was also investigated in this experiment. The experiment was conducted at the Mass Communication Technology building at RMUTT, Thailand, in an experimental booth.

## 1.4 Expected Contribution

1.4.1 This research is expected to determine the hue shift characteristics of color chips under different LED lights.

1.4.2 This research is expected to propose the elementary color naming as an alternative method to study the color constancy index.

1.4.3 The study aims to establish the color constancy index using the perceptual color space.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Human Color Vision

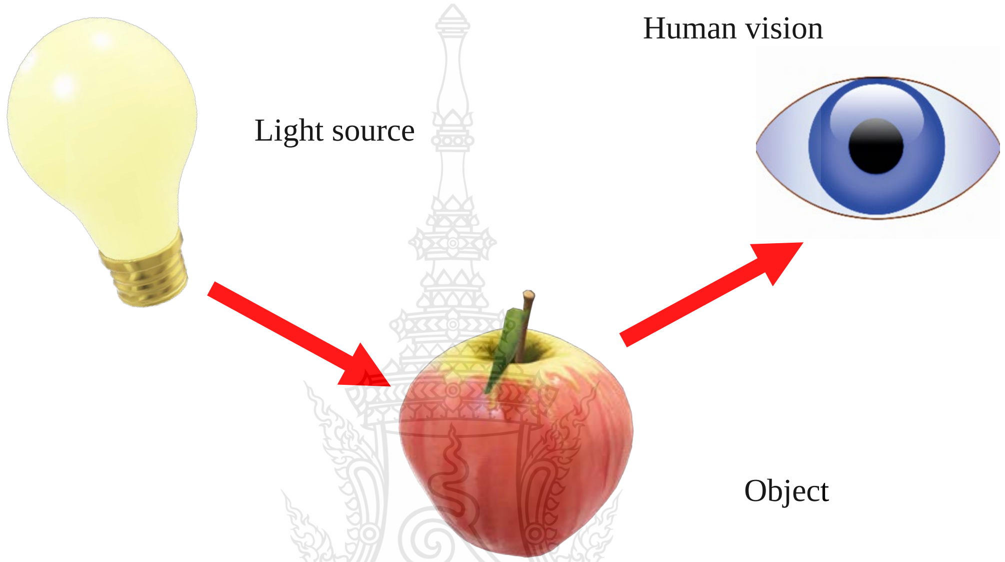



**Figure 2.1** Human perception factors

In Figure 2.1, we can see that there are three essential factors that are required for human beings to see colors. As reflected light from an object enter our eyes, they interact with the photoreceptor cells in the retina, which then send signals to the brain for processing. However, the way in which we perceive colors is not solely determined by the presence of light. Light has a characteristic called spectral power distribution, which plays a crucial role in color perception.

The spectral power distribution of light refers to the distribution of energy across the different wavelengths of light. It determines the intensity of different wavelengths of light that enter our eyes and affects how we perceive colors. Different spectral power distributions can create different hues and shades of color.

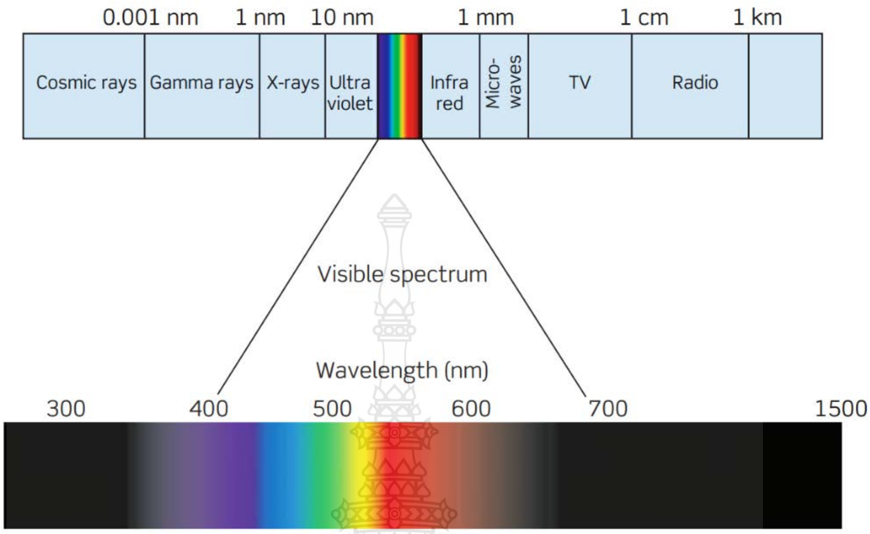



**Figure 2.2** The electromagnetic spectrum and visible light

**Source:** Snowden, Thompson, & Troscianko (2012). Basic Vision: An Introduction to Visual Perception

Light is a form of electromagnetic radiation and only occupies a small portion of the electromagnetic spectrum, known as the visible light spectrum as proposed by Newton (1704). He used a prism to split the white light into seven colors, as red, orange, yellow, green, blue, indigo, and violet. This spectrum ranges from 380 nm on the short-wave side to 780 nm on the long-wave side. Beyond the visible spectrum are gamma rays at the short-wavelength end and radio waves at the long-wavelength end. The ability to see color is made possible through the interaction between light and objects in the environment, which allows us to perceive color through the mixed information that enters our eyes.

## 2.2 CIE Standard Illumination

The concern in the industry is about what is considered a standard illuminant source, as there is a wide variety of light sources available in the market such as the sun, tungsten, and fluorescent. The International Commission on Illumination (CIE) is an organization that has the responsibility to announce the standard illuminant. For example, CIE standard illuminant D65 or D65, which is a part of the D series, is a daylight illuminant that represents the average midday light in Europe. The correlated color temperature of D65 is 6,504 Kelvin (Hunt & Pointer, 2011), and it has relative tristimulus values of X=95.047, Y=100, and Z=108.883, when normalization of Y equals to 100. Figure 2.3 shows the CIE D65 average daylight spectrum. This standard is widely used in the field of colorimetry, and it is considered a reference point for evaluating and comparing the color rendering properties of different light sources.

Another important illuminant in the D series is CIE standard illuminant D50 or D50, which represents a more neutral, daylight-like color temperature. The correlated color temperature of D50 is approximately 5,000 Kelvin, making it suitable for applications in graphic arts, photography, and color proofing (ISO 12647). It has relative tristimulus values of X=96.422, Y=100, and Z=82.521, when normalization of Y equals to 100. The D50 illuminant is often used as a reference point for color matching and color management systems, ensuring color consistency across various devices and viewing conditions.

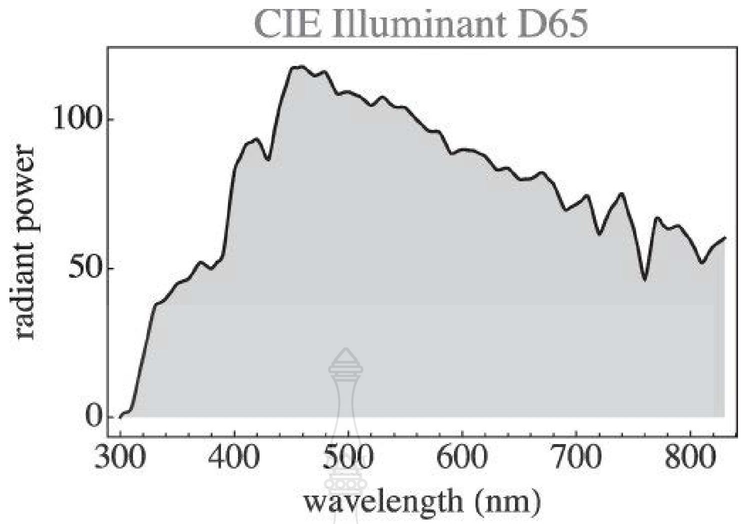



**Figure 2.3** The CIE D65 average daylight spectrum

**Source:** Jan Koenderink, Andrea van Doorn, & Karl Gegenfurtner (2020). Colors and Things

## 2.3 Light Source

There are two types of light sources: natural light and artificial light source. The commonly known light source is the Sun and Moonlight. However, natural light sources can be uncontrolled and inconvenient in some situations, so humans have been trying to create alternative light sources. There are several types of light sources that have been developed to mimic natural light, such as incandescent bulbs. Incandescent bulbs produce light by passing an electric current through a filament, which heats up and emits light. Another example is fluorescent lamps, which produce light by passing an electric current through a gas, which excites some mercury vapor, which causes phosphor inside the lamp to emit light. Cangeloso (2012) wrote that "LED or Light Emitting Diode is a solid state light source which is another type of light source that generates light by passing an electric current through a semiconductor material". Unlike incandescent and fluorescent lights, some types of LEDs can generate a variety of colors, such as RGB-LEDs, which are composed of three individual LEDs, red, green, and blue diodes. With the combination of these three lights, it is possible to produce millions of colored lights and vary the intensity of light. This feature makes LEDs a versatile light source that can be used in many different applications such as streetlights, automotive lighting, and even in smartphones and televisions. Additionally, LED's also have a longer lifespan and are more energy-efficient compared to traditional light sources (U.S. Department of Energy, 2008).

Figure 2.4 shows the anode is the positive terminal of the LED, and the cathode is the negative terminal. When the LED is properly connected and a voltage is applied, electrons flow from the negative terminal (cathode) to the positive terminal (anode) through the semiconductor material inside the LED. When the electrons encounter holes (missing electrons) in the semiconductor material, they fall into these holes and release energy in the form of light (Nair & Dhoble, 2020).

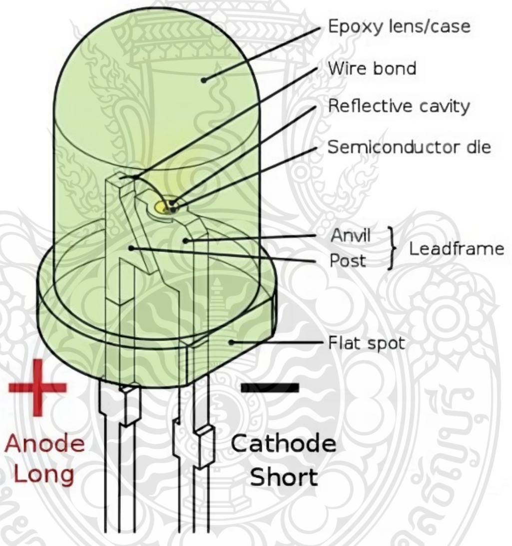



**Figure 2.4** The schematic structure of LED

**Source:** LED VS Traditional light sources. [Website]. Receive from https://www.microstarlight.com/led-lighting-vs-traditional-light-sources/

The color rendering defined by CIE is “The effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant". Hunt & Pointer (2011) described in their book that the word reference illuminant which given by CIE means there is no absolute colour appearance but the choice of reference is the question. Anyway, D65 is the preferred illuminant adopted in colorimetry. Color rendering index (CRI) is a quantitative measure of a light source's ability to accurately render colors in comparison to a reference light source. The reference light source has a CRI value of 100, and it represents the ideal light source that can accurately reveal the true colors of objects.

Nair & Dhoble (2020) wrote in their book that "In the recent CIE addressed the shortcoming of color rendering index that often led to a mismatched perception for solid-state lighting source against the perception made by a human eye. CRI has failed to accurately define the gamut and describe the color fidelity of a light source."

## 2.4 Colorimetry

Colorimetry is a science of measuring and analyzing color. It involves the use of color measurement instruments and mathematical models to quantify the color values.

### 2.4.1 Tristimulus

One of the key aspects of colorimetry is the concept of tristimulus values. Tristimulus values are used to represent a color in a specific color space, such as the CIE XYZ color space. The RGB color matching function is not always suitable for color measurements, as it can have negative values in certain areas, such as when the reference color is around cyan. To avoid mistakes in calculations and negative values, tristimulus values (XYZ) were created by converting the original color matching function. XYZ color space is a common space used to communicate and represent color.

### 2.4.2 Chromaticity

Chromacity is the quality of color based on hue and saturation only. It is typically represented by two numbers known as chromaiticity coordinates as plotted on a graph as in a two-dimensional space. One of the most common chromaticity coordinates is xy chromaticity, which represents color corresponding to the x and y values. However, xy chromaticity is a non-uniform color space, which can lead to problems in color representation. To solve this problem, the u'v' chromaticity diagram as shown in Figure 2.5 was created to represent the perceptual uniform or equal distances in the diagram. This allows for more accurate and precise color representation and measurement. The equation (CIE, 1978) to transform the light measured value to u'v' chromaticity or CIE 1976 UCS is shown in Equation 2.1 and 2.2.

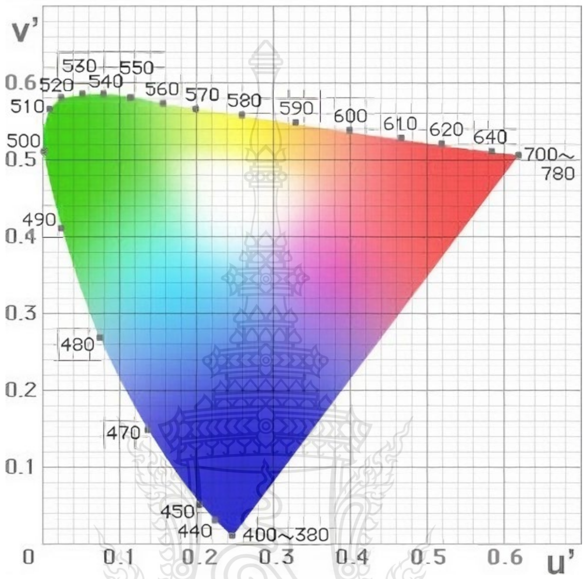



**Figure 2.5** CIE 1976 UCS Diagram or u'v' chromaticity diagram

**Source:** Precise Color Communication. [Website]. Receive from https://www.konicaminolta.com/instruments/knowledge/color/part4/08.html

$$u' = \frac{4X}{X + 15Y + 3Z} = \frac{4x}{-2x + 12y + 3} \quad (2.1)$$

$$v' = \frac{9Y}{X + 15Y + 3Z} = \frac{9y}{-2x + 12y + 3} \quad (2.2)$$

2.4.3 CIE1976 L*a*b* color space

Another important aspect of colorimetry is the use of color scales and color spaces. The CIE XYZ and L*a*b* color spaces are commonly used to standardize the measurement of colors and to make comparisons between different light sources and viewing conditions. The CIE XYZ color space is a device-independent color space, which means that it is not tied to any particular device or medium. This allows for the accurate representation of colors across different devices and mediums.

The L*a*b* color space is based on the CIE XYZ color space, but it is designed to be perceptually uniform, meaning that equal distances in the color space correspond to equal perceived differences in color. This makes it a useful tool to study color difference. Equation 2.3 represents the L* component of the L*a*b* color space, where Y is the tristimulus value of interest, and $Y_n$ is the reference white tristimulus value. This equation helps to convert the Y values into a relative scale, making the L* component more perceptually meaningful. The exponent of 1/3 in the equation accounts for the non-linear nature of human vision, as our perception of lightness is not directly proportional to the actual amount of light.

Equations 2.4 and 2.5 represent the a* and b* components of the L*a*b* color space, respectively. The a* component corresponds to the chromatic information along the red-green axis, while the b* component represents the chromatic information along the yellow-blue axis. These axes provide a more intuitive representation of color differences and enable easier interpretation of color variations in comparison to the CIE XYZ color space. To calculate the a* and b* components, the tristimulus values X, Y, and Z of the color sample are compared to the reference white tristimulus values $X_n$, $Y_n$, and $Z_n$. These reference values represent the ideal white point in the color space, which is typically derived from the chosen standard illuminant. By comparing the color sample to the reference white, the a* and b* components provide an accurate measure of the chromatic differences. For example, the difference between two color samples can be known by calculating the difference in Euclidean distance of these samples in the Lab* color space.

$$L^* = \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 \tag{2.3}$$

$$a^* = 500 \times \left( \left( \frac{X}{X_n} \right)^{\frac{1}{3}} - \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} \right) \tag{2.4}$$

$$b^* = 200 \times \left( \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left( \frac{Z}{Z_n} \right)^{\frac{1}{3}} \right) \tag{2.5}$$

## 2.5 Hering's Opponent Colors Theory

Hering (1920) proposed and discussed a theory of opponent colors based on his subjective observations of color appearance. He observed that certain hues were never perceived simultaneously. For instance, red and green were never perceived as a reddish-green, similar to yellow and blue which were never perceived as yellowish blue. Hering explained that afterimages could easily be explained by complementary colors and that light-dark afterimages could be described by his opponent theory.

## 2.6 Color Constancy

Color constancy is a human ability to perceive the stable color of an object, despite changes in the color of the surrounding illumination. The human visual system is able to achieve this by adjusting the color perception based on the information retrieved from the eyes. As proposed by Von Kries (1902), the human visual system adapts to changes in the spectral properties of the illuminant by adjusting the sensitivity of the three types of cone cells in the retina. This process is known as chromatic adaptation and allows the visual system to maintain a relatively stable perception of color despite changes in the spectral composition of the light. This allows us to perceive the colors of objects in a consistent way, regardless of the surrounding lighting conditions. As the visual system gathering lots of information from the visual field, if the information reflected from the object in the scence containing lots of long wavelength (red). The visual system would adjusted the system by compensating the long wavelength.

There are several theories and models that have been proposed to explain the mechanism of color constancy, one of which is the Retinex theory which was proposed by Edwin Land (1971). The Retinex theory proposes that color perception is achieved through a complex interaction between the retina, the brain, and the environment.

According to this theory, the visual system compares the signals received from different regions of the retina and uses this information to separate the color and brightness components of an image. This process allows us to perceive the colors of objects accurately under different lighting conditions.

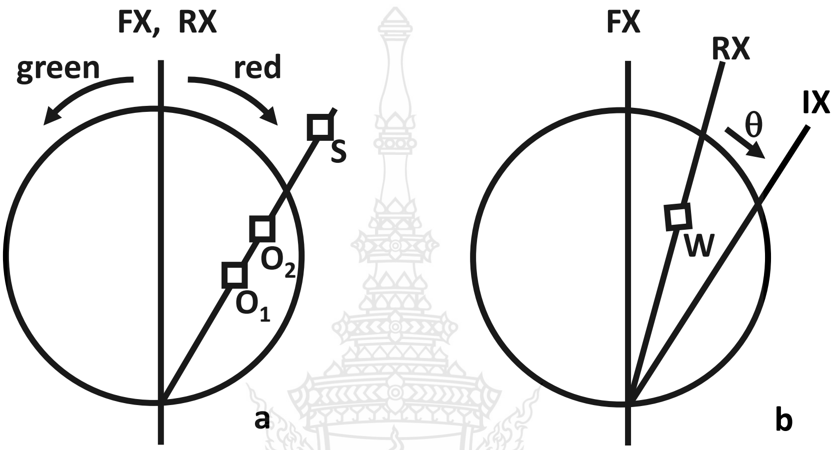



**Figure 2.6** RVSI Diagram

**Source:** Ikeda, M. (2004). Color appearance explained, predicted and confirmed by the concept of recognized visual space of illumination. Optical Review, 11, 217-225.

The concept of Recognized Space of Illumination (RVSI) is another concept of the explaination. It was introduced by Ikeda (2004) to explain the process of chromatic adaptation in human vision. As human's brain understands and construct state of illumination of a space by gathering any information in the space called the initial visual information (IVI) where the human is looking at. The diagram in Figure 2.6 illustrates the RVSI concept, RVSI has two main properties. One is the brightness of the space as shown in the left Figure 2.6 (a) which is example of color sample namely red sample on the clockwise direction. The fundamental axis (FX) being a standard axis that the brain recognizes through its color memory. When the brain understand the state of illumination, any objects in the space is determined by the recognized axis (RX). As in the Figure 2.6(a), there were three red samples in the graph. $O_1$ as the reddish sample with low lightness, $O_2$ as the reddish sample with high lightness, and S as the same reddish with the highest brightness than the space causing this sample to appear to be unnatural object color or the light souce mode in the space. If the illuminance level is increased , the new size of RVSI will also renew but there is a lightness constancy existed in the human vision system resulting the position of object in the scene changes according to the new size. For the right graph of Figure 2.6 (b), It is another example when the color of illumiant axis (IX) is not be a white light resulting the recognized axis to be changed closer to the IX. The achromatic sample (W) even illuminated by the colored light but it appears to be achromatic again as color constancy system. The degree of color change by discount illumination and chromatic adaption of these axis was found to be complementary or opposite colors, as observed in previous studies (Phuangsuwan & Ikeda, 2017).

In conclusion, color constancy is a complex process that is still not fully understood. However, it is clear that the human visual system is able to adjust the perception of color based on the surrounding illumination, to perceive the stable color of an object.

## 2.7 Literature Review

Kraft and Brainard (1999) researched about what's mechanisms of color constancy under nearly natural viewing. They made an experiment to find about three mechanisms which were debated a lot about which one is really strong effect to color constancy. Three mechanisms are local adaptation, spatial mean, and maximum flux. Local adaptation is object adaptation which mean as a human being to see stably colored object, he or she need to adapt to a colored object. The second mechanism is spatial mean which is adapted to illumination as the whole world of visual field is a gray world. The last one is maximum flux relating to Retinex theory in which a human being gets color constancy ability because of adapted to the white standard in which some path between retina and brain comparison the lightness image to find the white standard. In their experiment, they tried to control any individual mechanism to see which one is the most effective to color constancy. A result showed that each mechanism alone cannot produce good color constancy index to reach 0.8 index or 80% as the usual color constancy experiment. Moreover, with the control experiment when all mechanism information appears to a subject eye. The result became clear to reach color constancy index above 0.8 indicating how the visual system adjusts to changes in illumination from the action of various mechanisms of adaptation.

Hansen, Walter, and Gegenfurtner (2007) researched about effects of spatial and temporal context on categories and color constancy. They tried to find color constancy index via color naming instead of matching which can get chromaticity ordinates easily. It's the method to use naming result data to find the boundary between two categories. The boundary could be reached by using statistic called false classification to get the direction line with minimum false classifications by rotating the angle in steps of 1°. The average of two boundary indicates the hue direction of each color naming. The intersection point between all of hue directions and boundaries indicates the convergence point which is used for color constancy index calculation. In the experiment, they divided experiment condition into 6 groups, 1.) having both spatial and temporal condition with small test patch and surrounding field, 2.) having both spatial and temporal condition with small test patch but no surrounding field, 3.) having both spatial and temporal condition with large test patch and surrounding field, 4.) having only spatial condition with large test patch, 5.) having only temporal condition with large test patch, and no spatial and temporal condition with small test patch. The result shows that color constancy index is the highest when a subject judged a test patch in experiment 1 which full of information coming from surrounding as illumination information, information coming from background as local information, and temporal information in the same area as test patch. Moreover, convergent point always shifts to the colored illumination and color categories can be well described by radial line converging at a single point and quite stable within and across observers and under illumination changes as shown in their result that matching result of color constancy could get reach 80% or C.I = 0.8 as color naming did in this experiment.

Troost and Weert (1991) repeated an experiment previously conducted by Arend and Reeves in 1989. This study was designed to examine both simultaneous matching and successive matching. The results of the simultaneous matching were consistent with the previous study. Additionally, the second part of the experiment proposed a new method called categorical color constancy. Participants were asked to provide color names for 144 simulated patches in Dutch. However, there was no comparison made between the two methods as they had different factors such as blockwise presentation in categorical naming, and a random mix in the matching experiment. The difference in background was also a factor, as there was only one background in the naming task, but surround color in the matching. Despite these differences, the color naming task could serve as an alternative method and participants could easily understand the procedure.

Ruiqing Ma, Ningfang Liao, Pengfei Yan, and Keizo Shinomori (2018) have experimented with color constancy under LED illumination by using a naming method called categorical color naming. 240 Munsell chips were used in this experiment under 5 illuminations, neutral, red, green, yellow, and blue. The results of color naming were plotted on chromaticity diagram by using coordinates of the surface under chromatic illumination which were classified in this category under the neutral illumination. It showed that color constancy index was low under blue and yellow illumination. They recommend not using the RGB-LED light source to produce blue and yellow illuminations because of the poor color constancy. The problem is that in this experiment they used LED lamps which are the low quality showing by producing low color rendering index. Moreover, this study only focused on young subjects with normal eyes. The color constancy of old people and color deficient people under RGB-LED light sources was not investigated because the color vision of old people is affected by complex aging effects related to the S-cone and that of color deficient people is affected by the lack or mutation of the L- or M-cone. They recommended investigating both groups in the future.

Pungrassamee, Ikeda, Katemake, and Hansuebsai (2005) conducted a study on the color appearance of a test patch using the two-room technique. The test patch was placed in a room lit by daylight-type lamps, while the subject room was lit by two fluorescent lamps covered by colored filters. The four colored filters used were red, yellow, green, and blue. The subjects were seated in the subject room, which was lit by the colored illumination, and viewed the test patch through a small window in the middle wall between the rooms. The experiment was special because it included five different window sizes, with two sizes (W1 and W2) that were so small that the subjects couldn't see any other objects in the test room. In this case, the test patch was reported to look like a part of the front wall of the subject room. However, as the size of the window increased and the subjects were able to see other objects in the space, the color appearance of the test patch was judged to be closer to the original color.

Phuangsuwan and Ikeda (2017) conducted a study on chromatic adaptation using the two-room technique, which consisted of a test room and a subject room. The test room contained a whiteboard, which could be viewed through a window connecting the two rooms. The subject room was illuminated by either RGB-LED lights or fluorescent lamps, with 7 colored filters used to create different colored lights in the latter. The subjects were asked to judge the color of the white board using elementary color names. The state of adaptation was determined by $\Delta\theta$, which showed that both the fluorescent and LED lights produced similar results. Additionally, the results indicated that $\Delta\theta$ was more closely related to complementary colors than elementary colors when considering the degree of adaptation.

In their study, Pipornpong, Phuangsuwan, and Ikeda (2017) examined the appearance of 24 colored objects under ten different LED illuminations. The illuminations included five colors: white (D65), red, yellow, green, and blue. The red, green, and blue colored lights were further divided into three levels of saturation, represented as R1, R2, and R3, respectively. Five subjects participated in the study and judged the color of each patch using the elementary color naming method. To analyze the data, the researchers selected 11 colored objects to plot on a polar diagram, where the area under the condition was determined by connecting the 11 colored chip points and counting the space within the resulting shape. The area ratio, calculated as the area of the colored illumination condition divided by the area of D65, was proposed as a degree of color constancy. A ratio higher than 0.8 was considered to indicate good color constancy. The results showed that Y1, G2, B3, and R3 had poor color constancy.

Panitanang, Ikeda, and Phuangsuwan (2018) studied color appearance of objects under vibrant colored LED lights. Five subjects used the elementary color naming method to judge 24 color chips under 10 different illuminations, starting from a white light (D65) and incrementally increasing the amount of red, resulting in R1, R2, R3, ..., and R9, which is the pure red. Only 11 color chips were selected for analysis. The study utilized the two-room technique to examine the physical color of the objects and compare the ratio of appearance to physical color. The results showed that as the step of red increased from R1 to R9, the ratio of physical color became smaller more quickly than the appearance.

Hedrich, Bloj, and Ruppertsberg (2009) conducted a study on color constancy by comparing 2D and 3D stimuli. They used the color memory method, where only observers who passed the color memory screening experiment were allowed to proceed to the main experiment. The experiment was conducted under four different lighting conditions and the results showed that color constancy was significantly better for 3D stimuli, with a higher hit rate of correct answers. The overall color constancy index for 2D and 3D stimuli was 0.58 and 0.79 respectively.

Bao and Wei (2020) conducted a study on the performance of CIECAM02 under different light intensities ranging from 100 to 3000 cd/m2. They performed this research because existing color appearance models were developed based on data collected at luminance levels below 700 $cd/m^2$. Their study involved a haloscopic matching experiment in which observers adjusted the color appearance of a stimulus in the right booth by hue, chroma, and intensity to match the color appearance of a stimulus in the left booth (either red, green, yellow, or blue). The experiment was carried out under two different light temperature conditions: 2700K and 6500K. The results of their study were consistent with the Hunt effect, which states that higher adapting luminance leads to a less colorful perception of a stimulus. CIECAM02 was mostly successful in estimating five color attributes accurately: hue, lightness, chroma, colorfulness, and saturation. However, it failed to estimate brightness accurately in this study.

# CHAPTER 3
# COLOR APPEARANCE OF COLOR CHIPS WITH CHROMATIC ADAPTATION

## 3.1 Introduction

Human perception, especially color perception is a complex phenomenon, influenced by the properties of the light source, the reflective properties of the object, and the visual system of the observer. One of the remarkable features of human color vision is the ability to maintain the appearance of an object's color under varying illumination conditions whether natural illumination or artificial lighting in typical environments (Lucassen, M. P., & Walraven, J., 1996), a phenomenon known as color constancy. This ability is derived from chromatic adaptation. Chromatic adaptation is a process by which the visual system adjusts its sensitivity to the spectral composition of the illuminant, as described in the Von Kries model (1970). Additionally, the visual system recognizes the color and brightness of illumination and adjusts color perception based on the constructed model, as proposed by the RVSI model from Ikeda (2004).

Color appearance models as CIECAM02 (CIE, 2004) have been developed to predict the perceived color of an object under different illumination conditions. The model was designed to estimate color appearance which may be influenced by surrounding factors. This model is used in various applications such as color reproduction, and color matching. However, the performance of this model may be affected by the spectral characteristics of the illuminant, particularly when it comes to colored light sources.

Recent advancements in lighting technology, such as the widespread use of LED lights, have led to an increased interest in understanding the impact of colored illumination on color perception. The appearance of color chips under colored illumination is an important aspect of this, as it can have implications for both lighting design and color reproduction. However, existing research on this topic is limited, and there is a need for a comprehensive study that investigates the effect of colored illumination on the appearance of color chips and assesses the performance of existing color appearance models under these conditions especially under vivid color illumination.

This study aims to investigate the color appearance of color chips under various colored illuminations, both less vivid and vivid illumination conditions. Additionally, it aims to evaluate the color appearance of color chips under colored illumination in comparison to the reference illumination, which is D65. Through the entire contents of this dissertation, from Chapter 1 to the last chapter, the findings may provide insights into potential areas for further research and improvement of color appearance models.

## 3.2 Purpose

The purpose of this study is to investigate how the various color illuminations affect the appearance of color chips.

## 3.3 Methodology

### 3.3.1 Apparatus

The experimental booth was designed to be large 120 cm in width, 200 cm in height and 210 cm in depth. The room was decorated with artificial flowers, books, and a picture on the wall in order to demonstrate real life situation of a subject as shown in Figure 3.1. In front of the subject, there was a table which a rectangular paper (Munsell N6) of 33 × 33 cm dimensions giving 22.5 degree of visual angle with a viewing distance position (60 cm) placed on the table. A color chip size of 6 × 6 cm dimensions giving 5.7 degree was placed on this rectangular paper. Figure 3.2 shows the photography of the experimental booth.

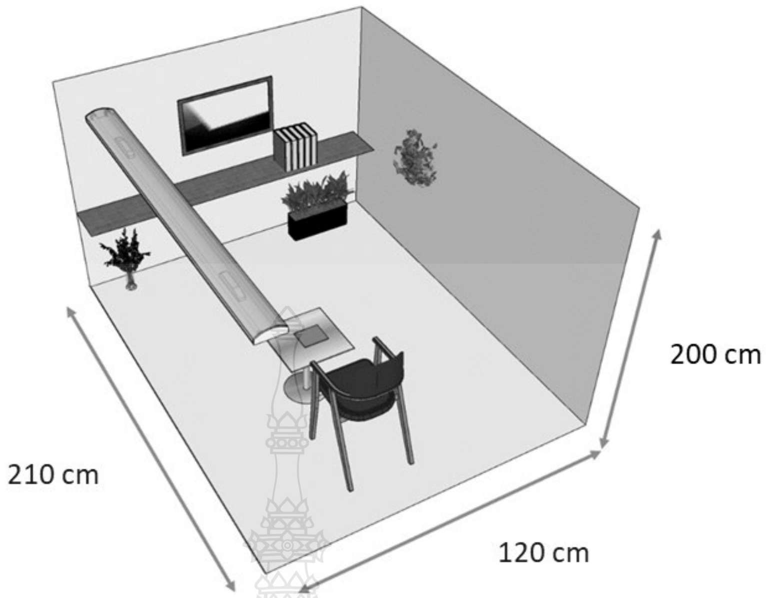



**Figure 3.1** Experimental booth

**Figure 3.2** The experimental booth photographs

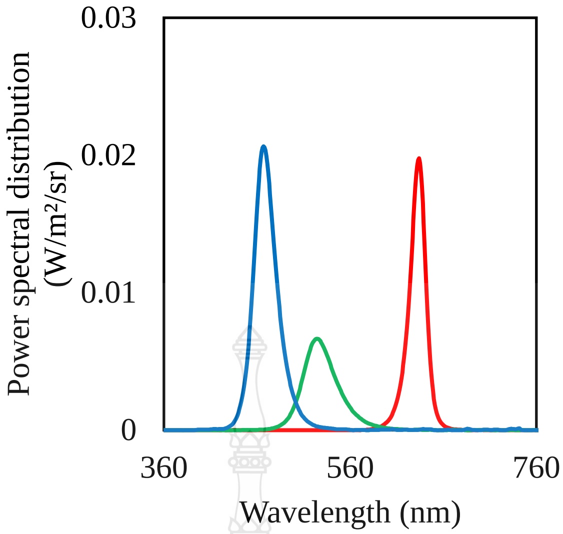



**Figure 3.3** Spectral power distribution of LED illumination

The room was illuminated by five LED lamps, Philips color kinetics, a color cove MX Power core, size 305 mm (1 ft) and 1.2 m (4 ft). The LEDs are connected by data enabler pro, a power core technology to integrate data and power. The spectral power distribution, which is the radiant power emitted by a light source at each wavelength in the visible region of these LEDs measured by Konica Minolta CL-500A with 10 nm interval, is shown in Figure 3.3 to show the maximum capacity of each light, red, green, and blue, as represented by the color. The light is an RGB-LED type which a variety color lights can be mixed by each of red, green, and blue diodes controlled by a computer outside the booth.

3.3.2 Illumination conditions

A total of 13 colored illuminations, including D65, were utilized in this study, as depicted in Figure 3.4 and shown in Table 3.1. Six hues—red, yellow, green, cyan, blue, and magenta—were employed in the experiment. The points marked by black circle symbols, connected by a red line, represent the saturated color coordinates R2, Y2, G2, C2, B2, and M2, respectively. These coordinates were selected based on the maximum color gamut of the LED lights used in the experiment. At the graph's center, a black square indicates the D65 illumination or white light. Between the white standard illumination coordinates and each vivid light, there are additional color illumination sets that share the same color as the saturated color group but exhibit less vivid illumination conditions. A blue line connects these less vivid colored illuminations as R1, Y1, G1, C1, B1, and M1. Illuminance was maintained at 100 lx for all conditions, except for the B2 condition, in which the maximum intensity of the lights was 80 lx. Figure 3.5 displays the spectral power distribution of all light conditions, measured by a Konica Minolta CL-500A, as shown in Figure 3.6.

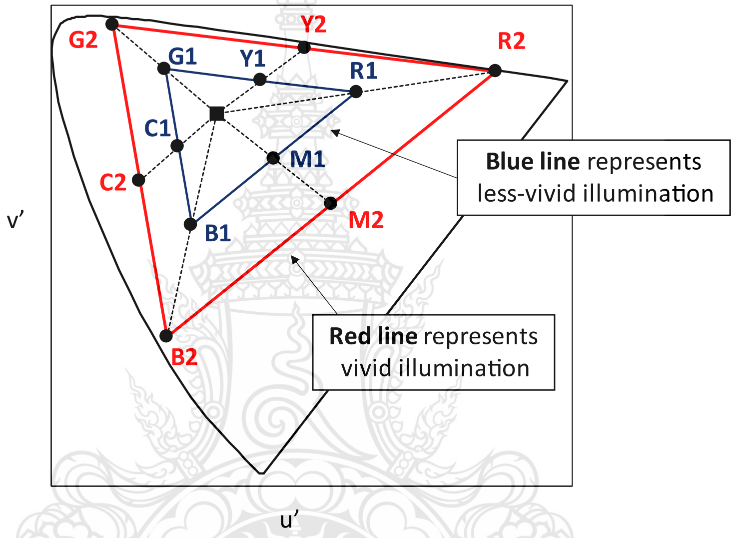



**Figure 3.4** Illumination condition ordinates on u'v' color space

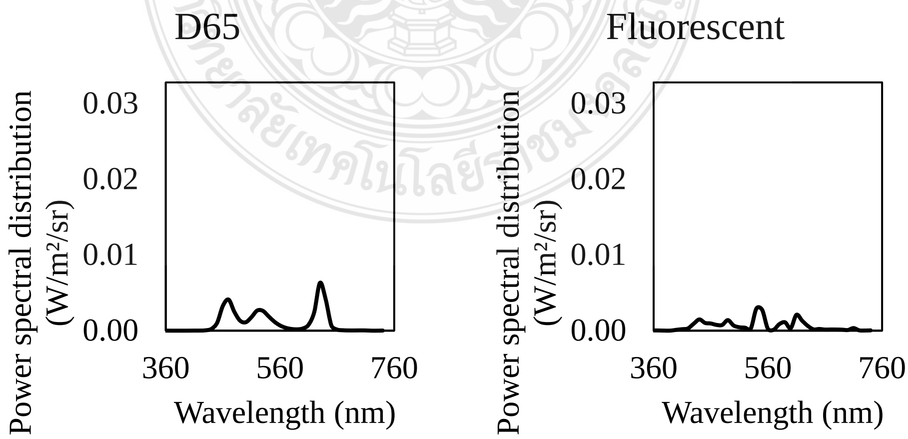



**Figure 3.5** Spectral power distribution of all colored illuminations

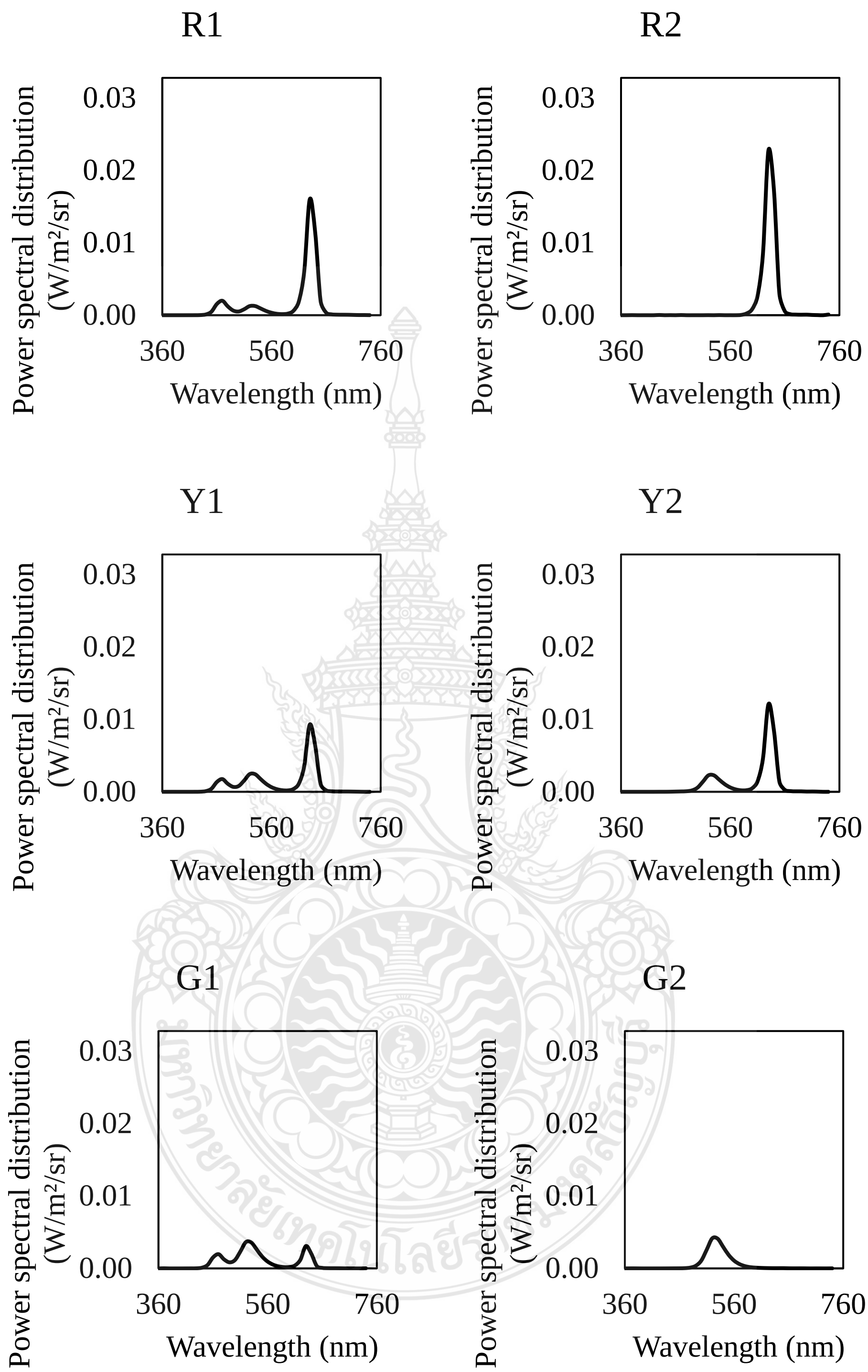



**Figure 3.5** Spectral power distribution of all colored illuminations (Cont.)

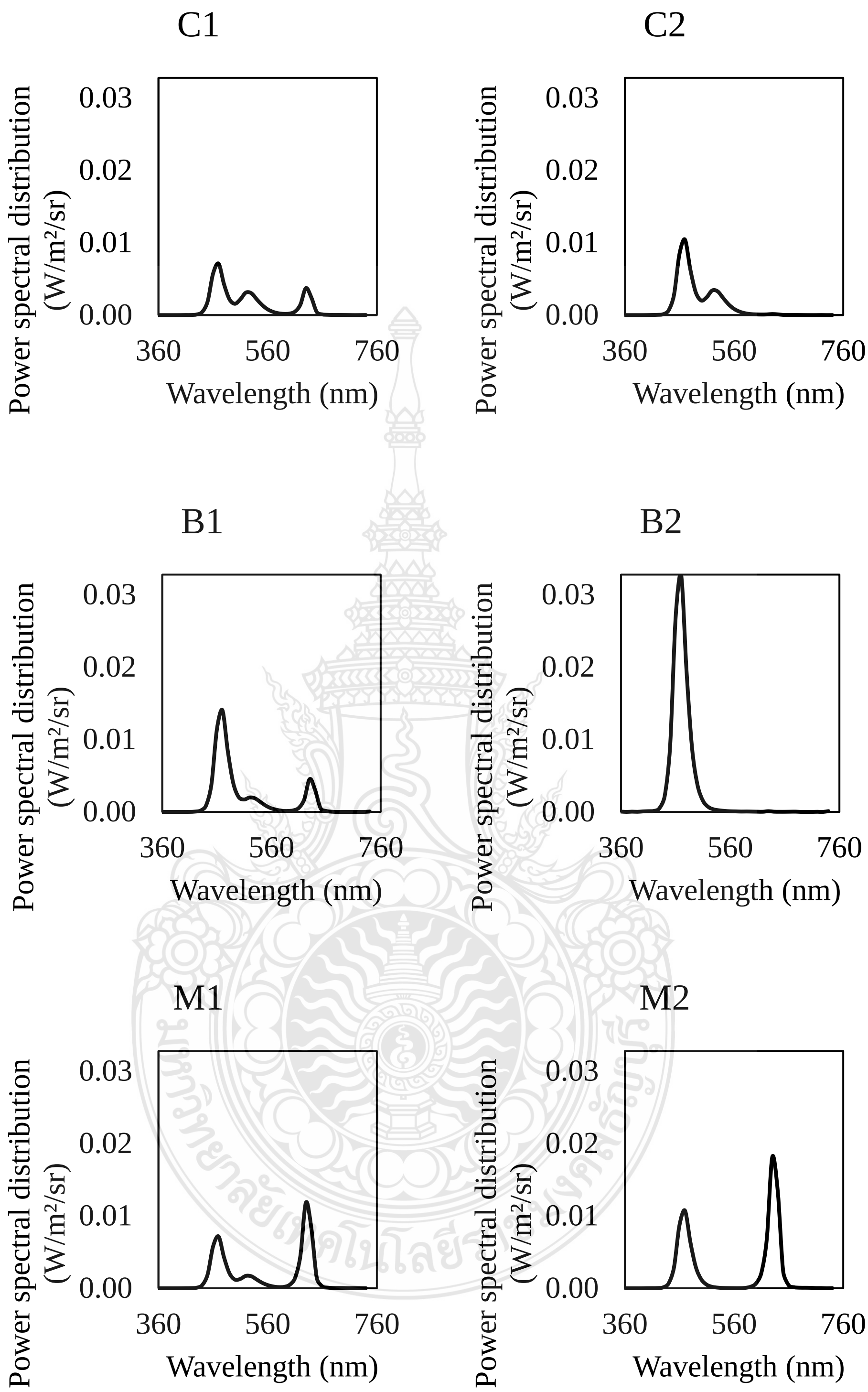



**Figure 3.5** Spectral power distribution of all colored illuminations (Cont.)

**Figure 3.6** Konica Minolta CL-500A

**Table 3.1** Light condition co-ordinates and illuminants

| Illuminations | u' | v' | illuminance (lx) |
|---|---|---|---|
| D65 | 0.200 | 0.466 | 100.9 |
| R1 | 0.369 | 0.492 | 97.9 |
| R2 | 0.538 | 0.518 | 99.1 |
| Y1 | 0.253 | 0.506 | 98.6 |
| Y2 | 0.307 | 0.546 | 97.1 |
| G1 | 0.138 | 0.520 | 99.4 |
| G2 | 0.075 | 0.575 | 98.5 |
| C1 | 0.154 | 0.423 | 100.6 |
| C2 | 0.108 | 0.381 | 101.0 |
| B1 | 0.170 | 0.326 | 95.2 |
| B2 | 0.140 | 0.187 | 80.6 |
| M1 | 0.270 | 0.409 | 98.6 |
| M2 | 0.339 | 0.352 | 97.2 |

3.3.3 Color chips

A total of twenty-six color chips were created using a Konica Minolta Accurio Press C83HC, as illustrated in Figure 3.7. The color chips, each with dimensions of 6 × 6 cm, were printed on a 330 g/m² matte paper using the percent screen technique. Each color chip was then measured with a Konica Minolta FD-7 spectrophotometer under D65 illumination and a 2-degree observer angle, as shown in Figure 3.8. The measurement results were plotted in the a*b* color space, as displayed in Figure 3.9.

**Figure 3.7** Konica Minolta Accurio Press C83HC


**Figure 3.8** Konica Minolta FD-7

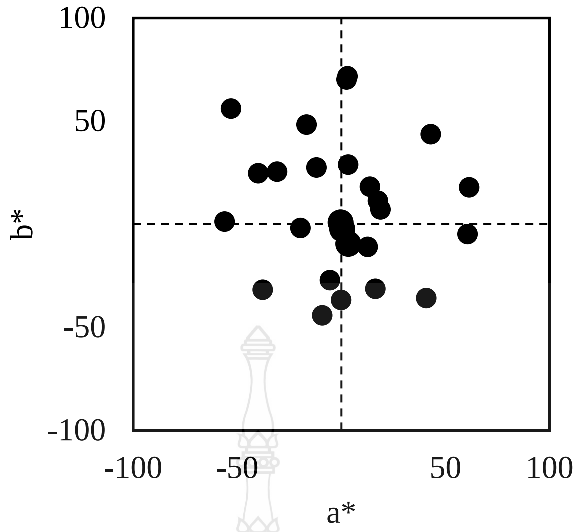



**Figure 3.9** Color chips coordinates on a*b* color space

3.3.4 Procedure and tasks

Upon entering the room, subjects were given three minutes to adapt to the lighting and were instructed to look around the room during this time. Experimenters presented the color chips individually on a table in front of the subjects in random order. In the first task, subjects were asked to evaluate each color chip using the elementary color naming method by assigning chromaticness, whiteness, and blackness percentages, with the total sum equaling 100 percent. In the second task, subjects estimated the percentages of red, yellow, green, and blue in each color chip, based on the opponent color theory. According to this theory, red and green, as well as blue and yellow, cannot be evaluated simultaneously.

After assessing the 26 color chips under the initial illumination setting, subjects proceeded to the next illumination. During the transition between lighting conditions, they were instructed to close their eyes and continue the adaptation period and subsequent tasks in sequence. Evaluating one illumination condition took subjects approximately one hour. A daily limit of three hours was imposed, and the average number of days needed to complete the experiment was four. There was only one repetition and only 10 subjects had participated in 3 repetitions to check the consistency of the subjects.

### 3.3.5 Subjects

There were 100 subjects, aged 18 to 30 years old, participating in this experiment, including 40 males and 60 females. Most of them were undergraduate students from Rajamangala University of Technology Thanyaburi, Thailand. To familiarize the participants with the basic concepts of the experiment, they took a color science and vision course and learned the elementary color naming method. The participants were also tested for color vision deficiency using the Ishihara test. It was confirmed that all subjects had normal color vision and normal visual acuity. To ensure that the participants were properly prepared, they received training on naming color chips under D65 prior to the experiment and received credit for their participation.

### 3.3.6 Data analysis

#### 3.3.6.1 Polar diagram

Elementary color naming results can be represented on a polar diagram, as shown in Figure 3.10, which is a perceptual color space based on opponent color theory. This diagram features a horizontal axis for Red and Green and a vertical axis for Blue and Yellow. In Equation 3.1, the naming results for each elementary color are multiplied by their corresponding unique hue angle on the polar diagram: Red (R) by 0, Yellow (Y) by 90, Green (G) by 180, and Blue (B) by 270. However, if a subject names both Red and Blue, the result falls within the fourth quadrant on the polar diagram, and Equation 3.2 should be utilized. Changing Red's multiplier from 0 to 360 ensures that the hue angle calculation accurately reflects the color appearance in the fourth quadrant. The x and y values are the coordinates on the polar diagram, and they are calculated based on the chromaticness and hue angle of the color chip judged by a subject. These values are obtained using Equations 3.3 and 3.4 for the x and y coordinates, respectively. The x-axis signifies perceptions from greenish (-100) to reddish (100), while the y-axis represents perceptions from yellowish (-100) to bluish (100).

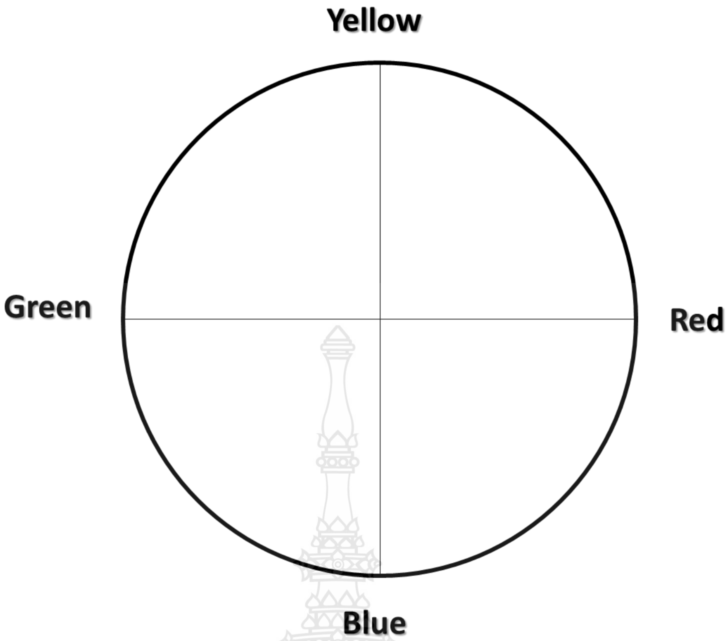



**Figure 3.10** An example of polar diagram

$$\text{If } R = 0 \text{ or } B = 0$$

$$\theta = \frac{\left((R \times 0) + (Y \times 90) + (G \times 180) + (B \times 270)\right)}{100} \tag{3.1}$$

$$\text{If } R > 0 \ \& \ B > 0$$

$$\theta = \frac{\left((R \times 360) + (Y \times 90) + (G \times 180) + (B \times 270)\right)}{100} \tag{3.2}$$

Then co-ordinates on polar diagram can be calculated by

$$x = \text{chromaticness } \times \cos(\theta) \tag{3.3}$$

$$y = \text{chromaticness } \times \sin(\theta) \tag{3.4}$$

3.3.6.2 Root mean square error

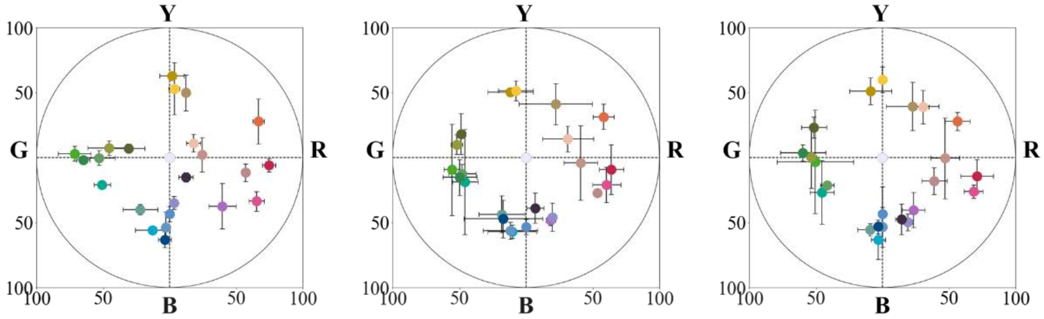
Root Mean Square Error (RMSE) is a widely used method in statistical analysis to measure the difference between observed and predicted values. It is calculated by taking the square root of the mean of the squared differences between the observed and predicted values. The RMSE value indicates the average deviation of predicted values from observed values. In this study, individual elements such as chromaticness, whiteness, blackness, and hue were separately calculated to examine the differences between the naming results under colored illumination conditions and the reference illumination condition, D65. Each element was normalized by its respective maximum value to enable the comparison of the different magnitudes of each factor. The maximum values for chromaticness, whiteness, and blackness were normalized by 100, while the maximum value for hue was normalized by 360. Equation 3.5 was employed for each element to determine the individual RMSE. where $\alpha$ is the value of each element which is under the test illumination and D65 illumination in the equation.

$$\mathrm{RMSE} = \sqrt{\frac{1}{26}\sum_{i=1}^{26}(\alpha,\mathrm{test}_i - \alpha,\mathrm{D65}_i)^2} \tag{3.5}$$

## 3.4 Results and Discussion

3.4.1 The individual result on polar diagram

Figure 3.11 shows the individual naming results of three subjects which had a chance to do a repetition task under D65 illumination. Each color plot represents the average color chip naming result after transformation, plotted on the polar diagram, while the error bars indicate the results of three repetitions. The figure demonstrates that each subject had their own criteria, as evidenced by the inconsistencies in some color chips between subjects. However, the overall trend of the color chips can be observed in the graph, and the inconsistencies could be reduced by increasing the number of subjects.




(a) (b) (c)

**Figure 3.11** The example under D65 of three individual naming results

3.4.2 Fluorescence and LED

Figure 3.12 presents an example of the average results of 100 subjects under two different lighting systems: fluorescent on the left (a) and LEDs on the right (b), both under D65 illumination. Each color plot corresponds to the color naming result of a color chip, and the error bars represent standard error. The results show that the naming result of color chips under D65 was distributed across the polar diagram. A T-test with the significance level of $\alpha = 0.05$ was conducted to determine whether there was a significant difference between the means of the two groups in terms of three variables: the x and y coordinates, and hue. The results showed p-values for each variable equal to 0.96, 0.81, and 0.96, respectively, indicating no significant difference between the two lighting systems under D65 illumination.

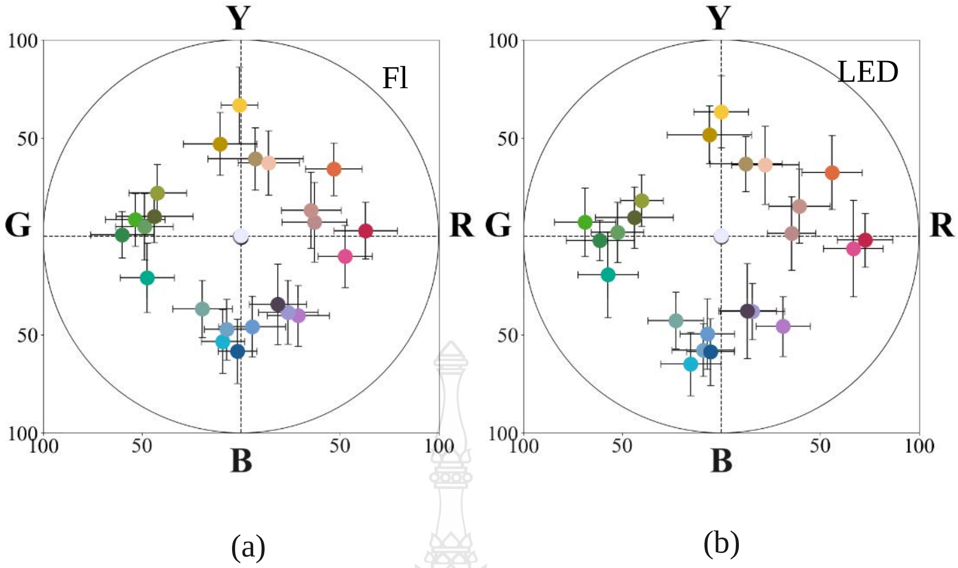



**Figure 3.12** The average color appearance of color chip results under fluorescent light D65 (a) and LED D65 (b)

3.4.3 Color appearance of color chip with chromatic adaption result

Figures 3.13 shows the average results of 100 subjects under various colored illumination conditions, including red, yellow, green, cyan, blue, and magenta illumination. In each figure, the graph on the left represents the results under less vivid illumination, while the graph on the right displays the results under vivid illumination. The outcomes under the less vivid illumination conditions demonstrated a similar pattern across all conditions. However, a significant shift in the perceived color pattern was observed in the vivid illumination group. The perceived colors were repositioned to different coordinates depending on the color illumination.

The color appearance of the color chips did not seem to be significantly saturated in the direction of color illumination, particularly in the R2, C2, and M2 conditions. For instance, under R2, the color appearance of the color chips shifted away from the 0-degree hue angle, which is the unique hue of red. Similarly, under C2, no color appearance of the color chips showed high chromaticness in the direction of cyan illumination, which lies between the green and blue axes. Instead, the chips showed high chromaticness in the yellowish-green and blue directions. Likewise, under M2, no high chromaticness of color chips was observed in the direction of magenta, which is located between the red and blue axes. This finding aligns with the results of a study by Webster and Mollon (1993), in which the researchers used an asymmetric matching task to investigate whether color vision models can account for changes in color appearance following adaptation. Their experimental results indicated that adaptation alters the perceived color of chromatic test stimuli both by decreasing their saturation (contrast) and by changing their hue. The changes in color appearance shown in Figure 3.13 might be related to the relationship between the color illumination and color chips in the context of opponent color theory. For example, under the vivid red (R2) condition, green color chips appeared to shift towards blue. Similarly, under the vivid yellow (Y2) condition, blue color chips shifted towards the green axis. However, some color chips that initially appeared red were still perceived as red on the red axis under vivid green illumination (G2). Overall, color chips that were opposite to the vivid color light tended to shift away from their original hue direction.

For achromatic chips, which include black, neutral grey, and white colors, they were mostly located at the origin points of the polar diagram. However, despite the coordinates of each achromatic chip being at the center of the graph, the hue angle of each color chip could still be investigated. For instance, black color chips were perceived in the direction of blue colors, with an average hue angle of 261 degrees across all color conditions from various color illuminations. This result may be due to some subjects judging the black color chip as being tinged with a hint of blue. On the other hand, the hue angles for other achromatic chips, such as neutral and white, changed according to the illumination. For example, under less vivid red illumination (R1), neutral and white color chips were perceived at hue angles of 3.29 and 4.51 degrees, respectively. When the light changed to less vivid yellow illumination (Y1), the hue angles for the chips shifted to 91.04 and 88.89 degrees, respectively.

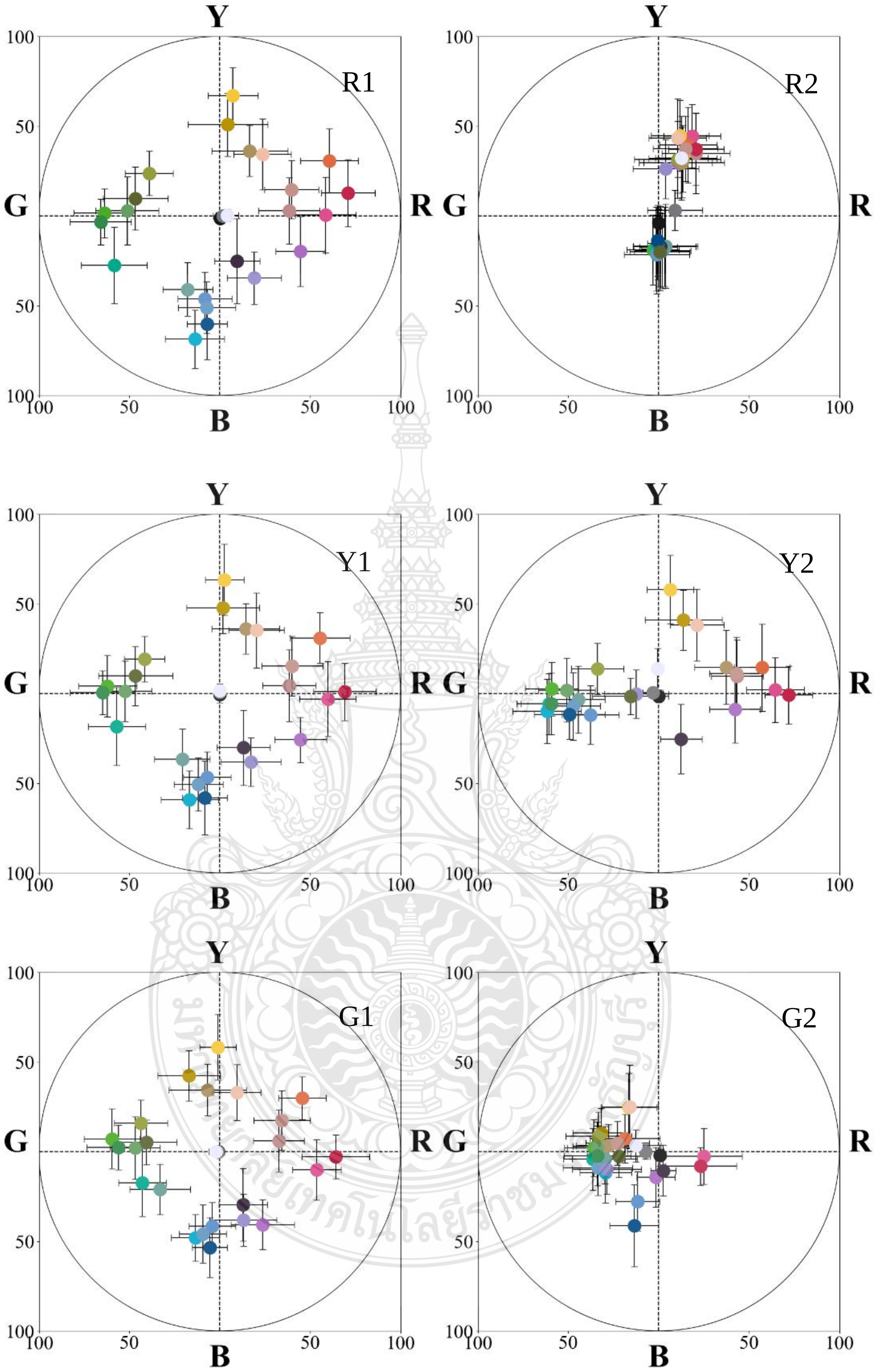



**Figure 3.13** The average naming results of 100 subjects under each color illumination condition

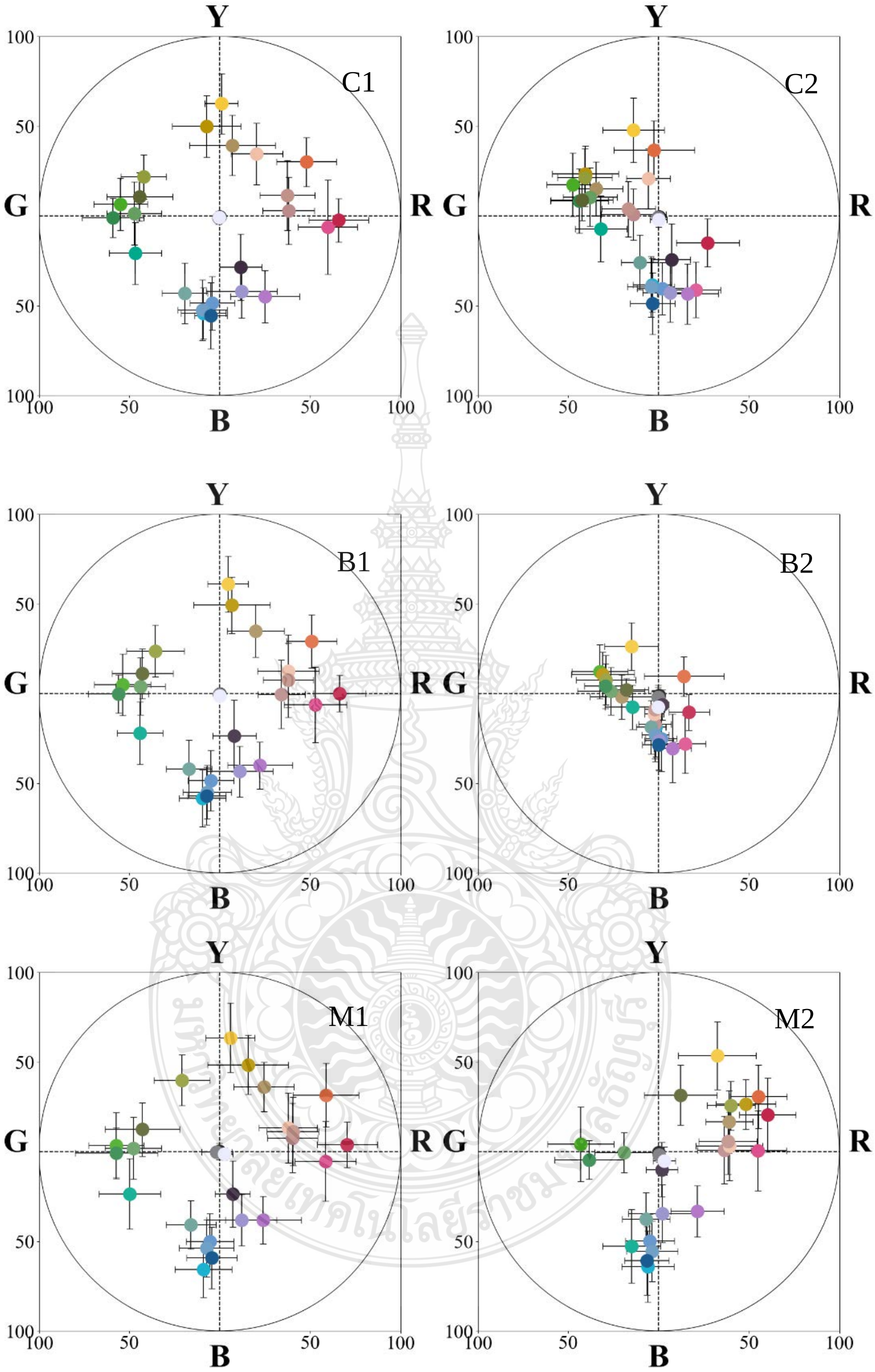



**Figure 3.13** The average naming results of 100 subjects under each color illumination condition (Cont.)

3.4.4 Root mean square error

Figures 3.14 and 3.15 display the root mean square error (RMSE) from the normalization in each of the four elements, which include hue, chromaticness, blackness, and whiteness, for the less vivid illumination and vivid illumination groups, respectively. In each figure, elements such as hue, chromaticness, blackness, and whiteness are independently calculated as root mean square errors. The least error, 0, indicates that an element has the same amount as the reference D65 illumination. The largest errors occurred in vivid red (R2), vivid green (G2), and vivid blue (B2) conditions, with RMSE values of 0.281 for R2, 0.246 for G2, and 0.249 for B2. These errors for R2, G2, and B2 correspond to the gamut of illumination used in these experiments, as there is only one peak in the spectral power distribution under these conditions. Conversely, the least error was observed in C1 and Y1 conditions. The reason for these minimal errors might be that both conditions had the coordinates closed to the black body locus which corresponds to the natural illumination (Lucassen, Walraven, 1996) that humans are typically familiar with under these conditions.

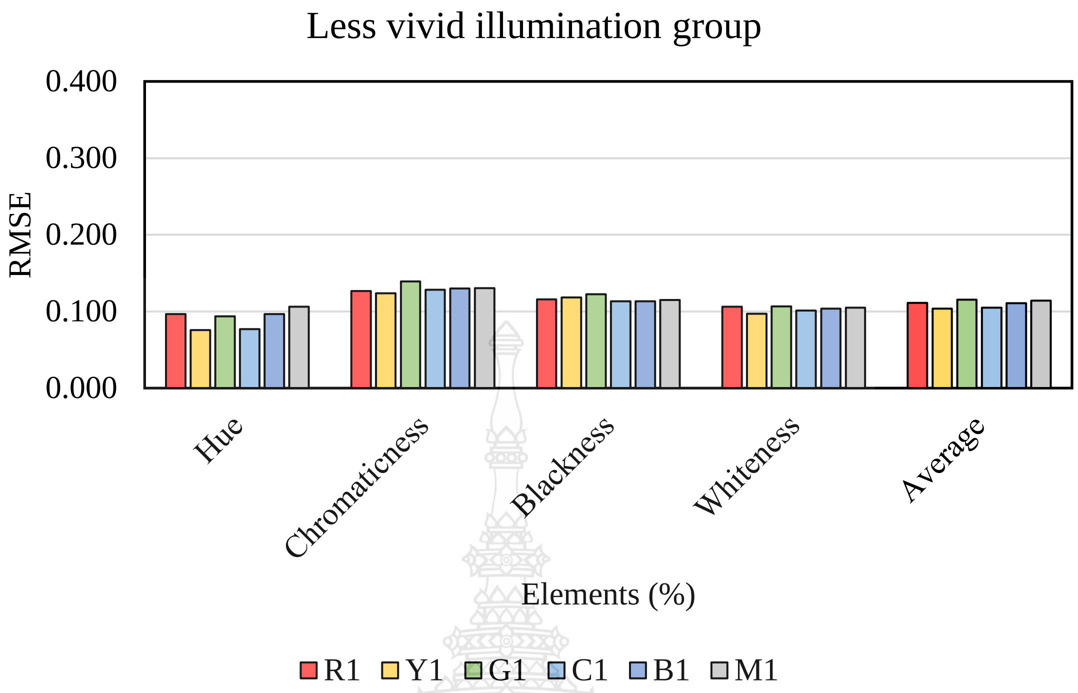



**Figure 3.14** The root mean square error of less vivid illumination group

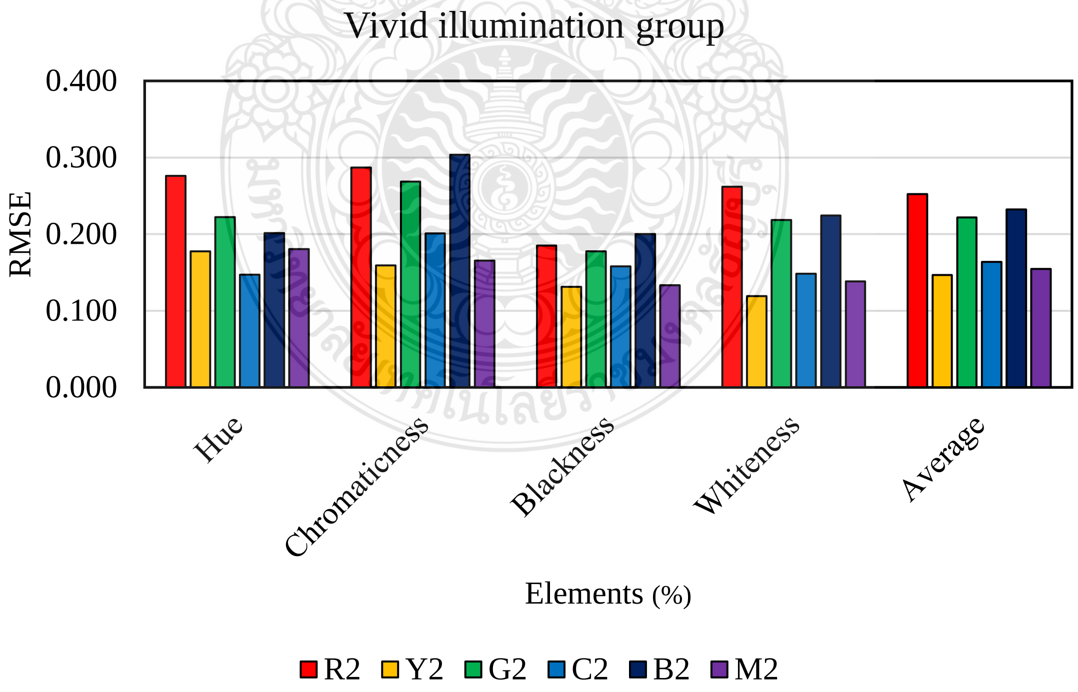



**Figure 3.15** The root mean square error of vivid illumination group

### 3.5 Conclusion

In conclusion, this study investigated the effects of various colored illuminations on the appearance of color chips through chromatic adaptation. The results revealed that the perceived color of color chips exhibited notable changes under vivid illumination conditions compared to less vivid illumination conditions, emphasizing the significant impact of extreme illumination on color perception. A comparison between fluorescent and LED lighting systems under D65 illumination showed no significant differences in the naming results of color chips, with p-values for x and y coordinates and hue being 0.96, 0.81, and 0.96, respectively. This suggests that both lighting systems produce similar color perception outcomes under D65 illumination. The research also demonstrated that the color appearance of achromatic chips and chromatic chips changed according to the illumination conditions. For achromatic chips, black color chips were perceived with a hue angle in the direction of blue colors across various color illuminations, while neutral and white chips had hue angles that changed depending on the illumination conditions. The chromatic chips displayed shifts in hue and chromaticness under different illumination conditions, as evidenced by the vivid illumination groups. Root mean square error analysis showed high errors in the vivid red, blue, and green conditions, while minimal errors were observed in the natural illumination conditions. Overall, this study shows the more vivid illumination resulting the more error of color appearance of the color chips. The hue shift showed in color condition will be discussed later in the discussion part.

# CHAPTER 4
# COLOR APPEARANCE OF COLOR CHIPS WITHOUT CHROMATIC ADAPTATION

## 4.1 Introduction

In order to quantify the degree of color constancy, it is necessary to determine the color appearance of color chips without chromatic adaptation. Common color matching methods involve measuring samples with instruments under colored illumination. However, obtaining this value through a simple method such as instrument measurement is challenging. Morimoto, Yamauchi, & Uchikawa (2023) investigated color category constancy across changes in illumination. They controlled an LC projector to serve as the light source, spotlighting only the test sample while the background remained illuminated by white light, such as D65, in order to obtain categorical naming results without color constancy as a baseline measurement. In other words, the results obtained from this controlled spotlight experiment provided a reference point, showing how the perceived color of the test sample changed solely due to the color illumination, and not influenced by chromatic adaptation as their subject could still adapt the perception to the background color as the white light still illuminated the background.

An alternative method, the two-room technique, is also used to study the color appearance of color chips without participants perceiving and judging color appearance alongside chromatic adaptation. For instance, Phuangsuwan and Ikeda (2017) explored chromatic adaptation to illumination using the two-room technique, in which two separate illuminations illuminated different rooms. In their experiment, participants sat in a room illuminated only by white light and could see a neutral sample, such as a Munsell N6, placed on the wall through a small window. They referred to the result of this judgment as the adapting color. The adapting color is the color of room illumination which a participant doesn't adapt to the test illumination.

In this study, we adopted this technique to perform a similar procedure, which allowed us to explore the color appearance of color chips without chromatic adaptation using the same perceptual color space on the polar diagram.

## 4.2 Purpose

The purpose of this study is to investigate the color appearance of color chips without chromatic adaptation using the two-room technique.

## 4.3 Methodology

4.3.1 Apparatus

In this study, the experiment room was the same booth used for examining the color appearance of color chips with chromatic adaptation in the previous chapter; however, the room was extended and divided into two sections: the test room and the subject room, as shown in Figure 4.1. The test room, located on the left, was illuminated by the same RGB-LED light, which changed according to the color illumination condition. A color chip was placed in this room on a standing pole. Unlike the experiment conducted in the previous chapter, participants had to move to another room called the subject room, shown on the right side of Figure 4.1. This room was illuminated only by white LED, D65, hung from the ceiling. A small rectangular window between the rooms allowed participants to see the color chip in the test room. The gray wall about Munsell N6, served as the background, similar to the background used in the previous chapter's experiment. The luminance of this grey background was maintained at 6 cd/m$^2$. The illumination of the white LED in the subject room was controlled to maintain the same 100 lx as the test room.

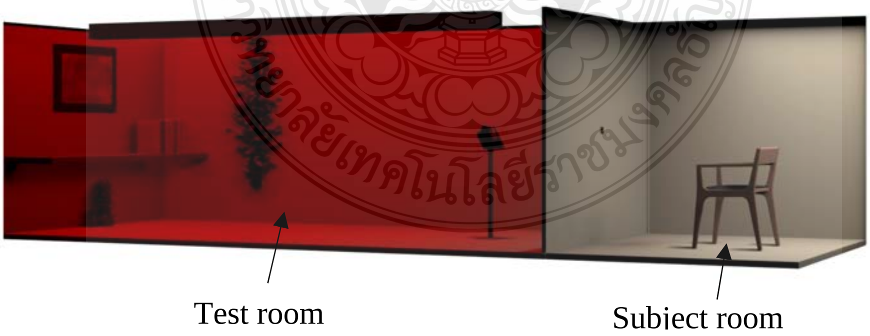



**Figure 4.1** Experiment room

4.3.2 Illumination condition, color chips, and procedure tasks

The illumination conditions were the same as those in the Chapter 3 experiment, with 13 illumination conditions. Additionally, the same 26 color chips and elementary color naming method were used with one repetition. Each of the color chips and illumination conditions was randomly presented to the subjects to prevent slow chromatic adaptation. Schultz, Doerschner, and Maloney (2006) studied color constancy by presenting only a test patch with a black background to participants. During what they termed a 'block session,' they exposed the color test patch to a consistent set of illumination conditions throughout. Their findings suggested that color constancy still occurred even though there were no cues available to the participants about the illumination condition.

4.3.3 Subject

A total of thirty subjects with normal color vision participated in this experiment. They were students from Rajamangala University of Technology Thanyaburi, Thailand. The participants included 14 males and 16 females, with ages ranging from 19 to 30 years old. There were only ten subjects who had a chance to participate in the experiment in the previous chapter.

## 4.4 Results and Discussion

In this study, the neutral color chip played a crucial role as it served as the color of illumination. In essence, the color appearance of the room light was reflected in this neutral color chip. Subjects adapted solely to the white light illumination in the subject room, and as such, the color appearance of the neutral color chip provided a clear indication of the color appearance of the colored light which shown as triangle symbol in Figure 4.2

Figure 4.2 presents the naming results for all color chips under each colored illumination, depicted in polar diagram graphs. The left graph represents the less vivid illumination, while the right graph illustrates its corresponding vivid illumination. Each data point corresponds to an individual color chip, with error bars indicating the standard deviation from 30 subjects. In the absence of a chromatic adaptation mechanism, the color appearance of color chips tends to shift in the direction corresponding to the colored light, as each color chip is affected by the colored illumination.

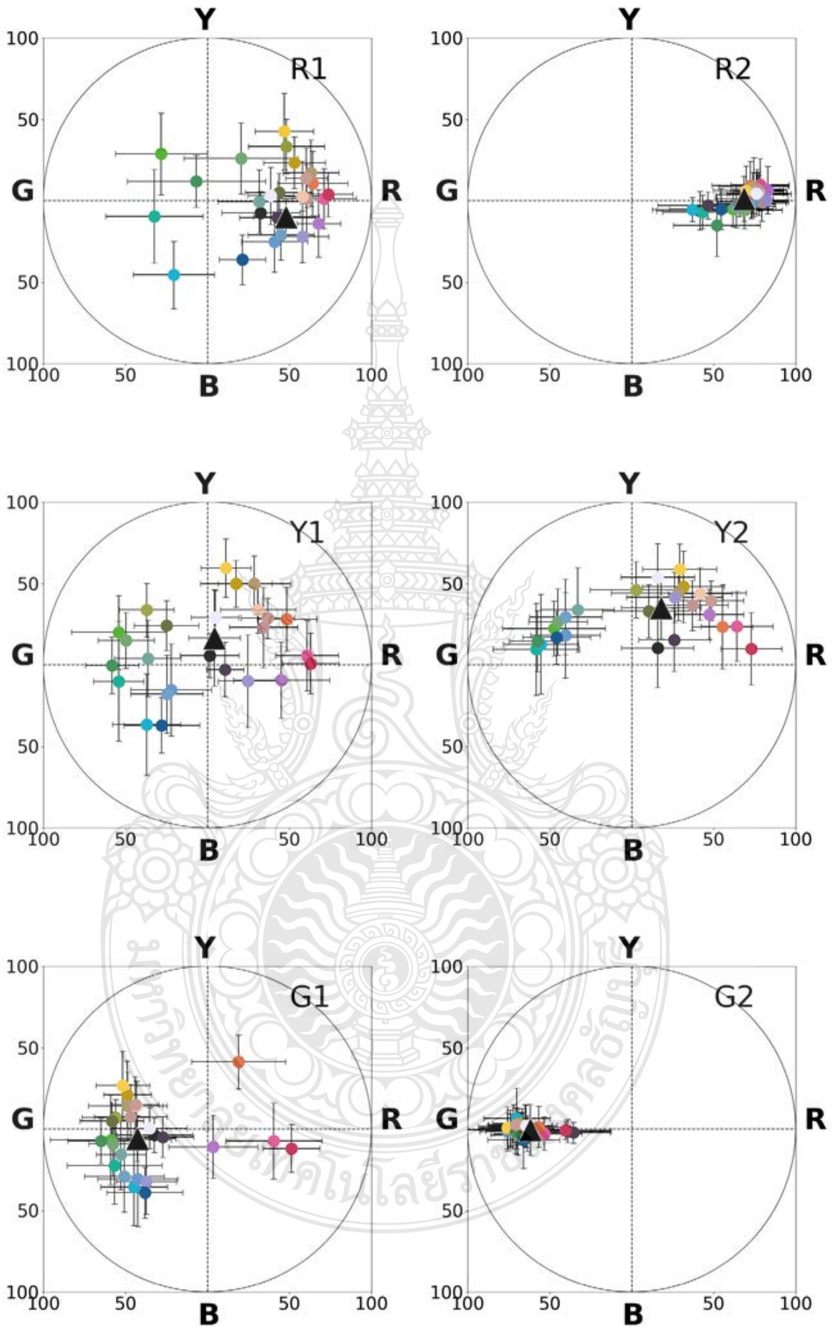



**Figure 4.2** The average naming result of 30 subjects under each color illumination condition without chromatic adaptation

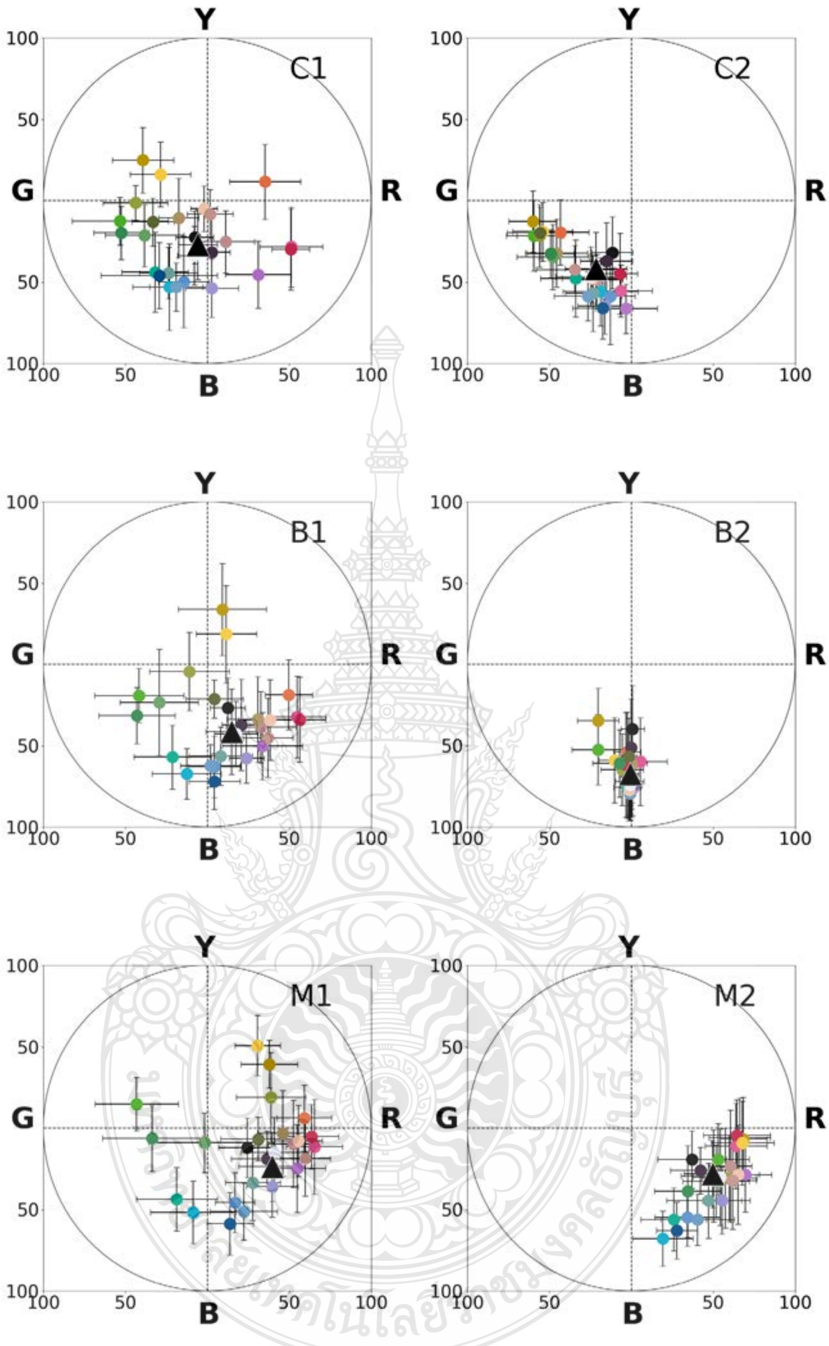



**Figure 4.2** The average naming result of 30 subjects under each color illumination condition without chromatic adaptation (Cont.)

These findings align with the results of Panitanang, Phuangsuwan, & Ikeda (2018), where the color appearance of color chips, in the absence of chromatic adaptation, tended to shift in the direction of red, proportional to the saturation of the red-light illumination. However, the results from Chapter 3 demonstrated the chromatic adaptation effect, showing that subjects could judge color appearance closer to the results under white light when the color constancy mechanism was active. Both the colored light results and the results in this chapter will serve as the baseline for calculating the color constancy index in the next chapter.

## 4.5 Conclusion

The study investigated the color appearance of color chips without chromatic adaptation using the two-rooms technique. The results indicated that the color appearance of color chips tends to shift in the direction corresponding to the color light, as each color chip is affected by the color illumination when there is no chromatic adaptation mechanism.

# CHAPTER 5
# PERCEPTUAL COLOR CONSTANCY INDEX

## 5.1 Introduction

Color constancy is a human mechanism that allows us to perceive a stable color appearance under various color illuminations. The color constancy index is a numerical ratio ranging from 0 to 1, with 0 indicating no color constancy and 1 representing perfect color constancy as Arend & Reeves's experiment (1986), Brainard's experiment (1997, 1998), Foster's experiment (2011). The color constancy index can be calculated as the ratio between the distance of the color appearance of each color chip under the test illumination condition away from the color appearance of the same chip under the reference light (white light) and the distance of the color appearance of the same color chip under the test illumination condition without chromatic adaptation (baseline coordinates) away from the color appearance of the same chip under a reference light. Typically, the color constancy index is studied in a color space, where the distance of each axis of the space corresponds to the Euclidean distance. However, the color constancy index based on a polar diagram, which is a perceptual color space, has not yet been extensively explored or understood.

## 5.2 Purpose

The aim is to propose a method for calculating the color constancy index based on the polar diagram graph.

## 5.3 Data Analysis

### 5.3.1 The lightness axis

In the polar diagram, subjects are required to judge elements such as chromaticness, whiteness, blackness, and color components. The chromaticness and color components are related as coordinates on the polar diagram. However, whiteness and blackness can also be combined to form another axis called lightness. In this study, the lightness is calculated by subtracting blackness from whiteness to create the lightness axis.

$$\text{Lightness} = \text{Whiteness} - \text{Blackness} \quad (5.1)$$

### 5.3.2 The uniformity relationship of lightness and chromaticness

Someone might question whether the whiteness and blackness on this polar diagram have the same equal distance step as chromaticness. To address this concern, a supplementary experiment was conducted, focusing on four color conditions derived from the unique hues on the polar diagram: red, yellow, green, and blue. The objective of the supplementary experiment was to create a weighting function and apply it to whiteness and blackness, aiming to achieve nearly uniform scales for the chromaticness axis and either the whiteness or blackness axis. The full methodology and results of this experiment can be found in Appendix E. For the brief of the concept of this supplement experiment, the different distance between color naming method, and the corresponding colorimetry value or the physical color value of the Munsell color chip which matched to the color naming was compared in term of the ratio between chromaticness and one of the lightness. For example, in the case of whiteness 20% to whiteness 40% which is 20% interval compared to the chromaticness of unique red as 10% to 30% which is also 20% interval. The subject would have picked the Munsell samples which matched the given condition. The selected Munsell sample would be measured as L*a*b* color values. Then, the measured color unit between chromaticness difference would be determined by the whiteness difference as the ratio which can be used to apply in the future. As the ratio equals to 1 meaning that both chromaticness and whiteness had the same distance. As the naming the result is not always be the same chromaticness, whiteness, and blackness as the supplement color naming condition. The fitting functions were proposed. Equations 5.2-5.5 depict the weighting function derived for the blackness modification, while equations 5.6-5.9 represent the function for whiteness modification. By applying these weighting functions to the results, new values for whiteness and blackness can be calculated. For example, a red color chip that is placed on the unique hue of red on the polar diagram. This chip has chromaticness = 60, whiteness = 20, and blackness = 20. By applying the chromaticness value in Equation 5.2, the blackness can be modified, and by applying it in Equation 5.6, the whiteness can be modified. In this way, the ratio of the weighting function can be obtained. However, there was a case in which unique hue cannot be judged by the subject then another linear interpolation of these unique hue of red, yellow, green, and blue needed to be perform.

For blackness modification

$$\text{Unique red ratio} = (0.0050\times \text{chromaticness}) + 0.7610 \quad (5.2)$$

$$\text{Unique yellow ratio} = (0.0168\times \text{chromaticness}) + 0.6991 \quad (5.3)$$

$$\text{Unique green ratio} = (0.0095\times \text{chromaticness}) + 0.5825 \quad (5.4)$$

$$\text{Unique blue ratio} = (0.0026\times \text{chromaticness}) + 0.5529 \quad (5.5)$$

For whiteness modification

$$\text{Unique red ratio} = (-0.0129\times \text{chromaticness}) + 1.626 \quad (5.6)$$

$$\text{Unique yellow ratio} = (-0.0003\times \text{chromaticness}) + 1.415 \quad (5.7)$$

$$\text{Unique green ratio} = (-0.0013\times \text{chromaticness}) + 1.030 \quad (5.8)$$

$$\text{Unique blue ratio} = (-0.0050 \times \text{chromaticness}) + 0.932 \quad (5.9)$$

### 5.3.3 The ordinary color constancy index (OCCI)

The ordinary color constancy index (OCCI) is a common method for calculating color constancy based on Arend and Reeves (1986). The index is a ratio between the Euclidean distances of perception and baseline, as shown in Figure 5.1 by the blue and red dotted lines, respectively, on the polar diagram. There are three symbols in the figure: the open square represents the color naming result under D65, the open triangle represents the color naming result under test illumination, and the closed triangle represents the color naming result under test illumination without adaptation to the test illumination.

The perception distance is the length between two coordinates, from the elementary color naming result of a color chip under D65 to the naming result of the same color chip under illumination conditions. The baseline distance is calculated based on the points between the naming result of the same color chip under D65 and the naming result of the same color chip under illumination conditions in which the subject did not adapt to the illumination. Three axes are used in this distance calculation: the red (R) and green (G) axis, the blue (B) and yellow (Y) axis, and the whiteness (W) and blackness (K) axis.

The OCCI equation, shown in Equation 5.10, is designed to be 1 when the color appearance under test illumination points overlaps with the same color chip under D65 points and 0 when the color appearance positions are exactly the same as the points under the baseline condition. In the equation, ‘a’ is a distance between the perception result under test illumination (open triangle symbol in Figure 5.1) to the perception result under reference illumination (open square) as shown in Equation 5.11. Similar to ‘b’ which is a distance between the perception result under test illumination without chromatic adaptation to the test light (solid square) to the perception result under reference illumination (open square) as shown in Equation 5.12.

$$\mathrm{OCCI} = 1 - \frac{a}{b} \qquad (5.10)$$

Where,

$$a = \sqrt{(RG_{obs} - RG_{D65})^2 + (YB_{obs} - YB_{D65})^2 + (WK_{obs} - WK_{D65})^2} \qquad (5.11)$$

$$b = \sqrt{(RG_{base} - RG_{D65})^2 + (YB_{base} - YB_{D65})^2 + (WK_{base} - WK_{D65})^2} \qquad (5.12)$$

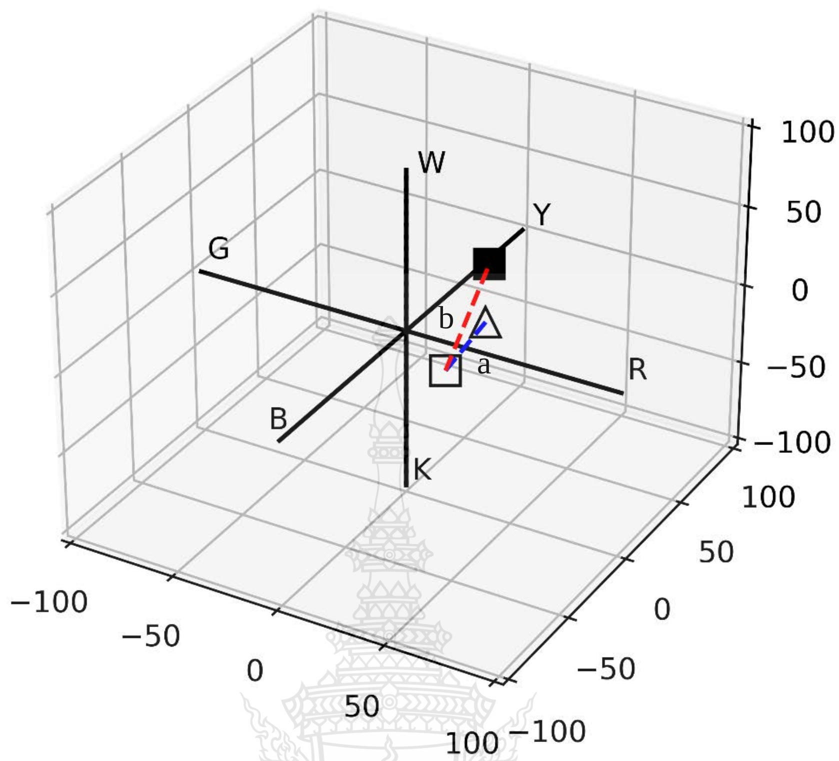



**Figure 5.1** The illustration of the color constancy index in the polar diagram is represented in a three-dimensional space

### 5.3.4 Hue Constancy Index (HCI)

The Ordinary Color Constancy Index (OCCI) can be described as a change in saturation and lightness, which does not encompass other components of color such as hue. OCCI is a scalar unit rather than a vector unit. The hue shift is another factor to consider, which is shown in Figure 5.2 through the blue arc ($\theta$a), representing a deviation of hue from the reference illumination (D65). The red arc line ($\theta$b) illustrates the difference in hue between the results under D65 and the color appearance without adaptation to the test illumination. A similar equation to OCCI can be used to calculate the hue constancy index (HCI) as outlined in Equation (5.13). However, if $\theta$a is larger than $\theta$b resulting the negative value then it mean there was no hue color constancy in this case or another word HCI equals to 0.

$$HCI = 1 - \left|\frac{\theta a}{\theta b}\right| \tag{5.13}$$

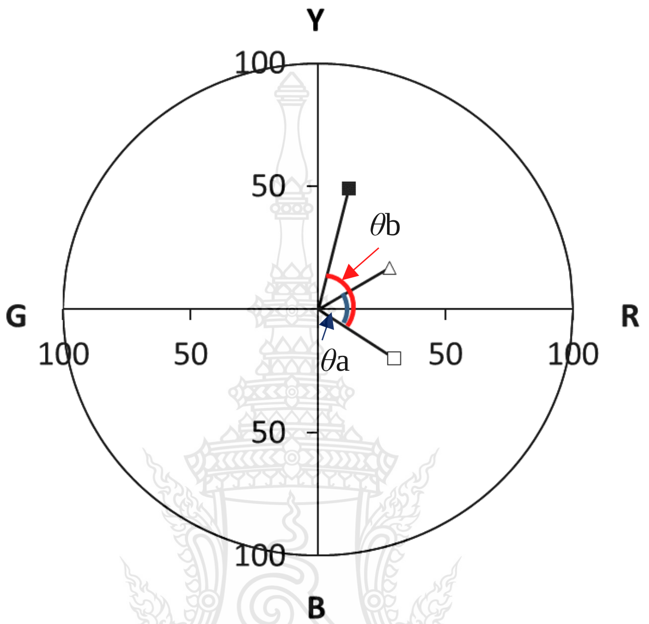



**Figure 5.2** The illustration of the hue color constancy index in the polar diagram in two-dimensional space

### 5.3.5 The Perceptual color constancy index

Both OCCI and HCI are combined to create a complete vector color constancy index in the perceptual color space represented by the polar diagram. The Perceptual Color Constancy Index (PCCI) can be calculated using the equation shown in Equation 5.14.

$$PCCI = OCCI \times HCI \tag{5.14}$$

## 5.4 Results and Discussion

The results of the perceptual color constancy index of three individuals (#1, #2, and #3) under R2 illumination (vivid red) are presented in Figure 5.3. The data was processed with fitting weights function to achieve uniformity between the chromaticness and lightness axis, and the index is plotted on the vertical axis. A value of 1 indicates perfect color constancy while a value of 0 represents no color constancy. The results display an individual judgement and color constancy index among the subjects. Despite these variations due to differing judgement criteria, a clear trend in the Color Constancy Index (CCI) was observed in this study. For instance, a consistently low CCI was seen across all three subjects for the blue color chip (near 270 degrees), as shown in Figure 5.3. As discussed in Chapter 3, employing a large sample size of 100 subjects significantly reduces the impact of individual differences, allowing for a more accurate observation of the overall CCI trend.

Figure 5.4 displays the average perceptual color constancy index on the ordinate and color chips under D65 which the average color appearance result under D65 on the abscissa for the color chip stimuli on the left panel and the achromatic color chips as neutral (N), black (B), and white (W) on the right panel. The upper part shows the less vivid illumination condition, and the lower part displays the vivid illumination condition. The perceptual color constancy index was significantly higher in the less vivid illumination condition than in the vivid illumination, as determined by T-test analysis, with P-values of 0.0001, 0.0022, 0.0018, 0.0217, 0.0041, and 0.6793 corresponding to red, yellow, green, cyan, blue, and magenta illumination conditions, respectively. The statistical results showed that only M1 and M2 had no significant difference, which might be affected by The peak of red and blue wavelength as shown in the Figure 5.5 which information from both peak excited wavelength could give much information under the vivid illumination resulting there was no much difference between M1 and M2. Also, in this study, no systematic pattern change between the less vivid illumination and vivid illumination condition groups was found, as the correlation coefficients between them were -0.02, -0.06, 0.11, -0.35, 0.06, and -0.0. For the achromatic color chips, the black color chip consistently exhibited a higher color constancy index across all color conditions. This differed from the neutral and white color chips. Specifically, when the color light was red, green, or blue—which corresponded to the RGB diodes used in this study—the white color chip demonstrated a higher color constancy index under vivid illumination compared to the neutral chip.

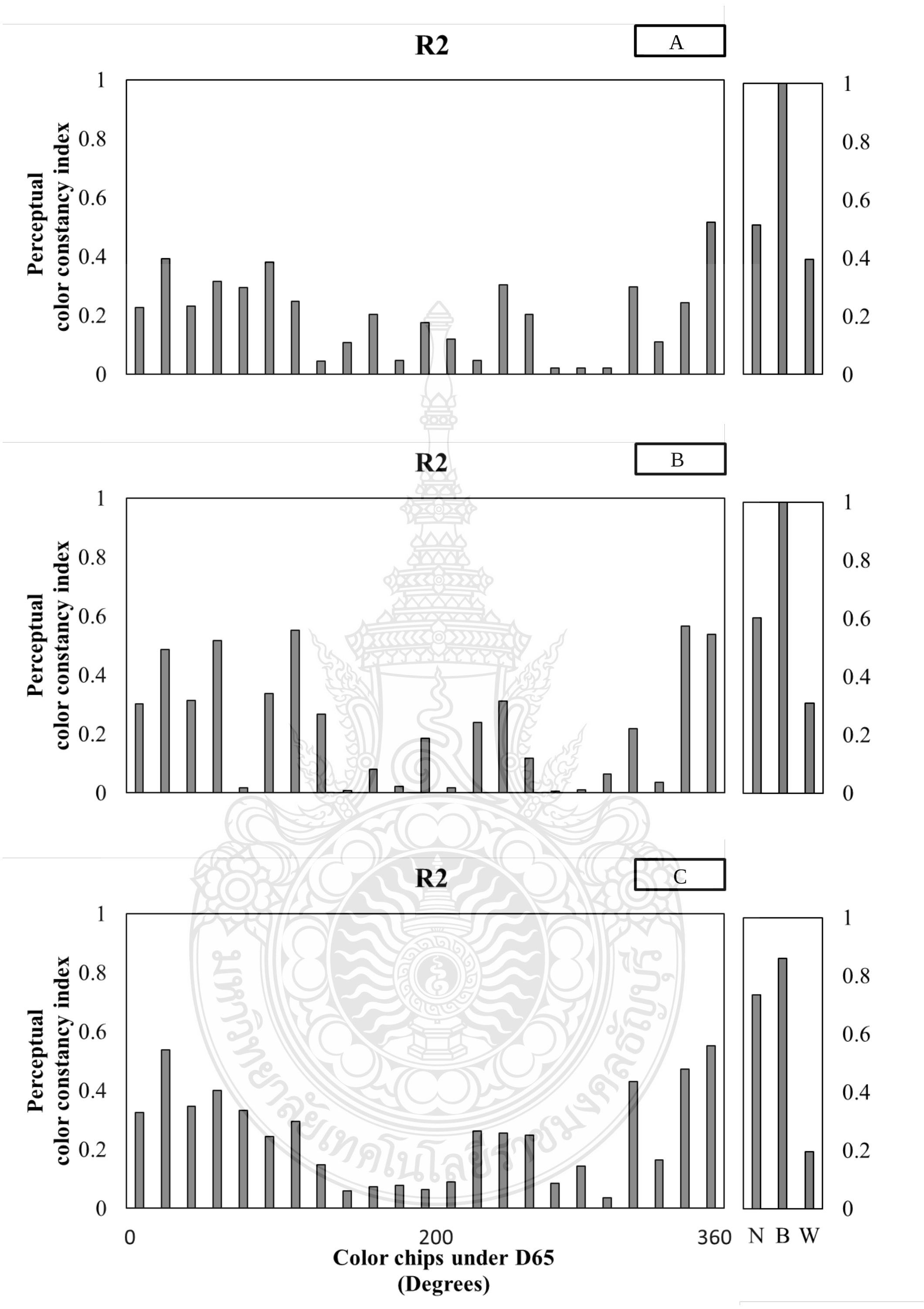



**Figure 5.3** The results of individual subjects #1, #2, and #3 are displayed in the figure, as A, B, and C respectively

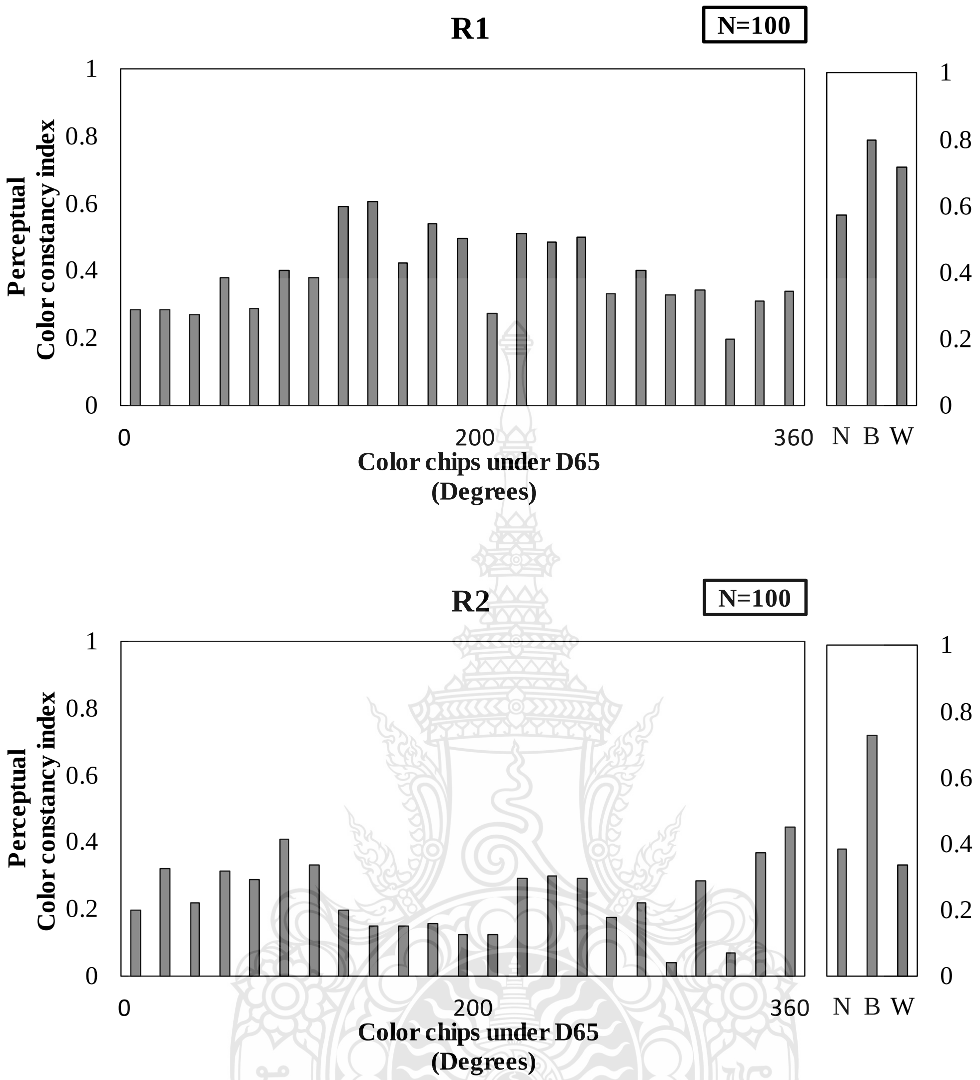
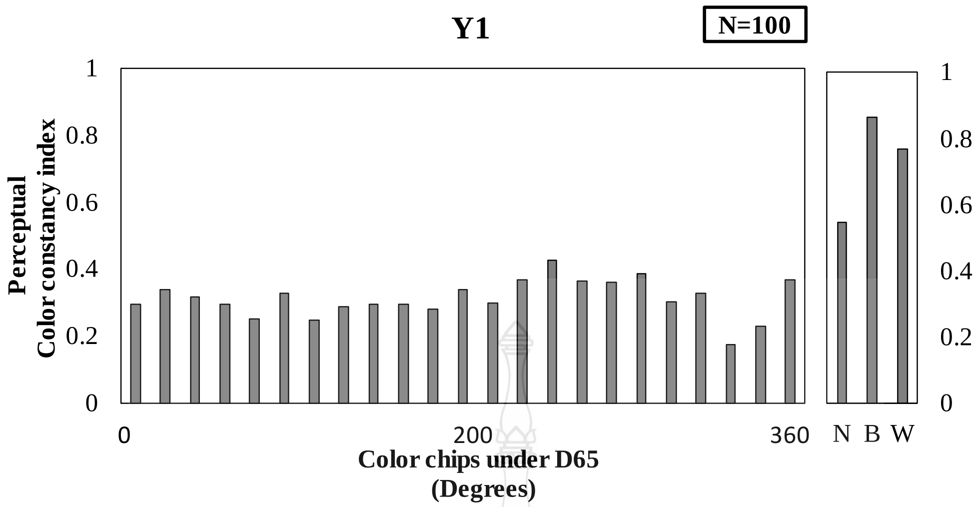



**Figure 5.4** The average perceptual constancy index of less vivid (upper) and vivid condition (below)



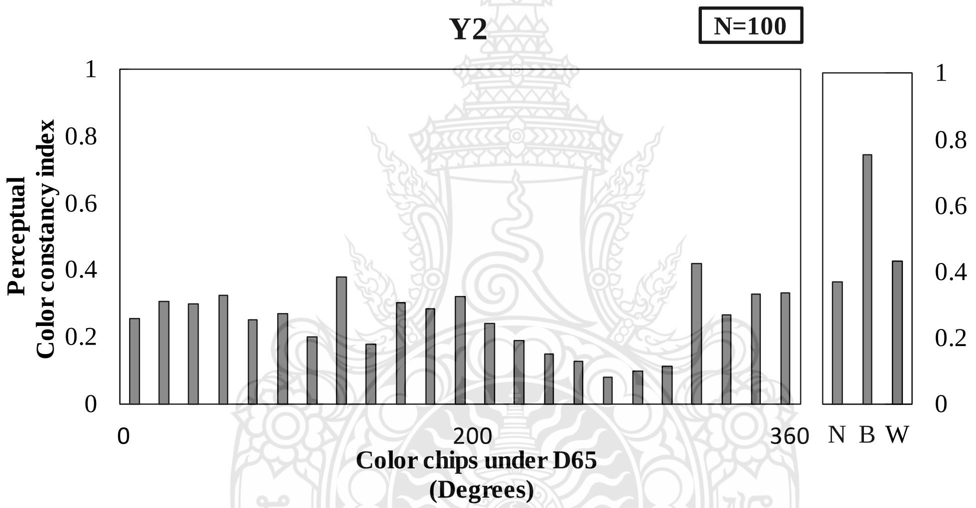
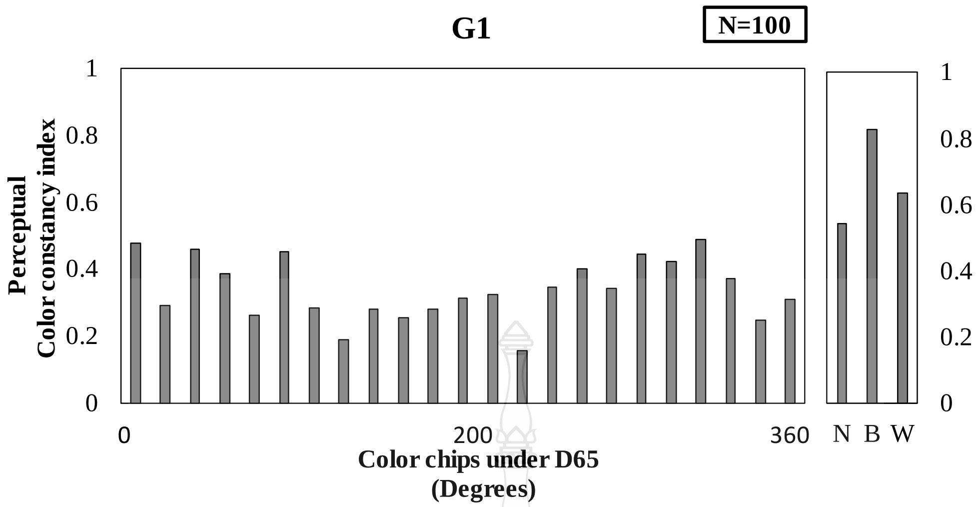




**Figure 5.4** The average perceptual constancy index of less vivid (upper) and vivid condition (below) (Cont.)



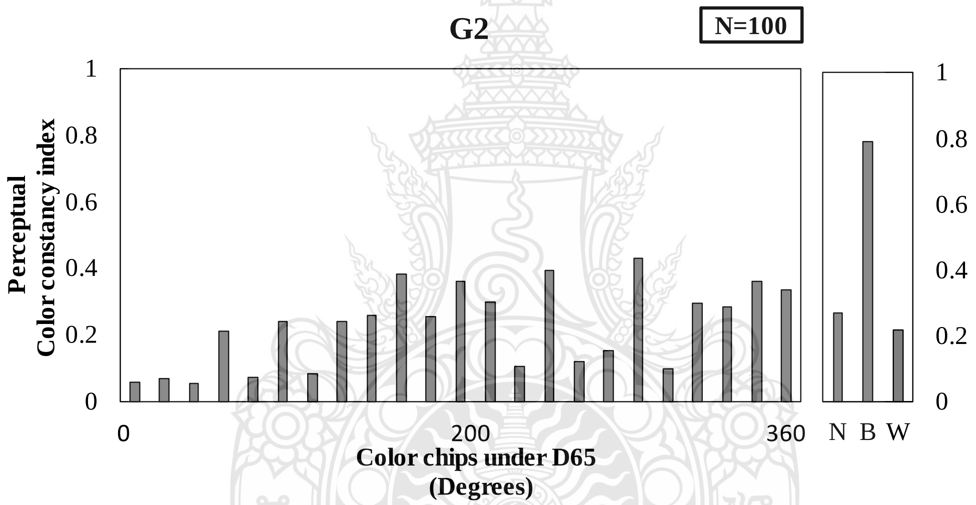




**Figure 5.4** The average perceptual constancy index of less vivid (upper) and vivid condition (below) (Cont.)

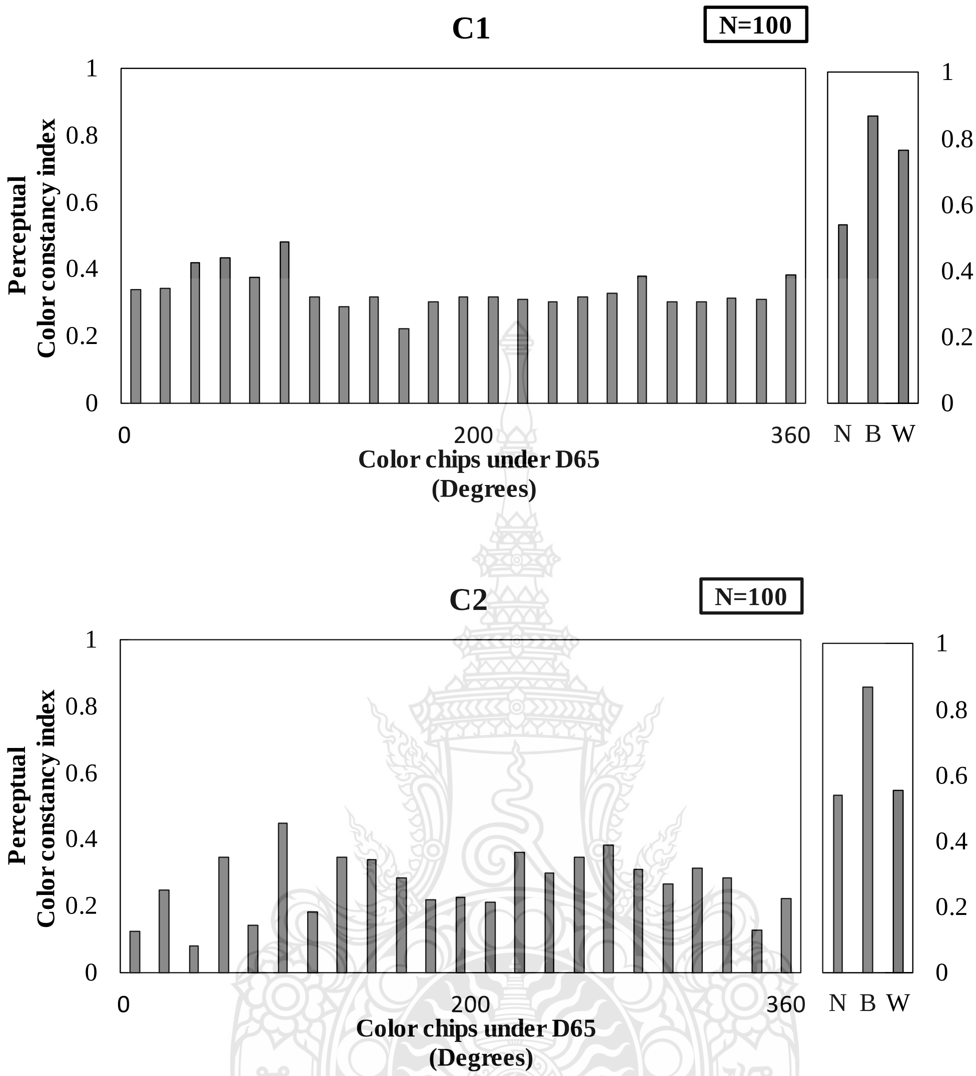
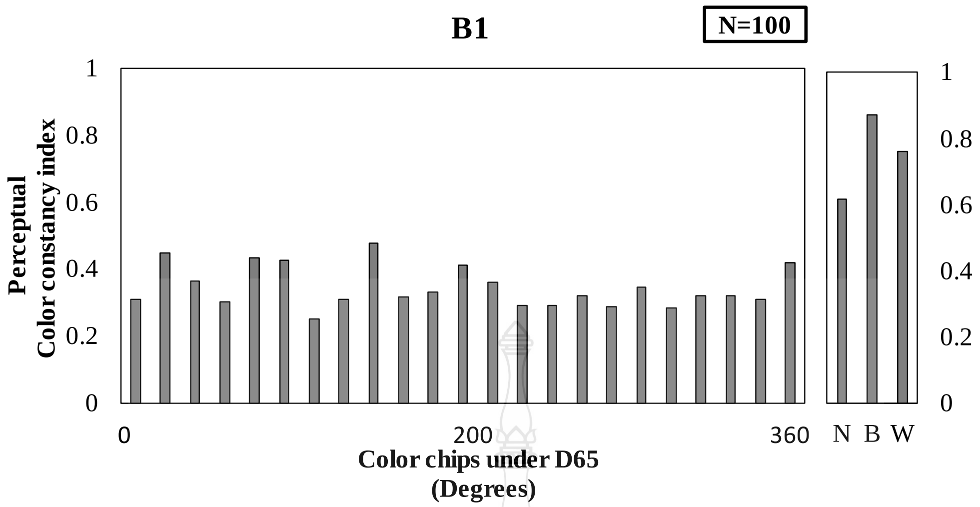



**Figure 5.4** The average perceptual constancy index of less vivid (upper) and vivid condition (below) (Cont.)



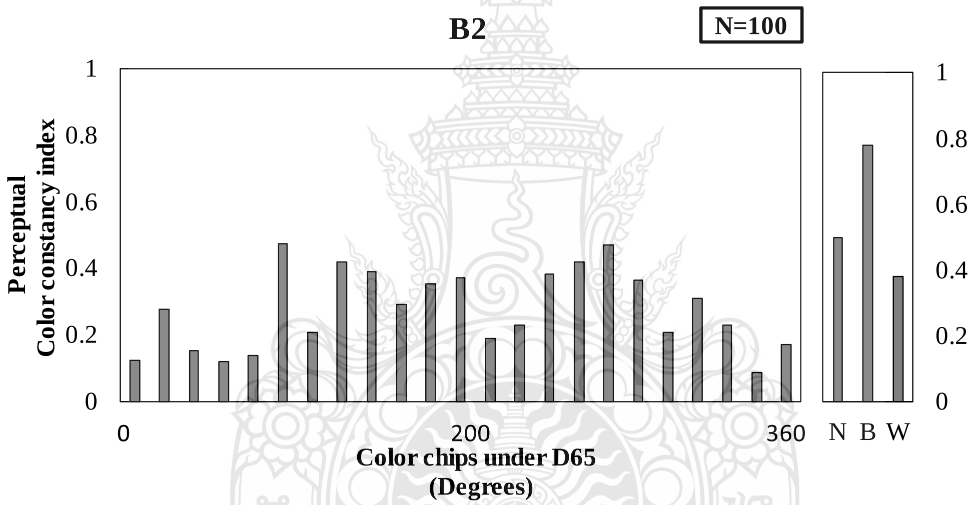
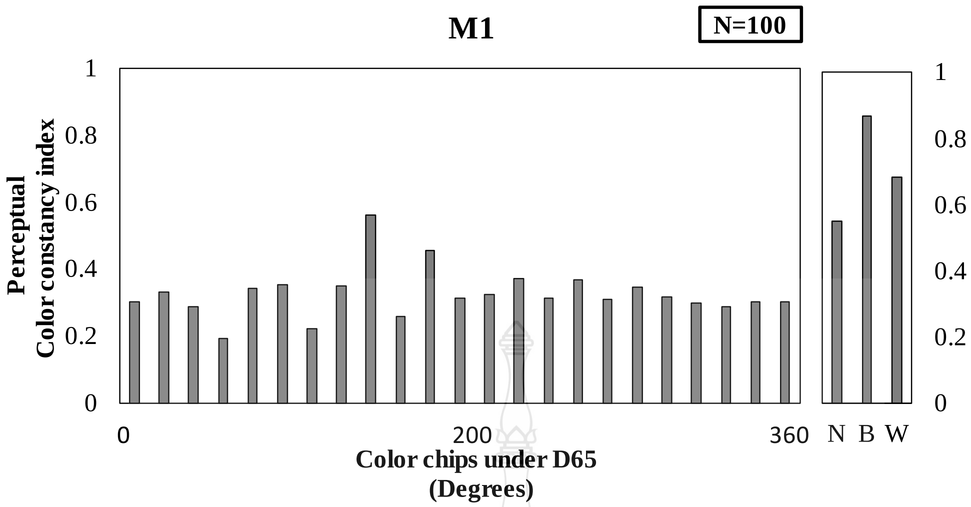




**Figure 5.4** The average perceptual constancy index of less vivid (upper) and vivid condition (below) (Cont.)



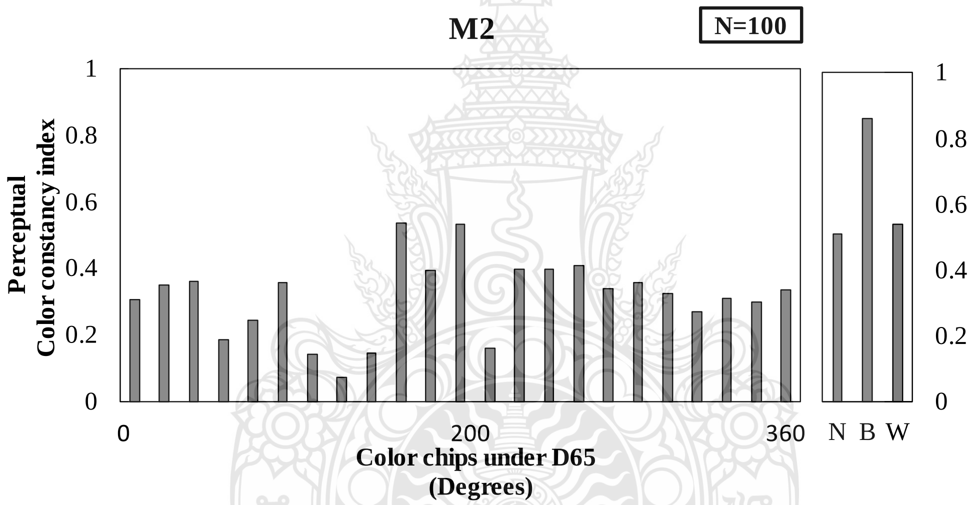




**Figure 5.4** The average perceptual constancy index of less vivid (upper) and vivid condition (below) (Cont.)

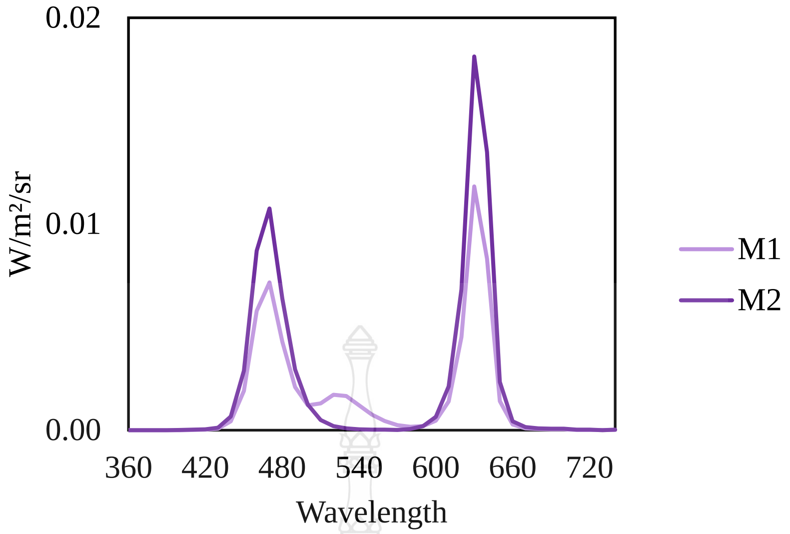



**Figure 5.5** The spectral power distribution comparison between M1 and M2 conditions

It appears that there is a trend in the lowest perceptual color constancy index, as shown in Figure 5.6. The abscissa represents the hue of illumination conditions, and the ordinate represents the hue of color appearance of color chips under D65. There are two symbols in the figure: square symbols and triangle symbols, corresponding to the less vivid and vivid illumination conditions, respectively. For the less vivid group, it is evident that the lowest color constancy index was found for the color chip with a 317 degree under yellow illumination at 77 degrees. When the illumination changed to green at 186 degrees, the lowest color constancy index still occurred for the color chip with a 317 degree. The lowest color constancy index then changed as the illumination increased and the hue of color appearance of color chips under D65 changed in a counterclockwise direction in the polar diagram. However, the trend was unclear for the vivid illumination group, as the change in color on the ordinate was quite large between illuminations from 241 degrees to 330 degrees. But before 241 degrees, a similar clockwise pattern of color appearance of color chip under D65 was still observed.

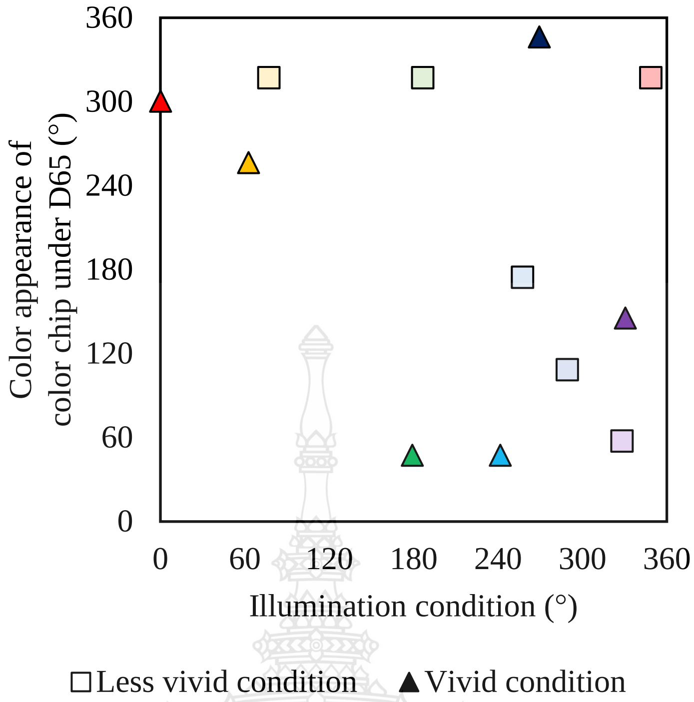



**Figure 5.6** The lowest color constancy index when the hue of illumination changed

The graph in Figure 5.7 shows the average perceptual color constancy index of all color chips under each color illumination on the ordinate axis, while the horizontal axis represents the u'v' distance from D65 illumination. This distance is the Euclidean difference between color illumination coordinates and D65 coordinates on u'v' chromaticities, as shown in Equation 5.5. In the figure, the color constancy index under cyan, yellow, and green illumination decreased abruptly compared to other color illuminations when determined by the distance away from D65.

$$u'v'distance = \sqrt{(u'_{test} - u'_{D65}) + (v'_{test} - v'_{D65})^2} \quad (5.5)$$

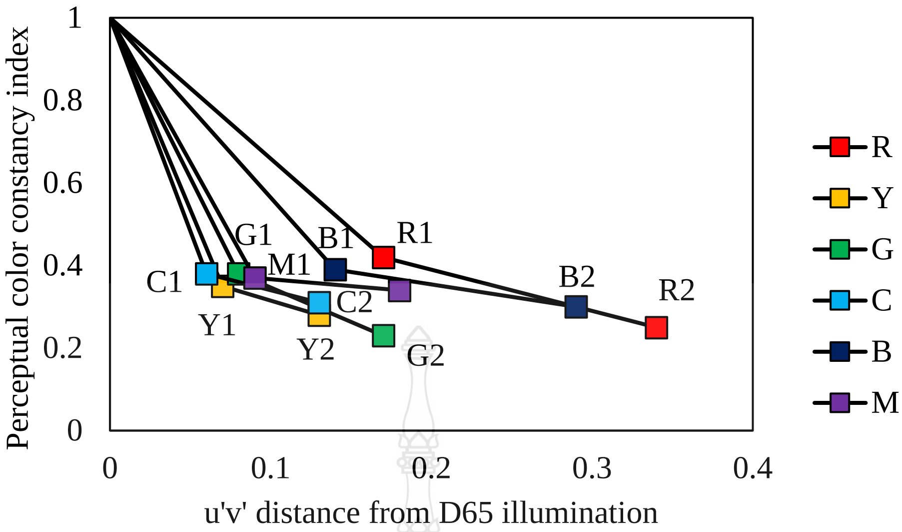



**Figure 5.7** The average result of the color constancy index of all subjects and color chips when determined by u'v' distance from D65 illumination

In this study, the saturation differences among the six colors used for illumination were not consistent. Specifically, the saturation shifts from D65 to less vivid light, and then from less vivid to vivid light, were not equal distance on u'v' color space. Figure 5.7 was used to demonstrate the rate at which the color constancy index (CCI) decreases as the light saturation increases. As illustrated in the graph, the CCIs for cyan, yellow, and green illuminations declined more rapidly than those for the other colors. This decrease was most pronounced under vivid green (G2) illumination, which registered the lowest CCI. Due to the limit of this study which had only 2 saturation steps, there might be a case in which the less saturation than our less vivid illumination condition in red (R1) that CCI would not be high as the connected line plot in this figure. However, the result showed that the higher saturation of red light still maintained the color constancy index of the less vivid illumination condition.

A similar trend of poor color constancy index was observed in the experiment conducted by Ma, Liao, Yan, and Shinomori (2018), where they studied color constancy under RGB-LEDs using the categorical color naming method. The blue illumination in their study had coordinates on the u'v' distance comparable to the cyan in this experiment, which supports the finding that color constancy under cyan and yellow illumination was lower than under other illuminations. However, in this study, it was also observed that the perceptual color constancy index under green illumination decreased rapidly, as determined by the distance in u'v' coordinates away from D65. Notably, green illumination had the lowest color constancy index among all the vivid illuminations.

## 5.5 Conclusion

In conclusion, this chapter proposes a method for calculating the color constancy index based on the polar diagram graph. The ordinary color constancy index (OCCI) and the hue constancy index (HCI) are combined to create a complete vector color constancy index in the perceptual color space represented by the polar diagram, known as the Perceptual Color Constancy Index (PCCI). The results show that the PCCI was significantly higher in the less vivid illumination condition than in the vivid illumination condition, and poor color constancy index was observed under cyan, yellow and green illuminations compared to other illuminations. Additionally, the weighting function utilized in this study represents one method of compensating for the disparity between chromaticness and lightness to achieve uniformity. However, further experiments are necessary to enhance understanding and refine this approach.

# CHAPTER 6
# GENERAL DISCUSSION AND CONCLUSION

## 6.1 General Discussion

### 6.1.1 Hue Shift Direction

In Chapter 3, the color appearance of color chips under varying illumination was presented. However, the specific hue changes of color chips under different illumination conditions were not yet shown. The illumination of color, as in the test room illumination, required the results of the experiment in Chapter 4, in which neutral color chips were judged by subjects without adapting to the illumination conditions, but rather adapting to D65 or white light instead. Understanding hue shifts would be useful for estimating the color of the color chips of interest under specific color illuminations.

In this study, it was found that under certain illumination conditions, particularly vivid ones, color chips tended to group together in a similar hue direction. The concept of hue shift direction was proposed to demonstrate which hue direction a color would shift towards under specific illumination conditions. K-means clustering analysis was employed in this study to classify the members within each hue shift direction. The analysis involved twenty-three color chips, excluding the achromatic color chip. This exclusion was due to the absence of a hue angle for achromatic color chips, and the central coordinates of these chips could potentially skew the classification results in cluster analysis. The analysis of the achromatic color chips will be conducted separately and presented later in this chapter.

To initiate the clustering method, it was necessary to firstly determine the optimal number of clusters, or K, for this study. The silhouette score, a method for evaluating the optimal number of clusters proposed by Rousseeue, P.J. (1987), was used to calculate how well the data could be organized within (Cohesion) and between groups (separation). The silhouette score ranges from 1, representing the maximum and best classification score for ideal data, to lower values that indicate that it is not appropriate to assign to its current cluster.

Figure 6.1 displays the silhouette scores for the less vivid illumination condition group. The results reveal that the highest score was achieved when K=4 across all six conditions in the group. The four clusters for each color illumination condition are illustrated in Figure 6.2, where each distinct symbol represents a difference cluster. In this figure, the black symbol, or the rightmost cluster, comprises six members, while the white symbol has four members, the dark gray symbol has six members, and the light gray symbol has seven members under the R1 condition. When the illumination condition shifted to Y1, the coordinates changed slightly, but the number of members in each cluster remained the same. However, when the illumination changed to G1, the composition of each cluster altered in a clockwise direction, with the black symbol's membership decreasing by one and the dark gray symbol's membership increasing by one. Similar changes in cluster membership also occurred under other illumination conditions, raising the question of which colors were responsible for these movements.

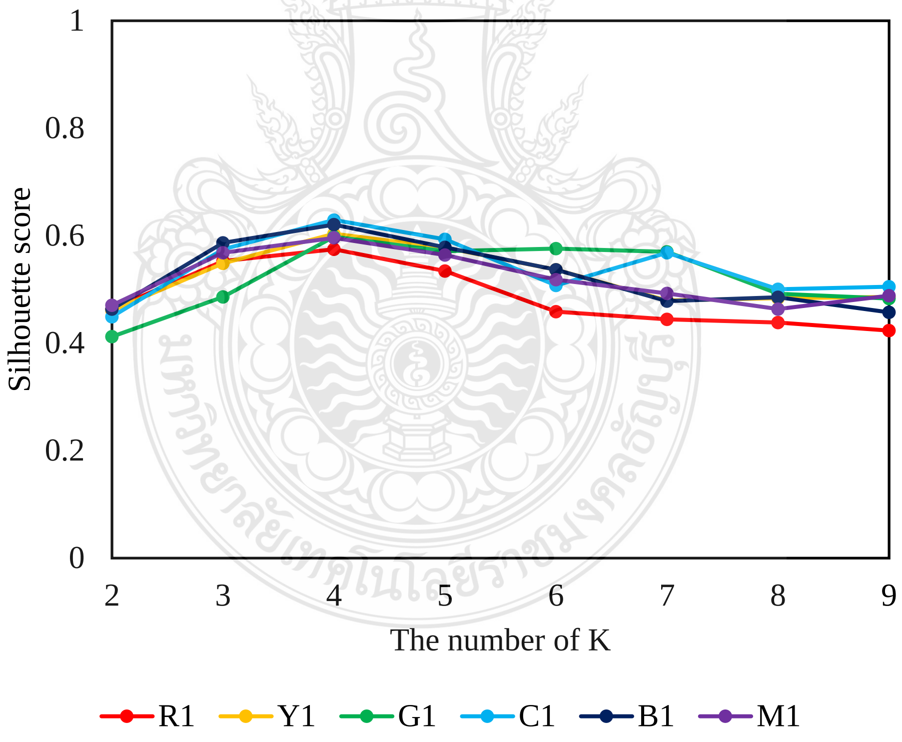



**Figure 6.1** The silhouette scores of less vivid illumination group determined by the number of K from 2 to 9

Table 6.1 presents the hue of each cluster for each color appearance under D65 in the first column, with individual less vivid illumination conditions detailed in subsequent columns. The table indicates that each row, or color chip, maintained a similar cluster grouping across different illumination conditions. For the color illumination columns, there were four distinct hue angles, positioned close to the red, yellow, green, and blue axes. For instance, under Y1 illumination, red color chips (3 degrees to 30 degrees) were classified as 4 degrees, while orange to yellow color chips (59 degrees to 97 degrees) were classified as yellow, represented by 78 degrees, and so on, as shown in the table.

The hue shift direction might vary for a color chip as illumination changes. For example, a hue of 3 degrees under D65 was categorized as 4 degrees under Y1, but the hue shift varied between 4 to 11 degrees when illumination changed. This variation could be attributed to the inherent variability in the results of elementary color naming and the subjectivity involved in judgment. However, overall, the range between 4 to 11 degrees could still be considered as maintaining similar clusters despite changes in illumination.

An anomaly was found with four color chips that did not maintain consistency when illumination changed, as shown in the table. These chips, at hue color chip under D65 at 59, 156, 242, and 304 degrees, present an anomaly that this study could not fully account for. It is likely that these color chips were particularly influenced by the illumination and their placement at the cluster boundary.

Figure 6.3 illustrates the hue of each cluster from Table 6.1 as illumination conditions change. Each line plot represents one of the clusters: red, yellow, green, and blue. The lines demonstrate stable hue clusters across various illumination conditions. The average values for each cluster line are 8, 82, 78, and 269 degrees, respectively, which are close to the unique hues on the polar diagram. This observation indicates that color chips generally maintain consistent hue clusters under different illumination conditions as color constancy mechanism occurred in the less vivid illumination conditions.

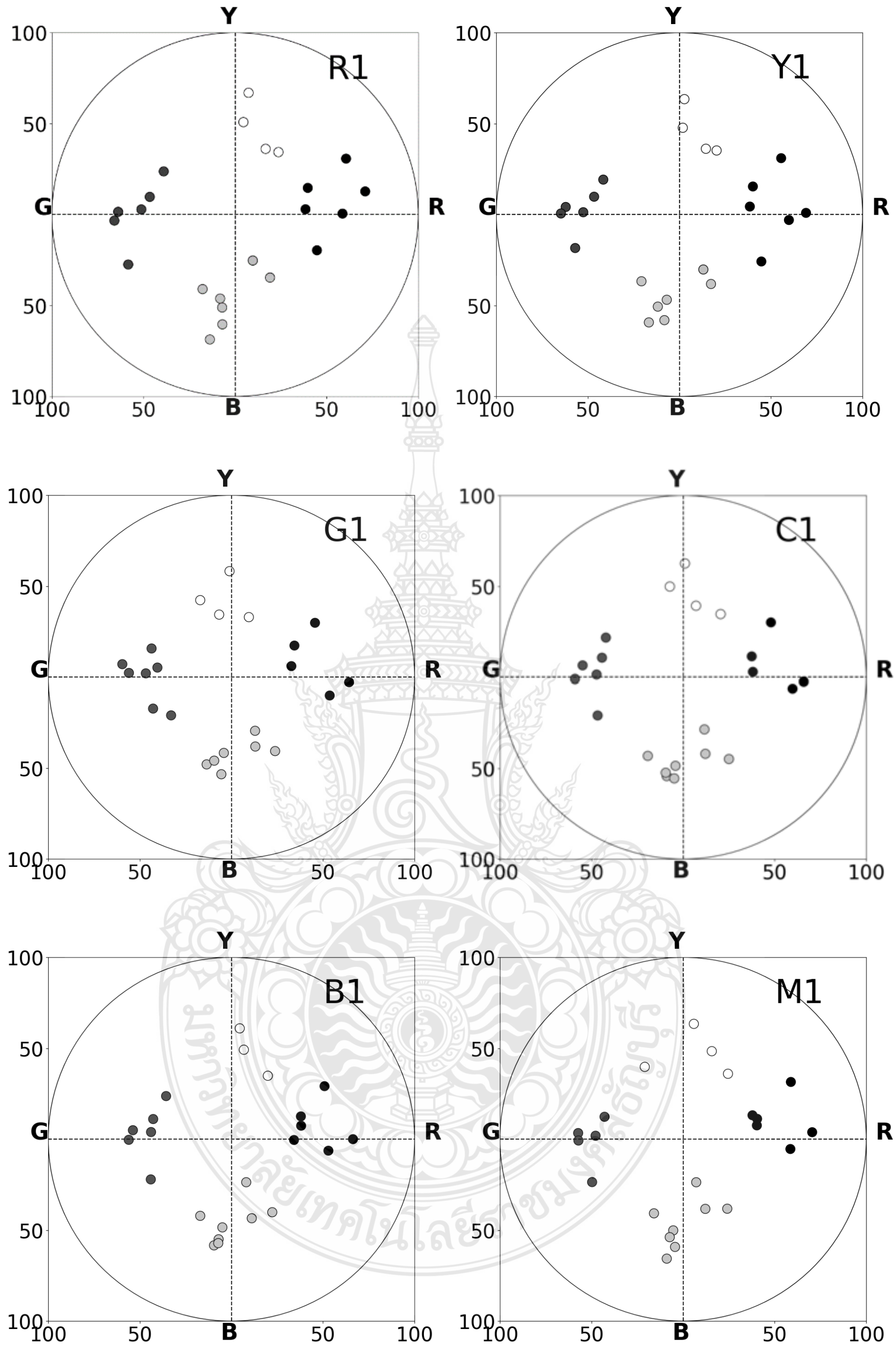



**Figure 6.2** The classification by K-mean cluster analysis of each less vivid illumination condition (Each symbol, black, white, dark grey, and light grey corresponds to a different cluster.)

**Table 6.1** The hue angles of centroid cluster of each color chip under less vivid illumination conditions

| D65(°) | Y1(°) | G1(°) | C1(°) | B1(°) | M1(°) | R1(°) |
|---|---|---|---|---|---|---|
| 3 | 4 | 10 | 8 | 9 | 11 | 8 |
| 21 | 4 | 10 | 8 | 9 | 11 | 8 |
| 30 | 4 | 10 | 8 | 9 | 11 | 8 |
| 59 | 78 | 95 | 83 | 9 | 11 | 75 |
| 71 | 78 | 95 | 83 | 78 | 82 | 75 |
| 90 | 78 | 95 | 83 | 78 | 82 | 75 |
| 97 | 78 | 95 | 83 | 78 | 82 | 75 |
| 156 | 177 | 181 | 176 | 176 | 82 | 179 |
| 168 | 177 | 181 | 176 | 176 | 181 | 179 |
| 174 | 177 | 181 | 176 | 176 | 181 | 179 |
| 178 | 177 | 181 | 176 | 176 | 181 | 179 |
| 182 | 177 | 181 | 176 | 176 | 181 | 179 |
| 199 | 177 | 181 | 176 | 176 | 181 | 179 |
| 242 | 264 | 181 | 270 | 269 | 270 | 266 |
| 257 | 264 | 273 | 270 | 269 | 270 | 266 |
| 261 | 264 | 273 | 270 | 269 | 270 | 266 |
| 262 | 264 | 273 | 270 | 269 | 270 | 266 |
| 265 | 264 | 273 | 270 | 269 | 270 | 266 |
| 289 | 264 | 273 | 270 | 269 | 270 | 266 |
| 292 | 264 | 273 | 270 | 269 | 270 | 266 |
| 304 | 4 | 273 | 270 | 269 | 270 | 8 |
| 355 | 4 | 10 | 8 | 9 | 11 | 8 |
| 359 | 4 | 10 | 8 | 9 | 11 | 8 |

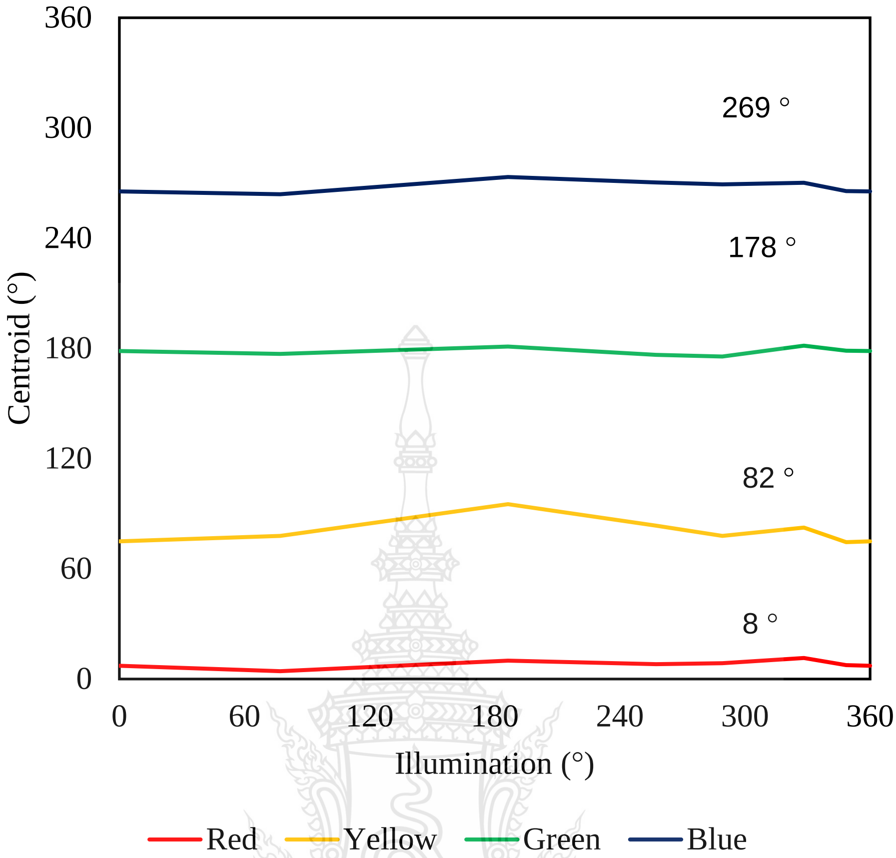



**Figure 6.3** The four clusters were determined by the hue of illumination

In addition to the less vivid illumination condition, a similar analysis process was applied to the vivid illumination condition. Figure 6.4 presents the silhouette scores for the vivid illumination group. The results reveal that the highest overall score was achieved when K=2, except for G2 and M2, where the highest scores were 5 and 3, respectively. An interesting observation from the results is that the higher number of clusters in G2 might be due to the scatter of data in the blue and magenta area. Approximately two-color chip coordinates, which were close together, scattered into three groups. This dispersion led to a higher K number when performing the K-cluster analysis. In contrast, while M2 also displayed a varying K cluster, the specific scatter coordinate pattern in M2 resulted in only K=3 under this condition.

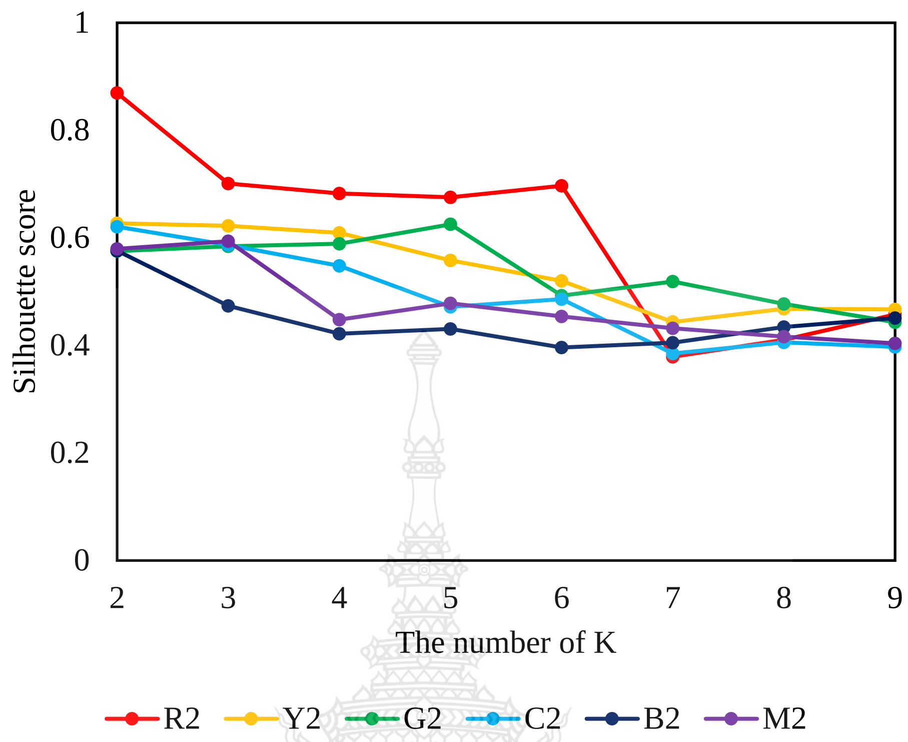



**Figure 6.4** The silhouette scores of vivid illumination group determined by the number of K from 2 to 9

Figure 6.5 demonstrates that the clusters were well organized into two distinct groups under vivid red illumination (R2), with one group leaning towards the orange side and the other towards the blue direction. In contrast, under Y2 conditions, some color chips exhibited a hue shift direction towards the green side, while others were scattered in magenta, red, and yellow directions. This clustering result may be due to the scattering of the data, resulting in larger classifications. However, the clustering of this data suggests that colors tend to shift towards either the green or red direction under Y2 conditions.

For G2, as mentioned earlier, the small number of color chips led to two color chips appearing close together on the diagram, resulting in K=5 for this study. For C2 and B2, the clustering results displayed a similar trend, with colors leaning towards either yellowish-green or blue, as these two conditions had nearby hue illuminations. Meanwhile, M2 featured three clusters: orange, green, and blue.

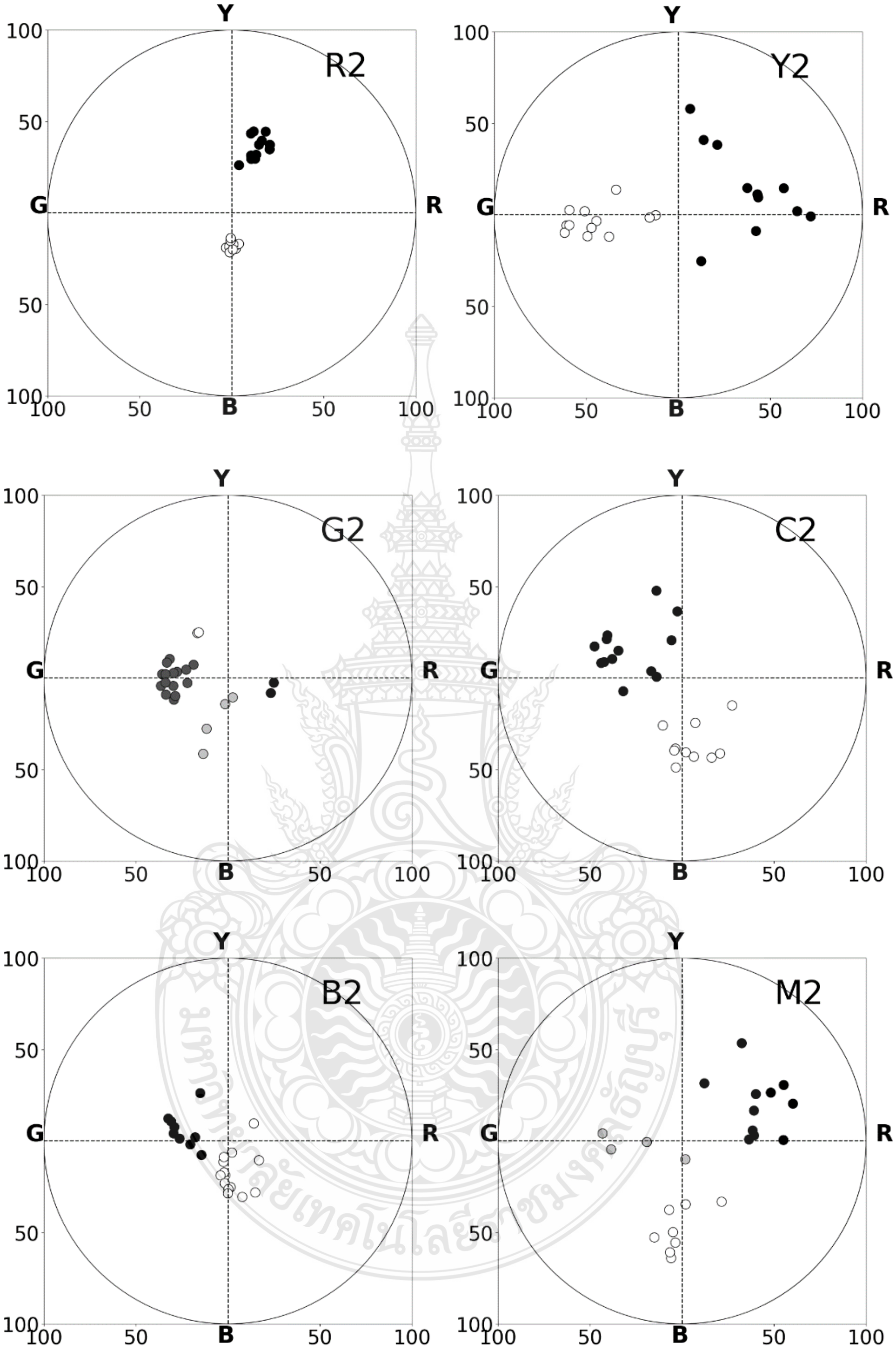



**Figure 6.5** The classification by K-mean cluster analysis of each vivid illumination condition

**Table 6.2** The hue angles of centroid cluster of each color chip under vivid illumination conditions

| D65(°) | R2(°) | Y2(°) | G2(°) | C2(°) | B2(°) | M2(°) |
|---|---|---|---|---|---|---|
| 3 | 69 | 20 | 180 | 151 | 280 | 25 |
| 21 | 69 | 20 | 180 | 151 | 280 | 25 |
| 30 | 69 | 20 | 180 | 151 | 280 | 25 |
| 59 | 69 | 20 | 123 | 151 | 280 | 25 |
| 71 | 69 | 20 | 180 | 151 | 166 | 25 |
| 90 | 69 | 20 | 123 | 151 | 166 | 25 |
| 97 | 69 | 20 | 180 | 151 | 166 | 25 |
| 156 | 69 | 184 | 180 | 151 | 166 | 25 |
| 168 | 271 | 184 | 180 | 151 | 166 | 25 |
| 174 | 271 | 184 | 180 | 151 | 166 | 186 |
| 178 | 271 | 184 | 180 | 151 | 166 | 186 |
| 182 | 271 | 184 | 180 | 151 | 166 | 186 |
| 199 | 271 | 184 | 180 | 151 | 166 | 267 |
| 242 | 271 | 184 | 180 | 279 | 280 | 267 |
| 257 | 271 | 184 | 180 | 279 | 280 | 267 |
| 261 | 271 | 184 | 180 | 279 | 280 | 267 |
| 262 | 271 | 184 | 250 | 279 | 280 | 267 |
| 265 | 271 | 184 | 250 | 279 | 280 | 267 |
| 289 | 271 | 20 | 272 | 279 | 280 | 267 |
| 292 | 69 | 184 | 180 | 279 | 280 | 267 |
| 304 | 69 | 20 | 272 | 279 | 280 | 267 |
| 355 | 69 | 20 | 348 | 279 | 280 | 25 |
| 359 | 69 | 20 | 348 | 279 | 280 | 25 |

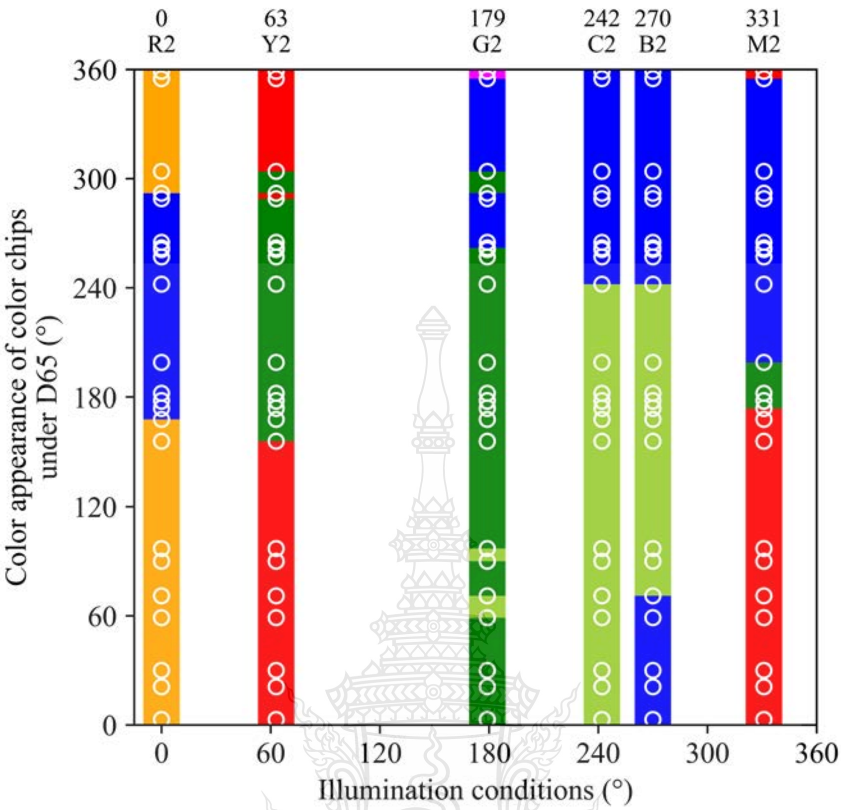



**Figure 6.6** The color scheme represents the relationship between the illumination conditions and the color appearance of color chip under D65

Figure 6.6 illustrates the relationship between the illumination conditions on the abscissa axis and the color appearance of color chips under D65 on the ordinate axis. Each color bar within the figure corresponds to a specific cluster for each illumination condition, with an open circle inside the bar which corresponds to the color chip under D65. The visualization in the figure highlights the trends of how each color chip under D65 changes under various color illumination conditions.

Furthermore, the differing silhouette scores of Figures 6.4 result in hue shift direction movements, as shown in Figure 6.6. For example, a color chip with a hue of 304 degrees under D65 appears orange under R2 conditions and shifts in a clockwise direction to appear red under Y2 conditions, ultimately shifting to blue under other conditions. Meanwhile, a color chip with a hue of 359 degrees under D65 appears magenta under G2 conditions, similar to the boundary color in the less vivid illumination group. This demonstrates that the hue shift direction is not stable for boundary colors. However, the boundary color threshold couldn't be confirmed by this study since the limit of color chip numbers.

Figure 6.6 indicates that blue and green clusters have a significant impact on hue shift direction clustering. Under each vivid illumination condition, there's consistently a blue or green hue shift direction. For instance, in R2, only a blue cluster is present as green is its opponent color. In the same vein, Y2 shows a green cluster due to blue being its opponent color. For other colors, blue and green clusters were often represented in multiple illumination scenarios. The reason for the frequent occurrence of blue and green clusters is not explicitly defined in this study and needs further research to find out.

Figure 6.7 illustrates the hue shifts of achromatic color chips, including black, neutral (gray), and white, under varying color illumination conditions. The white, gray, and black color chips are represented by white, gray, and black circles, respectively. The dashed line in the figure indicates the color chip's hue shift in response to changes in the color of illumination. The results show that white and gray color chips tend to shift their hue according to the color of illumination, while the black color chip remains relatively stable, appearing blue across the illumination changes. As a black color chip tended to not reflected much information of color light to the subject's eye and the chromatic adaptation in the vivid illumination might affect to the only blue color appearance to this color chip as blue also closed to dark color. A correlation coefficient analysis was performed to quantify the relationship between the color chips and the color illumination. The white color chip exhibited the highest correlation coefficient of 0.98, followed by the gray color chip at 0.93. The black color chip showed the lowest correlation, with a coefficient of 0.44, indicating that its hue remains mostly unaffected by changes in the color of illumination.

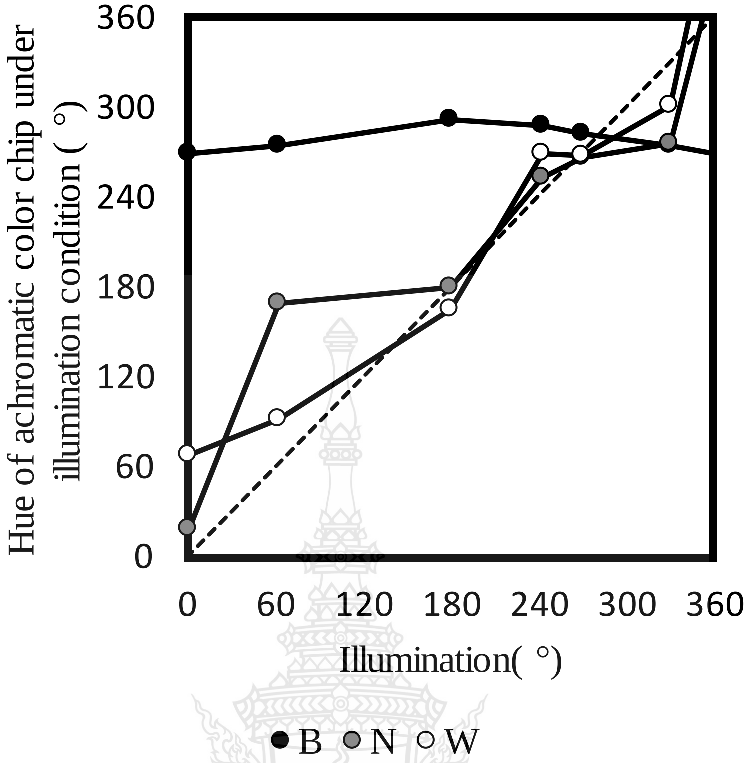



**Figure 6.7** The hue of an achromatic color chip changes under different illumination conditions

In this study, it was found that color chips tend to group together in a similar hue direction under specific illumination conditions, with the hue shift direction displaying inconsistencies across various conditions. The results from the less vivid illumination group demonstrated stable hue clusters, indicating that color constancy mechanisms are effective under these conditions. In contrast, the vivid illumination group exhibited less stable hue shift directions. The study also identified two common hue shift directions under vivid illumination, typically resulting in either green or blue color appearances. Further research could help elucidate the underlying mechanisms and thresholds involved in hue shift directions, which can ultimately benefit applications such as color estimation under specific illumination conditions and improving color constancy algorithms.

6.1.2 Color Density and Hue Shift Direction

The hue shift direction was analyzed based on the combination of ink density, as color chips were reproduced using CMYK colorants, with a focus on cyan, magenta, and yellow inks in this study. Each color chip was measured using a Techkon D-61462 spectro densitometer, and the results are presented in Table 6.3. The table reveals a relationship between color illumination and color pigment density concerning the hue shift direction, as proposed earlier in the previous section. For instance, a color chip with a higher density of cyan (C) pigment under red illumination, which are complementary colors (red being an additive color and cyan being a subtractive color), results in a higher cyan density (more than 0.63 in this case), affecting the hue shift direction towards a blue appearance as shown in Table 6.4. In this study, the hue shift direction of the complementary color of the color pigment to the color light is referred to as the major color, while the minor color refers to another hue shift direction, such as yellow. The same pattern can be observed under yellow illumination, which is complementary to blue. Color chips with a higher combination of cyan and magenta pigments (with densities of more than 0.41 and 0.31, respectively) tend to shift towards the major color, green, while others appear to be red. Similar results are observed under other illumination conditions, as displayed in Table 6.4. These findings demonstrate that the relationship between color illumination and color pigment density plays a significant role in influencing the hue shift direction.

This study also sought to analyze the results of color pigment based on the relationship between additive and subtractive color. We accomplished this by converting the subtractive color of the pigment into additive color to facilitate a comparison with color light. Pigment amounts were classified based on density, with values over 0.5 deemed strong. As shown in Figure 6.8 as the relationship between subtractive color of color density to color additive. Subsequently, the converted pigment was examined for complementary effects and light adaptation, and the resulting values were used to predict color. For instance (as depicted in Figure 6.9), under Y2 illumination, a color chip with a color appearance equal to 355 degrees under D65 had a pigment value of 0.19, 0.97, and 0.63 corresponding to CMY. The transformation from subtractive to additive color resulted in gb, RB, RG (with capital letters indicating strong values). Under vivid yellow light, which is complementary to blue, the b value was reduced to the point of disappearance, leaving only g,Rb and RG. After light adaptation, the power of RG reduced, leaving g, Rb, and rg, which can be predicted as red as only Rb in Magenta still had a large power. This prediction aligned with the study's results. This trend was also apparent in other results, as shown in Appendix F. However, it is important to note that this analysis is not applicable to all color chips and light conditions. Future research is needed to delve into these effects. From this preliminary analysis, it appears that complementary color and light adaptation may influence the hue shift in color appearance in this study.

**Table 6.3** Color pigment density measured by the Spectro-densitometer

| Color appearance under D65 (°) | C | M | Y | K |
|---|---|---|---|---|
| 3 | 0.31 | 0.57 | 0.61 | 0.45 |
| 30 | 0.15 | 0.77 | 1.06 | 0.41 |
| 59 | 0.07 | 0.28 | 0.42 | 0.18 |
| 90 | 0.06 | 0.2 | 0.82 | 0.14 |
| 71 | 0.37 | 0.56 | 0.85 | 0.49 |
| 97 | 0.32 | 0.51 | 1.27 | 0.42 |
| 174 | 0.73 | 0.32 | 1.02 | 0.5 |
| 178 | 0.64 | 0.4 | 0.77 | 0.52 |
| 199 | 1.12 | 0.33 | 0.48 | 0.6 |
| 182 | 1.03 | 0.58 | 1.05 | 0.77 |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 |
| 242 | 0.63 | 0.43 | 0.46 | 0.53 |
| 261 | 0.7 | 0.43 | 0.27 | 0.56 |
| 262 | 0.72 | 0.48 | 0.23 | 0.6 |
| 292 | 0.49 | 0.51 | 0.23 | 0.52 |
| 257 | 1.2 | 0.31 | 0.2 | 0.59 |
| 265 | 1.36 | 0.84 | 0.47 | 1.09 |
| 304 | 0.38 | 0.73 | 0.31 | 0.56 |
| 156 | 0.41 | 0.4 | 0.93 | 0.42 |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 |
| 262 | 0.72 | 0.48 | 0.23 | 0.6 |
| 358 | 0.31 | 1.49 | 1.09 | 0.66 |

**Table 6.4** Color pigment density and the major and minor hue shift direction

| Light Condition | C | M | Y | Hue shift Major | Hue shift Minor |
|---|---|---|---|---|---|
| Red | >0.63 | | | Blue | Yellow |
| Yellow | >0.41 | >0.31 | | Green | Red |
| Green | | >0.97 | | Magenta | Green & Blue |
| Cyan | | <0.43 | >0.42 | Green | Blue |
| Blue | | <0.77 | >0.48 | Green | Blue |
| Magenta | >0.38 | | <0.42 | Green & Blue | Red |

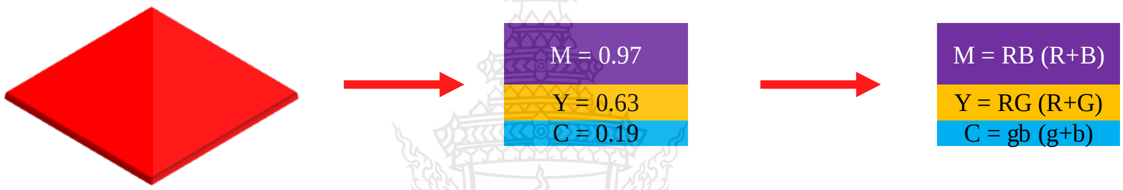



**Figure 6.8** The example diagram of convert the color density to additive color

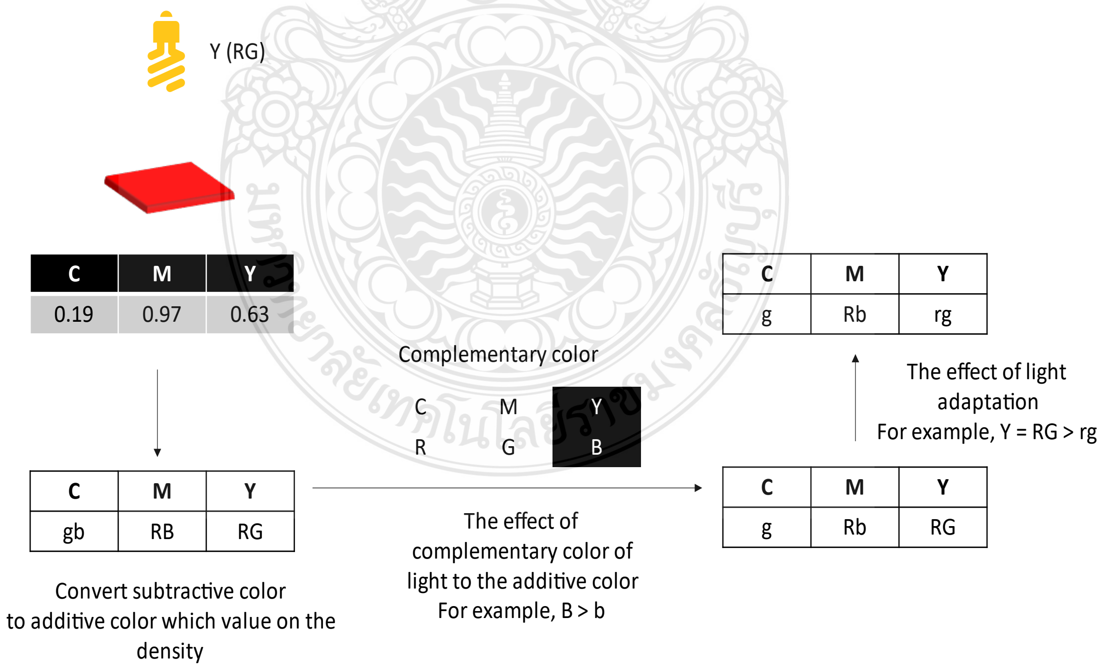



**Figure 6.9** The diagram of complementary color and illumination effect

6.1.3 Area Ratio

Previous studies (Pipornpong, Phuangsuwan, and Ikeda, 2017; Panitanang, Phuangsuwan, and Ikeda,2018) employed similar methodologies to examine the color appearance of color chips under various illumination conditions. These studies generally compared the area between the set of color appearances under test illumination and the set under reference illumination, such as white light. This comparison yielded an area ratio, which represents the proportionate area under the light condition relative to the reference illumination. The area ratio obtained in this way provides an estimate of the quantitative color area as determined by the white light. However, several factors need consideration when deriving this area. These include the quantity of color stimuli, and the method of delineating the area, which is typically done counterclockwise based on the hue appearance under D65. Further, the area ratio alone cannot confirm that the color appearances under test and reference conditions have the same coordinates. For example, if the test area is an ellipse, with its farthest points directed towards blue and yellow, and the reference is also an ellipse, but its farthest points are directed towards the green and red axes, these ellipses may have the same area, resulting in an area ratio of 1. However, they do not have the same color appearance. Nevertheless, the area ratio does provide a means to gauge the magnitude of the quantitative change in response to the test illumination.

In this study, the area of each illumination condition was calculated using the shoelace formula (Braden, 1986). The area quantification for each illumination condition is presented in Table 6.5. The table consists of four columns: illumination condition, u'v' distance, area, and area ratio. The u'v' distance is calculated based on the Euclidean distance between the test illumination coordinates and the coordinates of D65 on the u'v' color space. The third column, area, is calculated using the shoelace method. Lastly, the area ratio column represents the proportion of the test area compared to the D65 reference area, with 1 indicating that the test area is equal to the D65 area. Figure 6.10 shows the example of illustrate area of color appearance under D65 of present study.

Pipornpong, Phuangsuwan, and Ikeda (2017) conducted a study examining 11 color chips under five color illumination conditions, including the white light D65. A comparison between their results and the present study is shown in Figure 6.11. In this figure, the area ratio from the present study is represented by square symbols connected by a solid line, while circle symbols connected by a dashed line represent the results from the previous research. In the less vivid illumination conditions of their study, both red and blue illuminations exhibited area ratios greater than 1. This could be attributed to the selection and number of color chips used in their research. However, the present study also found the highest area ratio under the less vivid red illumination (R1), which is similar to the findings of Pipornpong, Phuangsuwan, and Ikeda (2017). Both experiments displayed similar results in the case of vivid red and green illumination conditions, with area ratios almost overlapping in their respective positions, as illustrated in Figure 6.11. This suggests that there is a degree of consistency in the findings between the two studies, particularly when it comes to vivid red and green illumination conditions and their effects on the area ratio of color chips.

Panitanang, Phuangsuwan, and Ikeda (2018) conducted a study focusing on red illumination, where they divided the saturation of red illumination into nine steps, ranging from less vivid to vivid red illumination. They used a similar methodology and color stimuli as those employed by Pipornpong and colleagues in their previous research. A comparison between the two experiments is shown in Figure 6.12 with similar symbols.

The area ratio in the present experiment aligns closely with the results of Panitanang's experiment, as depicted by the dashed line in Figure 6.12. This demonstrates a level of consistency between the two studies. Additionally, Panitanang's experiment revealed a trend of decreasing area ratio as saturation increased for the higher saturation steps. The correspondence between the results of the two experiments indicates that the methodologies and stimuli used in both studies provide consistent findings, particularly in terms of the area ratio's response to changes in saturation for red illumination conditions.

This study used the shoelace formula to calculate the area of each color illumination condition and compared it to a reference illumination. The area ratio column represented the proportion of the test area compared to the D65 reference area. The study found a degree of consistency in the findings between their study and previous studies, particularly when it comes to vivid red and green illumination conditions and their effects on the area ratio of color chips. The comparison of two experiments focusing on red illumination revealed a trend of decreasing area ratio as saturation increased for the higher saturation steps, and the methodologies and stimuli used in both studies provide consistent findings.

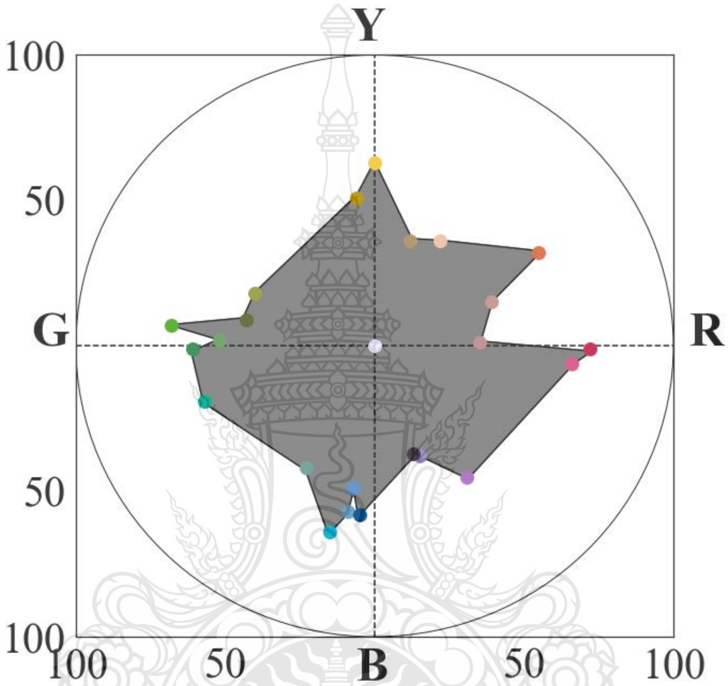



**Figure 6.10** Average area result under the D65 condition (Each plot was connected by order of average result under the D65 condition.)

**Table 6.5** This table displays the area information regarding the color perception under test illumination

| Illumination condition | u'v' distance | Area | Area Ratio |
|---|---|---|---|
| D65 | 0 | 8085.43 | 1.00 |
| R1 | 0.17 | 7559.40 | 0.93 |
| R2 | 0.34 | 119.26 | 0.01 |
| Y1 | 0.07 | 7230.09 | 0.89 |
| Y2 | 0.13 | 3588.70 | 0.44 |
| G1 | 0.08 | 6143.73 | 0.76 |
| G2 | 0.17 | 987.83 | 0.12 |
| C1 | 0.06 | 7201.71 | 0.89 |
| C2 | 0.13 | 2003.38 | 0.25 |
| B1 | 0.14 | 6242.01 | 0.77 |
| B2 | 0.29 | 529.61 | 0.07 |
| M1 | 0.09 | 6887.02 | 0.85 |
| M2 | 0.18 | 4265.90 | 0.53 |

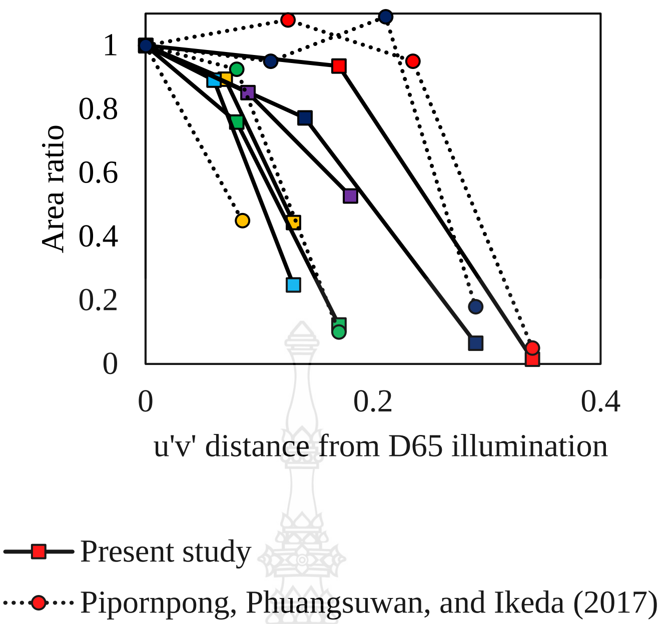



**Figure 6.11** The area ratio comparison between present study (the square symbol and solid line) and Pipornpong, Phuangsuwan, Ikeda (the circle symbol and dashed line)

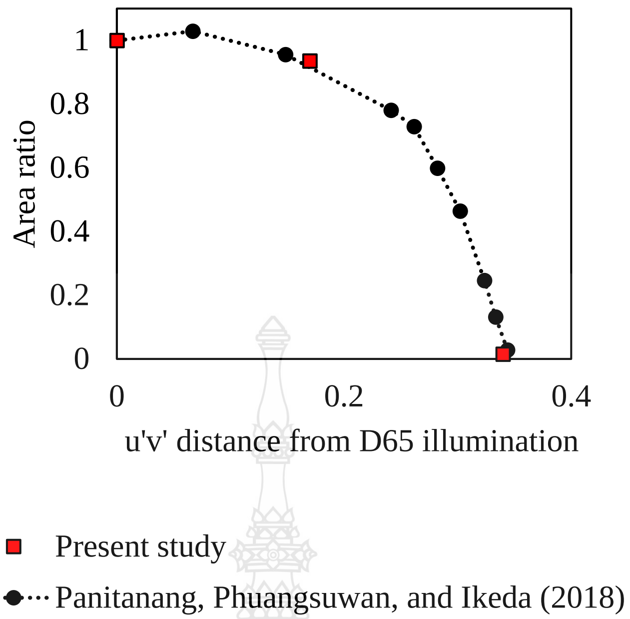



**Figure 6.12** The area ratio comparison between present study (the square symbol and solid line) and Panitanang, Phuangsuwan, Ikeda (the circle symbol and dashed line)

6.1.4 Corresponding Color to CIECAM02

CIECAM02, the CIE Color Appearance Model 2002, is a model that describes how colors are perceived by humans using mathematical correlates calculated through a set of equations. In this study, the hue angle calculated by CIECAM02 is compared to the hue obtained in the color naming results to evaluate the correspondence of CIECAM02 in predicting the color appearance of color chips under various illumination conditions.

To compare the results between the two different color spaces, it is essential to ensure that the unique hues are as close to each other as possible. In a polar diagram, unique hues are situated along the axes at 0, 90, 180, and 270 degrees, corresponding to unique red, yellow, green, and blue hues, respectively. However, the unique hues in CIECAM02 are positioned at different angles (Moroney, Fairchild, Hunt, Li, Lua, & Newman,2002): 20.14, 90, 164.25, 237.53, and 380.14 degrees, corresponding to the same order of unique hues as in the polar diagram.

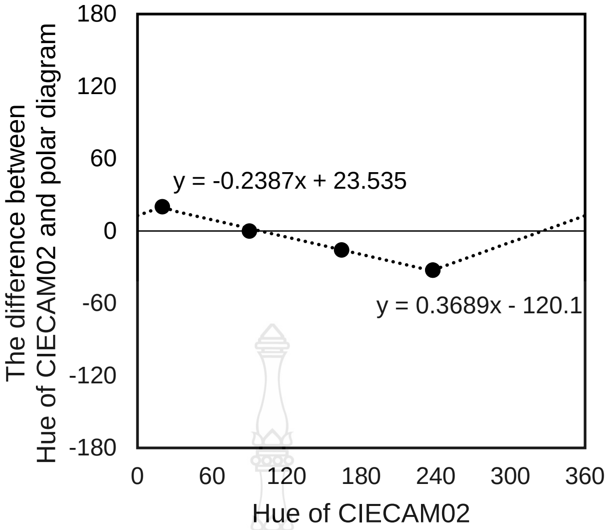



**Figure 6.13** The difference between unique hue of CIECAM02 – unique hue of polar diagram

In order to compare the unique hues of CIECAM02 and the polar diagram, the differences between their unique hues are calculated by subtracting the unique hues of the polar diagram from those of CIECAM02. This allows us to assess the characteristics of the differences between these color spaces.

Figure 6.13 presents a plot of CIECAM02 hues against the hue differences, and the data is fitted using linear regression. Two distinct regression lines are observed: For CIECAM02 hues ranging from 20 degrees to 237.63 degrees, the hue difference (H.D.) can be calculated using the following equation: $H.D. = -0.2387(hue_{CIECAM02}) + 23.535$. For CIECAM02 hues greater than 237.63 degrees and below 20 degrees, the hue difference (H.D.) can be calculated using this equation: $H.D. = 0.3689(hue_{CIECAM02}) - 120.1$.

The comparison of hue angles between the present study and CIECAM02 is shown in Table 6.6. For some color chips, the angles are quite close, while for others, they differ significantly. To better understand these differences across various illumination conditions, the root mean square error (RMSE) is used as a measure. Lower

RMSE values indicate closer agreement between the present study and CIECAM02 predictions, while higher values suggest larger discrepancies between the methods under specific illumination conditions.

The correspondence of estimating hue for color chips under each illumination condition, as predicted by CIECAM02, was calculated using Equation 6.1 in this study. This equation is based on the concept of RMSE for the illumination conditions of interest. A lower error value, such as 0, indicates a perfect prediction with a correspondence of 100%. Conversely, a higher error value, corresponding to the opposite degree on the polar diagram, suggests poor prediction with a correspondence of 0%.

$$\text{Correspondence} = \left(1 - \left(\frac{\text{RMSE}}{180}\right)\right) \times 100 \qquad (6.1)$$

The correspondence calculation results are displayed in Figure 6.14, which presents a bar graph with color illumination conditions on the abscissa and correspondence on the ordinate. The upper panel represents less vivid illumination conditions, while the lower panel represents vivid illumination conditions. The results show that the CIECAM02 model can predict the hue of the present study with more than 80% correspondence for less vivid illumination conditions. However, for vivid illumination conditions, the model's prediction correspondence is lower, particularly for R2 (only 48% correspondence) and B2, where CIECAM02 fails to predict hue for some color chips, as shown in Table 6.7. Despite this, CIECAM02 still predicts hues with over 80% correspondence for green and cyan illumination conditions. The lower correspondence of CIECAM02's predictions indicates that the model requires further improvements in its mathematical framework to accurately predict hues under vivid illumination conditions.

**Table 6.6** The comparison hue of precent color naming and calculated CIECAM02

| R1 | | Y1 | | G1 | |
|---|---|---|---|---|---|
| Present | CIECAM02 | Present | CIECAM02 | Present | CIECAM02 |
| 4 | 2 | 7 | 2 | 11 | 22 |
| 20 | 9 | 21 | 9 | 27 | 34 |
| 27 | 12 | 29 | 12 | 33 | 20 |
| 55 | 14 | 60 | 14 | 74 | 49 |
| 65 | 27 | 68 | 27 | 101 | 70 |
| 84 | 49 | 88 | 49 | 91 | 86 |
| 85 | 48 | 88 | 48 | 112 | 83 |
| 149 | 81 | 155 | 81 | 160 | 112 |
| 168 | 71 | 168 | 71 | 173 | 113 |
| 179 | 163 | 176 | 163 | 173 | 143 |
| 177 | 157 | 179 | 157 | 177 | 146 |
| 183 | 174 | 179 | 174 | 178 | 153 |
| 205 | 206 | 198 | 206 | 202 | 190 |
| 247 | 207 | 241 | 207 | 213 | 192 |
| 259 | 229 | 254 | 229 | 254 | 233 |
| 262 | 250 | 257 | 250 | 258 | 247 |
| 260 | 264 | 262 | 264 | 264 | 263 |
| 263 | 261 | 262 | 261 | 264 | 263 |
| 291 | 347 | 293 | 347 | 294 | 327 |
| 299 | 314 | 294 | 314 | 289 | 284 |
| 336 | 342 | 330 | 342 | 300 | 322 |
| 0 | 356 | 357 | 356 | 349 | 351 |
| 10 | 359 | 1 | 359 | 358 | 356 |

**Table 6.6** The comparison hue of precent color naming and calculated CIECAM02 (Cont.)

| C1 | | B1 | | M1 | |
|---|---|---|---|---|---|
| Present | CIECAM02 | Present | CIECAM02 | Present | CIECAM02 |
| 4 | 2 | 359 | 351 | 11 | 358 |
| 17 | 18 | 11 | 358 | 16 | 7 |
| 32 | 17 | 30 | 10 | 28 | 12 |
| 59 | 29 | 18 | 4 | 19 | 11 |
| 80 | 56 | 60 | 30 | 56 | 29 |
| 89 | 79 | 86 | 61 | 85 | 55 |
| 98 | 77 | 82 | 60 | 72 | 54 |
| 153 | 105 | 146 | 91 | 118 | 88 |
| 167 | 106 | 165 | 88 | 164 | 80 |
| 173 | 141 | 175 | 147 | 177 | 159 |
| 178 | 147 | 175 | 158 | 178 | 160 |
| 181 | 154 | 180 | 166 | 181 | 173 |
| 204 | 198 | 207 | 212 | 205 | 208 |
| 246 | 212 | 248 | 236 | 249 | 220 |
| 261 | 239 | 261 | 241 | 262 | 232 |
| 260 | 257 | 263 | 260 | 262 | 253 |
| 265 | 268 | 264 | 267 | 264 | 265 |
| 265 | 265 | 263 | 261 | 266 | 260 |
| 292 | 321 | 289 | 320 | 287 | 339 |
| 286 | 286 | 284 | 286 | 288 | 300 |
| 299 | 319 | 299 | 320 | 302 | 335 |
| 354 | 349 | 353 | 349 | 355 | 354 |
| 358 | 355 | 0 | 355 | 3 | 359 |

**Table 6.6** The comparison hue of precent color naming and calculated CIECAM02 (Cont.)

| R2 | | Y2 | | G2 | |
|---|---|---|---|---|---|
| Present | CIECAM02 | Present | CIECAM02 | Present | CIECAM02 |
| 59 | 349 | 12 | 357 | 173 | 180 |
| 68 | 349 | 15 | 358 | 168 | 166 |
| 68 | 347 | 14 | 357 | 159 | 109 |
| 76 | 351 | 61 | 360 | 122 | 154 |
| 67 | 351 | 21 | 4 | 175 | 156 |
| 75 | 352 | 84 | 14 | 124 | 135 |
| 67 | 349 | 71 | 12 | 162 | 133 |
| 72 | 352 | 158 | 67 | 166 | 152 |
| 272 | 350 | 186 | 51 | 186 | 164 |
| 261 | 83 | 178 | 196 | 177 | 167 |
| 281 | 3 | 178 | 193 | 177 | 174 |
| 268 | 129 | 186 | 201 | 184 | 178 |
| 270 | 173 | 185 | 210 | 187 | 198 |
| 278 | 357 | 184 | 206 | 188 | 194 |
| 266 | 180 | 189 | 217 | 202 | 222 |
| 266 | 2 | 189 | 222 | 195 | 219 |
| 276 | 357 | 198 | 230 | 247 | 230 |
| 268 | 349 | 193 | 236 | 253 | 244 |
| 273 | 348 | 296 | 353 | 284 | 216 |
| 81 | 353 | 181 | 332 | 199 | 229 |
| 69 | 347 | 348 | 350 | 265 | 259 |
| 67 | 347 | 2 | 355 | 354 | 317 |
| 61 | 346 | 359 | 356 | 341 | 344 |

**Table 6.6** The comparison hue of precent color naming and calculated CIECAM02 (Cont.)

| C2 | | B2 | | M2 | |
|---|---|---|---|---|---|
| Present | CIECAM02 | Present | CIECAM02 | Present | CIECAM02 |
| 177 | 230 | 263 | - | 1 | 230 |
| 167 | 125 | 257 | - | 9 | 125 |
| 93 | 71 | 34 | - | 29 | 71 |
| 105 | 114 | 258 | - | 4 | 114 |
| 156 | 107 | 185 | 225 | 23 | 107 |
| 105 | 101 | 120 | 335 | 59 | 101 |
| 149 | 100 | 161 | 342 | 29 | 100 |
| 152 | 108 | 165 | 330 | 33 | 108 |
| 168 | 114 | 173 | - | 69 | 114 |
| 159 | 115 | 159 | - | 175 | 115 |
| 164 | 123 | 177 | - | 182 | 123 |
| 169 | 122 | 172 | 344 | 187 | 122 |
| 193 | 181 | 208 | - | 254 | 181 |
| 248 | 224 | 258 | - | 260 | 224 |
| 265 | 262 | 266 | - | 265 | 262 |
| 264 | 271 | 266 | 322 | 266 | 271 |
| 274 | 274 | 273 | - | 264 | 274 |
| 267 | 271 | 270 | - | 264 | 271 |
| 287 | 281 | 289 | - | 280 | 281 |
| 279 | 278 | 271 | - | 273 | 278 |
| 291 | 284 | 284 | 333 | 303 | 284 |
| 297 | 302 | 298 | 341 | 0 | 302 |
| 331 | 326 | 328 | 344 | 19 | 326 |

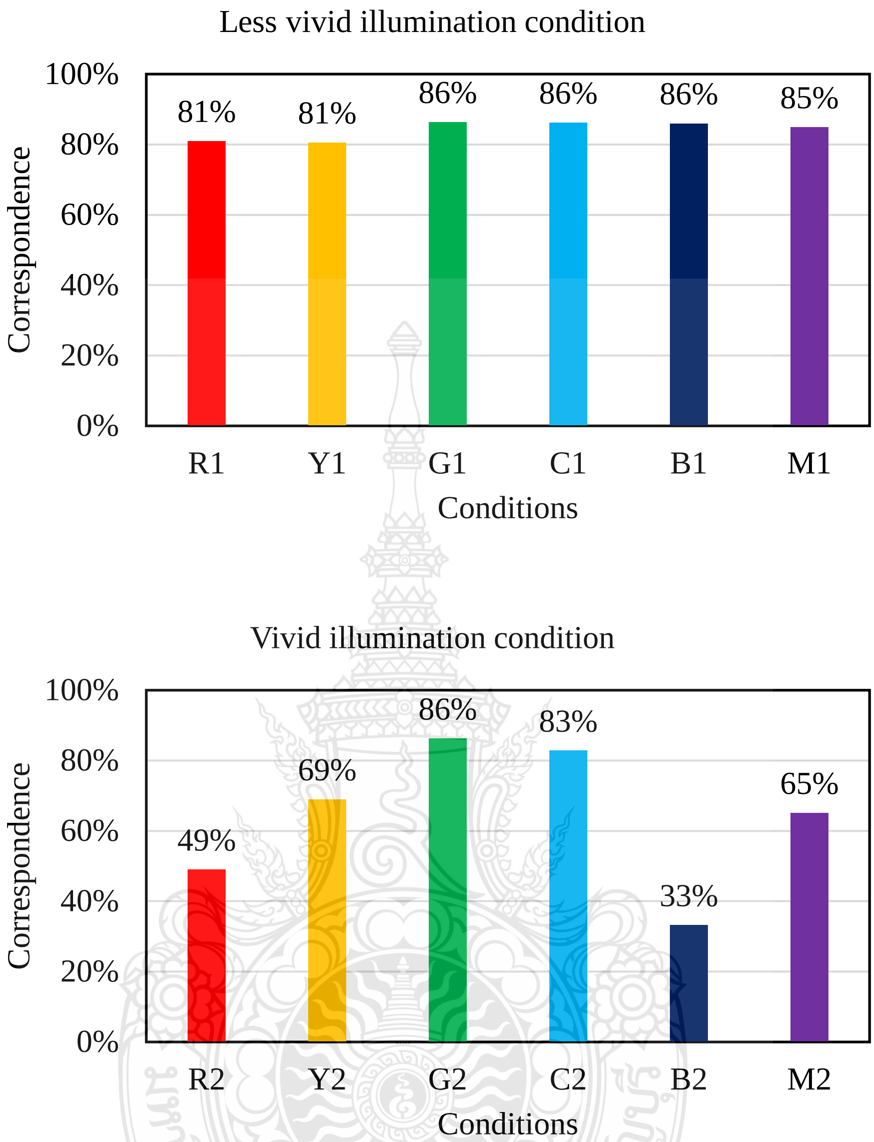



**Figure 6.14** Correspondence of hue predicted by CIECAM02

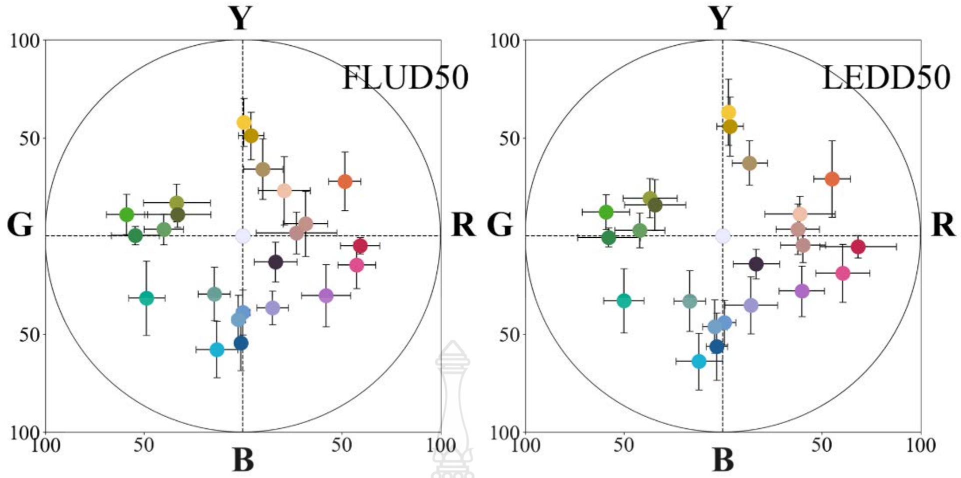
6.1.5 Metamerism

Metamerism is a phenomenon in which two objects (or, in the context of this experiment, two color chips) appear to be the same color under one type of illumination but display different colors under another type of illumination. A quantitative measure known as the metameric difference (ME) can be used to assess the degree of metamerism between two objects, as outlined by Vik, M., Viková, M., & Hes, L. (2006). This measure is calculated by taking the Euclidean distance between the CIE Lab* coordinates of the two objects under different lighting conditions. A lower index signifies greater similarity in the appearance of the two objects under diverse lighting conditions. In instances where the ME is equal to 0, it indicates a perfect match between the two objects under different illuminations. A metamerism level below 0.5 is generally considered acceptable. However, in this study, no evidence of metamerism was detected under any of the illumination conditions for any of the samples.

#### 6.1.6 The author's supplement experiments

##### 6.1.6.1 The D50 fluorescence and D50 LED

In the printing industry, not only D65 but also D50 are standard illuminations. This study conducted a similar experiment to the one comparing Fluorescent D65 and LED D65, but this time under D50 conditions. The aim was to determine whether there is a difference in color appearance under fluorescent versus LED illumination. The results from four subjects, with three repetitions each, are presented in Figure 6.15. The results showed a similarity between the two conditions. A T-test was employed to statistically evaluate any differences in the x, y, and hue values, in the same manner as for the D65 experiment. The results indicated no statistical difference as the P-values were 0.59, 0.73, and 0.68, respectively. The absence of a difference can be attributed to the color constancy function of human vision, which ensures stable color appearance under these conditions, given that both illuminations are white standard illuminations. Since no difference was found, transitioning to an LED lighting system can offer advantages to both industry and household users, such as a longer lifespan and the ability to generate a variety of color lights.




(a) (b)

**Figure 6.15** The average color appearance of color chip results under fluorescent light D50 (a) and LED D50 (b)

6.1.6.2 The Perceptual Color Constancy Between Thai and Japanese

The question of consistency in experimental results and interest in comparing outcomes across different nations led to a similar experiment being conducted as a replication at Yamagata University in Japan. The same twenty-six color chips were used in this experiment under identical illumination conditions, as shown in Figure 6.16. The illumination used in Japan was Thouslite LED cubes C15, instead of RGB-LED. The experimental booth, designed to simulate real-life situations for the subjects, was similar to the one used in Thailand, as shown in Figure 6.17. The booth was surrounded by grey fabric paper with the same Munsell N6 value as in the Thai experiment. The multi-channel LED cube was hung from the ceiling of the booth. The same color chips were placed under this light following the same procedure as in Thailand.

Additionally, the color appearance of the color chips without adaptation to the colored illumination was also investigated, as shown in Figure 6.18. In the second part of the experiment, another gray wall was added to cover the open side of the booth. The additional wall could be moved to change color chips if needed. This movable wall had an opening in the center, allowing subjects to see the color chips placed inside the booth. In the subject's position, another LED light with D65 was hung from the ceiling and illuminated the area at 100 lx, the same as in the experimental booth.

Five Japanese subjects participated in the study, each completing three repetitions. All of them were trained in elementary color naming and understood the experiment's procedure. Similar to the experiment conducted in Thailand, subjects had to adapt to the illumination for 3 minutes before judging the color appearance of color chips under the test illumination condition using the elementary color naming method. There was no time limit during the naming process, but to prevent exhaustion, subjects could only participate for 2-3 hours per day, including break time whenever the illumination condition changed.

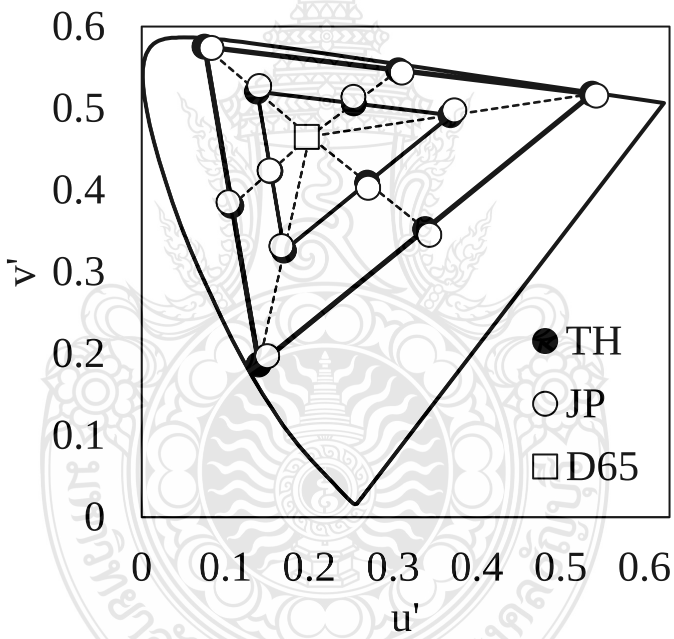



**Figure 6.16** The color illumination conditions on u’v’ color space between condition Thailand and condition in Japan

**Figure 6.17** The experimental booth of the follow-up experiment of the initial trial in Thailand was in Japan

**Figure 6.18** The experimental booth for the second repeated experiment in Japan

The Japanese results under D65 are shown in Figure 6.19. Each plot corresponds to each color chip in the study, and the results were distributed well under D65, covering various angles in the polar diagram. However, chromaticness in Japan was lower than the Thai results. A similar RMSE analysis was performed on the Japanese results, revealing that the RMSE in both less vivid illumination and vivid illumination condition groups were lower overall than the Thai results (Figures 6.20-6.21). Notably, in Figure 6.20, the RMSE in the six color illumination for each element was not much different compared to the hue element, emphasizing that hue changes the most when illumination changes under less vivid illumination. Furthermore, the Japanese RMSE results showed consistency with the Thai results, as C1 and Y1 had the lowest RMSE. Also, in the RMSE of the vivid illumination, R2, G2, and B2 had higher RMSEs, similar to the Thai results. The large values in these illumination conditions came from the main additive illumination colors on the light.

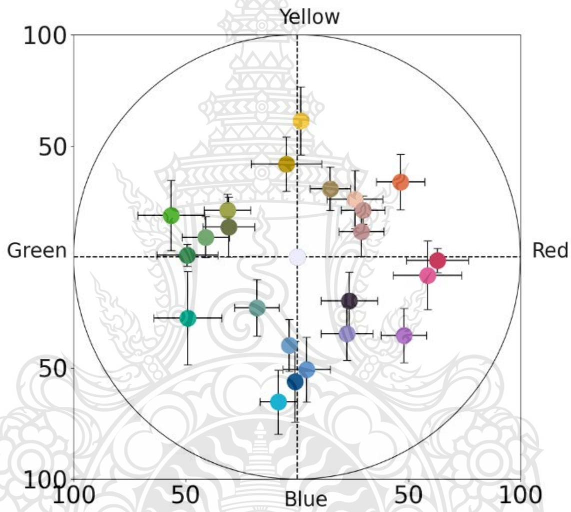



**Figure 6.19** The average naming results of Japanese observers under D65 condition

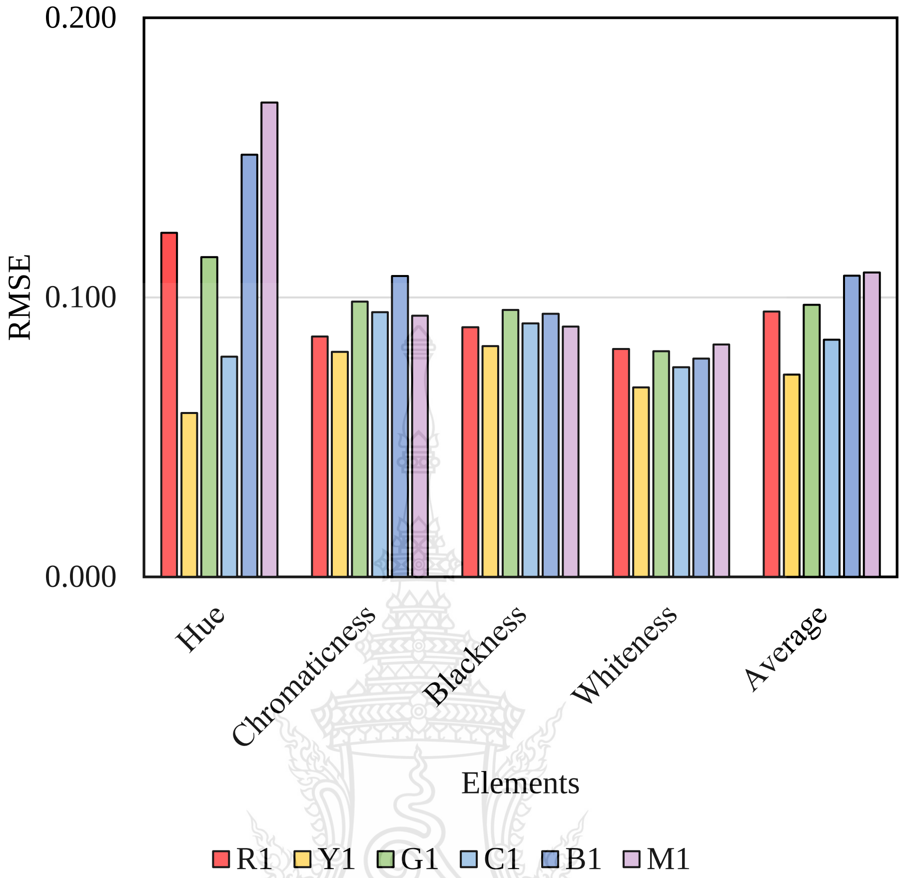



**Figure 6.20** RMSE of the less vivid illumination condition in Japan

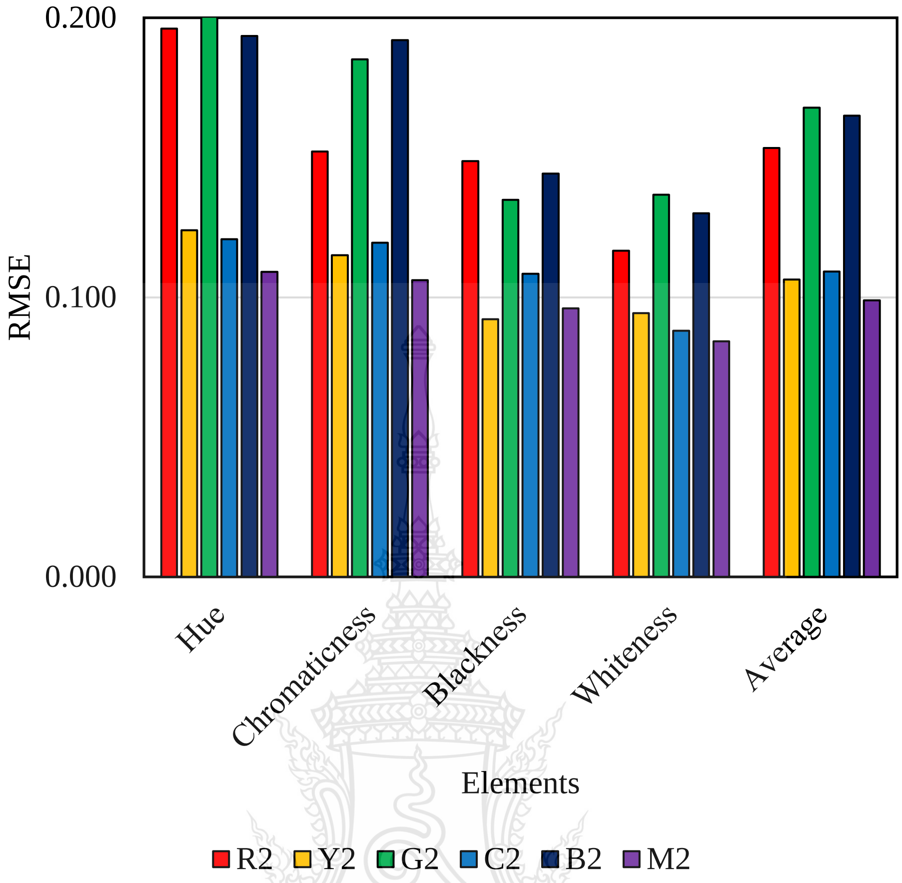



**Figure 6.21** RMSE of the vivid illumination condition in Japan

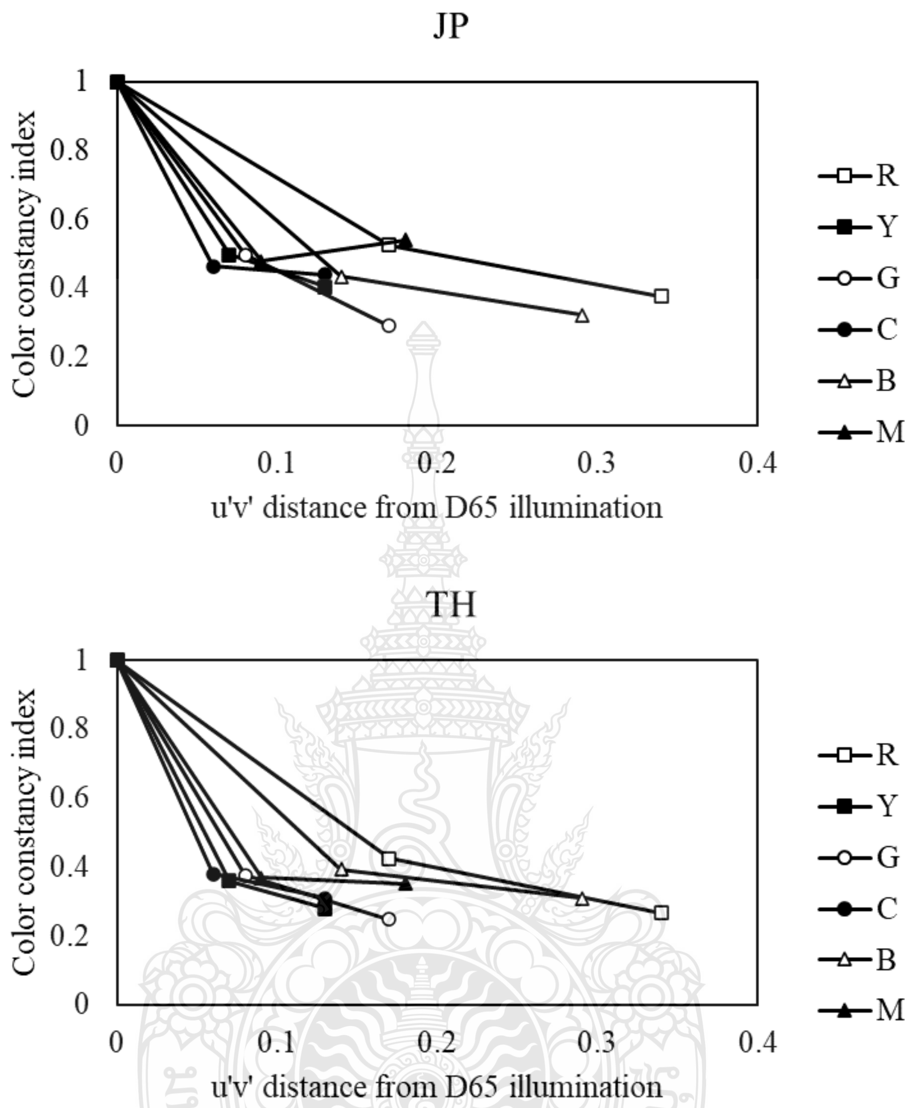



**Figure 6.22** The perceptual color constancy index of the Japanese (JP) and Thai (TH)

The perceptual color constancy index was calculated and is shown in Figure 6.22. The figure (JP) reveals that magenta illumination (solid triangle) had a higher perceptual color constancy index in M2 than M1. This raises the question: does the vividness of magenta increase the perceptual color constancy index? To investigate this question, Figure 6.23 displays the spectral power distribution of M2 illumination for Thai (dash line) and Japanese (solid line) lights. The graph indicates that there are multiple channels in M2 with a lot of variation, which may provide initial information to subjects for accurately judging color appearance relative to the reference light.

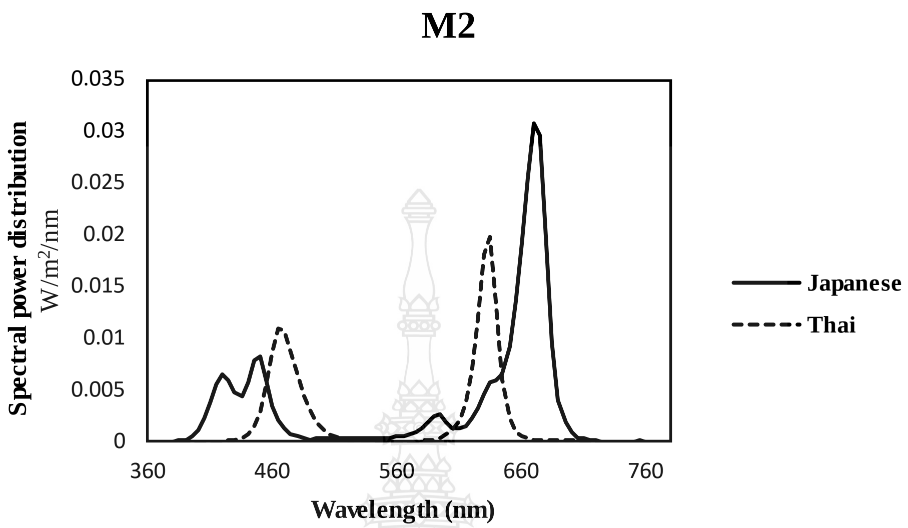



**Figure 6.23** The spectral power distribution of M2 light between Thai (dash line), and Japanese (solid line)

While the result patterns were similar for Thai and Japanese participants in Figure 6.22, the perceptual color constancy index was higher for Japanese participants in all cases. On average, the color constancy index for less vivid illumination conditions was 0.38 for Thai participants and 0.48 for Japanese participants. For vivid illumination conditions, the average color constancy index values were 0.29 and 0.40 for Thai and Japanese participants, respectively. These results indicate that the color constancy index for Japanese participants was higher than that for Thai participants, consistent with the findings of Phuangsuwan, Ikeda, and Shinoda (2014). They studied color constancy in photographs using a stereoscope and D-up viewer and found that the CCI of Ritsumeikan University participants (Japanese) was higher than that of Chula University participants (Thai). Further research is needed to confirm these results and determine the factors that contribute to differences in color constancy between nations.

## 6.2 Conclusion

The mechanisms of human vision are complex and warrant further exploration. Concurrently, human innovation continues to evolve, as seen in the transition from fluorescent to LED lighting. Today, we inhabit a world not only tinged with white light of varying correlated color temperatures but also awash with a variety of colors. This study investigated the color appearance of twenty-six color chips under 13 LED illuminations using the elementary color naming method.

For the first objective of this study which to explore the appearance of color chips under a variety of LED illuminations. The results showed that less vivid illuminations did not differ significantly from the D65 standard illumination used in this study. Furthermore, when analyzed using the K-means clustering technique, four distinct hue shift directions were identified under less vivid illuminations - red, yellow, green, and blue. This is consistent with the established opponent color theory. However, under more vivid illuminations, colors exhibited shifts in at least two hue shift directions.

This study's findings about hue shift directions led to a deeper examination of the chromatic adaptation under these conditions. The Perceptual Color Constancy Index (PCCI) was introduced as a measure of this ability, providing an alternative approach to studying color constancy with the elementary color naming method as the second objective of this study.

The study also found that color pigments might play significant roles in color illumination. It revealed the existence of a hue shift direction that requires further research to confirm and enhance the pattern. This information could be useful in the future for creating and modifying color prediction models. It could also help refine the mathematical framework for lighting instruments, as we now live not just in a white world, but a colorful one.

## 6.3 Implication for Practice and Future Research

This research was generously supported by the Research and Researchers for Industries (RRi) Ph.D. scholarship (Code: PHD61I0023), awarded by the National Research Council of Thailand (NRCT) under the Ministry of Higher Education, Science, Research and Innovation, Royal Thai Government. Further support was provided in collaboration with Konica Minolta Business Solutions, Thailand. The primary aim of this research was to create a comprehensive database that could shed light on the color appearance of color chips under various color illuminations. This data could be a beneficial tool in a sales context, for instance, determining the complementary nature of color printing products to illumination could influence the perceived color of the printing. The study on color constancy under various illuminations could provide insight into which color illuminations exhibit weaker color constancy. Furthermore, the outcomes of this research can bolster future academic investigations aimed at discovering color prediction models or mathematical frameworks in support of future lighting instruments.

This study has several limitations that could be addressed in future research. First, the experiment tested only two saturation levels for each colored light; exploring more saturation levels would offer a more comprehensive understanding of chromatic adaptation. Second, the experiment covered only six hues, and additional research is needed to examine hues situated between them. Third, the limited number of color stimuli used in the experiment, with only 26 color chips, may have impacted the results, as it might not have been sufficient for more complex analyses such as K-mean cluster analysis. Finally, the uniformity of the perceptual color space polar diagram requires further investigation for validation.

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# APPENDICES

# APPENDIX A

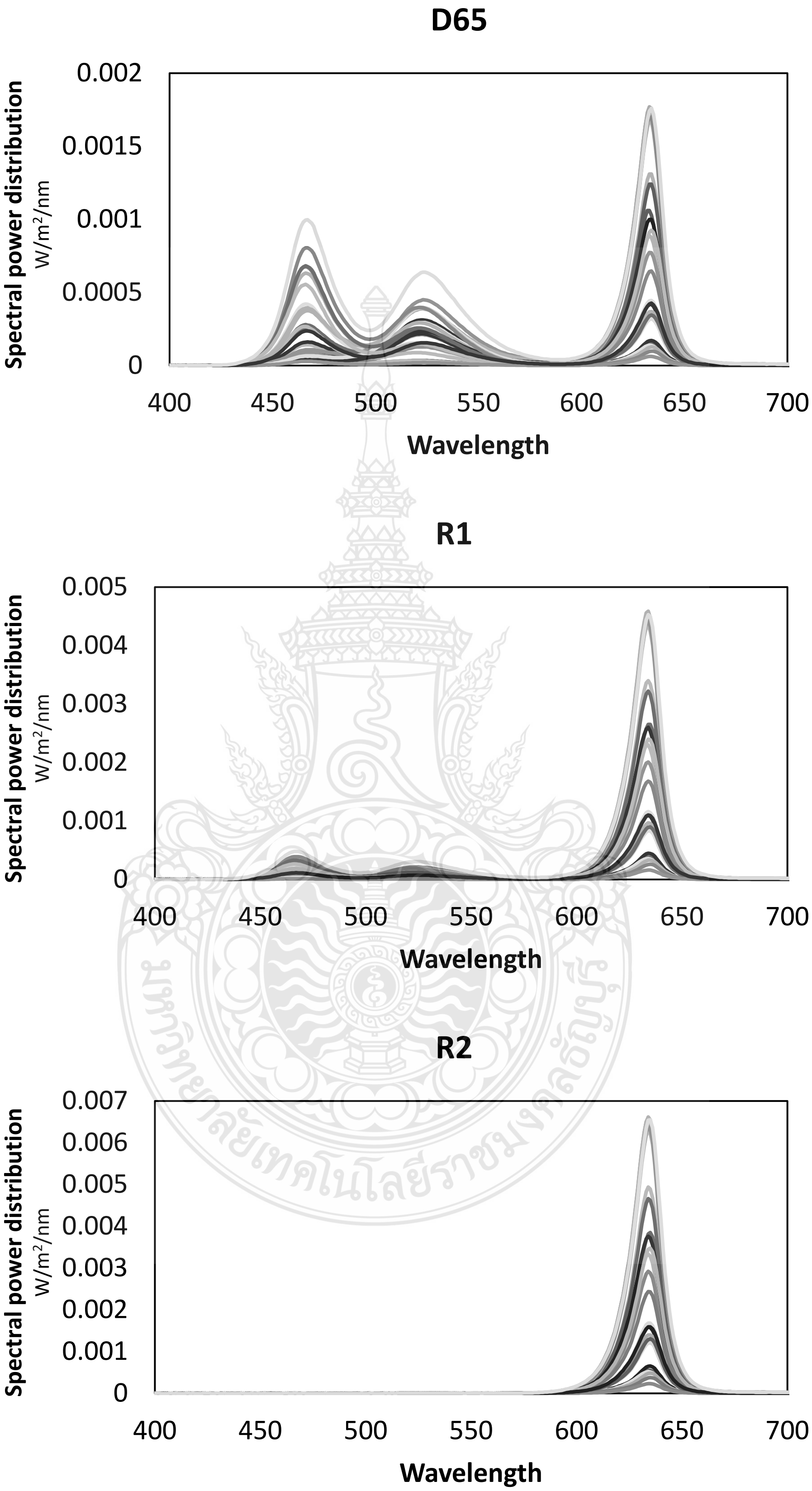
Color chips measured by Konica Minolta FD-7

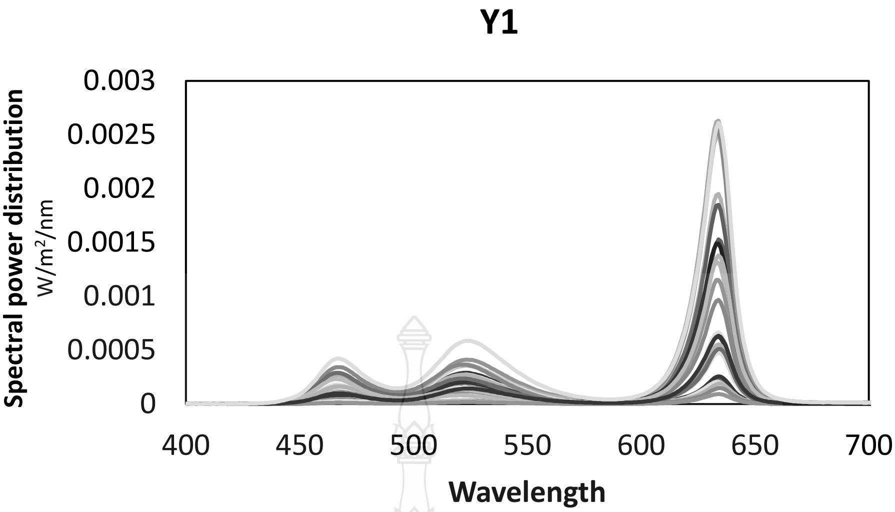
**Table 1.1** The L*a*b* of each color chip under D65 measured by Konica Minolta FD-7

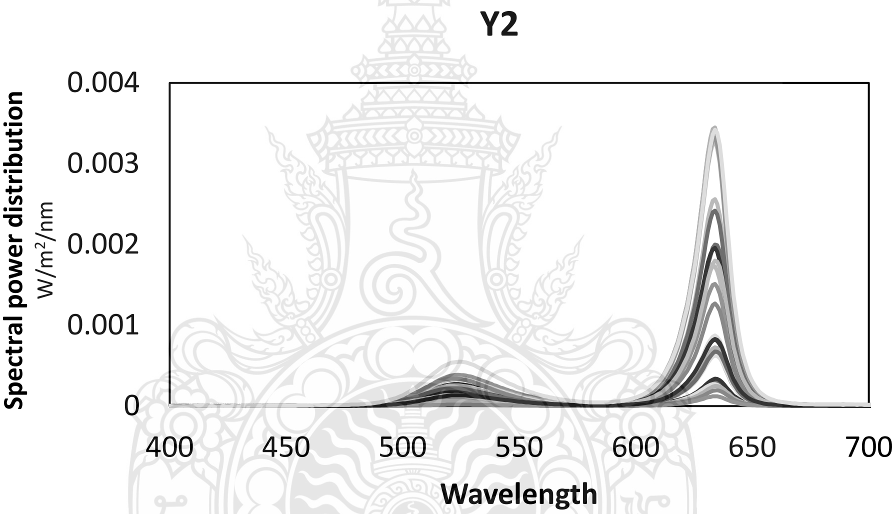
| Chipname | L* | a* | b* |
|---|---|---|---|
| TCS01 | 62.56 | 18.84 | 7.22 |
| TCS02 | 61.37 | 3.35 | 28.88 |
| TCS03 | 62.14 | -16.74 | 48.30 |
| TCS04 | 60.28 | -30.80 | 25.56 |
| TCS05 | 61.35 | -19.63 | -1.80 |
| TCS06 | 60.37 | -5.45 | -27.05 |
| TCS07 | 61.16 | 16.44 | -31.35 |
| TCS08 | 21.14 | 12.62 | -10.96 |
| TCS09 | 43.33 | 61.49 | 17.93 |
| TCS10 | 82.52 | 3.03 | 71.75 |
| TCS11 | 50.87 | -39.93 | 24.79 |
| TCS12 | 28.00 | -9.09 | -44.09 |
| TCS13 | 81.29 | 13.83 | 18.17 |
| TCS14 | 40.76 | -11.86 | 27.61 |
| TCS15 | 64.84 | 17.60 | 11.39 |
| B | 7.69 | -0.26 | 0.80 |
| N | 50.27 | 0.61 | -2.44 |
| W | 93.56 | 3.45 | -9.59 |
| C0 | 55.38 | 60.61 | -4.75 |
| C45 | 58.75 | 43.02 | 43.74 |
| C90 | 62.43 | 2.57 | 70.28 |
| C135 | 62.81 | -52.95 | 56.13 |
| C180 | 60.62 | -56.05 | 1.28 |
| C225 | 61.99 | -37.67 | -31.69 |
| C270 | 57.76 | -0.12 | -36.67 |
| C315 | 55.42 | 40.90 | -35.81 |

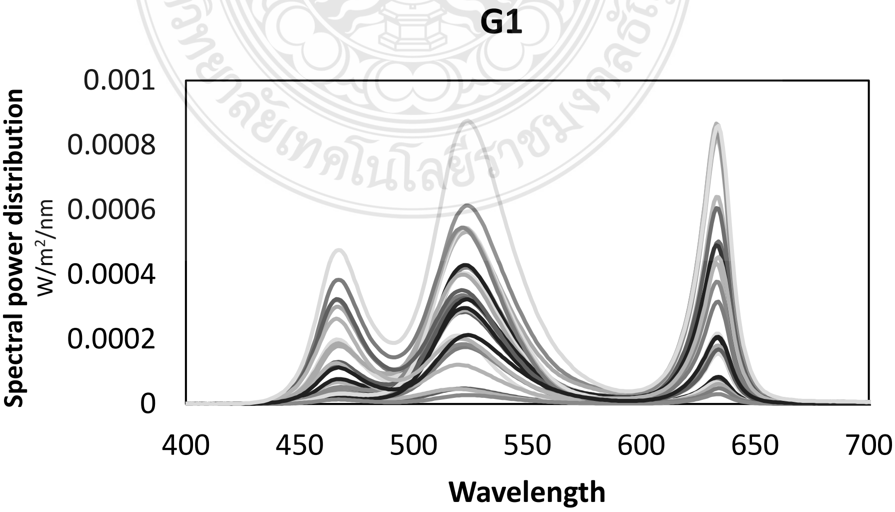
# APPENDIX B

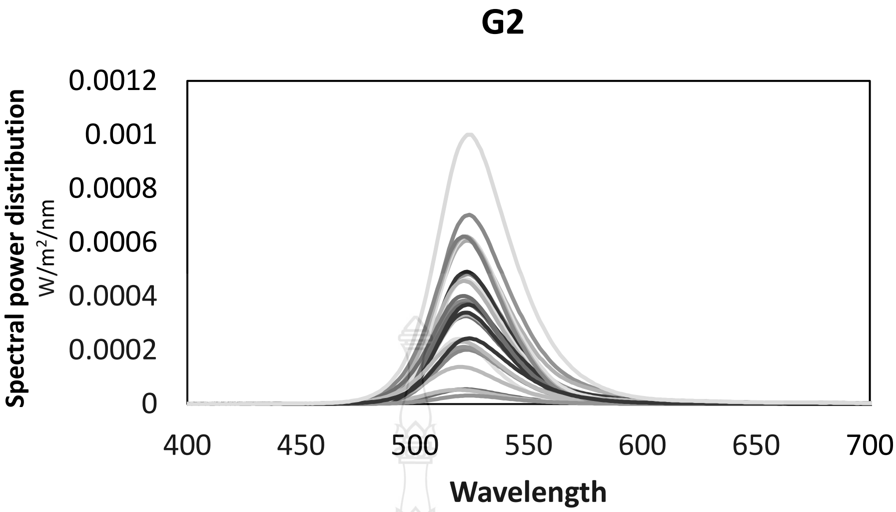
Spectral power distribution of color chips under illuminations

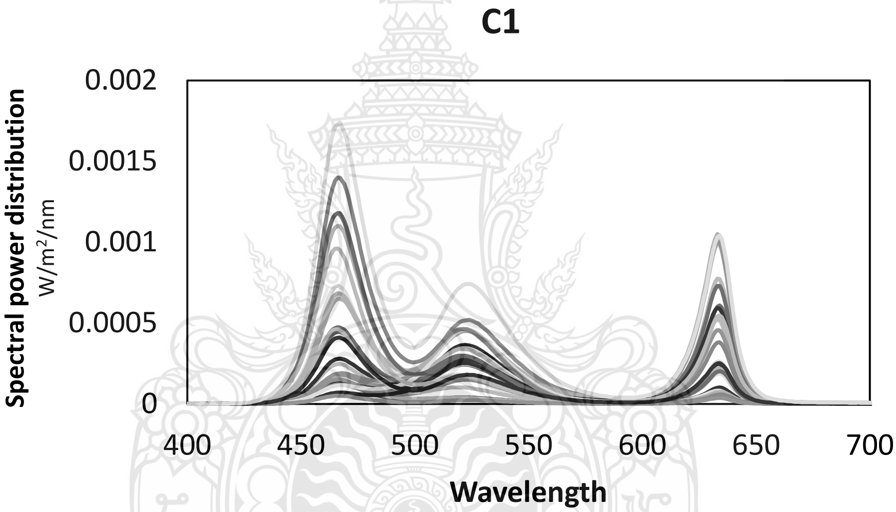

D65
Spectral power distribution
W/m²/nm
0.002
0.0015
0.001
0.0005
0
400
450
500
550
600
650
700
Wavelength
R1
Spectral power distribution
W/m²/nm
0.005
0.004
0.003
0.002
0.001
0
400
450
500
550
600
650
700
Wavelength
R2
Spectral power distribution
W/m²/nm
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
400
450
500
550
600
650
700
Wavelength

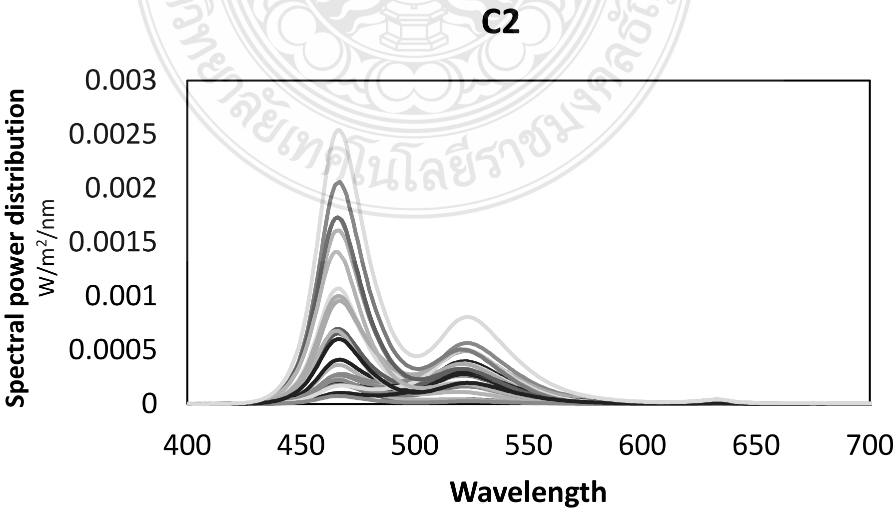

Y1
Spectral power distribution
W/m²/nm
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
400
450
500
550
600
650
700
Wavelength

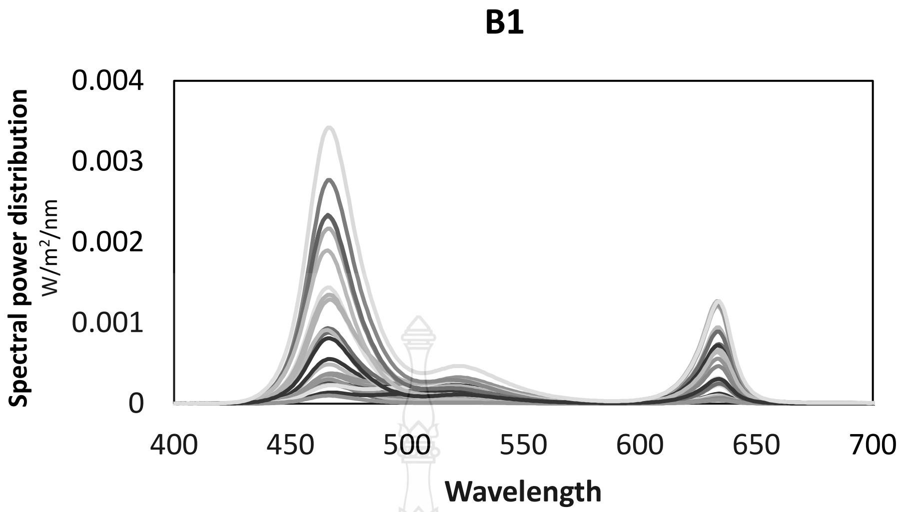

Y2
Spectral power distribution
W/m²/nm
0.004
0.003
0.002
0.001
0
400
450
500
550
600
650
700
Wavelength

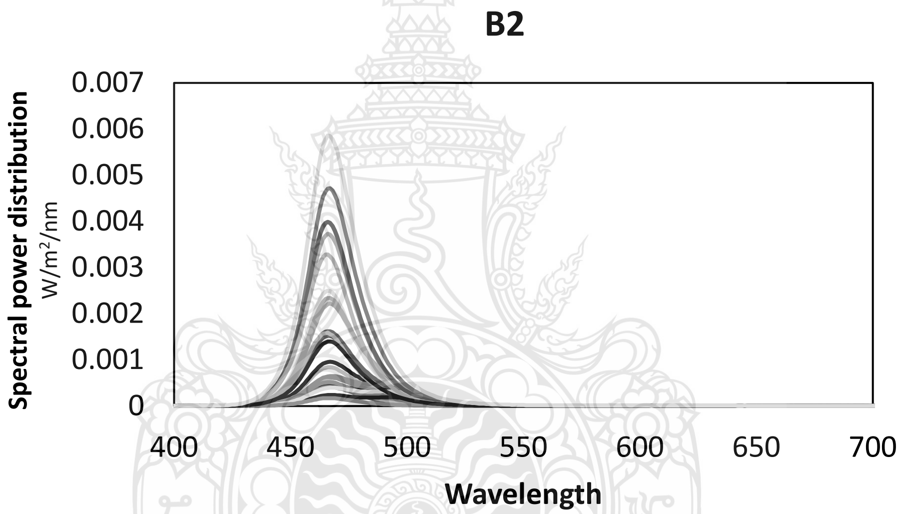

G1
Spectral power distribution
W/m²/nm
0.001
0.0008
0.0006
0.0004
0.0002
0
400
450
500
550
600
650
700
Wavelength

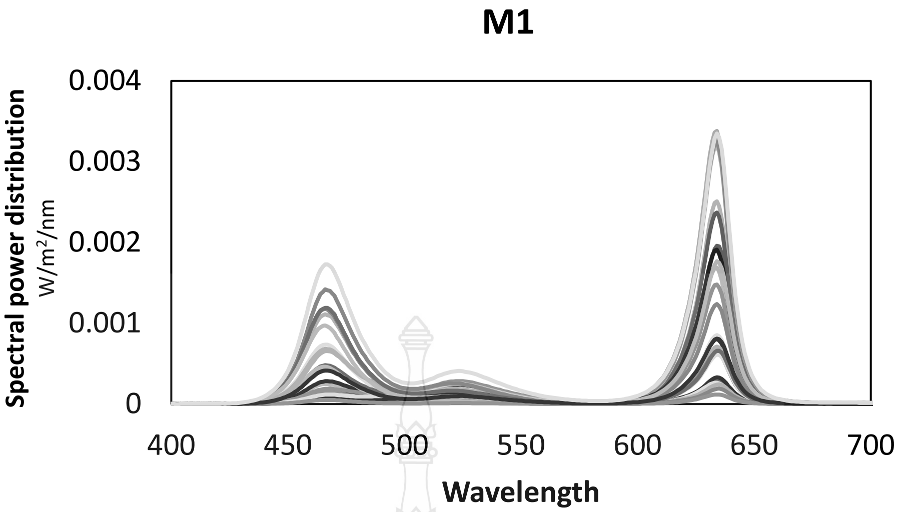

G2
Spectral power distribution
W/m²/nm
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
400
450
500
550
600
650
700
Wavelength

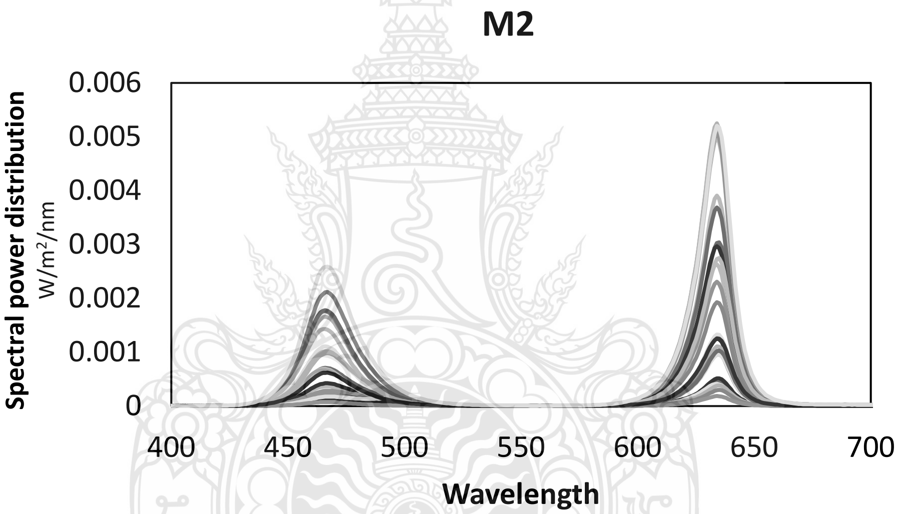

C1
Spectral power distribution
W/m²/nm
0.002
0.0015
0.001
0.0005
0
400
450
500
550
600
650
700
Wavelength


C2
Spectral power distribution
W/m²/nm
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
400
450
500
550
600
650
700
Wavelength


B1
0.004
0.003
0.002
0.001
0
Spectral power distribution
W/m2/nm
400
450
500
550
600
650
700
Wavelength


B2
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Spectral power distribution
W/m2/nm
400
450
500
550
600
650
700
Wavelength


M1
Spectral power distribution
W/m²/nm
0.004
0.003
0.002
0.001
0
400
450
500
550
600
650
700
Wavelength


M2
Spectral power distribution
W/m²/nm
0.006
0.005
0.004
0.003
0.002
0.001
0
400
450
500
550
600
650
700
Wavelength

**APPENDIX C**

Color appearance of color chip under color illumination data

**Table 1.1** The perceptual naming data of 100 subjects under D65

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 39.67 | 41.60 | 18.72 | 2.58 | 35.55 | 1.60 | 13.69 | 15.00 | 10.88 | 12.28 | 18.62 |
| 2 | 21.26 | 45.58 | 33.88 | 20.54 | 21.26 | 39.42 | 15.34 | 17.51 | 18.90 | 14.02 | 15.54 | 18.84 |
| 3 | 30.20 | 67.12 | 23.99 | 8.89 | 30.20 | 55.94 | 32.56 | 16.50 | 14.39 | 8.08 | 15.24 | 18.92 |
| 4 | 58.52 | 45.72 | 46.44 | 7.85 | 58.52 | 22.22 | 36.28 | 20.02 | 19.45 | 8.58 | 17.00 | 19.85 |
| 5 | 71.34 | 42.42 | 32.37 | 25.20 | 71.34 | 12.45 | 36.85 | 15.58 | 13.42 | 12.78 | 18.23 | 14.11 |
| 6 | 90.03 | 65.42 | 26.58 | 8.00 | 90.03 | -0.03 | 63.43 | 16.36 | 13.68 | 8.37 | 13.81 | 18.31 |
| 7 | 96.61 | 56.18 | 21.50 | 22.32 | 96.61 | -6.01 | 51.81 | 15.12 | 12.19 | 11.62 | 21.31 | 14.61 |
| 8 | 155.53 | 45.92 | 33.66 | 20.42 | 155.53 | -40.23 | 18.30 | 11.60 | 10.26 | 9.76 | 10.86 | 13.16 |
| 9 | 167.66 | 47.33 | 14.43 | 38.24 | 167.66 | -43.99 | 9.62 | 20.43 | 8.81 | 16.84 | 19.78 | 15.49 |
| 10 | 174.02 | 71.60 | 19.32 | 9.08 | 174.02 | -68.87 | 7.21 | 14.38 | 12.11 | 7.28 | 15.45 | 17.40 |
| 11 | 177.63 | 54.71 | 27.92 | 17.37 | 177.63 | -52.47 | 2.17 | 13.17 | 11.71 | 11.06 | 13.22 | 15.35 |
| 12 | 181.84 | 62.29 | 16.93 | 20.78 | 181.84 | -61.38 | -1.97 | 17.06 | 9.30 | 13.55 | 17.19 | 10.24 |
| 13 | 198.77 | 64.54 | 26.82 | 8.64 | 198.77 | -57.36 | -19.49 | 14.43 | 12.25 | 7.80 | 15.26 | 21.79 |
| 14 | 241.67 | 50.34 | 33.45 | 16.21 | 241.67 | -23.08 | -42.81 | 15.27 | 12.36 | 10.60 | 13.97 | 14.42 |
| 15 | 256.55 | 68.64 | 25.18 | 6.18 | 256.55 | -15.51 | -64.89 | 15.10 | 13.24 | 6.27 | 15.27 | 16.03 |
| 16 | 261.06 | 60.54 | 28.47 | 10.99 | 261.06 | -9.09 | -57.82 | 13.69 | 10.84 | 7.83 | 15.84 | 13.33 |
| 17 | 261.93 | 51.92 | 27.99 | 20.09 | 261.93 | -7.04 | -49.65 | 18.07 | 15.70 | 13.15 | 13.83 | 17.83 |
| 18 | 264.69 | 60.26 | 13.58 | 26.16 | 264.69 | -5.46 | -58.79 | 16.91 | 9.63 | 14.14 | 12.00 | 16.96 |
| 19 | 289.20 | 42.35 | 7.71 | 49.94 | 289.20 | 13.22 | -37.96 | 24.75 | 9.53 | 23.70 | 14.54 | 24.08 |
| 20 | 292.40 | 43.82 | 40.80 | 15.37 | 292.40 | 15.73 | -38.16 | 15.82 | 13.72 | 10.27 | 16.20 | 14.37 |
| 21 | 304.32 | 56.93 | 26.72 | 16.34 | 304.32 | 31.23 | -45.74 | 15.69 | 12.67 | 10.11 | 13.80 | 15.21 |
| 22 | 354.77 | 71.67 | 22.61 | 5.72 | 354.77 | 66.72 | -6.11 | 13.39 | 10.71 | 8.01 | 15.04 | 24.60 |
| 23 | 358.54 | 74.07 | 17.55 | 8.38 | 358.54 | 72.67 | -1.86 | 13.36 | 10.64 | 7.53 | 14.00 | 13.61 |
| B | 266.68 | 0.33 | 0.96 | 98.71 | 266.68 | -0.02 | -0.33 | 1.34 | 3.31 | 3.57 | 0.15 | 1.33 |
| N | 182.44 | 0.33 | 58.78 | 40.89 | 182.44 | -0.29 | -0.01 | 1.78 | 23.63 | 23.49 | 1.58 | 0.83 |
| W | 89.51 | 0.52 | 97.92 | 1.56 | 89.51 | 0.00 | 0.51 | 2.43 | 4.36 | 3.32 | 0.17 | 2.43 |

**Table 1.2** The perceptual naming data of 100 subjects under R1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 42.21 | 41.52 | 16.27 | 4.33 | 38.42 | 2.91 | 18.00 | 18.38 | 12.82 | 16.87 | 18.41 |
| 2 | 21.26 | 44.76 | 34.69 | 20.55 | 20.28 | 39.66 | 14.65 | 16.38 | 18.93 | 15.48 | 14.94 | 16.21 |
| 3 | 30.20 | 70.40 | 23.54 | 6.07 | 26.91 | 60.56 | 30.74 | 15.19 | 12.76 | 9.61 | 16.03 | 17.88 |
| 4 | 58.52 | 45.26 | 46.50 | 8.24 | 55.44 | 23.65 | 34.34 | 18.16 | 19.60 | 9.02 | 15.93 | 19.71 |
| 5 | 71.34 | 44.75 | 30.60 | 24.65 | 65.26 | 16.64 | 36.11 | 14.76 | 14.41 | 15.16 | 21.03 | 14.16 |
| 6 | 90.03 | 68.77 | 23.41 | 7.81 | 83.75 | 7.33 | 66.94 | 15.52 | 12.56 | 10.35 | 13.84 | 15.69 |
| 7 | 96.61 | 55.43 | 23.82 | 20.75 | 84.93 | 4.51 | 50.81 | 17.77 | 12.24 | 14.02 | 21.95 | 17.55 |
| 8 | 155.53 | 46.89 | 30.20 | 22.91 | 148.69 | -38.99 | 23.71 | 14.54 | 13.49 | 13.92 | 13.30 | 12.29 |
| 9 | 167.66 | 50.42 | 12.29 | 37.28 | 168.23 | -46.60 | 9.71 | 18.71 | 10.54 | 16.83 | 18.02 | 17.44 |
| 10 | 174.02 | 65.37 | 20.04 | 14.59 | 178.66 | -63.86 | 1.49 | 16.61 | 11.86 | 12.15 | 16.87 | 13.63 |
| 11 | 177.63 | 54.98 | 23.93 | 21.10 | 176.84 | -51.22 | 2.83 | 16.60 | 14.17 | 14.28 | 17.52 | 19.04 |
| 12 | 181.84 | 67.36 | 14.59 | 18.06 | 182.91 | -65.92 | -3.35 | 16.23 | 11.29 | 11.29 | 16.81 | 12.75 |
| 13 | 198.77 | 68.34 | 19.37 | 12.28 | 205.20 | -58.38 | -27.47 | 16.62 | 12.89 | 10.43 | 18.23 | 21.35 |
| 14 | 241.67 | 46.59 | 29.65 | 23.76 | 246.55 | -17.79 | -41.00 | 15.41 | 16.69 | 15.04 | 13.79 | 14.93 |
| 15 | 256.55 | 72.07 | 18.82 | 9.11 | 258.64 | -13.80 | -68.70 | 15.62 | 12.22 | 9.56 | 16.34 | 16.22 |
| 16 | 261.06 | 53.81 | 28.69 | 17.50 | 262.09 | -7.10 | -51.11 | 15.01 | 12.95 | 13.82 | 15.86 | 14.47 |
| 17 | 261.93 | 49.19 | 27.80 | 23.02 | 259.97 | -8.18 | -46.20 | 14.85 | 13.79 | 12.51 | 14.97 | 14.70 |
| 18 | 264.69 | 61.89 | 11.76 | 26.35 | 263.43 | -6.96 | -60.38 | 19.24 | 10.37 | 14.45 | 11.10 | 19.57 |
| 19 | 289.20 | 28.30 | 6.00 | 65.70 | 290.85 | 9.63 | -25.29 | 25.40 | 9.94 | 27.13 | 12.44 | 23.66 |
| 20 | 292.40 | 41.67 | 43.18 | 15.15 | 298.79 | 19.05 | -34.67 | 16.30 | 16.71 | 13.07 | 15.05 | 14.57 |
| 21 | 304.32 | 52.18 | 30.06 | 17.76 | 336.24 | 44.68 | -19.67 | 15.02 | 13.79 | 11.49 | 13.72 | 19.49 |
| 22 | 354.77 | 62.21 | 31.59 | 6.20 | 0.49 | 58.62 | 0.50 | 16.82 | 15.41 | 6.97 | 16.68 | 21.03 |
| 23 | 358.54 | 74.45 | 19.11 | 6.44 | 10.15 | 71.02 | 12.72 | 15.00 | 13.94 | 6.63 | 14.79 | 18.59 |
| B | 266.68 | 1.52 | 1.11 | 97.37 | 283.25 | 0.31 | -1.32 | 4.12 | 2.60 | 5.78 | 2.34 | 3.45 |
| N | 182.44 | 2.04 | 43.61 | 54.35 | 3.29 | 1.86 | 0.11 | 5.78 | 12.72 | 13.11 | 5.39 | 2.24 |
| W | 89.51 | 4.50 | 92.20 | 3.30 | 4.51 | 4.11 | 0.32 | 6.87 | 12.10 | 9.50 | 6.26 | 3.37 |

**Table 1.3** The perceptual naming data of 100 subjects under R2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 44.94 | 37.46 | 17.60 | 59.33 | 20.62 | 34.78 | 21.68 | 21.32 | 18.54 | 18.86 | 22.42 |
| 2 | 21.26 | 43.88 | 37.06 | 19.07 | 68.32 | 14.85 | 37.35 | 18.54 | 16.18 | 16.22 | 17.97 | 18.25 |
| 3 | 30.20 | 44.93 | 47.08 | 7.99 | 67.49 | 16.38 | 39.51 | 22.38 | 22.33 | 12.31 | 15.81 | 21.01 |
| 4 | 58.52 | 47.10 | 45.83 | 7.07 | 76.46 | 10.46 | 43.42 | 22.32 | 21.66 | 11.65 | 15.79 | 21.79 |
| 5 | 71.34 | 39.26 | 31.93 | 28.81 | 66.69 | 12.78 | 29.65 | 20.86 | 20.21 | 19.04 | 23.52 | 19.64 |
| 6 | 90.03 | 48.74 | 45.06 | 6.20 | 74.99 | 11.95 | 44.56 | 19.87 | 19.84 | 12.01 | 15.97 | 19.74 |
| 7 | 96.61 | 38.34 | 31.45 | 30.21 | 67.29 | 13.33 | 31.85 | 20.40 | 19.86 | 20.79 | 18.81 | 18.51 |
| 8 | 155.53 | 40.40 | 27.13 | 32.46 | 71.50 | 10.50 | 31.39 | 22.15 | 17.38 | 19.78 | 23.95 | 21.42 |
| 9 | 167.66 | 26.21 | 19.21 | 54.59 | 271.86 | 0.65 | -19.93 | 21.23 | 14.42 | 19.30 | 16.56 | 21.63 |
| 10 | 174.02 | 22.34 | 20.74 | 56.93 | 260.73 | -3.10 | -19.01 | 21.38 | 17.35 | 26.57 | 14.43 | 19.45 |
| 11 | 177.63 | 25.62 | 24.37 | 50.01 | 280.74 | 3.26 | -17.18 | 20.93 | 17.76 | 18.93 | 17.40 | 22.11 |
| 12 | 181.84 | 16.33 | 10.31 | 73.36 | 267.83 | -0.58 | -15.32 | 20.22 | 14.82 | 25.44 | 5.74 | 20.19 |
| 13 | 198.77 | 19.71 | 7.46 | 72.83 | 269.62 | -0.12 | -17.48 | 22.19 | 11.65 | 25.67 | 10.35 | 21.65 |
| 14 | 241.67 | 26.41 | 24.86 | 48.73 | 283.03 | 3.91 | -16.90 | 21.41 | 17.59 | 20.41 | 17.76 | 23.31 |
| 15 | 256.55 | 19.58 | 5.03 | 75.39 | 265.88 | -1.32 | -18.37 | 23.82 | 7.77 | 24.41 | 8.19 | 23.34 |
| 16 | 261.06 | 27.41 | 19.74 | 52.84 | 267.22 | -1.05 | -21.52 | 22.80 | 15.34 | 21.23 | 18.13 | 21.92 |
| 17 | 261.93 | 24.49 | 25.10 | 50.41 | 276.38 | 2.19 | -19.57 | 21.64 | 16.16 | 20.13 | 15.63 | 20.93 |
| 18 | 264.69 | 13.96 | 4.01 | 82.03 | 267.73 | -0.55 | -13.78 | 19.94 | 7.40 | 22.02 | 2.86 | 19.85 |
| 19 | 289.20 | 18.20 | 3.18 | 78.62 | 273.25 | 0.98 | -17.26 | 22.67 | 4.49 | 23.46 | 5.58 | 22.70 |
| 20 | 292.40 | 31.11 | 32.11 | 36.79 | 81.35 | 3.97 | 26.11 | 18.27 | 16.82 | 18.13 | 18.25 | 16.53 |
| 21 | 304.32 | 35.38 | 37.61 | 27.01 | 70.19 | 10.63 | 29.51 | 19.31 | 17.88 | 19.39 | 18.97 | 16.82 |
| 22 | 354.77 | 50.63 | 44.19 | 5.18 | 67.45 | 18.46 | 44.47 | 17.70 | 18.19 | 6.86 | 15.74 | 17.68 |
| 23 | 358.54 | 45.58 | 39.79 | 14.63 | 60.89 | 20.75 | 37.27 | 19.42 | 18.02 | 16.99 | 15.26 | 20.10 |
| B | 266.68 | 3.87 | 1.92 | 94.21 | 269.16 | -0.06 | -3.78 | 7.64 | 4.40 | 10.58 | 1.44 | 7.55 |
| N | 182.44 | 13.02 | 33.72 | 53.26 | 19.19 | 9.12 | 3.17 | 16.74 | 17.10 | 16.48 | 15.21 | 11.22 |
| W | 89.51 | 36.22 | 60.31 | 3.46 | 68.44 | 12.74 | 32.23 | 25.40 | 25.92 | 5.83 | 14.53 | 23.37 |

**Table 1.4** The perceptual naming data of 100 subjects under Y1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 43.10 | 39.79 | 17.11 | 6.53 | 38.45 | 4.40 | 16.17 | 16.67 | 12.07 | 14.83 | 20.11 |
| 2 | 21.26 | 46.37 | 32.38 | 21.25 | 21.05 | 40.11 | 15.44 | 16.05 | 16.98 | 13.12 | 16.92 | 16.64 |
| 3 | 30.20 | 65.26 | 26.04 | 8.70 | 29.17 | 55.54 | 31.00 | 15.99 | 15.19 | 8.58 | 16.46 | 14.12 |
| 4 | 58.52 | 45.02 | 46.90 | 8.07 | 60.05 | 20.30 | 35.23 | 17.21 | 17.95 | 9.44 | 15.42 | 20.87 |
| 5 | 71.34 | 43.42 | 32.75 | 23.83 | 68.24 | 14.44 | 36.18 | 13.30 | 12.44 | 13.97 | 18.70 | 14.07 |
| 6 | 90.03 | 64.86 | 27.99 | 7.15 | 87.56 | 2.70 | 63.46 | 18.38 | 17.60 | 7.99 | 10.80 | 19.87 |
| 7 | 96.61 | 51.77 | 25.54 | 22.69 | 87.81 | 1.83 | 47.73 | 14.42 | 13.39 | 12.17 | 20.21 | 14.19 |
| 8 | 155.53 | 47.39 | 35.08 | 17.53 | 155.20 | -41.58 | 19.21 | 11.87 | 12.91 | 11.45 | 11.25 | 12.75 |
| 9 | 167.66 | 50.64 | 13.54 | 35.82 | 168.11 | -46.59 | 9.81 | 19.94 | 12.29 | 17.62 | 20.57 | 16.55 |
| 10 | 174.02 | 64.63 | 24.52 | 10.84 | 176.16 | -62.09 | 4.17 | 15.66 | 13.85 | 9.51 | 16.13 | 17.09 |
| 11 | 177.63 | 55.27 | 30.26 | 14.47 | 178.60 | -52.51 | 1.28 | 14.51 | 13.56 | 10.35 | 14.84 | 16.98 |
| 12 | 181.84 | 66.29 | 17.99 | 15.72 | 179.48 | -64.70 | 0.59 | 16.34 | 10.56 | 11.68 | 18.11 | 12.17 |
| 13 | 198.77 | 63.73 | 27.75 | 8.52 | 197.92 | -56.92 | -18.41 | 15.30 | 14.99 | 9.24 | 15.79 | 21.70 |
| 14 | 241.67 | 45.11 | 38.45 | 16.44 | 240.52 | -20.74 | -36.68 | 16.19 | 19.82 | 12.65 | 15.42 | 16.89 |
| 15 | 256.55 | 63.55 | 28.62 | 7.83 | 254.28 | -16.69 | -59.31 | 16.38 | 15.69 | 8.34 | 15.91 | 16.11 |
| 16 | 261.06 | 53.54 | 33.79 | 12.67 | 256.88 | -11.80 | -50.62 | 15.34 | 14.96 | 10.84 | 13.57 | 14.74 |
| 17 | 261.93 | 49.22 | 28.80 | 21.98 | 261.61 | -6.91 | -46.86 | 14.33 | 16.24 | 13.15 | 13.22 | 14.52 |
| 18 | 264.69 | 60.21 | 13.82 | 25.97 | 261.95 | -8.21 | -58.07 | 19.71 | 8.96 | 15.91 | 12.46 | 20.53 |
| 19 | 289.20 | 34.58 | 7.36 | 58.06 | 293.37 | 13.05 | -30.21 | 23.20 | 7.86 | 24.88 | 14.70 | 20.87 |
| 20 | 292.40 | 44.69 | 41.68 | 13.63 | 294.29 | 17.23 | -38.18 | 14.51 | 15.65 | 11.57 | 16.51 | 13.51 |
| 21 | 304.32 | 53.02 | 28.10 | 18.88 | 330.02 | 44.73 | -25.80 | 14.72 | 14.46 | 12.75 | 14.29 | 12.59 |
| 22 | 354.77 | 63.58 | 29.48 | 6.94 | 357.12 | 59.78 | -3.00 | 14.85 | 13.45 | 6.48 | 15.70 | 20.92 |
| 23 | 358.54 | 70.96 | 21.66 | 7.38 | 0.77 | 69.11 | 0.92 | 17.21 | 15.23 | 8.03 | 17.32 | 16.01 |
| B | 266.68 | 0.65 | 0.62 | 98.73 | 270.80 | 0.01 | -0.65 | 4.62 | 2.98 | 5.48 | 0.05 | 4.62 |
| N | 182.44 | 0.70 | 46.08 | 53.21 | 91.04 | -0.01 | 0.70 | 2.49 | 10.10 | 9.30 | 0.08 | 2.49 |
| W | 89.51 | 1.69 | 96.57 | 1.74 | 88.89 | 0.03 | 1.69 | 3.66 | 9.72 | 8.43 | 0.20 | 3.65 |

**Table 1.5** The perceptual naming data of 100 subjects under Y2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 48.60 | 33.61 | 17.79 | 12.35 | 43.40 | 9.50 | 15.16 | 14.57 | 10.02 | 14.34 | 20.39 |
| 2 | 21.26 | 48.30 | 31.61 | 20.10 | 14.62 | 42.97 | 11.21 | 16.43 | 15.89 | 12.81 | 14.82 | 20.34 |
| 3 | 30.20 | 63.76 | 29.60 | 6.64 | 14.22 | 57.30 | 14.52 | 15.84 | 15.41 | 7.20 | 15.39 | 24.30 |
| 4 | 58.52 | 47.07 | 44.98 | 7.95 | 61.01 | 21.19 | 38.25 | 17.82 | 18.99 | 7.66 | 14.86 | 20.05 |
| 5 | 71.34 | 45.55 | 25.19 | 29.26 | 21.31 | 37.50 | 14.63 | 16.59 | 15.07 | 14.47 | 17.55 | 20.63 |
| 6 | 90.03 | 59.77 | 33.39 | 6.84 | 83.66 | 6.44 | 57.93 | 18.81 | 16.77 | 8.56 | 12.89 | 19.09 |
| 7 | 96.61 | 48.77 | 27.34 | 23.89 | 71.39 | 13.78 | 40.92 | 14.55 | 12.76 | 13.42 | 21.23 | 16.71 |
| 8 | 155.53 | 38.97 | 38.52 | 22.52 | 157.90 | -33.82 | 13.73 | 14.91 | 15.25 | 12.54 | 14.35 | 14.28 |
| 9 | 167.66 | 16.87 | 28.94 | 54.19 | 185.61 | -15.58 | -1.53 | 22.42 | 18.80 | 19.00 | 20.96 | 10.15 |
| 10 | 174.02 | 61.16 | 25.79 | 13.05 | 177.52 | -59.17 | 2.56 | 14.26 | 14.27 | 9.66 | 14.65 | 14.95 |
| 11 | 177.63 | 53.82 | 26.66 | 19.52 | 177.81 | -50.83 | 1.94 | 15.82 | 12.77 | 12.57 | 15.67 | 17.79 |
| 12 | 181.84 | 61.89 | 17.84 | 20.28 | 185.46 | -59.23 | -5.66 | 16.88 | 10.80 | 14.24 | 16.87 | 17.07 |
| 13 | 198.77 | 63.45 | 25.16 | 11.39 | 185.49 | -60.67 | -5.84 | 17.04 | 15.89 | 10.72 | 17.70 | 17.05 |
| 14 | 241.67 | 48.03 | 29.98 | 21.98 | 184.35 | -44.43 | -3.38 | 15.84 | 13.77 | 13.46 | 14.87 | 18.82 |
| 15 | 256.55 | 65.34 | 23.64 | 11.02 | 189.02 | -61.75 | -9.81 | 17.83 | 15.51 | 10.41 | 18.97 | 17.93 |
| 16 | 261.06 | 51.14 | 28.04 | 20.82 | 188.59 | -47.16 | -7.12 | 15.41 | 14.34 | 15.39 | 15.00 | 18.86 |
| 17 | 261.93 | 42.89 | 26.11 | 30.99 | 197.66 | -37.61 | -11.97 | 15.33 | 13.12 | 15.93 | 15.80 | 16.43 |
| 18 | 264.69 | 52.97 | 10.59 | 36.44 | 193.42 | -49.32 | -11.76 | 18.25 | 9.43 | 17.25 | 19.63 | 13.57 |
| 19 | 289.20 | 29.58 | 7.02 | 63.40 | 296.14 | 12.45 | -25.37 | 20.70 | 8.02 | 22.60 | 11.47 | 19.35 |
| 20 | 292.40 | 15.14 | 48.16 | 36.70 | 181.10 | -12.28 | -0.24 | 20.44 | 16.53 | 18.03 | 17.73 | 13.51 |
| 21 | 304.32 | 46.86 | 27.52 | 25.61 | 348.12 | 42.22 | -8.88 | 14.23 | 11.43 | 13.48 | 13.99 | 18.54 |
| 22 | 354.77 | 67.18 | 26.09 | 6.73 | 1.75 | 64.56 | 1.97 | 15.51 | 15.56 | 7.93 | 16.00 | 18.14 |
| 23 | 358.54 | 73.85 | 18.86 | 7.29 | 359.31 | 71.94 | -0.87 | 12.42 | 11.75 | 6.72 | 13.20 | 16.13 |
| B | 266.68 | 1.47 | 1.39 | 97.14 | 274.72 | 0.12 | -1.44 | 3.49 | 5.51 | 6.39 | 0.50 | 3.46 |
| N | 182.44 | 3.53 | 38.29 | 58.18 | 168.54 | -3.13 | 0.64 | 6.25 | 17.20 | 18.68 | 5.61 | 3.13 |
| W | 89.51 | 14.02 | 84.60 | 1.39 | 92.12 | -0.51 | 13.68 | 11.49 | 12.69 | 3.85 | 3.05 | 11.48 |

**Table 1.6** The perceptual naming data of 100 subjects under G1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 37.07 | 36.85 | 26.07 | 10.50 | 32.73 | 6.07 | 15.29 | 15.96 | 13.01 | 14.10 | 17.42 |
| 2 | 21.26 | 41.67 | 31.32 | 27.01 | 26.79 | 34.39 | 17.36 | 16.38 | 14.79 | 14.23 | 15.65 | 16.67 |
| 3 | 30.20 | 55.57 | 24.62 | 19.81 | 33.21 | 45.63 | 29.87 | 14.17 | 11.30 | 12.81 | 13.12 | 11.97 |
| 4 | 58.52 | 36.23 | 52.31 | 11.46 | 73.91 | 9.52 | 33.00 | 16.78 | 19.17 | 10.79 | 13.15 | 15.58 |
| 5 | 71.34 | 40.73 | 32.44 | 26.83 | 101.02 | -6.69 | 34.38 | 15.10 | 17.19 | 13.58 | 21.37 | 14.40 |
| 6 | 90.03 | 59.26 | 30.53 | 10.21 | 91.03 | -1.04 | 58.25 | 17.93 | 14.43 | 11.32 | 10.12 | 18.37 |
| 7 | 96.61 | 48.76 | 25.89 | 25.35 | 111.92 | -17.04 | 42.34 | 14.17 | 12.54 | 14.96 | 17.32 | 14.09 |
| 8 | 155.53 | 47.92 | 36.43 | 15.65 | 160.13 | -43.61 | 15.76 | 15.40 | 14.03 | 11.12 | 14.62 | 13.08 |
| 9 | 167.66 | 42.41 | 15.20 | 42.40 | 172.59 | -40.42 | 5.26 | 17.15 | 11.20 | 17.37 | 16.61 | 12.49 |
| 10 | 174.02 | 62.38 | 27.87 | 9.75 | 173.18 | -59.57 | 7.12 | 15.01 | 11.97 | 9.55 | 15.54 | 16.68 |
| 11 | 177.63 | 49.73 | 33.68 | 16.59 | 177.45 | -46.74 | 2.08 | 14.27 | 14.73 | 10.10 | 13.80 | 17.32 |
| 12 | 181.84 | 57.30 | 20.92 | 21.78 | 177.64 | -55.98 | 2.31 | 17.79 | 13.17 | 13.09 | 17.58 | 12.38 |
| 13 | 198.77 | 49.80 | 37.98 | 12.22 | 202.02 | -42.79 | -17.30 | 13.21 | 13.13 | 9.68 | 13.13 | 18.84 |
| 14 | 241.67 | 42.02 | 40.70 | 17.28 | 212.54 | -32.94 | -21.02 | 15.50 | 17.88 | 12.37 | 16.77 | 14.14 |
| 15 | 256.55 | 51.37 | 39.36 | 9.27 | 254.24 | -13.54 | -47.98 | 13.90 | 13.64 | 8.45 | 13.36 | 13.02 |
| 16 | 261.06 | 48.42 | 38.50 | 13.08 | 258.42 | -9.41 | -45.93 | 16.86 | 15.95 | 11.36 | 12.98 | 16.22 |
| 17 | 261.93 | 43.69 | 33.02 | 23.28 | 264.32 | -4.14 | -41.68 | 13.87 | 14.46 | 14.05 | 12.93 | 13.45 |
| 18 | 264.69 | 54.54 | 19.33 | 26.14 | 264.10 | -5.51 | -53.40 | 16.62 | 12.98 | 13.46 | 9.64 | 16.62 |
| 19 | 289.20 | 33.58 | 8.54 | 57.88 | 293.62 | 12.91 | -29.51 | 22.38 | 9.44 | 22.62 | 13.44 | 20.28 |
| 20 | 292.40 | 43.89 | 40.46 | 15.65 | 288.87 | 13.04 | -38.15 | 15.90 | 15.82 | 12.08 | 18.50 | 14.60 |
| 21 | 304.32 | 50.20 | 27.88 | 21.93 | 300.39 | 23.85 | -40.66 | 14.26 | 13.41 | 11.58 | 17.56 | 13.96 |
| 22 | 354.77 | 57.13 | 27.58 | 15.29 | 349.34 | 53.66 | -10.10 | 13.44 | 10.67 | 11.57 | 13.41 | 16.88 |
| 23 | 358.54 | 65.48 | 18.02 | 16.50 | 357.51 | 64.24 | -2.79 | 18.55 | 11.74 | 12.12 | 18.71 | 12.15 |
| B | 266.68 | 0.76 | 0.54 | 98.69 | 188.67 | -0.65 | -0.10 | 2.62 | 2.35 | 3.85 | 2.57 | 0.66 |
| N | 182.44 | 1.03 | 46.48 | 52.49 | 192.80 | -0.91 | -0.21 | 4.48 | 11.66 | 11.65 | 3.58 | 2.73 |
| W | 89.51 | 2.50 | 95.27 | 2.23 | 179.45 | -1.98 | 0.02 | 4.69 | 7.20 | 4.62 | 4.04 | 2.84 |

**Table 1.7** The perceptual naming data of 100 subjects under G2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 29.56 | 33.96 | 36.48 | 172.93 | -27.68 | 3.43 | 19.10 | 18.87 | 20.21 | 17.99 | 11.74 |
| 2 | 21.26 | 24.99 | 35.94 | 39.07 | 168.46 | -22.73 | 4.64 | 19.33 | 19.85 | 21.68 | 17.65 | 12.22 |
| 3 | 30.20 | 25.21 | 21.37 | 53.42 | 158.68 | -18.70 | 7.30 | 17.95 | 14.86 | 20.99 | 19.36 | 13.48 |
| 4 | 58.52 | 33.85 | 54.48 | 11.67 | 122.39 | -15.89 | 25.04 | 22.66 | 23.17 | 12.01 | 15.64 | 23.18 |
| 5 | 71.34 | 31.24 | 31.85 | 36.91 | 174.53 | -29.54 | 2.83 | 18.70 | 17.74 | 19.51 | 17.91 | 11.18 |
| 6 | 90.03 | 33.23 | 58.73 | 8.04 | 123.90 | -16.58 | 24.67 | 19.47 | 20.13 | 8.56 | 15.52 | 18.99 |
| 7 | 96.61 | 35.33 | 29.21 | 35.46 | 161.72 | -31.66 | 10.46 | 17.31 | 14.16 | 17.45 | 15.74 | 13.76 |
| 8 | 155.53 | 36.17 | 43.91 | 19.92 | 165.62 | -33.17 | 8.50 | 19.38 | 19.70 | 19.04 | 18.20 | 13.46 |
| 9 | 167.66 | 23.99 | 21.34 | 54.67 | 186.78 | -22.02 | -2.62 | 18.94 | 14.80 | 18.80 | 17.45 | 11.78 |
| 10 | 174.02 | 38.85 | 42.67 | 18.48 | 176.57 | -35.74 | 2.14 | 15.61 | 15.87 | 16.27 | 14.93 | 15.79 |
| 11 | 177.63 | 36.77 | 40.65 | 22.57 | 176.39 | -33.91 | 2.14 | 18.53 | 17.72 | 17.13 | 18.30 | 14.41 |
| 12 | 181.84 | 37.23 | 31.58 | 31.19 | 184.08 | -33.93 | -2.42 | 19.62 | 21.61 | 20.24 | 18.42 | 16.64 |
| 13 | 198.77 | 40.19 | 45.15 | 14.66 | 186.63 | -36.40 | -4.23 | 16.90 | 15.28 | 11.79 | 16.26 | 17.21 |
| 14 | 241.67 | 32.73 | 43.05 | 24.23 | 188.09 | -29.72 | -4.22 | 18.42 | 18.04 | 16.49 | 17.93 | 13.75 |
| 15 | 256.55 | 34.90 | 48.44 | 16.66 | 201.89 | -29.37 | -11.80 | 16.24 | 15.31 | 13.10 | 14.29 | 16.67 |
| 16 | 261.06 | 37.99 | 39.99 | 22.02 | 194.99 | -33.67 | -9.01 | 19.45 | 17.75 | 18.95 | 19.21 | 15.48 |
| 17 | 261.93 | 32.05 | 33.16 | 34.79 | 247.25 | -11.60 | -27.67 | 16.94 | 16.17 | 19.76 | 12.04 | 16.43 |
| 18 | 264.69 | 45.96 | 18.50 | 35.54 | 251.97 | -13.48 | -41.41 | 22.07 | 16.11 | 20.14 | 13.51 | 22.84 |
| 19 | 289.20 | 11.44 | 3.91 | 84.65 | 283.84 | 2.59 | -10.52 | 15.45 | 6.55 | 18.77 | 6.97 | 14.28 |
| 20 | 292.40 | 32.43 | 34.35 | 33.23 | 198.93 | -28.61 | -9.81 | 20.37 | 17.25 | 22.08 | 19.01 | 13.83 |
| 21 | 304.32 | 16.55 | 22.24 | 61.21 | 263.77 | -1.55 | -14.20 | 17.81 | 14.80 | 18.93 | 10.53 | 16.63 |
| 22 | 354.77 | 29.31 | 14.44 | 56.25 | 354.24 | 24.94 | -2.52 | 21.58 | 12.76 | 19.27 | 21.36 | 15.56 |
| 23 | 358.54 | 26.24 | 6.03 | 67.73 | 340.71 | 23.27 | -8.14 | 20.55 | 7.54 | 21.46 | 19.78 | 10.61 |
| B | 266.68 | 2.49 | 0.81 | 96.69 | 291.26 | 0.85 | -2.20 | 6.43 | 3.38 | 7.66 | 2.96 | 5.77 |
| N | 182.44 | 7.65 | 33.85 | 58.51 | 180.27 | -7.26 | -0.03 | 10.48 | 20.87 | 20.83 | 9.97 | 4.02 |
| W | 89.51 | 14.13 | 83.94 | 1.94 | 165.24 | -12.56 | 3.31 | 15.51 | 17.51 | 4.40 | 13.84 | 8.96 |

**Table 1.8** The perceptual naming data of 100 subjects under C1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 42.26 | 39.11 | 18.63 | 4.29 | 38.09 | 2.85 | 15.00 | 15.16 | 11.72 | 14.22 | 18.78 |
| 2 | 21.26 | 43.40 | 31.50 | 25.11 | 16.86 | 37.46 | 11.35 | 15.97 | 13.59 | 15.10 | 15.23 | 19.43 |
| 3 | 30.20 | 58.19 | 23.80 | 18.01 | 32.08 | 47.95 | 30.06 | 16.60 | 10.69 | 13.82 | 16.52 | 13.69 |
| 4 | 58.52 | 42.68 | 47.98 | 9.34 | 59.44 | 20.47 | 34.66 | 17.18 | 17.91 | 8.54 | 14.32 | 17.14 |
| 5 | 71.34 | 46.37 | 29.86 | 23.76 | 79.84 | 7.03 | 39.24 | 16.64 | 13.00 | 14.20 | 23.71 | 16.75 |
| 6 | 90.03 | 63.20 | 28.26 | 8.54 | 89.09 | 0.99 | 62.54 | 16.80 | 14.49 | 7.60 | 9.16 | 16.77 |
| 7 | 96.61 | 53.77 | 22.91 | 23.32 | 98.28 | -7.26 | 49.84 | 17.21 | 11.82 | 14.66 | 18.97 | 17.14 |
| 8 | 155.53 | 48.64 | 34.57 | 16.79 | 152.79 | -42.19 | 21.69 | 13.86 | 15.50 | 10.66 | 12.59 | 12.26 |
| 9 | 167.66 | 47.35 | 14.35 | 38.30 | 166.53 | -44.30 | 10.62 | 18.67 | 9.11 | 16.23 | 18.24 | 13.55 |
| 10 | 174.02 | 57.22 | 28.59 | 14.19 | 173.36 | -54.89 | 6.39 | 14.44 | 8.49 | 10.93 | 14.78 | 14.57 |
| 11 | 177.63 | 50.41 | 35.17 | 14.41 | 178.34 | -47.25 | 1.37 | 15.01 | 15.01 | 9.95 | 15.10 | 17.52 |
| 12 | 181.84 | 60.05 | 20.48 | 19.47 | 180.95 | -59.04 | -0.98 | 17.05 | 12.61 | 12.23 | 17.05 | 10.94 |
| 13 | 198.77 | 53.89 | 33.80 | 12.31 | 204.11 | -46.68 | -20.89 | 14.59 | 12.88 | 9.87 | 14.39 | 17.21 |
| 14 | 241.67 | 48.90 | 35.88 | 15.22 | 245.91 | -19.30 | -43.17 | 17.02 | 15.73 | 10.85 | 12.62 | 16.96 |
| 15 | 256.55 | 56.43 | 34.98 | 8.59 | 260.63 | -8.96 | -54.31 | 14.27 | 12.52 | 8.19 | 12.42 | 14.33 |
| 16 | 261.06 | 55.10 | 34.47 | 10.43 | 259.74 | -9.49 | -52.44 | 16.59 | 16.11 | 9.35 | 13.75 | 16.84 |
| 17 | 261.93 | 50.26 | 28.86 | 20.88 | 265.08 | -4.19 | -48.63 | 15.22 | 14.14 | 12.91 | 12.36 | 14.96 |
| 18 | 264.69 | 56.52 | 18.90 | 24.58 | 265.02 | -4.85 | -55.56 | 18.28 | 12.66 | 13.70 | 9.00 | 18.37 |
| 19 | 289.20 | 32.20 | 9.45 | 58.36 | 292.15 | 11.63 | -28.56 | 19.68 | 8.86 | 22.52 | 11.72 | 18.34 |
| 20 | 292.40 | 47.75 | 39.72 | 12.53 | 286.13 | 12.15 | -42.01 | 15.37 | 15.23 | 9.97 | 19.55 | 14.98 |
| 21 | 304.32 | 54.65 | 25.07 | 20.28 | 299.12 | 25.01 | -44.89 | 15.12 | 11.12 | 10.88 | 19.18 | 14.46 |
| 22 | 354.77 | 65.43 | 22.65 | 11.92 | 354.07 | 59.74 | -6.20 | 16.60 | 12.45 | 10.70 | 16.29 | 26.25 |
| 23 | 358.54 | 67.05 | 20.37 | 12.59 | 357.90 | 65.84 | -2.42 | 16.24 | 12.67 | 10.48 | 16.58 | 12.04 |
| B | 266.68 | 0.50 | 0.72 | 98.78 | 270.23 | 0.00 | -0.50 | 2.07 | 3.06 | 4.02 | 0.02 | 2.07 |
| N | 182.44 | 1.30 | 45.80 | 52.89 | 244.19 | -0.54 | -1.11 | 4.09 | 12.87 | 11.25 | 2.15 | 3.51 |
| W | 89.51 | 0.72 | 97.11 | 2.17 | 258.64 | -0.14 | -0.67 | 2.36 | 3.38 | 2.62 | 0.61 | 2.29 |

**Table 1.9** The perceptual naming data of 100 subjects under C2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 17.04 | 48.08 | 34.88 | 177.04 | -13.81 | 0.71 | 20.67 | 17.99 | 19.25 | 18.03 | 14.23 |
| 2 | 21.26 | 22.18 | 43.31 | 34.50 | 167.28 | -16.69 | 3.77 | 15.95 | 21.14 | 20.88 | 14.78 | 15.39 |
| 3 | 30.20 | 42.92 | 20.59 | 36.50 | 93.94 | -2.52 | 36.51 | 16.29 | 10.94 | 15.36 | 22.36 | 16.51 |
| 4 | 58.52 | 24.61 | 60.88 | 14.50 | 105.40 | -5.70 | 20.69 | 16.70 | 19.62 | 11.63 | 12.07 | 16.72 |
| 5 | 71.34 | 39.87 | 32.20 | 27.93 | 156.48 | -34.56 | 15.04 | 16.64 | 15.75 | 15.00 | 14.75 | 15.16 |
| 6 | 90.03 | 52.98 | 36.64 | 10.38 | 106.21 | -13.90 | 47.79 | 16.58 | 17.72 | 8.61 | 16.97 | 17.89 |
| 7 | 96.61 | 49.52 | 25.24 | 25.24 | 150.04 | -40.52 | 23.36 | 17.51 | 10.43 | 14.10 | 18.22 | 15.55 |
| 8 | 155.53 | 48.46 | 35.76 | 15.78 | 152.47 | -40.90 | 21.32 | 16.27 | 16.25 | 10.96 | 15.19 | 16.05 |
| 9 | 167.66 | 44.58 | 16.19 | 39.23 | 168.28 | -42.34 | 8.78 | 17.48 | 10.96 | 16.61 | 17.17 | 11.37 |
| 10 | 174.02 | 54.02 | 32.02 | 13.97 | 159.94 | -47.50 | 17.35 | 12.60 | 11.33 | 8.89 | 14.51 | 17.65 |
| 11 | 177.63 | 42.23 | 41.75 | 16.02 | 164.55 | -37.91 | 10.48 | 15.78 | 15.16 | 12.28 | 14.89 | 16.30 |
| 12 | 181.84 | 47.99 | 25.78 | 26.23 | 169.30 | -43.90 | 8.29 | 16.34 | 10.44 | 14.03 | 16.09 | 17.84 |
| 13 | 198.77 | 37.27 | 48.12 | 14.61 | 192.62 | -31.94 | -7.15 | 14.93 | 18.74 | 12.63 | 14.35 | 18.37 |
| 14 | 241.67 | 28.72 | 52.50 | 18.79 | 248.04 | -10.43 | -25.88 | 16.89 | 17.24 | 12.33 | 10.13 | 15.14 |
| 15 | 256.55 | 39.93 | 50.52 | 9.55 | 264.74 | -3.55 | -38.51 | 15.41 | 18.57 | 10.92 | 10.59 | 14.97 |
| 16 | 261.06 | 41.50 | 47.07 | 11.43 | 263.91 | -4.22 | -39.56 | 17.70 | 17.13 | 9.90 | 13.06 | 16.84 |
| 17 | 261.93 | 42.72 | 39.24 | 18.04 | 272.91 | 2.06 | -40.59 | 15.24 | 17.47 | 14.00 | 13.93 | 14.58 |
| 18 | 264.69 | 50.44 | 25.41 | 24.15 | 266.08 | -3.35 | -48.83 | 17.31 | 13.03 | 14.22 | 12.51 | 17.11 |
| 19 | 289.20 | 26.50 | 7.66 | 65.84 | 286.44 | 7.22 | -24.46 | 21.22 | 8.06 | 23.47 | 10.23 | 19.94 |
| 20 | 292.40 | 45.80 | 40.26 | 13.94 | 278.53 | 6.44 | -42.94 | 16.91 | 17.05 | 13.24 | 15.26 | 16.35 |
| 21 | 304.32 | 49.11 | 25.97 | 24.93 | 290.33 | 16.10 | -43.46 | 17.34 | 14.94 | 14.93 | 16.89 | 16.78 |
| 22 | 354.77 | 48.57 | 18.60 | 32.83 | 296.64 | 20.68 | -41.22 | 13.85 | 9.54 | 12.42 | 13.68 | 15.47 |
| 23 | 358.54 | 33.40 | 10.10 | 56.50 | 331.23 | 27.22 | -14.94 | 18.22 | 9.91 | 21.09 | 17.47 | 13.38 |
| B | 266.68 | 0.83 | 1.01 | 98.16 | 287.24 | 0.18 | -0.57 | 2.75 | 5.96 | 6.54 | 0.96 | 2.65 |
| N | 182.44 | 0.83 | 45.65 | 53.51 | 253.32 | -0.22 | -0.73 | 2.62 | 14.74 | 13.56 | 1.46 | 2.20 |
| W | 89.51 | 2.81 | 95.73 | 1.46 | 268.98 | -0.04 | -2.14 | 5.79 | 8.11 | 3.97 | 4.57 | 4.00 |

**Table 1.10** The perceptual naming data of 100 subjects under B1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 38.75 | 40.85 | 20.40 | 359.33 | 34.16 | -0.40 | 14.25 | 15.76 | 13.68 | 13.09 | 19.19 |
| 2 | 21.26 | 43.30 | 35.96 | 20.75 | 11.04 | 38.04 | 7.42 | 15.60 | 16.92 | 15.02 | 13.92 | 20.61 |
| 3 | 30.20 | 60.31 | 25.29 | 14.40 | 29.86 | 50.83 | 29.18 | 14.48 | 11.32 | 10.04 | 13.97 | 14.79 |
| 4 | 58.52 | 44.02 | 49.89 | 6.08 | 18.34 | 37.92 | 12.57 | 18.75 | 19.06 | 7.22 | 16.93 | 20.24 |
| 5 | 71.34 | 43.20 | 29.65 | 27.15 | 60.35 | 19.87 | 34.91 | 14.38 | 12.97 | 14.77 | 15.72 | 14.66 |
| 6 | 90.03 | 62.28 | 28.16 | 9.57 | 85.75 | 4.53 | 60.97 | 15.12 | 13.11 | 7.49 | 11.34 | 15.55 |
| 7 | 96.61 | 53.89 | 23.06 | 23.05 | 82.16 | 6.78 | 49.22 | 15.93 | 13.23 | 12.21 | 21.10 | 15.74 |
| 8 | 155.53 | 45.52 | 29.86 | 24.61 | 146.36 | -35.68 | 23.73 | 15.11 | 14.17 | 13.13 | 16.01 | 14.50 |
| 9 | 167.66 | 45.99 | 15.82 | 38.19 | 165.43 | -42.73 | 11.10 | 17.70 | 12.11 | 15.86 | 16.94 | 13.93 |
| 10 | 174.02 | 56.81 | 25.62 | 17.57 | 174.72 | -53.80 | 4.97 | 15.00 | 13.55 | 11.45 | 15.65 | 17.06 |
| 11 | 177.63 | 46.79 | 33.69 | 19.52 | 174.85 | -43.89 | 3.96 | 13.95 | 12.54 | 11.10 | 13.67 | 16.03 |
| 12 | 181.84 | 57.08 | 19.63 | 23.29 | 180.32 | -56.06 | -0.32 | 16.53 | 12.24 | 14.85 | 16.63 | 10.64 |
| 13 | 198.77 | 52.24 | 33.48 | 14.29 | 206.64 | -44.03 | -22.08 | 12.51 | 12.59 | 10.34 | 12.63 | 17.38 |
| 14 | 241.67 | 46.65 | 35.48 | 17.88 | 247.98 | -17.04 | -42.12 | 17.54 | 14.81 | 13.09 | 12.74 | 16.05 |
| 15 | 256.55 | 60.48 | 32.99 | 6.52 | 260.75 | -9.50 | -58.36 | 15.86 | 13.57 | 7.55 | 12.83 | 15.82 |
| 16 | 261.06 | 56.92 | 33.42 | 9.66 | 262.75 | -7.00 | -55.01 | 15.28 | 13.94 | 8.60 | 13.33 | 14.89 |
| 17 | 261.93 | 50.36 | 31.12 | 18.52 | 264.17 | -4.95 | -48.47 | 16.83 | 13.93 | 13.62 | 12.72 | 16.89 |
| 18 | 264.69 | 58.48 | 20.34 | 21.18 | 262.82 | -7.20 | -57.13 | 16.37 | 11.79 | 14.43 | 10.57 | 16.16 |
| 19 | 289.20 | 26.47 | 8.02 | 65.52 | 288.86 | 8.07 | -23.63 | 21.69 | 8.40 | 24.46 | 12.04 | 20.07 |
| 20 | 292.40 | 48.11 | 38.11 | 13.78 | 284.32 | 11.09 | -43.45 | 15.07 | 16.33 | 12.34 | 18.24 | 14.17 |
| 21 | 304.32 | 48.96 | 33.53 | 17.51 | 299.05 | 22.29 | -40.13 | 14.37 | 12.27 | 11.99 | 18.01 | 13.21 |
| 22 | 354.77 | 57.14 | 29.27 | 13.59 | 353.22 | 52.94 | -6.30 | 17.76 | 15.17 | 13.62 | 17.24 | 21.08 |
| 23 | 358.54 | 67.16 | 21.19 | 11.66 | 0.04 | 66.35 | 0.05 | 14.18 | 10.94 | 9.43 | 14.37 | 10.12 |
| B | 266.68 | 0.43 | 0.79 | 98.76 | 277.08 | 0.05 | -0.38 | 1.63 | 4.28 | 5.40 | 0.72 | 1.47 |
| N | 182.44 | 0.67 | 46.56 | 52.77 | 257.29 | -0.14 | -0.62 | 2.49 | 11.73 | 10.89 | 0.92 | 2.32 |
| W | 89.51 | 1.25 | 97.75 | 0.99 | 270.14 | 0.00 | -1.25 | 3.22 | 5.09 | 2.80 | 0.19 | 3.22 |

**Table 1.11** The perceptual naming data of 100 subjects under B2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 18.54 | 44.58 | 36.88 | 262.95 | -2.13 | -17.19 | 20.08 | 22.98 | 19.98 | 9.06 | 19.10 |
| 2 | 21.26 | 9.77 | 45.20 | 45.03 | 256.05 | -2.17 | -8.75 | 10.82 | 18.05 | 17.81 | 5.48 | 10.07 |
| 3 | 30.20 | 23.30 | 17.28 | 59.42 | 34.30 | 14.04 | 9.58 | 18.78 | 13.50 | 20.20 | 22.07 | 11.03 |
| 4 | 58.52 | 13.19 | 57.64 | 29.17 | 257.92 | -2.44 | -11.40 | 12.08 | 13.46 | 11.68 | 5.37 | 12.47 |
| 5 | 71.34 | 22.79 | 29.60 | 47.61 | 185.18 | -20.48 | -1.86 | 18.95 | 18.94 | 20.88 | 17.42 | 12.35 |
| 6 | 90.03 | 33.82 | 39.18 | 27.00 | 119.88 | -15.06 | 26.21 | 12.84 | 11.91 | 9.52 | 14.84 | 13.27 |
| 7 | 96.61 | 34.76 | 15.98 | 49.26 | 160.84 | -30.87 | 10.73 | 17.76 | 12.95 | 18.94 | 17.48 | 12.31 |
| 8 | 155.53 | 32.28 | 26.12 | 41.60 | 165.29 | -29.10 | 7.64 | 17.99 | 16.79 | 21.26 | 16.49 | 13.77 |
| 9 | 167.66 | 18.79 | 17.90 | 63.31 | 173.50 | -17.83 | 2.03 | 12.49 | 11.04 | 14.94 | 12.09 | 6.41 |
| 10 | 174.02 | 37.22 | 26.81 | 35.97 | 159.28 | -32.43 | 12.27 | 16.78 | 15.24 | 19.35 | 15.52 | 15.01 |
| 11 | 177.63 | 28.77 | 35.49 | 35.74 | 177.16 | -26.23 | 1.30 | 19.58 | 18.34 | 20.44 | 18.62 | 13.25 |
| 12 | 181.84 | 31.99 | 22.72 | 45.29 | 172.00 | -29.54 | 4.15 | 12.52 | 11.17 | 12.40 | 11.59 | 12.54 |
| 13 | 198.77 | 19.12 | 61.45 | 19.43 | 207.98 | -14.34 | -7.62 | 16.78 | 21.56 | 15.05 | 15.22 | 12.34 |
| 14 | 241.67 | 20.09 | 48.53 | 31.38 | 257.71 | -4.09 | -18.79 | 16.13 | 20.39 | 14.85 | 8.32 | 15.01 |
| 15 | 256.55 | 19.31 | 72.98 | 7.70 | 265.34 | -1.52 | -18.69 | 16.94 | 20.45 | 11.34 | 5.42 | 16.70 |
| 16 | 261.06 | 23.88 | 63.72 | 12.40 | 265.52 | -1.80 | -23.03 | 15.44 | 17.90 | 10.10 | 7.46 | 14.83 |
| 17 | 261.93 | 26.43 | 59.55 | 14.02 | 273.33 | 1.47 | -25.25 | 18.63 | 20.21 | 13.93 | 8.72 | 18.17 |
| 18 | 264.69 | 29.87 | 44.70 | 25.43 | 269.96 | -0.02 | -28.61 | 14.30 | 18.60 | 14.81 | 9.07 | 14.00 |
| 19 | 289.20 | 6.94 | 7.81 | 85.25 | 288.90 | 2.17 | -6.34 | 8.98 | 6.31 | 11.42 | 3.62 | 8.42 |
| 20 | 292.40 | 27.30 | 59.50 | 13.20 | 270.53 | 0.24 | -26.29 | 17.07 | 22.74 | 13.65 | 8.09 | 16.74 |
| 21 | 304.32 | 32.91 | 47.35 | 19.74 | 284.23 | 7.75 | -30.57 | 19.52 | 20.85 | 16.61 | 10.30 | 19.08 |
| 22 | 354.77 | 32.84 | 28.17 | 38.99 | 297.71 | 14.79 | -28.16 | 17.90 | 17.52 | 20.41 | 11.31 | 16.13 |
| 23 | 358.54 | 21.45 | 10.27 | 68.28 | 328.03 | 16.82 | -10.49 | 12.48 | 7.62 | 13.67 | 11.20 | 9.90 |
| B | 266.68 | 1.21 | 1.14 | 97.64 | 282.02 | 0.23 | -1.07 | 3.11 | 4.83 | 6.12 | 0.91 | 3.02 |
| N | 182.44 | 2.30 | 45.82 | 51.88 | 266.04 | -0.14 | -2.07 | 6.25 | 15.43 | 16.70 | 3.37 | 5.36 |
| W | 89.51 | 7.60 | 90.35 | 2.06 | 267.31 | -0.35 | -7.45 | 12.19 | 13.85 | 4.30 | 2.26 | 12.07 |

**Table 1.12** The perceptual naming data of 100 subjects under M1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 44.98 | 38.90 | 16.12 | 10.70 | 40.25 | 7.61 | 14.83 | 15.61 | 11.44 | 13.86 | 19.37 |
| 2 | 21.26 | 45.58 | 32.44 | 21.98 | 15.53 | 40.40 | 11.22 | 15.61 | 14.13 | 14.76 | 14.26 | 19.04 |
| 3 | 30.20 | 69.21 | 23.21 | 7.58 | 28.17 | 58.82 | 31.50 | 17.51 | 16.51 | 7.43 | 18.21 | 17.75 |
| 4 | 58.52 | 44.05 | 46.81 | 9.14 | 19.20 | 37.85 | 13.18 | 17.28 | 18.39 | 9.82 | 16.06 | 19.42 |
| 5 | 71.34 | 46.18 | 31.17 | 22.65 | 55.79 | 24.48 | 36.01 | 15.09 | 14.02 | 12.35 | 16.62 | 13.79 |
| 6 | 90.03 | 65.83 | 27.17 | 7.00 | 84.74 | 5.85 | 63.45 | 16.82 | 14.99 | 8.24 | 13.52 | 19.42 |
| 7 | 96.61 | 55.67 | 23.23 | 21.10 | 72.10 | 15.64 | 48.42 | 16.00 | 13.48 | 13.26 | 22.39 | 16.40 |
| 8 | 155.53 | 47.42 | 27.36 | 25.22 | 117.77 | -20.96 | 39.80 | 14.60 | 15.51 | 14.69 | 15.54 | 14.11 |
| 9 | 167.66 | 47.31 | 14.64 | 38.06 | 163.95 | -42.92 | 12.35 | 20.01 | 13.66 | 18.71 | 20.60 | 14.87 |
| 10 | 174.02 | 60.54 | 19.64 | 19.82 | 176.61 | -57.32 | 3.40 | 14.27 | 10.72 | 12.80 | 15.24 | 18.50 |
| 11 | 177.63 | 50.72 | 28.86 | 20.42 | 177.69 | -47.81 | 1.93 | 15.95 | 15.17 | 11.79 | 15.56 | 17.25 |
| 12 | 181.84 | 60.56 | 16.62 | 22.82 | 180.72 | -57.17 | -0.71 | 17.77 | 12.86 | 13.51 | 22.94 | 13.87 |
| 13 | 198.77 | 58.62 | 26.31 | 15.07 | 205.36 | -49.70 | -23.56 | 16.14 | 14.50 | 9.53 | 17.05 | 19.60 |
| 14 | 241.67 | 45.40 | 32.87 | 21.73 | 248.64 | -15.93 | -40.74 | 14.99 | 17.14 | 13.04 | 13.77 | 13.57 |
| 15 | 256.55 | 68.13 | 24.07 | 7.80 | 262.24 | -8.94 | -65.65 | 15.37 | 13.00 | 7.62 | 15.76 | 15.55 |
| 16 | 261.06 | 56.36 | 33.82 | 9.82 | 262.26 | -7.32 | -53.85 | 16.10 | 15.52 | 8.58 | 15.16 | 15.95 |
| 17 | 261.93 | 52.46 | 26.97 | 20.57 | 263.84 | -5.41 | -50.12 | 14.35 | 11.10 | 10.68 | 13.12 | 15.70 |
| 18 | 264.69 | 61.34 | 19.62 | 19.04 | 265.72 | -4.43 | -59.21 | 15.92 | 14.30 | 12.46 | 13.95 | 17.25 |
| 19 | 289.20 | 26.01 | 6.74 | 67.25 | 286.79 | 7.14 | -23.65 | 19.20 | 7.77 | 22.38 | 9.66 | 18.49 |
| 20 | 292.40 | 43.94 | 39.76 | 16.30 | 287.56 | 12.12 | -38.29 | 15.96 | 16.02 | 14.28 | 19.26 | 14.31 |
| 21 | 304.32 | 49.97 | 30.78 | 19.26 | 302.24 | 24.09 | -38.20 | 12.49 | 12.68 | 11.58 | 21.06 | 13.17 |
| 22 | 354.77 | 62.71 | 31.85 | 5.44 | 354.76 | 58.55 | -5.37 | 17.39 | 16.91 | 8.72 | 16.90 | 22.27 |
| 23 | 358.54 | 71.83 | 20.12 | 8.06 | 3.14 | 70.46 | 3.87 | 16.09 | 12.98 | 8.21 | 16.64 | 12.78 |
| B | 266.68 | 0.76 | 0.64 | 98.60 | 154.72 | -0.31 | 0.15 | 5.54 | 3.35 | 8.42 | 3.21 | 4.56 |
| N | 182.44 | 1.79 | 46.13 | 52.07 | 191.45 | -1.70 | -0.34 | 8.60 | 11.19 | 11.35 | 8.42 | 1.79 |
| W | 89.51 | 3.47 | 94.26 | 2.27 | 331.20 | 2.54 | -1.40 | 5.53 | 11.54 | 8.99 | 4.78 | 3.39 |

**Table 1.13** The perceptual naming data of 100 subjects under M2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 40.55 | 42.04 | 17.40 | 1.36 | 36.38 | 0.87 | 15.80 | 18.64 | 14.83 | 14.84 | 18.76 |
| 2 | 21.26 | 42.64 | 36.66 | 20.70 | 8.53 | 38.37 | 5.75 | 16.98 | 18.01 | 17.53 | 16.14 | 18.52 |
| 3 | 30.20 | 65.33 | 27.14 | 7.53 | 29.01 | 55.26 | 30.64 | 16.84 | 16.48 | 7.19 | 15.74 | 17.73 |
| 4 | 58.52 | 43.00 | 46.60 | 10.40 | 4.41 | 39.14 | 3.02 | 19.86 | 19.65 | 11.04 | 18.53 | 19.02 |
| 5 | 71.34 | 45.48 | 27.60 | 26.93 | 23.06 | 39.08 | 16.64 | 14.37 | 15.46 | 15.48 | 12.96 | 17.46 |
| 6 | 90.03 | 66.60 | 25.97 | 7.44 | 58.75 | 32.46 | 53.50 | 17.32 | 14.98 | 9.29 | 21.54 | 18.95 |
| 7 | 96.61 | 57.07 | 19.51 | 23.41 | 28.76 | 48.23 | 26.46 | 15.31 | 11.68 | 12.16 | 16.57 | 13.90 |
| 8 | 155.53 | 49.14 | 26.22 | 24.64 | 32.62 | 40.12 | 25.68 | 14.68 | 13.43 | 12.49 | 13.31 | 13.63 |
| 9 | 167.66 | 38.72 | 16.04 | 45.24 | 68.97 | 12.13 | 31.55 | 18.12 | 12.28 | 20.48 | 20.22 | 16.69 |
| 10 | 174.02 | 48.40 | 16.32 | 35.27 | 174.50 | -43.17 | 4.16 | 17.36 | 10.29 | 16.52 | 18.32 | 20.78 |
| 11 | 177.63 | 20.93 | 35.62 | 43.45 | 181.54 | -19.09 | -0.51 | 17.86 | 19.48 | 20.08 | 16.35 | 11.21 |
| 12 | 181.84 | 40.09 | 11.88 | 48.03 | 186.79 | -38.51 | -4.59 | 19.43 | 10.22 | 19.99 | 19.15 | 10.71 |
| 13 | 198.77 | 58.40 | 19.25 | 22.35 | 254.07 | -15.05 | -52.72 | 16.30 | 12.62 | 14.92 | 15.97 | 20.47 |
| 14 | 241.67 | 40.29 | 30.16 | 29.55 | 259.53 | -6.96 | -37.66 | 15.41 | 14.47 | 16.44 | 13.26 | 14.82 |
| 15 | 256.55 | 65.94 | 25.11 | 8.95 | 264.70 | -5.94 | -64.03 | 19.79 | 15.65 | 11.08 | 14.52 | 19.90 |
| 16 | 261.06 | 57.44 | 30.69 | 11.88 | 266.28 | -3.61 | -55.53 | 16.68 | 14.37 | 11.21 | 14.08 | 16.84 |
| 17 | 261.93 | 51.83 | 30.50 | 17.75 | 264.39 | -4.90 | -49.85 | 15.12 | 12.02 | 12.12 | 13.55 | 14.95 |
| 18 | 264.69 | 62.60 | 17.87 | 19.54 | 263.86 | -6.55 | -60.85 | 18.47 | 14.13 | 15.64 | 12.26 | 19.10 |
| 19 | 289.20 | 11.46 | 7.68 | 80.86 | 280.48 | 1.85 | -10.00 | 16.78 | 10.60 | 21.78 | 8.84 | 15.22 |
| 20 | 292.40 | 38.54 | 43.35 | 18.12 | 273.29 | 1.99 | -34.60 | 18.02 | 19.88 | 19.23 | 18.78 | 16.07 |
| 21 | 304.32 | 41.51 | 40.55 | 17.94 | 302.92 | 21.49 | -33.19 | 16.13 | 18.37 | 13.27 | 14.75 | 14.29 |
| 22 | 354.77 | 59.31 | 33.17 | 7.52 | 0.55 | 55.09 | 0.53 | 16.14 | 14.18 | 8.82 | 15.67 | 22.38 |
| 23 | 358.54 | 66.83 | 23.86 | 9.36 | 18.72 | 60.26 | 20.42 | 15.60 | 14.03 | 10.45 | 15.52 | 20.57 |
| B | 266.68 | 0.63 | 1.04 | 98.33 | 274.35 | 0.05 | -0.59 | 2.35 | 6.41 | 7.30 | 0.70 | 2.25 |
| N | 182.44 | 1.98 | 44.40 | 53.63 | 275.96 | 0.19 | -1.77 | 4.49 | 13.97 | 13.36 | 1.79 | 4.21 |
| W | 89.51 | 6.97 | 89.98 | 3.06 | 301.06 | 3.12 | -5.18 | 9.23 | 13.26 | 5.82 | 6.10 | 7.76 |

# APPENDIX D

Color appearance of color chip under color illumination data without chromatic adaptation

**Table 1.1** The perceptual naming data of 100 subjects under R1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 64.39 | 25.47 | 10.13 | 1.20 | 61.07 | 1.28 | 15.75 | 14.92 | 9.07 | 16.01 | 20.47 |
| 2 | 21.26 | 65.03 | 29.89 | 5.08 | 13.13 | 60.90 | 14.20 | 11.59 | 11.84 | 4.90 | 12.37 | 17.55 |
| 3 | 30.20 | 70.37 | 27.16 | 2.47 | 10.57 | 64.47 | 12.03 | 13.03 | 12.26 | 5.02 | 20.68 | 20.28 |
| 4 | 58.52 | 62.71 | 34.92 | 2.37 | 4.32 | 58.45 | 4.42 | 15.01 | 14.97 | 4.61 | 16.19 | 21.76 |
| 5 | 71.34 | 68.76 | 20.08 | 11.16 | 14.74 | 63.38 | 16.68 | 14.72 | 12.55 | 10.49 | 16.36 | 19.83 |
| 6 | 90.03 | 68.47 | 27.29 | 4.24 | 41.76 | 47.80 | 42.67 | 14.93 | 14.90 | 3.77 | 17.52 | 22.70 |
| 7 | 96.61 | 61.03 | 29.66 | 9.32 | 23.77 | 53.75 | 23.67 | 17.02 | 16.06 | 10.50 | 18.31 | 15.37 |
| 8 | 155.53 | 62.63 | 24.61 | 12.76 | 34.17 | 48.15 | 32.68 | 14.82 | 13.60 | 11.14 | 22.48 | 16.28 |
| 9 | 167.66 | 47.45 | 17.42 | 35.13 | 6.85 | 44.25 | 5.32 | 15.89 | 11.09 | 21.76 | 19.78 | 11.53 |
| 10 | 174.02 | 50.21 | 22.53 | 27.26 | 132.17 | -26.78 | 29.56 | 20.03 | 19.72 | 20.09 | 27.65 | 24.34 |
| 11 | 177.63 | 49.21 | 28.95 | 21.84 | 49.12 | 22.17 | 25.61 | 16.68 | 17.11 | 15.03 | 33.83 | 21.04 |
| 12 | 181.84 | 39.68 | 21.97 | 38.34 | 112.27 | -5.35 | 13.05 | 22.84 | 17.22 | 23.19 | 41.05 | 15.79 |
| 13 | 198.77 | 46.26 | 23.21 | 30.53 | 196.86 | -32.03 | -9.71 | 22.83 | 16.00 | 19.09 | 28.54 | 27.47 |
| 14 | 241.67 | 40.79 | 34.63 | 24.58 | 358.82 | 32.36 | -0.67 | 17.74 | 14.53 | 15.59 | 24.39 | 18.77 |
| 15 | 256.55 | 55.61 | 19.08 | 25.32 | 245.54 | -20.66 | -45.42 | 18.35 | 13.77 | 18.84 | 23.74 | 19.78 |
| 16 | 261.06 | 51.82 | 30.45 | 17.74 | 335.82 | 44.47 | -19.97 | 16.86 | 17.03 | 11.13 | 19.28 | 15.16 |
| 17 | 261.93 | 51.21 | 25.79 | 23.00 | 329.99 | 41.26 | -23.83 | 19.42 | 15.16 | 16.93 | 19.36 | 19.09 |
| 18 | 264.69 | 44.13 | 15.13 | 40.74 | 300.70 | 21.97 | -36.99 | 17.83 | 13.83 | 19.20 | 13.91 | 14.96 |
| 19 | 289.20 | 46.05 | 7.37 | 46.58 | 347.43 | 42.79 | -9.54 | 22.21 | 8.36 | 24.61 | 22.65 | 13.60 |
| 20 | 292.40 | 63.26 | 28.21 | 8.53 | 339.52 | 57.71 | -21.56 | 16.10 | 15.74 | 7.91 | 15.35 | 15.39 |
| 21 | 304.32 | 72.13 | 23.11 | 4.76 | 348.04 | 68.08 | -14.42 | 13.77 | 12.31 | 6.36 | 12.78 | 19.90 |
| 22 | 354.77 | 74.74 | 22.68 | 2.58 | 359.73 | 71.87 | -0.33 | 16.61 | 16.54 | 4.38 | 19.08 | 18.54 |
| 23 | 358.54 | 75.55 | 20.34 | 4.11 | 2.48 | 74.17 | 3.21 | 14.02 | 14.25 | 5.81 | 14.77 | 13.42 |
| B | 266.68 | 35.53 | 5.66 | 58.82 | 347.25 | 32.66 | -7.39 | 23.39 | 8.23 | 26.22 | 22.94 | 12.86 |
| N | 182.44 | 50.47 | 24.00 | 25.53 | 348.55 | 48.31 | -9.78 | 19.48 | 12.56 | 15.46 | 19.29 | 11.33 |
| W | 89.51 | 42.76 | 54.21 | 3.03 | 5.92 | 39.64 | 4.11 | 15.63 | 16.25 | 3.59 | 14.03 | 17.16 |

**Table 1.2** The perceptual naming data of 100 subjects under R2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 80.42 | 15.00 | 4.58 | 359.25 | 79.34 | -1.05 | 14.23 | 12.57 | 8.56 | 15.70 | 11.46 |
| 2 | 21.26 | 78.29 | 19.61 | 2.11 | 4.75 | 76.82 | 6.38 | 13.67 | 12.43 | 5.77 | 15.45 | 11.82 |
| 3 | 30.20 | 75.97 | 21.34 | 2.68 | 7.80 | 72.90 | 9.99 | 20.23 | 18.15 | 5.40 | 22.69 | 16.21 |
| 4 | 58.52 | 78.82 | 20.08 | 1.11 | 4.17 | 77.85 | 5.68 | 13.55 | 13.23 | 2.82 | 14.56 | 9.67 |
| 5 | 71.34 | 78.13 | 11.29 | 10.58 | 5.88 | 75.03 | 7.73 | 17.42 | 12.35 | 17.17 | 20.67 | 17.39 |
| 6 | 90.03 | 73.13 | 25.03 | 1.84 | 4.93 | 71.07 | 6.13 | 18.33 | 17.79 | 4.57 | 19.87 | 14.42 |
| 7 | 96.61 | 74.47 | 20.00 | 5.53 | 2.02 | 73.82 | 2.60 | 20.23 | 19.79 | 9.25 | 21.01 | 7.76 |
| 8 | 155.53 | 79.61 | 13.74 | 6.66 | 2.36 | 77.94 | 3.21 | 16.52 | 13.97 | 10.64 | 18.83 | 13.33 |
| 9 | 167.66 | 66.87 | 12.34 | 20.79 | 357.66 | 66.40 | -2.71 | 20.71 | 9.76 | 17.48 | 20.70 | 7.59 |
| 10 | 174.02 | 64.00 | 11.03 | 24.97 | 354.72 | 62.91 | -5.81 | 20.94 | 15.96 | 18.57 | 20.76 | 10.73 |
| 11 | 177.63 | 70.79 | 10.26 | 18.95 | 354.63 | 69.50 | -6.53 | 21.91 | 17.66 | 16.17 | 22.04 | 11.66 |
| 12 | 181.84 | 56.58 | 8.42 | 35.00 | 344.41 | 53.11 | -14.82 | 28.97 | 14.75 | 23.68 | 25.83 | 18.37 |
| 13 | 198.77 | 46.18 | 7.00 | 46.82 | 351.14 | 44.82 | -6.99 | 24.61 | 14.65 | 26.82 | 24.14 | 10.01 |
| 14 | 241.67 | 74.71 | 11.39 | 13.89 | 358.63 | 74.15 | -1.77 | 19.76 | 17.43 | 10.75 | 20.00 | 8.56 |
| 15 | 256.55 | 39.95 | 4.21 | 55.84 | 351.98 | 38.67 | -5.45 | 23.87 | 7.10 | 26.69 | 24.20 | 7.51 |
| 16 | 261.06 | 74.45 | 8.29 | 17.26 | 359.67 | 73.51 | -0.42 | 18.90 | 11.98 | 12.87 | 20.00 | 9.95 |
| 17 | 261.93 | 66.63 | 9.87 | 23.50 | 356.35 | 64.71 | -4.13 | 21.30 | 15.36 | 14.98 | 23.18 | 12.56 |
| 18 | 264.69 | 56.58 | 5.13 | 38.29 | 355.06 | 54.80 | -4.74 | 29.84 | 9.34 | 29.23 | 30.38 | 12.15 |
| 19 | 289.20 | 48.55 | 5.00 | 46.45 | 356.83 | 47.59 | -2.63 | 29.48 | 7.26 | 30.91 | 29.89 | 7.95 |
| 20 | 292.40 | 82.18 | 11.89 | 5.92 | 0.16 | 82.06 | 0.24 | 12.49 | 10.17 | 8.21 | 12.54 | 4.36 |
| 21 | 304.32 | 84.13 | 12.21 | 3.66 | 3.83 | 82.65 | 5.53 | 10.21 | 7.52 | 6.45 | 10.94 | 14.37 |
| 22 | 354.77 | 81.58 | 15.79 | 2.63 | 6.54 | 78.95 | 9.05 | 14.19 | 12.46 | 4.08 | 17.11 | 16.06 |
| 23 | 358.54 | 76.16 | 21.34 | 2.50 | 3.50 | 74.84 | 4.58 | 19.09 | 17.93 | 6.23 | 19.88 | 12.31 |
| B | 266.68 | 44.21 | 6.45 | 49.34 | 351.92 | 42.46 | -6.03 | 25.89 | 7.70 | 29.56 | 25.66 | 11.42 |
| N | 182.44 | 70.21 | 11.45 | 18.34 | 0.12 | 68.94 | 0.15 | 17.45 | 15.59 | 10.79 | 17.13 | 13.87 |
| W | 89.51 | 78.37 | 20.05 | 1.58 | 3.12 | 76.96 | 4.19 | 14.33 | 13.13 | 3.46 | 16.22 | 12.22 |

**Table 1.3** The perceptual naming data of 100 subjects under Y1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 47.53 | 37.47 | 14.87 | 35.04 | 33.68 | 23.62 | 19.45 | 18.22 | 11.54 | 20.14 | 23.56 |
| 2 | 21.26 | 48.84 | 33.53 | 17.63 | 38.37 | 36.53 | 28.92 | 12.92 | 12.80 | 15.67 | 15.65 | 11.97 |
| 3 | 30.20 | 60.16 | 27.37 | 12.47 | 30.39 | 48.08 | 28.20 | 12.39 | 14.66 | 11.80 | 17.80 | 19.04 |
| 4 | 58.52 | 50.61 | 42.13 | 7.26 | 47.80 | 30.78 | 33.94 | 14.45 | 15.09 | 7.02 | 22.21 | 13.76 |
| 5 | 71.34 | 60.26 | 23.71 | 16.03 | 59.71 | 28.55 | 48.88 | 17.05 | 15.35 | 14.86 | 21.16 | 16.79 |
| 6 | 90.03 | 61.61 | 29.39 | 9.00 | 79.24 | 11.17 | 58.76 | 17.30 | 16.52 | 6.22 | 14.72 | 17.49 |
| 7 | 96.61 | 56.89 | 24.00 | 19.11 | 70.37 | 17.84 | 50.01 | 14.85 | 10.36 | 13.42 | 21.19 | 14.14 |
| 8 | 155.53 | 52.39 | 32.03 | 15.58 | 136.69 | -36.28 | 34.20 | 16.06 | 14.75 | 13.60 | 16.35 | 16.04 |
| 9 | 167.66 | 37.76 | 19.61 | 42.63 | 135.33 | -24.63 | 24.35 | 18.66 | 14.21 | 23.47 | 19.06 | 14.76 |
| 10 | 174.02 | 64.61 | 26.18 | 9.21 | 158.33 | -53.48 | 21.25 | 19.54 | 15.45 | 11.77 | 27.85 | 22.18 |
| 11 | 177.63 | 53.68 | 32.21 | 14.11 | 161.72 | -48.72 | 16.09 | 17.53 | 16.30 | 10.02 | 16.71 | 16.86 |
| 12 | 181.84 | 60.47 | 21.32 | 18.21 | 179.86 | -58.07 | 0.14 | 15.34 | 14.31 | 9.09 | 15.59 | 16.87 |
| 13 | 198.77 | 65.66 | 23.34 | 11.00 | 189.93 | -54.36 | -9.52 | 14.12 | 13.77 | 8.33 | 14.80 | 35.77 |
| 14 | 241.67 | 43.18 | 38.79 | 18.03 | 171.63 | -35.88 | 5.28 | 18.61 | 16.19 | 9.62 | 19.49 | 23.04 |
| 15 | 256.55 | 60.61 | 26.16 | 13.24 | 223.19 | -38.47 | -36.12 | 20.06 | 14.73 | 12.03 | 20.52 | 29.90 |
| 16 | 261.06 | 38.66 | 40.37 | 20.97 | 213.17 | -24.93 | -16.30 | 20.75 | 18.84 | 15.01 | 21.28 | 24.53 |
| 17 | 261.93 | 35.05 | 40.39 | 24.55 | 214.62 | -22.02 | -15.21 | 27.93 | 21.12 | 22.68 | 23.73 | 27.26 |
| 18 | 264.69 | 52.63 | 13.82 | 33.55 | 231.68 | -29.18 | -36.93 | 16.13 | 11.05 | 13.94 | 23.25 | 17.02 |
| 19 | 289.20 | 15.82 | 17.42 | 66.76 | 346.03 | 9.87 | -2.46 | 15.27 | 21.39 | 27.13 | 11.28 | 16.02 |
| 20 | 292.40 | 33.47 | 47.13 | 19.39 | 339.09 | 23.24 | -8.88 | 23.53 | 22.30 | 17.17 | 17.85 | 27.38 |
| 21 | 304.32 | 53.37 | 31.18 | 15.45 | 347.67 | 44.34 | -9.69 | 22.13 | 16.00 | 12.50 | 28.21 | 22.44 |
| 22 | 354.77 | 64.92 | 28.95 | 6.13 | 4.10 | 60.96 | 4.37 | 17.19 | 17.20 | 6.76 | 18.47 | 21.14 |
| 23 | 358.54 | 66.18 | 21.68 | 12.13 | 359.90 | 63.14 | -0.11 | 14.25 | 11.87 | 10.04 | 16.43 | 18.36 |
| B | 266.68 | 14.34 | 9.97 | 75.68 | 76.50 | 1.29 | 5.37 | 17.01 | 13.93 | 22.40 | 17.21 | 13.16 |
| N | 182.44 | 28.63 | 32.82 | 38.55 | 77.12 | 3.93 | 17.19 | 22.86 | 18.84 | 19.24 | 15.25 | 28.51 |
| W | 89.51 | 31.58 | 61.18 | 7.24 | 80.80 | 4.67 | 28.84 | 17.56 | 20.05 | 14.92 | 14.04 | 16.09 |

**Table 1.4** The perceptual naming data of 100 subjects under Y2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 56.11 | 31.05 | 12.84 | 44.03 | 37.94 | 36.68 | 16.94 | 19.18 | 11.51 | 20.95 | 14.86 |
| 2 | 21.26 | 64.08 | 23.74 | 12.18 | 39.41 | 48.14 | 39.55 | 16.45 | 15.82 | 12.52 | 19.02 | 11.78 |
| 3 | 30.20 | 66.55 | 25.32 | 8.13 | 23.70 | 55.45 | 24.34 | 13.15 | 13.71 | 8.80 | 18.18 | 25.00 |
| 4 | 58.52 | 63.61 | 29.21 | 7.18 | 46.01 | 42.10 | 43.61 | 14.53 | 13.53 | 6.73 | 18.71 | 15.55 |
| 5 | 71.34 | 65.50 | 21.45 | 13.05 | 55.80 | 29.77 | 43.81 | 17.77 | 16.68 | 10.50 | 39.69 | 16.27 |
| 6 | 90.03 | 69.32 | 25.13 | 5.55 | 62.90 | 29.89 | 58.41 | 14.30 | 13.94 | 6.31 | 21.96 | 15.31 |
| 7 | 96.61 | 63.71 | 23.87 | 12.42 | 55.95 | 32.25 | 47.72 | 16.32 | 15.08 | 9.69 | 24.12 | 21.13 |
| 8 | 155.53 | 53.89 | 31.50 | 14.87 | 84.27 | 4.64 | 46.29 | 17.30 | 20.49 | 12.14 | 27.92 | 16.73 |
| 9 | 167.66 | 43.76 | 21.45 | 34.79 | 71.78 | 10.80 | 32.81 | 17.97 | 15.15 | 18.24 | 28.53 | 15.82 |
| 10 | 174.02 | 59.34 | 27.08 | 13.58 | 153.26 | -46.56 | 23.46 | 19.13 | 16.12 | 17.12 | 30.20 | 16.70 |
| 11 | 177.63 | 54.79 | 27.61 | 17.61 | 148.39 | -44.01 | 27.09 | 18.76 | 17.58 | 12.00 | 17.49 | 19.65 |
| 12 | 181.84 | 61.63 | 19.68 | 18.68 | 164.83 | -56.76 | 15.38 | 16.26 | 14.42 | 14.31 | 16.71 | 18.29 |
| 13 | 198.77 | 67.74 | 21.68 | 10.58 | 168.91 | -57.74 | 11.32 | 16.19 | 13.50 | 12.88 | 25.42 | 27.79 |
| 14 | 241.67 | 54.82 | 30.18 | 15.00 | 132.57 | -32.18 | 35.04 | 18.90 | 16.71 | 10.13 | 21.80 | 25.36 |
| 15 | 256.55 | 64.84 | 22.21 | 12.95 | 166.12 | -55.58 | 13.74 | 20.43 | 15.94 | 12.70 | 22.19 | 29.61 |
| 16 | 261.06 | 55.82 | 28.13 | 16.05 | 142.66 | -39.62 | 30.23 | 17.66 | 16.29 | 8.95 | 21.23 | 22.58 |
| 17 | 261.93 | 50.45 | 30.47 | 19.08 | 153.96 | -39.31 | 19.21 | 20.52 | 19.90 | 16.90 | 20.60 | 25.39 |
| 18 | 264.69 | 50.34 | 10.05 | 39.61 | 158.83 | -45.30 | 17.54 | 21.56 | 11.22 | 23.39 | 19.87 | 15.78 |
| 19 | 289.20 | 33.50 | 6.71 | 59.79 | 30.68 | 24.69 | 14.65 | 22.33 | 8.08 | 26.14 | 21.22 | 18.83 |
| 20 | 292.40 | 56.26 | 26.71 | 17.03 | 57.32 | 26.70 | 41.62 | 17.22 | 15.56 | 13.26 | 28.42 | 15.13 |
| 21 | 304.32 | 58.47 | 24.74 | 16.79 | 33.16 | 47.49 | 31.04 | 20.60 | 13.65 | 17.52 | 20.14 | 14.99 |
| 22 | 354.77 | 73.55 | 23.32 | 3.13 | 19.28 | 65.19 | 22.81 | 15.93 | 15.13 | 5.08 | 21.39 | 21.30 |
| 23 | 358.54 | 77.55 | 16.50 | 5.95 | 6.57 | 72.95 | 8.41 | 12.99 | 13.34 | 6.56 | 17.88 | 22.08 |
| B | 266.68 | 29.13 | 13.37 | 57.50 | 33.97 | 14.69 | 9.90 | 21.23 | 16.88 | 27.55 | 21.54 | 23.16 |
| N | 182.44 | 43.97 | 23.26 | 32.76 | 62.80 | 17.80 | 34.64 | 21.25 | 19.05 | 18.66 | 23.30 | 18.36 |
| W | 89.51 | 60.00 | 33.68 | 6.32 | 73.62 | 15.96 | 54.28 | 21.17 | 24.09 | 8.67 | 21.56 | 19.83 |

**Table 1.5** The perceptual naming data of 100 subjects under G1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 50.68 | 32.05 | 17.26 | 169.52 | -46.07 | 8.52 | 21.18 | 18.65 | 14.18 | 21.49 | 19.25 |
| 2 | 21.26 | 48.05 | 33.13 | 18.82 | 159.45 | -42.76 | 16.03 | 16.19 | 17.34 | 13.28 | 14.59 | 16.70 |
| 3 | 30.20 | 51.47 | 22.95 | 25.58 | 64.39 | 19.30 | 40.27 | 18.69 | 17.12 | 20.40 | 27.50 | 16.32 |
| 4 | 58.52 | 46.97 | 42.76 | 10.26 | 160.43 | -42.28 | 15.03 | 16.22 | 16.18 | 8.38 | 15.55 | 14.81 |
| 5 | 71.34 | 55.16 | 27.16 | 17.68 | 161.56 | -46.08 | 15.37 | 20.27 | 18.92 | 13.03 | 26.36 | 20.42 |
| 6 | 90.03 | 61.05 | 31.05 | 7.89 | 151.74 | -50.53 | 27.16 | 14.98 | 15.63 | 6.94 | 16.24 | 20.22 |
| 7 | 96.61 | 56.05 | 26.05 | 17.63 | 155.84 | -48.20 | 21.63 | 15.25 | 14.00 | 14.97 | 14.12 | 19.84 |
| 8 | 155.53 | 57.26 | 33.18 | 9.53 | 171.09 | -54.95 | 8.62 | 19.16 | 19.97 | 8.52 | 20.14 | 12.32 |
| 9 | 167.66 | 59.21 | 13.11 | 27.68 | 175.18 | -57.98 | 4.89 | 18.62 | 13.28 | 18.86 | 18.77 | 10.85 |
| 10 | 174.02 | 72.24 | 21.76 | 6.00 | 183.47 | -58.73 | -3.56 | 16.76 | 16.64 | 5.73 | 35.52 | 28.68 |
| 11 | 177.63 | 61.32 | 28.39 | 10.29 | 186.66 | -57.57 | -6.72 | 14.77 | 15.11 | 10.90 | 14.40 | 20.54 |
| 12 | 181.84 | 67.00 | 17.74 | 15.26 | 185.95 | -64.74 | -6.74 | 18.50 | 15.22 | 13.55 | 19.64 | 14.70 |
| 13 | 198.77 | 69.05 | 25.00 | 5.95 | 200.65 | -56.92 | -21.45 | 15.90 | 14.24 | 5.45 | 27.83 | 24.00 |
| 14 | 241.67 | 58.95 | 30.92 | 10.13 | 196.18 | -52.80 | -15.32 | 15.17 | 14.51 | 8.31 | 14.64 | 21.92 |
| 15 | 256.55 | 63.45 | 29.92 | 6.63 | 217.61 | -45.86 | -35.32 | 14.72 | 12.71 | 7.63 | 19.96 | 22.62 |
| 16 | 261.06 | 64.97 | 25.74 | 9.29 | 209.59 | -51.06 | -28.99 | 13.67 | 14.49 | 6.55 | 23.30 | 20.95 |
| 17 | 261.93 | 61.47 | 28.16 | 10.37 | 215.46 | -43.02 | -30.64 | 17.55 | 14.45 | 9.49 | 23.50 | 27.80 |
| 18 | 264.69 | 59.26 | 19.08 | 21.66 | 224.12 | -39.56 | -38.37 | 16.15 | 15.11 | 15.90 | 22.71 | 15.24 |
| 19 | 289.20 | 30.45 | 9.50 | 60.05 | 189.32 | -28.12 | -4.61 | 19.10 | 13.24 | 25.34 | 18.42 | 11.99 |
| 20 | 292.40 | 53.42 | 31.32 | 15.26 | 219.74 | -37.87 | -31.49 | 15.63 | 13.90 | 10.78 | 17.61 | 19.35 |
| 21 | 304.32 | 19.00 | 37.50 | 43.50 | 286.11 | 2.90 | -10.05 | 27.84 | 18.80 | 21.67 | 26.11 | 18.75 |
| 22 | 354.77 | 50.47 | 30.61 | 18.92 | 350.16 | 40.06 | -6.95 | 19.56 | 18.49 | 16.74 | 28.12 | 22.60 |
| 23 | 358.54 | 53.82 | 19.50 | 26.68 | 346.89 | 50.62 | -11.78 | 16.68 | 15.65 | 16.39 | 16.69 | 14.15 |
| B | 266.68 | 34.16 | 6.53 | 59.32 | 186.23 | -33.02 | -3.61 | 23.07 | 8.25 | 26.11 | 22.24 | 10.13 |
| N | 182.44 | 45.26 | 25.39 | 29.34 | 186.37 | -42.79 | -4.78 | 22.18 | 16.33 | 18.68 | 22.23 | 14.07 |
| W | 89.51 | 39.74 | 55.84 | 4.42 | 176.83 | -34.74 | 1.92 | 16.52 | 17.43 | 4.71 | 21.97 | 12.98 |

**Table 1.6** The perceptual naming data of 100 subjects under G2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 68.03 | 16.84 | 15.13 | 179.08 | -67.29 | 1.08 | 19.12 | 13.43 | 11.12 | 19.24 | 9.80 |
| 2 | 21.26 | 71.05 | 17.89 | 11.05 | 176.72 | -69.81 | 4.00 | 14.98 | 11.37 | 8.94 | 16.29 | 11.08 |
| 3 | 30.20 | 58.03 | 12.71 | 29.26 | 178.36 | -56.74 | 1.62 | 20.05 | 13.49 | 18.33 | 20.07 | 12.19 |
| 4 | 58.52 | 66.32 | 27.05 | 6.63 | 175.83 | -64.15 | 4.67 | 14.98 | 12.69 | 7.68 | 16.15 | 15.24 |
| 5 | 71.34 | 67.84 | 17.18 | 14.97 | 177.20 | -66.70 | 3.26 | 19.61 | 14.79 | 15.17 | 20.37 | 10.78 |
| 6 | 90.03 | 76.34 | 21.16 | 2.50 | 177.35 | -74.36 | 3.45 | 14.18 | 12.82 | 5.78 | 16.19 | 15.28 |
| 7 | 96.61 | 69.47 | 19.47 | 11.05 | 175.54 | -68.32 | 5.33 | 15.01 | 15.28 | 11.40 | 15.41 | 11.04 |
| 8 | 155.53 | 73.16 | 18.95 | 7.89 | 178.63 | -72.14 | 1.73 | 15.26 | 15.20 | 7.97 | 15.88 | 11.35 |
| 9 | 167.66 | 66.63 | 9.03 | 24.34 | 179.87 | -66.27 | 0.15 | 17.99 | 9.66 | 16.85 | 18.45 | 5.71 |
| 10 | 174.02 | 74.42 | 22.24 | 3.34 | 177.58 | -72.60 | 3.07 | 17.31 | 15.97 | 5.13 | 18.74 | 14.61 |
| 11 | 177.63 | 70.76 | 21.66 | 7.58 | 181.42 | -69.18 | -1.72 | 15.13 | 13.44 | 8.54 | 16.30 | 13.70 |
| 12 | 181.84 | 72.29 | 15.66 | 12.05 | 180.07 | -70.69 | -0.09 | 16.75 | 8.63 | 13.57 | 17.85 | 14.03 |
| 13 | 198.77 | 73.39 | 19.11 | 7.50 | 176.28 | -70.86 | 4.61 | 19.53 | 16.35 | 8.12 | 21.10 | 17.02 |
| 14 | 241.67 | 74.45 | 19.58 | 5.97 | 178.53 | -69.67 | 1.79 | 17.02 | 15.12 | 7.90 | 29.18 | 11.94 |
| 15 | 256.55 | 72.89 | 20.71 | 6.26 | 172.66 | -69.07 | 8.90 | 17.67 | 15.85 | 7.99 | 19.78 | 19.93 |
| 16 | 261.06 | 76.11 | 16.95 | 6.95 | 179.64 | -74.70 | 0.47 | 15.55 | 12.94 | 5.97 | 16.63 | 13.49 |
| 17 | 261.93 | 68.11 | 18.87 | 13.03 | 177.31 | -67.10 | 3.15 | 17.76 | 13.03 | 15.00 | 18.07 | 10.86 |
| 18 | 264.69 | 69.00 | 11.45 | 19.55 | 184.69 | -66.16 | -5.43 | 19.67 | 12.35 | 13.93 | 21.14 | 17.43 |
| 19 | 289.20 | 37.55 | 4.16 | 58.29 | 183.07 | -36.64 | -1.97 | 21.05 | 12.62 | 23.46 | 21.70 | 6.12 |
| 20 | 292.40 | 74.37 | 16.82 | 8.82 | 179.05 | -73.27 | 1.21 | 17.32 | 12.41 | 11.21 | 18.36 | 11.30 |
| 21 | 304.32 | 64.66 | 13.24 | 22.11 | 181.94 | -63.51 | -2.15 | 19.01 | 8.35 | 18.66 | 19.70 | 10.93 |
| 22 | 354.77 | 54.92 | 13.55 | 31.53 | 182.71 | -54.02 | -2.56 | 22.21 | 13.95 | 23.58 | 22.14 | 9.88 |
| 23 | 358.54 | 40.79 | 3.71 | 55.50 | 181.07 | -40.47 | -0.76 | 26.36 | 5.12 | 28.45 | 26.34 | 5.22 |
| B | 266.68 | 40.47 | 5.92 | 53.61 | 181.84 | -40.10 | -1.29 | 26.06 | 7.79 | 29.41 | 25.75 | 6.75 |
| N | 182.44 | 63.97 | 13.05 | 22.97 | 179.08 | -61.88 | 1.00 | 18.34 | 11.40 | 15.89 | 18.84 | 15.86 |
| W | 89.51 | 65.76 | 31.74 | 2.50 | 175.82 | -63.45 | 4.64 | 14.39 | 15.29 | 3.24 | 15.52 | 15.83 |

**Table 1.7** The perceptual naming data of 100 subjects under C1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 31.05 | 41.42 | 27.53 | 293.47 | 10.83 | -24.95 | 19.62 | 18.14 | 16.89 | 16.76 | 18.30 |
| 2 | 21.26 | 11.00 | 60.26 | 28.74 | 281.94 | 1.73 | -8.18 | 18.37 | 16.31 | 15.20 | 13.36 | 14.55 |
| 3 | 30.20 | 44.34 | 35.61 | 20.05 | 19.35 | 35.28 | 12.39 | 18.75 | 15.13 | 15.62 | 20.98 | 22.25 |
| 4 | 58.52 | 7.84 | 69.18 | 22.97 | 244.12 | -2.24 | -4.61 | 14.44 | 14.95 | 15.87 | 7.79 | 13.56 |
| 5 | 71.34 | 26.79 | 37.50 | 35.71 | 210.58 | -16.67 | -9.85 | 18.55 | 23.41 | 18.73 | 11.86 | 23.57 |
| 6 | 90.03 | 37.42 | 47.34 | 14.97 | 149.02 | -27.84 | 16.72 | 18.18 | 17.65 | 9.97 | 17.84 | 19.17 |
| 7 | 96.61 | 50.34 | 30.95 | 18.71 | 146.87 | -38.54 | 25.15 | 16.70 | 14.83 | 14.55 | 18.17 | 19.39 |
| 8 | 155.53 | 44.45 | 39.08 | 16.47 | 179.53 | -42.80 | 0.35 | 18.88 | 18.63 | 12.33 | 19.20 | 11.63 |
| 9 | 167.66 | 37.76 | 16.42 | 45.82 | 200.54 | -33.68 | -12.62 | 14.91 | 11.82 | 15.21 | 12.48 | 14.23 |
| 10 | 174.02 | 59.95 | 31.71 | 8.34 | 190.60 | -52.93 | -9.90 | 19.28 | 18.37 | 6.46 | 28.28 | 16.87 |
| 11 | 177.63 | 50.11 | 34.34 | 15.55 | 209.28 | -38.43 | -21.55 | 16.96 | 16.91 | 8.51 | 23.10 | 18.40 |
| 12 | 181.84 | 58.61 | 22.71 | 18.68 | 200.12 | -52.63 | -19.28 | 14.64 | 13.96 | 13.89 | 16.17 | 15.91 |
| 13 | 198.77 | 58.45 | 31.50 | 10.05 | 233.54 | -32.27 | -43.67 | 21.21 | 20.85 | 11.39 | 19.42 | 23.51 |
| 14 | 241.67 | 52.53 | 32.87 | 14.61 | 241.38 | -24.18 | -44.31 | 17.62 | 15.27 | 10.28 | 17.13 | 15.28 |
| 15 | 256.55 | 65.16 | 28.45 | 6.39 | 245.54 | -24.11 | -53.00 | 15.76 | 14.68 | 6.72 | 21.94 | 25.39 |
| 16 | 261.06 | 58.76 | 28.39 | 12.84 | 250.73 | -18.60 | -53.20 | 12.91 | 11.83 | 8.41 | 15.69 | 14.31 |
| 17 | 261.93 | 58.11 | 29.03 | 12.87 | 254.50 | -13.93 | -50.21 | 16.88 | 11.11 | 11.70 | 15.37 | 26.98 |
| 18 | 264.69 | 65.03 | 19.21 | 15.76 | 239.40 | -27.91 | -47.20 | 18.16 | 16.45 | 13.20 | 34.43 | 19.98 |
| 19 | 289.20 | 33.00 | 5.26 | 61.74 | 275.10 | 2.83 | -31.71 | 23.25 | 9.37 | 23.42 | 10.76 | 22.41 |
| 20 | 292.40 | 55.82 | 31.47 | 12.71 | 273.35 | 3.14 | -53.62 | 17.38 | 15.54 | 10.64 | 15.53 | 17.23 |
| 21 | 304.32 | 58.03 | 23.89 | 18.08 | 303.74 | 30.33 | -45.41 | 19.37 | 16.52 | 13.82 | 19.59 | 19.66 |
| 22 | 354.77 | 63.58 | 24.76 | 11.68 | 331.19 | 51.75 | -28.46 | 17.98 | 13.90 | 11.30 | 18.37 | 23.54 |
| 23 | 358.54 | 62.26 | 17.34 | 20.39 | 330.37 | 51.42 | -29.24 | 17.49 | 13.42 | 11.59 | 11.11 | 23.88 |
| B | 266.68 | 25.32 | 8.87 | 65.82 | 250.46 | -7.92 | -22.32 | 17.48 | 10.77 | 22.47 | 11.57 | 15.93 |
| N | 182.44 | 29.53 | 32.92 | 37.55 | 257.42 | -6.14 | -27.54 | 22.10 | 18.20 | 17.63 | 11.56 | 20.80 |
| W | 89.51 | 35.00 | 60.03 | 4.97 | 257.00 | -7.64 | -33.09 | 18.34 | 20.55 | 4.51 | 10.19 | 17.50 |

**Table 1.8** The perceptual naming data of 100 subjects under C2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 55.39 | 25.00 | 19.61 | 244.30 | -23.27 | -48.35 | 18.28 | 14.38 | 14.11 | 17.20 | 15.25 |
| 2 | 21.26 | 58.55 | 27.58 | 13.87 | 230.04 | -35.47 | -42.33 | 18.64 | 13.72 | 12.40 | 23.19 | 14.10 |
| 3 | 30.20 | 50.89 | 15.66 | 33.45 | 204.30 | -43.11 | -19.46 | 16.88 | 14.16 | 17.28 | 16.41 | 19.45 |
| 4 | 58.52 | 55.84 | 35.32 | 8.84 | 241.64 | -25.72 | -47.64 | 19.15 | 20.60 | 9.59 | 18.62 | 14.57 |
| 5 | 71.34 | 60.32 | 17.97 | 21.71 | 215.31 | -46.05 | -32.62 | 16.41 | 11.33 | 12.99 | 18.27 | 20.04 |
| 6 | 90.03 | 59.66 | 33.03 | 7.32 | 198.63 | -53.72 | -18.11 | 17.43 | 16.89 | 5.29 | 17.54 | 18.74 |
| 7 | 96.61 | 64.16 | 22.13 | 13.71 | 191.60 | -60.02 | -12.32 | 13.56 | 11.08 | 12.47 | 14.01 | 18.96 |
| 8 | 155.53 | 62.61 | 24.66 | 12.74 | 201.76 | -55.65 | -22.21 | 13.85 | 14.75 | 8.84 | 13.50 | 18.65 |
| 9 | 167.66 | 62.21 | 12.50 | 25.29 | 199.49 | -55.84 | -19.76 | 14.98 | 9.73 | 14.44 | 19.08 | 15.21 |
| 10 | 174.02 | 66.63 | 25.37 | 8.00 | 197.66 | -59.36 | -18.90 | 15.70 | 14.23 | 7.20 | 16.26 | 23.58 |
| 11 | 177.63 | 64.18 | 25.61 | 10.21 | 216.01 | -48.11 | -34.96 | 14.74 | 12.95 | 8.73 | 21.06 | 19.28 |
| 12 | 181.84 | 61.13 | 22.84 | 16.03 | 212.66 | -49.91 | -31.99 | 13.18 | 12.72 | 10.28 | 13.98 | 14.39 |
| 13 | 198.77 | 63.89 | 28.45 | 7.66 | 234.46 | -34.64 | -48.48 | 19.92 | 15.81 | 8.40 | 20.58 | 22.80 |
| 14 | 241.67 | 66.50 | 22.21 | 11.29 | 246.85 | -24.37 | -57.00 | 13.35 | 10.81 | 13.66 | 16.53 | 22.36 |
| 15 | 256.55 | 64.95 | 32.05 | 3.00 | 250.38 | -20.14 | -56.48 | 16.90 | 15.49 | 4.31 | 22.52 | 20.44 |
| 16 | 261.06 | 67.95 | 24.16 | 7.89 | 245.52 | -26.89 | -59.06 | 14.34 | 11.93 | 9.50 | 20.07 | 14.80 |
| 17 | 261.93 | 66.61 | 23.66 | 9.74 | 257.23 | -13.44 | -59.31 | 16.56 | 13.10 | 8.63 | 14.67 | 28.59 |
| 18 | 264.69 | 71.18 | 16.50 | 12.32 | 255.40 | -17.33 | -66.49 | 17.22 | 14.61 | 11.56 | 17.74 | 18.37 |
| 19 | 289.20 | 41.84 | 6.18 | 51.97 | 248.21 | -15.13 | -37.85 | 25.80 | 5.12 | 27.94 | 15.19 | 22.94 |
| 20 | 292.40 | 68.79 | 21.55 | 9.66 | 254.90 | -17.39 | -64.44 | 16.37 | 11.31 | 11.45 | 16.61 | 16.66 |
| 21 | 304.32 | 69.13 | 17.16 | 13.71 | 267.16 | -3.30 | -66.53 | 14.16 | 9.74 | 11.19 | 18.34 | 14.67 |
| 22 | 354.77 | 58.82 | 17.71 | 23.47 | 264.57 | -5.29 | -55.67 | 15.98 | 12.18 | 16.33 | 18.83 | 15.56 |
| 23 | 358.54 | 46.37 | 5.47 | 48.16 | 262.51 | -5.92 | -45.04 | 24.50 | 6.07 | 27.29 | 10.52 | 24.04 |
| B | 266.68 | 35.47 | 10.08 | 54.45 | 251.01 | -11.23 | -32.62 | 23.52 | 8.98 | 28.48 | 12.20 | 21.78 |
| N | 182.44 | 50.92 | 23.74 | 25.34 | 241.61 | -23.01 | -42.57 | 23.82 | 19.16 | 14.39 | 18.77 | 21.75 |
| W | 89.51 | 56.05 | 40.53 | 3.42 | 241.61 | -25.34 | -46.88 | 21.00 | 23.68 | 4.67 | 21.06 | 17.55 |

**Table 1.19** The perceptual naming data of 100 subjects under B1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 55.68 | 27.71 | 16.61 | 309.73 | 32.77 | -39.43 | 19.51 | 15.74 | 11.77 | 20.36 | 21.24 |
| 2 | 21.26 | 60.61 | 27.32 | 12.08 | 308.79 | 36.24 | -45.09 | 20.78 | 21.12 | 9.81 | 15.05 | 23.26 |
| 3 | 30.20 | 56.68 | 30.39 | 12.92 | 339.07 | 49.63 | -18.99 | 14.65 | 15.48 | 11.49 | 13.85 | 20.57 |
| 4 | 58.52 | 54.39 | 38.29 | 7.32 | 317.36 | 37.40 | -34.43 | 23.00 | 23.94 | 4.65 | 18.71 | 23.75 |
| 5 | 71.34 | 50.76 | 26.11 | 23.13 | 311.35 | 30.04 | -34.13 | 21.21 | 19.38 | 18.18 | 18.33 | 25.25 |
| 6 | 90.03 | 32.45 | 52.39 | 15.16 | 58.79 | 11.00 | 18.17 | 23.00 | 23.77 | 13.34 | 17.74 | 28.85 |
| 7 | 96.61 | 46.21 | 30.42 | 23.37 | 73.12 | 10.02 | 33.01 | 21.25 | 18.82 | 15.12 | 25.92 | 27.39 |
| 8 | 155.53 | 20.82 | 45.66 | 33.53 | 202.16 | -10.49 | -4.27 | 27.63 | 19.52 | 19.02 | 23.36 | 23.04 |
| 9 | 167.66 | 25.24 | 16.61 | 58.16 | 281.14 | 4.25 | -21.57 | 15.90 | 14.19 | 19.84 | 16.64 | 11.57 |
| 10 | 174.02 | 52.03 | 32.16 | 15.82 | 204.10 | -41.68 | -18.64 | 17.62 | 15.98 | 17.25 | 26.24 | 16.14 |
| 11 | 177.63 | 50.68 | 27.34 | 21.97 | 221.60 | -28.25 | -25.09 | 19.65 | 15.98 | 15.21 | 23.19 | 31.95 |
| 12 | 181.84 | 57.45 | 17.95 | 24.61 | 218.19 | -41.40 | -32.56 | 16.66 | 12.08 | 13.25 | 22.89 | 17.13 |
| 13 | 198.77 | 65.24 | 22.92 | 11.84 | 250.82 | -20.01 | -57.53 | 18.29 | 17.42 | 13.75 | 23.12 | 18.98 |
| 14 | 241.67 | 60.58 | 25.47 | 13.95 | 278.27 | 8.25 | -56.74 | 15.68 | 13.48 | 12.54 | 18.49 | 17.21 |
| 15 | 256.55 | 71.87 | 22.55 | 5.58 | 260.34 | -11.50 | -67.55 | 13.10 | 11.92 | 6.06 | 20.60 | 15.18 |
| 16 | 261.06 | 64.92 | 22.66 | 12.42 | 272.38 | 2.59 | -62.34 | 11.66 | 13.78 | 7.77 | 17.61 | 12.49 |
| 17 | 261.93 | 65.32 | 23.39 | 11.29 | 274.30 | 4.73 | -62.96 | 16.52 | 16.57 | 8.59 | 15.22 | 18.14 |
| 18 | 264.69 | 73.87 | 11.16 | 14.97 | 273.68 | 4.64 | -72.05 | 15.74 | 10.76 | 12.56 | 14.92 | 16.58 |
| 19 | 289.20 | 46.00 | 8.21 | 45.79 | 297.87 | 20.34 | -38.46 | 25.32 | 7.28 | 29.05 | 11.28 | 27.25 |
| 20 | 292.40 | 63.87 | 23.32 | 12.82 | 291.45 | 22.95 | -58.39 | 14.00 | 11.70 | 10.49 | 10.82 | 15.03 |
| 21 | 304.32 | 65.39 | 21.03 | 13.58 | 303.37 | 33.17 | -50.36 | 16.93 | 13.67 | 11.13 | 23.41 | 19.91 |
| 22 | 354.77 | 68.84 | 22.87 | 8.29 | 329.83 | 55.33 | -32.16 | 13.97 | 13.09 | 7.47 | 16.70 | 24.03 |
| 23 | 358.54 | 70.03 | 15.26 | 14.71 | 329.67 | 56.85 | -33.26 | 16.86 | 14.29 | 12.10 | 15.26 | 25.14 |
| B | 266.68 | 31.76 | 8.18 | 60.05 | 293.73 | 12.43 | -28.28 | 20.23 | 10.45 | 23.78 | 10.36 | 18.91 |
| N | 182.44 | 46.76 | 22.58 | 30.66 | 289.20 | 14.84 | -42.63 | 26.95 | 18.32 | 19.28 | 15.02 | 25.56 |
| W | 89.51 | 46.71 | 48.16 | 5.13 | 291.78 | 16.94 | -42.41 | 20.96 | 23.63 | 5.13 | 12.82 | 19.33 |

**Table 1.10** The perceptual naming data of 100 subjects under B2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 69.21 | 11.97 | 18.82 | 269.59 | -0.50 | -69.11 | 17.61 | 12.11 | 13.07 | 3.32 | 17.68 |
| 2 | 21.26 | 73.71 | 12.37 | 13.92 | 270.11 | 0.15 | -73.64 | 15.24 | 11.73 | 12.02 | 2.71 | 15.32 |
| 3 | 30.20 | 55.26 | 5.84 | 38.89 | 267.61 | -2.28 | -54.62 | 23.74 | 8.82 | 24.25 | 7.94 | 23.82 |
| 4 | 58.52 | 77.89 | 13.29 | 8.82 | 269.21 | -1.07 | -77.75 | 12.66 | 10.35 | 11.05 | 4.55 | 12.73 |
| 5 | 71.34 | 62.76 | 8.11 | 29.13 | 270.18 | 0.20 | -62.17 | 23.10 | 12.17 | 18.67 | 6.84 | 23.74 |
| 6 | 90.03 | 61.50 | 17.55 | 20.95 | 259.71 | -10.78 | -59.39 | 24.24 | 19.93 | 21.93 | 9.61 | 25.26 |
| 7 | 96.61 | 44.11 | 6.58 | 49.32 | 241.27 | -20.03 | -36.55 | 18.69 | 6.48 | 20.40 | 12.16 | 20.38 |
| 8 | 155.53 | 67.34 | 7.89 | 24.76 | 264.97 | -5.75 | -65.36 | 19.53 | 9.91 | 14.80 | 12.64 | 21.40 |
| 9 | 167.66 | 57.92 | 8.08 | 34.00 | 268.18 | -1.84 | -57.66 | 22.99 | 12.67 | 22.81 | 5.01 | 23.04 |
| 10 | 174.02 | 59.53 | 10.50 | 29.97 | 249.52 | -19.92 | -53.31 | 19.09 | 9.56 | 16.98 | 15.54 | 20.88 |
| 11 | 177.63 | 70.61 | 7.32 | 22.08 | 268.42 | -1.93 | -70.21 | 25.18 | 11.09 | 21.40 | 5.63 | 25.60 |
| 12 | 181.84 | 64.16 | 8.82 | 27.03 | 263.74 | -6.76 | -61.67 | 19.84 | 8.66 | 18.75 | 15.96 | 20.32 |
| 13 | 198.77 | 76.79 | 12.55 | 10.66 | 268.04 | -2.61 | -76.21 | 17.73 | 14.89 | 14.34 | 8.15 | 18.21 |
| 14 | 241.67 | 75.89 | 13.87 | 10.24 | 269.46 | -0.71 | -75.78 | 17.97 | 12.67 | 11.75 | 3.55 | 18.10 |
| 15 | 256.55 | 73.68 | 19.34 | 6.97 | 269.08 | -1.18 | -73.47 | 20.02 | 18.97 | 9.76 | 4.93 | 20.20 |
| 16 | 261.06 | 80.16 | 12.42 | 7.42 | 269.45 | -0.77 | -80.07 | 16.24 | 12.53 | 10.86 | 3.22 | 16.38 |
| 17 | 261.93 | 73.74 | 17.50 | 8.76 | 269.18 | -1.04 | -72.84 | 18.31 | 17.04 | 9.01 | 8.32 | 20.01 |
| 18 | 264.69 | 75.66 | 13.42 | 10.92 | 270.05 | 0.07 | -75.26 | 18.79 | 12.03 | 13.50 | 6.34 | 19.36 |
| 19 | 289.20 | 52.58 | 2.55 | 44.87 | 269.99 | -0.01 | -52.53 | 29.15 | 3.41 | 30.83 | 2.10 | 29.16 |
| 20 | 292.40 | 75.76 | 15.74 | 8.50 | 269.71 | -0.38 | -75.60 | 20.49 | 14.37 | 9.73 | 4.13 | 20.70 |
| 21 | 304.32 | 76.61 | 13.16 | 10.24 | 270.40 | 0.53 | -76.48 | 16.68 | 13.92 | 12.05 | 3.68 | 16.85 |
| 22 | 354.77 | 64.29 | 14.61 | 21.11 | 274.81 | 5.17 | -61.37 | 24.38 | 14.35 | 19.60 | 15.72 | 26.40 |
| 23 | 358.54 | 62.61 | 2.63 | 34.76 | 267.31 | -2.93 | -62.25 | 30.98 | 5.90 | 29.67 | 6.39 | 30.91 |
| B | 266.68 | 42.03 | 4.74 | 53.24 | 270.91 | 0.66 | -41.52 | 26.56 | 6.57 | 29.76 | 6.85 | 26.48 |
| N | 182.44 | 68.24 | 11.45 | 20.32 | 269.56 | -0.52 | -68.01 | 18.69 | 12.08 | 13.71 | 4.80 | 18.89 |
| W | 89.51 | 75.53 | 21.84 | 2.63 | 269.53 | -0.62 | -75.38 | 17.85 | 17.26 | 6.01 | 4.30 | 17.96 |

**Table 1.11** The perceptual naming data of 100 subjects under M1

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 59.68 | 32.97 | 7.34 | 349.00 | 53.22 | -10.35 | 15.72 | 14.81 | 7.82 | 14.95 | 25.75 |
| 2 | 21.26 | 66.34 | 27.87 | 5.79 | 342.84 | 59.70 | -18.44 | 13.77 | 13.86 | 4.11 | 14.69 | 22.00 |
| 3 | 30.20 | 63.61 | 32.18 | 4.21 | 6.40 | 59.76 | 6.70 | 14.86 | 14.26 | 4.58 | 16.18 | 19.99 |
| 4 | 58.52 | 60.26 | 34.42 | 5.32 | 351.60 | 55.76 | -8.23 | 13.18 | 15.90 | 4.56 | 14.03 | 21.06 |
| 5 | 71.34 | 52.92 | 33.16 | 13.92 | 355.43 | 46.91 | -3.75 | 16.72 | 16.44 | 10.32 | 15.32 | 25.42 |
| 6 | 90.03 | 61.00 | 34.55 | 4.45 | 57.13 | 32.02 | 49.56 | 17.07 | 17.22 | 5.20 | 14.29 | 18.23 |
| 7 | 96.61 | 57.50 | 30.61 | 12.16 | 45.51 | 38.49 | 39.18 | 13.49 | 10.30 | 10.65 | 16.77 | 14.08 |
| 8 | 155.53 | 51.03 | 35.97 | 13.00 | 26.48 | 38.95 | 19.40 | 19.51 | 19.01 | 9.72 | 20.37 | 26.38 |
| 9 | 167.66 | 38.08 | 22.21 | 39.71 | 348.16 | 31.75 | -6.65 | 15.61 | 15.62 | 24.68 | 22.05 | 12.90 |
| 10 | 174.02 | 49.03 | 31.34 | 19.63 | 159.81 | -42.15 | 15.50 | 21.58 | 22.33 | 16.37 | 24.70 | 15.91 |
| 11 | 177.63 | 27.26 | 43.61 | 29.13 | 264.48 | -0.80 | -8.33 | 26.33 | 17.88 | 16.05 | 32.76 | 17.64 |
| 12 | 181.84 | 43.68 | 21.32 | 35.00 | 190.02 | -33.06 | -5.84 | 21.01 | 17.02 | 19.24 | 29.39 | 19.49 |
| 13 | 198.77 | 53.29 | 25.53 | 21.18 | 245.75 | -19.53 | -43.35 | 18.36 | 15.89 | 17.57 | 24.03 | 18.82 |
| 14 | 241.67 | 48.05 | 32.50 | 19.45 | 308.66 | 27.07 | -33.83 | 17.88 | 15.45 | 10.39 | 16.29 | 22.31 |
| 15 | 256.55 | 58.74 | 26.89 | 13.84 | 260.25 | -8.87 | -51.63 | 16.46 | 14.30 | 14.25 | 25.38 | 18.75 |
| 16 | 261.06 | 59.13 | 26.42 | 14.45 | 293.28 | 22.00 | -51.13 | 16.30 | 16.75 | 10.60 | 19.83 | 16.77 |
| 17 | 261.93 | 50.58 | 32.32 | 17.11 | 290.80 | 17.44 | -45.90 | 17.46 | 15.00 | 12.70 | 11.80 | 17.79 |
| 18 | 264.69 | 61.61 | 16.05 | 22.34 | 283.12 | 13.62 | -58.45 | 18.12 | 13.16 | 16.72 | 13.48 | 18.58 |
| 19 | 289.20 | 43.16 | 9.61 | 47.24 | 331.09 | 35.61 | -19.67 | 23.20 | 9.82 | 26.24 | 21.35 | 17.20 |
| 20 | 292.40 | 54.79 | 34.87 | 10.34 | 318.54 | 40.13 | -35.46 | 20.45 | 21.48 | 7.50 | 15.18 | 18.03 |
| 21 | 304.32 | 65.13 | 23.95 | 10.92 | 335.65 | 55.13 | -24.95 | 18.52 | 11.38 | 11.61 | 16.64 | 25.75 |
| 22 | 354.77 | 73.42 | 23.34 | 3.24 | 349.40 | 66.06 | -12.36 | 13.24 | 13.23 | 5.22 | 16.76 | 28.15 |
| 23 | 358.54 | 67.53 | 28.08 | 4.39 | 354.51 | 64.40 | -6.19 | 15.43 | 17.51 | 6.82 | 15.94 | 19.21 |
| B | 266.68 | 29.13 | 10.92 | 59.95 | 333.64 | 23.82 | -11.80 | 21.14 | 13.94 | 27.01 | 16.82 | 17.60 |
| N | 182.44 | 47.97 | 27.18 | 24.84 | 328.23 | 39.08 | -24.21 | 24.79 | 18.26 | 19.58 | 19.41 | 20.76 |
| W | 89.51 | 47.29 | 45.87 | 6.84 | 340.32 | 40.98 | -14.65 | 21.43 | 24.09 | 14.63 | 19.93 | 20.33 |

**Table 1.12** The perceptual naming data of 100 subjects under M2

| Chip No. | Hue (D65) | Chr | Wh | Bl | Hue | x | y | SD Chr | SD Wh | SD Bl | SD x | SD y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.58 | 73.32 | 19.66 | 7.03 | 339.21 | 61.84 | -23.48 | 15.81 | 11.06 | 11.51 | 13.27 | 33.17 |
| 2 | 21.26 | 75.58 | 21.34 | 3.08 | 333.21 | 62.88 | -31.75 | 15.92 | 15.70 | 8.41 | 14.20 | 28.68 |
| 3 | 30.20 | 71.63 | 24.68 | 3.68 | 354.41 | 66.92 | -6.54 | 16.42 | 16.23 | 6.12 | 18.38 | 23.64 |
| 4 | 58.52 | 77.29 | 19.50 | 3.21 | 336.79 | 66.10 | -28.34 | 13.60 | 12.07 | 5.86 | 12.65 | 29.11 |
| 5 | 71.34 | 72.16 | 16.63 | 11.21 | 333.69 | 61.00 | -30.16 | 18.14 | 11.09 | 17.13 | 16.64 | 25.40 |
| 6 | 90.03 | 73.58 | 24.45 | 1.97 | 351.53 | 68.36 | -10.18 | 17.57 | 16.86 | 3.87 | 18.56 | 24.88 |
| 7 | 96.61 | 73.63 | 19.95 | 6.42 | 353.18 | 68.77 | -8.22 | 13.56 | 13.83 | 6.04 | 13.82 | 25.20 |
| 8 | 155.53 | 71.39 | 16.97 | 11.63 | 332.99 | 58.97 | -30.05 | 18.71 | 11.13 | 14.85 | 14.89 | 29.40 |
| 9 | 167.66 | 62.11 | 11.58 | 26.32 | 330.39 | 51.21 | -29.10 | 26.73 | 14.15 | 21.20 | 19.42 | 27.12 |
| 10 | 174.02 | 60.26 | 13.39 | 26.34 | 339.76 | 53.53 | -19.73 | 20.19 | 10.39 | 18.89 | 18.48 | 21.28 |
| 11 | 177.63 | 63.45 | 13.87 | 22.68 | 328.23 | 52.81 | -32.71 | 26.04 | 14.87 | 23.64 | 19.80 | 21.38 |
| 12 | 181.84 | 55.26 | 8.16 | 36.58 | 311.86 | 34.84 | -38.88 | 28.28 | 9.39 | 29.30 | 19.94 | 27.19 |
| 13 | 198.77 | 65.61 | 14.76 | 19.63 | 292.83 | 23.98 | -56.96 | 18.63 | 12.09 | 16.01 | 22.16 | 18.82 |
| 14 | 241.67 | 70.34 | 14.92 | 14.74 | 317.54 | 48.07 | -43.99 | 19.48 | 12.74 | 10.91 | 24.62 | 22.23 |
| 15 | 256.55 | 73.53 | 10.42 | 16.05 | 285.84 | 19.36 | -68.24 | 13.77 | 8.51 | 12.74 | 17.62 | 16.26 |
| 16 | 261.06 | 72.89 | 17.63 | 9.21 | 306.30 | 41.28 | -56.20 | 15.58 | 10.69 | 11.67 | 21.87 | 15.08 |
| 17 | 261.93 | 68.18 | 21.95 | 9.87 | 302.35 | 35.05 | -55.33 | 17.23 | 16.68 | 8.31 | 19.38 | 17.04 |
| 18 | 264.69 | 70.47 | 13.42 | 16.11 | 293.59 | 27.70 | -63.44 | 16.04 | 11.16 | 13.26 | 12.43 | 16.82 |
| 19 | 289.20 | 51.24 | 6.97 | 41.79 | 328.59 | 43.01 | -26.26 | 20.63 | 9.27 | 21.89 | 17.93 | 13.87 |
| 20 | 292.40 | 73.84 | 19.39 | 6.76 | 322.52 | 56.46 | -43.29 | 12.32 | 10.75 | 8.25 | 12.13 | 20.15 |
| 21 | 304.32 | 78.39 | 17.74 | 4.13 | 337.55 | 69.62 | -28.77 | 14.99 | 11.52 | 6.74 | 15.21 | 21.83 |
| 22 | 354.77 | 71.42 | 24.53 | 4.05 | 349.34 | 65.16 | -12.26 | 16.90 | 16.14 | 5.02 | 18.68 | 25.70 |
| 23 | 358.54 | 69.45 | 27.58 | 2.97 | 354.92 | 65.52 | -5.82 | 18.47 | 19.60 | 5.47 | 19.86 | 21.37 |
| B | 266.68 | 43.76 | 11.42 | 44.82 | 332.53 | 37.20 | -19.34 | 23.00 | 18.13 | 26.66 | 20.04 | 16.99 |
| N | 182.44 | 60.24 | 17.21 | 22.55 | 330.67 | 50.61 | -28.44 | 20.50 | 14.85 | 14.04 | 17.24 | 19.70 |
| W | 89.51 | 68.11 | 30.05 | 1.84 | 332.04 | 55.98 | -29.71 | 21.39 | 19.84 | 6.09 | 16.99 | 28.41 |

**APPENDIX E**

Uniformity of polar diagram

The color constancy index is typically calculated based on the Euclidean distance between two distances. The first distance represents the perception of color appearance of a stimulus under an illumination condition compared to its color appearance under a reference illumination. The second distance is the baseline of color appearance of the stimulus under the illumination condition, assuming that the subject has not adapted to the colored illumination. This means that the distance in each axis of the color space should be as uniform as possible. Many researchers calculate the color constancy index using well-known, uniform color spaces such as CIEL*a*b*. In this study, a supplementary experiment was conducted to verify and adjust the naming results obtained.

In this supplementary experiment, five participants were asked to select a sample from the Munsell hue book that they considered the most suitable or comparable to a given naming sample condition, as shown in Table 1.1. Participants were allowed to use interpolation if they thought the match was between samples or in close proximity to one. This task was repeated five times by each participant to complete the experiment.

The interval step was fixed at 20 percent for all conditions. The lightness condition varied from 20 to 40 to 60 to 80 percent for whiteness, and correspondingly for blackness in the opposite range. The chromaticness condition ranged from 10 to 30 to 50 to 70 percent. There were two groups in the chromaticness condition: fixed whiteness, where whiteness was fixed at 10 percent and blackness adjusted to the corresponding lightness condition pair, and fixed blackness, where blackness was fixed at 10 percent and whiteness adjusted to the corresponding lightness condition pair. In the chromaticness condition, there were four color conditions: red at 100 percent, yellow at 100 percent, green at 100 percent, and blue at 100 percent.

**Table 1.1** The naming condition of the preliminary experiment

| Lightness | | Color condition: Red 100%, Yellow 100%, Green 100 %, and Blue 100% | | | | | |
|---|---|---|---|---|---|---|---|
| | | Fixed whiteness | | | Fixed blackness | | |
| Wh% | Bl% | Chr% | Wh% | Bl% | Chr% | Wh% | Bl% |
| 20 | 80 | 10 | 10 | 80 | 70 | 20 | 10 |
| 40 | 60 | 30 | 10 | 60 | 50 | 40 | 10 |
| 60 | 80 | 50 | 10 | 40 | 30 | 60 | 10 |
| 80 | 20 | 70 | 10 | 20 | 10 | 80 | 10 |

The selected samples were measured using a Konica Minolta FD-7 to obtain CIE L*a*b* values. These physical values were used to calculate the Euclidean distance of each axis. The lightness distance (LD) was calculated by finding the difference between the L* values of two consecutive samples in the lightness condition, as shown in equation 1.1. Similarly, the chromaticness distance (CD) was calculated by finding the difference between the ab values of two consecutive samples in the chromaticness condition, as shown in equation 1.3.

The weight ratio was determined using equation 1.3, by dividing the chromaticness distance by the lightness distance. This ratio was then used to adjust the whiteness or blackness values of the naming results in the main experiment, depending on the condition. The fixed whiteness ratio was used for blackness because whiteness was fixed, meaning that the variation in these conditions was only due to blackness. Consequently, fixed whiteness is related to blackness. Similarly, the fixed blackness ratio was used for multiplying the whiteness.

Finally, by using the calculated weight ratio, new blackness and whiteness values that are more linear to the chromaticness axes were obtained. These adjusted values can then be utilized in the calculation of the color constancy index.

$$\text{Lightness distance} = \sqrt{(L_1 - L_2)^2} \tag{1.1}$$

$$\text{Chromaticness distance} = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2} \tag{1.2}$$

$$\text{Ratio} = \frac{\text{Chromaticness distance}}{\text{Lightness distance}} \tag{1.3}$$

The results of all selected Munsell samples are displayed in Tables 1.2 through 1.10. The calculated lightness distance (LD), chromatic distance (CD), and their ratios are shown in Tables 1.11 through 1.14, for unique red, yellow, green, and blue colors, respectively. To apply these findings to the present naming method, linear interpolation was used, as the naming method did not precisely match the chromaticness settings in this supplementary experiment. Linear regression lines were fitted for both fixed white and fixed black conditions, as demonstrated in Figures 1.1 through 1.4 for the unique color conditions. Equations 1.4 through 1.7 show the fitting lines for the fixed white condition and Equations 1.8 through 1.11 show the fitting lines for the fixed black condition.

Fixed white condition

$$\text{Unique red ratio} = (0.0050\times \text{chromaticness}) + 0.7610 \tag{1.4}$$

$$\text{Unique yellow ratio} = (0.0168\times \text{chromaticness}) + 0.6991 \tag{1.5}$$

$$\text{Unique green ratio} = (0.0095\times \text{chromaticness}) + 0.5825 \tag{1.6}$$

$$\text{Unique blue ratio} = (0.0026\times \text{chromaticness}) + 0.5529 \tag{1.7}$$

Fixed black condition

$$\text{Unique red ratio} = (-0.0129\times \text{chromaticness}) + 1.626 \tag{1.8}$$

$$\text{Unique yellow ratio} = (-0.0003\times \text{chromaticness}) + 1.415 \tag{1.9}$$

$$\text{Unique green ratio} = (-0.0013\times \text{chromaticness}) + 1.030 \tag{1.10}$$

$$\text{Unique blue ratio} = (-0.0050 \times \text{chromaticness}) + 0.932 \tag{1.11}$$

In the case of the fixed white condition, where white was fixed at 10% for all subsequent conditions and blackness changed in relation to the lightness condition, the fixed white equations were used for adjusting blackness, while the fixed black condition equations were used for adjusting whiteness.

These equations were applied depending on the whiteness or blackness adjustments needed. For example, when adjusting blackness, each unique red equation (1.4 to 1.7) would be used first to find the unique ratio for each color corresponding to the chromaticness value of the color chip in question. Then, hue interpolation was applied with the points (0, unique red ratio), (90, unique yellow ratio), (180, unique green ratio), and (270, unique blue ratio). The calculated interpolation ratio was then multiplied by the current blackness.

In this study, a linear interpolation function algorithm was implemented using Python programming. The process consisted of three steps: (1) selecting the blackness or whiteness to be calculated, (2) inputting the chromaticness into the respective equation (Equations 1.4-1.11) based on the fixed condition (whiteness or blackness), and (3) determining the hue angle of the naming result. Python then employed the "if else" method to determine the range of the hue angle and performed the interpolation method by finding the ordinate value. For example, if the hue angle was 45 degrees, the algorithm would select the pairs of red at 100% and yellow at 100% (0, the result of Equation 1.4 or 1.8) and (90, the result of Equation 1.5 or 1.9) to calculate the interpolation. This process was applied to both blackness and whiteness for all naming results from 100 subjects across all conditions.

**Table 1.2** The selecting sample result of lightness condition

| Whiteness | 20% | | 40% | | 60% | | 80% | |
|---|---|---|---|---|---|---|---|---|
| **Subject** | **Hue** | **Value** | **Hue** | **Value** | **Hue** | **Value** | **Hue** | **Value** |
| CP | N | 4.3 | N | 4.95 | N | 6.65 | N | 8 |
| PC | N | 3.35 | N | 4.475 | N | 6.125 | N | 7.65 |
| JM | N | 3.9 | N | 4.7 | N | 6.65 | N | 8.05 |
| CS | N | 3.5 | N | 4.25 | N | 6 | N | 7.25 |
| CN | N | 2.7 | N | 4.175 | N | 7.475 | N | 9.25 |
| Average | N | 3.55 | N | 4.51 | N | 6.58 | N | 8.04 |

**Table 1.3** The selecting sample result of chromaticness condition (Red 100% and Fixed whiteness condition)

| Chromaticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 5R | 3 | 2.8 | 5R | 3.75 | 3.55 | 5R | 3.95 | 5.9 | 5R | 3.7 | 8 |
| PC | 6R | 3.6 | 3.6 | 6R | 3.8 | 6.8 | 6R | 4 | 11.6 | 6R | 4 | 15.2 |
| JM | 7.5R | 2.4 | 2 | 7.5R | 3.1 | 4.8 | 7.5R | 4 | 8.4 | 7.5R | 5 | 11.6 |
| CS | 7.5R | 2 | 4.8 | 7.5R | 2.2 | 8 | 7.5R | 3 | 10.4 | 7.5R | 3.6 | 14 |
| CN | 7.5R | 3 | 5.6 | 7.5R | 4 | 8.2 | 7.5R | 3.6 | 12.6 | 7.5R | 4.1 | 15.6 |
| Average | 6.7R | 2.8 | 3.76 | 6.7R | 3.37 | 6.27 | 6.7R | 3.71 | 9.78 | 6.7R | 4.08 | 12.88 |

**Table 1.4** The selecting sample result of chromaticness condition (Red 100% and Fixed blackness condition)

| Chroma-ticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 5R | 7.9 | 2.8 | 5R | 5.85 | 5.55 | 5R | 4.7 | 7.8 | 5R | 4.1 | 8.25 |
| PC | 6R | 7.8 | 5 | 6R | 6.8 | 8 | 6R | 5.8 | 11.6 | 6R | 5 | 15.2 |
| JM | 7.5R | 8.6 | 2 | 7.5R | 8 | 6 | 7.5R | 7 | 9.4 | 7.5R | 6 | 12 |
| CS | 7.5R | 6.2 | 4.8 | 7.5R | 5.4 | 9.2 | 7.5R | 5.2 | 12.8 | 7.5R | 4.6 | 14 |
| CN | 7.5R | 8.9 | 2 | 7.5R | 7.8 | 6.2 | 7.5R | 6.6 | 10.8 | 7.5R | 4.6 | 14.8 |
| Average | 6.7R | 7.88 | 3.32 | 6.7R | 6.77 | 6.99 | 6.7R | 5.86 | 10.48 | 6.7R | 4.86 | 12.85 |

**Table 1.5** The selecting sample result of chromaticness condition (Yellow 100% and Fixed whiteness condition)

| Chroma-ticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 5Y | 3.85 | 2.7 | 5Y | 4.4 | 3.9 | 5Y | 6.1 | 7.4 | 5Y | 6.8 | 9.8 |
| PC | 3.75Y | 5 | 4.2 | 3.75Y | 5 | 7.4 | 3.75Y | 7 | 12 | 3.75Y | 8 | 16 |
| JM | 5Y | 2.6 | 2 | 5Y | 3.6 | 4.4 | 5Y | 5.2 | 8 | 5Y | 7.2 | 11.6 |
| CS | 3.75Y | 3.4 | 4.8 | 3.75Y | 4.4 | 6.4 | 3.75Y | 5.4 | 8.8 | 3.75Y | 6.4 | 10 |
| CN | 5Y | 3.4 | 2.8 | 5Y | 4.6 | 5 | 5Y | 7 | 11 | 4.38Y | 8 | 13.2 |
| Average | 4.5Y | 3.65 | 3.3 | 4.5Y | 4.4 | 5.42 | 4.5Y | 6.14 | 9.44 | 4.375Y | 7.28 | 12.12 |

**Table 1.6** The selecting sample result of chromaticness condition (Yellow 100% and Fixed blackness condition)

| Chroma-ticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 5Y | 8.35 | 3 | 5Y | 7.2 | 5.8 | 5Y | 7.25 | 7.75 | 5Y | 7.4 | 10 |
| PC | 3.75Y | 8.5 | 5 | 3.75Y | 8.5 | 7.8 | 3.75Y | 8.5 | 11.4 | 3.75Y | 8 | 16 |
| JM | 5Y | 8.8 | 2.8 | 5Y | 8.4 | 6.4 | 5Y | 8.3 | 9.6 | 5Y | 8.1 | 11.6 |
| CS | 3.75Y | 8.2 | 4.8 | 3.75Y | 7.8 | 8 | 3.75Y | 7 | 8.8 | 3.75Y | 6.8 | 10.8 |
| CN | 5Y | 9 | 2.6 | 5Y | 8.7 | 5.8 | 5Y | 8.4 | 8.8 | 5Y | 8.2 | 12.8 |
| Average | 4.5Y | 8.57 | 3.64 | 4.5Y | 8.12 | 6.76 | 4.5Y | 7.89 | 9.27 | 4.5Y | 7.7 | 12.24 |

**Table 1.7** The selecting sample result of chromaticness condition (Green 100% and Fixed whiteness condition)

| Chroma-ticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 5G | 3.55 | 2.75 | 5G | 4 | 3.65 | 5G | 4 | 5.25 | 5G | 3.5 | 7.5 |
| PC | 2.5G | 3.8 | 3.6 | 2.5G | 4 | 6.4 | 2.5G | 4 | 10 | 2.5G | 5 | 12 |
| JM | 2.5G | 2.9 | 2.4 | 2.5G | 3.4 | 4.4 | 2.5G | 3.4 | 7.2 | 2.5G | 3.8 | 10 |
| CS | 2.5G | 2 | 3.6 | 2.5G | 3 | 4.8 | 2.5G | 3 | 8 | 2.5G | 4 | 10.8 |
| CN | 2.5G | 2.8 | 2.8 | 2.5G | 3.4 | 4.8 | 2.5G | 3.4 | 8.8 | 2.5G | 4.4 | 10.2 |
| Average | 3G | 3.01 | 3.03 | 3G | 3.56 | 4.81 | 3G | 3.56 | 7.85 | 3G | 4.14 | 10.1 |

**Table 1.8** The selecting sample result of chromaticness condition (Green 100% and Fixed blackness condition)

| Chroma-ticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 5G | 7.9 | 2.3 | 5G | 5.8 | 4.55 | 5G | 4.9 | 6.55 | 5G | 4.2 | 7.7 |
| PC | 2.5G | 8.2 | 4.6 | 2.5G | 7.4 | 7.2 | 2.5G | 6.4 | 10 | 2.5G | 6 | 12 |
| JM | 2.5G | 8.2 | 3.2 | 2.5G | 7.2 | 7.2 | 2.5G | 5.8 | 10 | 2.5G | 5 | 11.2 |
| CS | 2.5G | 7.6 | 3.2 | 2.5G | 5.8 | 4.8 | 2.5G | 4.6 | 8 | 2.5G | 4.6 | 10.8 |
| CN | 2.5G | 9 | 2 | 2.5G | 8 | 5.8 | 2.5G | 7.2 | 8.2 | 1.875G | 5.4 | 11.6 |
| Average | 3G | 8.18 | 3.06 | 3G | 6.84 | 5.91 | 3G | 5.78 | 8.55 | 2.875G | 5.04 | 10.66 |

**Table 1.9** The selecting sample result of chromaticness condition (Green 100% and Fixed whiteness condition)

| Chroma-ticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 2.5PB | 3.3 | 2.9 | 2.5PB | 3.65 | 4.05 | 2.5PB | 3.95 | 6.55 | 2.5PB | 3.6 | 7.95 |
| PC | 10B | 3.8 | 4.4 | 10B | 3.8 | 6.8 | 10B | 3.8 | 10 | 10B | 5 | 12 |
| JM | 5PB | 2.7 | 2 | 5PB | 3 | 4.4 | 5PB | 3 | 7.6 | 5PB | 3.8 | 11.6 |
| CS | 8.75B | 2.6 | 2.4 | 8.75B | 3 | 5.2 | 8.75B | 2.8 | 7.2 | 8.75B | 3.6 | 9.6 |
| CN | 10B | 2.6 | 3.2 | 10B | 3.6 | 4.8 | 10B | 3.8 | 8 | 10B | 3.4 | 10.4 |
| Average | 1.6PB | 3 | 2.98 | 1.6PB | 3.41 | 5.05 | 1.6PB | 3.47 | 7.87 | 1.6PB | 3.88 | 10.31 |

**Table 1.10** The selecting sample result of chromaticness condition (Green 100% and Fixed blackness condition)

| Chroma-ticness | 10% | | | 30% | | | 50% | | | 70% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** | **H** | **V** | **C** |
| CP | 2.5PB | 8 | 3.25 | 2.5PB | 5.4 | 6.2 | 2.5PB | 4.7 | 7.15 | 2.5PB | 3.9 | 7.65 |
| PC | 10B | 8 | 5 | 10B | 7 | 7.6 | 10B | 6 | 10 | 10B | 5 | 12 |
| JM | 5PB | 8 | 3.4 | 5PB | 7.4 | 6.8 | 5PB | 5.8 | 9.2 | 5PB | 5 | 12 |
| CS | 8.75B | 8 | 2.8 | 8.75B | 5.8 | 5.2 | 8.75B | 4.8 | 8 | 8.75B | 4.6 | 11.2 |
| CN | 10B | 9 | 2 | 10B | 7.8 | 4.8 | 10B | 6.8 | 8.2 | 10B | 4.8 | 11 |
| Average | 1.6PB | 8.2 | 3.29 | 1.6PB | 6.68 | 6.12 | 1.6PB | 5.62 | 8.51 | 1.6PB | 4.66 | 10.77 |

**Table 1.11** Average ratio of each subject in the linear scale experiment (Red condition).

| Subjects | Whiteness 20 % to Whiteness 40 % | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| **CP** | 14.42 | 4.11 | 0.31 | 5.03 | 2.19 | 0.15 | 14.42 | 5.24 | 0.45 | 5.03 | 4.94 | 0.49 |
| **PC** | 16.21 | 13.33 | 0.88 | 3.18 | 6.52 | 0.55 | 16.21 | 13.84 | 0.91 | 3.18 | 4.84 | 0.47 |
| **JM** | 15.88 | 16.79 | 1.16 | 4.77 | 5.01 | 0.56 | 15.88 | 15.47 | 1.01 | 4.77 | 4.17 | 0.24 |
| **CS** | 12.74 | 14.53 | 1.14 | 0.09 | 3.05 | 0.24 | 12.74 | 12.82 | 1.01 | 0.09 | 8.33 | 0.66 |
| **CN** | 19.85 | 17.44 | 1.00 | 6.97 | 5.54 | 0.51 | 19.85 | 22.16 | 1.35 | 6.97 | 10.24 | 0.93 |
| **Average** | 15.82 | 13.24 | 0.90 | 4.86 | 6.54 | 0.51 | 15.82 | 13.91 | 0.95 | 4.86 | 8.40 | 0.62 |
| **Subjects** | **Whiteness 40 % to Whiteness 60 %** | | | | | | | | | | | |
| | **Fixed whiteness** | | | | | | **Fixed blackness** | | | | | |
| | **LD** | **CD** | **Ratio** | **STD. LD** | **STD. CD** | **STD. Ratio** | **LD** | **CD** | **Ratio** | **STD. LD** | **STD. CD** | **STD. Ratio** |
| **CP** | 17.15 | 10.52 | 0.62 | 4.42 | 8.07 | 0.48 | 17.15 | 13.07 | 0.90 | 4.42 | 6.93 | 0.72 |
| **PC** | 17.19 | 15.16 | 0.93 | 2.33 | 5.92 | 0.44 | 17.19 | 16.01 | 0.97 | 2.33 | 4.64 | 0.37 |
| **JM** | 20.10 | 18.32 | 1.03 | 6.20 | 4.18 | 0.56 | 20.10 | 17.76 | 0.98 | 6.20 | 4.13 | 0.42 |
| **CS** | 18.47 | 20.50 | 1.11 | 0.06 | 5.19 | 0.28 | 18.47 | 17.82 | 0.97 | 0.06 | 8.64 | 0.47 |
| **CN** | 33.65 | 23.68 | 0.73 | 8.89 | 8.76 | 0.31 | 33.65 | 24.35 | 0.78 | 8.89 | 5.29 | 0.33 |
| **Average** | 21.31 | 17.63 | 0.88 | 8.04 | 7.62 | 0.43 | 21.31 | 17.80 | 0.92 | 8.04 | 6.77 | 0.45 |
| **Subjects** | **Whiteness 60 % to Whiteness 80 %** | | | | | | | | | | | |
| | **Fixed whiteness** | | | | | | **Fixed blackness** | | | | | |
| | **LD** | **CD** | **Ratio** | **STD. LD** | **STD. CD** | **STD. Ratio** | **LD** | **CD** | **Ratio** | **STD. LD** | **STD. CD** | **STD. Ratio** |
| **CP** | 13.38 | 13.70 | 1.08 | 2.17 | 5.97 | 0.56 | 13.38 | 14.53 | 1.13 | 2.17 | 7.54 | 0.64 |
| **PC** | 14.85 | 18.71 | 1.26 | 3.80 | 7.32 | 0.51 | 14.85 | 16.62 | 1.25 | 3.80 | 4.65 | 0.66 |
| **JM** | 13.91 | 14.51 | 1.04 | 1.23 | 5.00 | 0.35 | 13.91 | 20.66 | 1.49 | 1.23 | 0.56 | 0.14 |
| **CS** | 11.67 | 15.52 | 1.33 | 0.04 | 9.50 | 0.81 | 11.67 | 25.11 | 2.15 | 0.04 | 9.93 | 0.86 |
| **CN** | 17.63 | 12.46 | 0.77 | 5.05 | 6.72 | 0.57 | 17.63 | 21.38 | 1.28 | 5.05 | 6.12 | 0.47 |
| **Average** | 14.29 | 14.98 | 1.10 | 3.42 | 6.80 | 0.56 | 14.29 | 19.66 | 1.46 | 3.42 | 7.09 | 0.67 |

**Table 1.12** Average ratio of each subject in the linear scale experiment (Yellow condition).

| Subjects | Whiteness 20 % to Whiteness 40 % | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 14.42 | 9.62 | 0.71 | 5.03 | 3.71 | 0.36 | 14.42 | 19.10 | 1.49 | 5.03 | 3.98 | 0.67 |
| PC | 16.21 | 19.87 | 1.28 | 3.18 | 4.08 | 0.44 | 16.21 | 29.94 | 1.92 | 3.18 | 4.22 | 0.53 |
| JM | 15.88 | 18.06 | 1.20 | 4.77 | 5.39 | 0.38 | 15.88 | 15.59 | 1.08 | 4.77 | 0.91 | 0.40 |
| CS | 12.74 | 10.80 | 0.85 | 0.09 | 3.44 | 0.27 | 12.74 | 18.81 | 1.48 | 0.09 | 7.12 | 0.56 |
| CN | 19.85 | 15.80 | 0.97 | 6.97 | 11.37 | 0.85 | 19.85 | 33.22 | 1.92 | 6.97 | 11.72 | 0.93 |
| Average | 15.82 | 14.83 | 1.00 | 4.86 | 7.08 | 0.51 | 15.82 | 23.33 | 1.58 | 4.86 | 9.33 | 0.67 |
| Subjects | Whiteness 40 % to Whiteness 60 % | | | | | | | | | | | |
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 17.15 | 25.99 | 1.64 | 4.42 | 11.62 | 0.96 | 17.15 | 14.55 | 0.99 | 4.42 | 8.41 | 0.75 |
| PC | 17.19 | 29.59 | 1.73 | 2.33 | 3.02 | 0.17 | 17.19 | 27.76 | 1.66 | 2.33 | 4.59 | 0.43 |
| JM | 20.10 | 24.42 | 1.49 | 6.20 | 15.13 | 1.17 | 20.10 | 24.25 | 1.25 | 6.20 | 8.34 | 0.36 |
| CS | 18.47 | 15.90 | 0.86 | 0.06 | 8.46 | 0.46 | 18.47 | 11.30 | 0.61 | 0.06 | 10.53 | 0.57 |
| CN | 33.65 | 45.79 | 1.47 | 8.89 | 7.09 | 0.57 | 33.65 | 22.29 | 0.78 | 8.89 | 14.25 | 0.65 |
| Average | 21.31 | 28.34 | 1.44 | 8.04 | 13.52 | 0.76 | 21.31 | 20.03 | 1.06 | 8.04 | 10.89 | 0.64 |
| Subjects | Whiteness 60 % to Whiteness 80 % | | | | | | | | | | | |
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 13.38 | 19.25 | 1.47 | 2.17 | 9.90 | 0.72 | 13.38 | 19.04 | 1.46 | 2.17 | 6.16 | 0.52 |
| PC | 14.85 | 31.57 | 2.25 | 3.80 | 5.61 | 0.68 | 14.85 | 19.02 | 1.39 | 3.80 | 3.19 | 0.57 |
| JM | 13.91 | 31.13 | 2.28 | 1.23 | 8.97 | 0.81 | 13.91 | 24.78 | 1.78 | 1.23 | 5.91 | 0.40 |
| CS | 11.67 | 10.38 | 0.89 | 0.04 | 7.10 | 0.61 | 11.67 | 21.35 | 1.83 | 0.04 | 12.07 | 1.04 |
| CN | 17.63 | 16.85 | 1.08 | 5.05 | 6.60 | 0.61 | 17.63 | 22.58 | 1.35 | 5.05 | 4.08 | 0.36 |
| Average | 14.29 | 21.84 | 1.59 | 3.42 | 11.06 | 0.86 | **14.29** | **21.35** | **1.56** | **3.42** | **6.77** | **0.61** |

**Table 1.13** Average ratio of each subject in the linear scale experiment (Green condition).

| Subjects | Whiteness 20 % to Whiteness 40 % | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 14.42 | 5.50 | 0.40 | 5.03 | 3.91 | 0.36 | 14.42 | 7.49 | 0.59 | 5.03 | 4.83 | 0.51 |
| PC | 16.21 | 19.08 | 1.19 | 3.18 | 4.97 | 0.24 | 16.21 | 15.39 | 0.98 | 3.18 | 0.37 | 0.19 |
| JM | 15.88 | 12.85 | 0.99 | 4.77 | 9.37 | 0.94 | 15.88 | 11.04 | 0.76 | 4.77 | 0.48 | 0.27 |
| CS | 12.74 | 7.40 | 0.58 | 0.09 | 10.07 | 0.79 | 12.74 | 21.64 | 1.70 | 0.09 | 5.28 | 0.42 |
| CN | 19.85 | 12.11 | 0.75 | 6.97 | 6.95 | 0.57 | 19.85 | 19.42 | 1.13 | 6.97 | 5.10 | 0.61 |
| Average | 15.82 | 11.39 | 0.78 | 4.86 | 8.35 | 0.65 | 15.82 | 15.00 | 1.03 | 4.86 | 6.42 | 0.55 |
| Subjects | Whiteness 40 % to Whiteness 60 % | | | | | | | | | | | |
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 17.15 | 8.92 | 0.53 | 4.42 | 2.76 | 0.16 | 17.15 | 11.87 | 0.79 | 4.42 | 4.69 | 0.59 |
| PC | 17.19 | 21.70 | 1.29 | 2.33 | 5.35 | 0.39 | 17.19 | 15.30 | 0.92 | 2.33 | 4.49 | 0.34 |
| JM | 20.10 | 16.85 | 1.03 | 6.20 | 5.22 | 0.81 | 20.10 | 15.86 | 0.97 | 6.20 | 6.00 | 0.79 |
| CS | 18.47 | 20.20 | 1.09 | 0.06 | 5.95 | 0.32 | 18.47 | 18.88 | 1.02 | 0.06 | 9.43 | 0.51 |
| CN | 33.65 | 23.93 | 0.77 | 8.89 | 4.00 | 0.28 | 33.65 | 12.64 | 0.37 | 8.89 | 4.93 | 0.11 |
| Average | 21.31 | 18.32 | 0.94 | 8.04 | 6.91 | 0.49 | 21.31 | 14.91 | 0.82 | 8.04 | 6.20 | 0.53 |
| Subjects | Whiteness 60 % to Whiteness 80 % | | | | | | | | | | | |
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 13.38 | 11.44 | 0.91 | 2.17 | 5.19 | 0.50 | 13.38 | 9.32 | 0.73 | 2.17 | 8.09 | 0.63 |
| PC | 14.85 | 15.06 | 1.08 | 3.80 | 0.04 | 0.35 | 14.85 | 13.57 | 0.98 | 3.80 | 2.27 | 0.34 |
| JM | 13.91 | 18.41 | 1.34 | 1.23 | 10.13 | 0.76 | 13.91 | 22.31 | 1.58 | 1.23 | 8.60 | 0.54 |
| CS | 11.67 | 16.55 | 1.42 | 0.04 | 7.26 | 0.62 | 11.67 | 8.50 | 0.73 | 0.04 | 4.31 | 0.37 |
| CN | 17.63 | 13.13 | 0.79 | 5.05 | 10.16 | 0.63 | 17.63 | 20.40 | 1.20 | 5.05 | 7.40 | 0.46 |
| Average | 14.29 | 14.92 | 1.11 | 3.42 | 7.34 | 0.59 | 14.29 | 14.82 | 1.04 | 3.42 | 8.33 | 0.55 |

**Table 1.14** Average ratio of each subject in the linear scale experiment (Blue condition).

| Subjects | Whiteness 20 % to Whiteness 40 % | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 14.42 | 4.67 | 0.32 | 5.03 | 2.09 | 0.08 | 14.42 | 5.63 | 0.46 | 5.03 | 6.08 | 0.59 |
| PC | 16.21 | 10.00 | 0.62 | 3.18 | 3.13 | 0.14 | 16.21 | 7.98 | 0.51 | 3.18 | 0.05 | 0.11 |
| JM | 15.88 | 10.60 | 0.70 | 4.77 | 3.81 | 0.23 | 15.88 | 13.57 | 0.91 | 4.77 | 4.09 | 0.30 |
| CS | 12.74 | 12.58 | 0.99 | 0.09 | 7.19 | 0.56 | 12.74 | 13.07 | 1.03 | 0.09 | 5.91 | 0.46 |
| CN | 19.85 | 10.15 | 0.61 | 6.97 | 4.11 | 0.47 | 19.85 | 13.19 | 0.70 | 6.97 | 4.38 | 0.26 |
| Average | 15.82 | 9.60 | 0.65 | 4.86 | 4.84 | 0.39 | 15.82 | 10.69 | 0.72 | 4.86 | 5.39 | 0.41 |
| Subjects | Whiteness 40 % to Whiteness 60 % | | | | | | | | | | | |
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 17.15 | 9.12 | 0.62 | 4.42 | 2.64 | 0.41 | 17.15 | 6.51 | 0.37 | 4.42 | 2.89 | 0.12 |
| PC | 17.19 | 11.69 | 0.67 | 2.33 | 3.78 | 0.16 | 17.19 | 10.29 | 0.60 | 2.33 | 1.99 | 0.06 |
| JM | 20.10 | 12.74 | 0.76 | 6.20 | 4.33 | 0.52 | 20.10 | 11.79 | 0.66 | 6.20 | 3.95 | 0.34 |
| CS | 18.47 | 7.45 | 0.40 | 0.06 | 0.27 | 0.02 | 18.47 | 12.96 | 0.70 | 0.06 | 6.90 | 0.37 |
| CN | 33.65 | 12.87 | 0.41 | 8.89 | 5.46 | 0.21 | 33.65 | 14.30 | 0.43 | 8.89 | 6.21 | 0.16 |
| Average | 21.31 | 10.78 | 0.57 | 8.04 | 4.05 | 0.33 | 21.31 | 11.17 | 0.55 | 8.04 | 5.15 | 0.26 |
| Subjects | Whiteness 60 % to Whiteness 80 % | | | | | | | | | | | |
| | Fixed whiteness | | | | | | Fixed blackness | | | | | |
| | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio | LD | CD | Ratio | STD. LD | STD. CD | STD. Ratio |
| CP | 13.38 | 7.00 | 0.53 | 2.17 | 3.16 | 0.26 | 13.38 | 14.30 | 1.10 | 2.17 | 2.11 | 0.29 |
| PC | 14.85 | 8.22 | 0.59 | 3.80 | 0.68 | 0.18 | 14.85 | 11.25 | 0.80 | 3.80 | 3.04 | 0.26 |
| JM | 13.91 | 16.25 | 1.16 | 1.23 | 5.78 | 0.39 | 13.91 | 12.92 | 0.93 | 1.23 | 5.36 | 0.38 |
| CS | 11.67 | 8.79 | 0.75 | 0.04 | 4.52 | 0.39 | 11.67 | 10.79 | 0.93 | 0.04 | 9.64 | 0.83 |
| CN | 17.63 | 9.46 | 0.57 | 5.05 | 2.52 | 0.21 | 17.63 | 12.26 | 0.77 | 5.05 | 3.52 | 0.37 |
| Average | 14.29 | 9.94 | 0.72 | 3.42 | 4.78 | 0.36 | 14.29 | 12.30 | 0.90 | 3.42 | 5.12 | 0.45 |

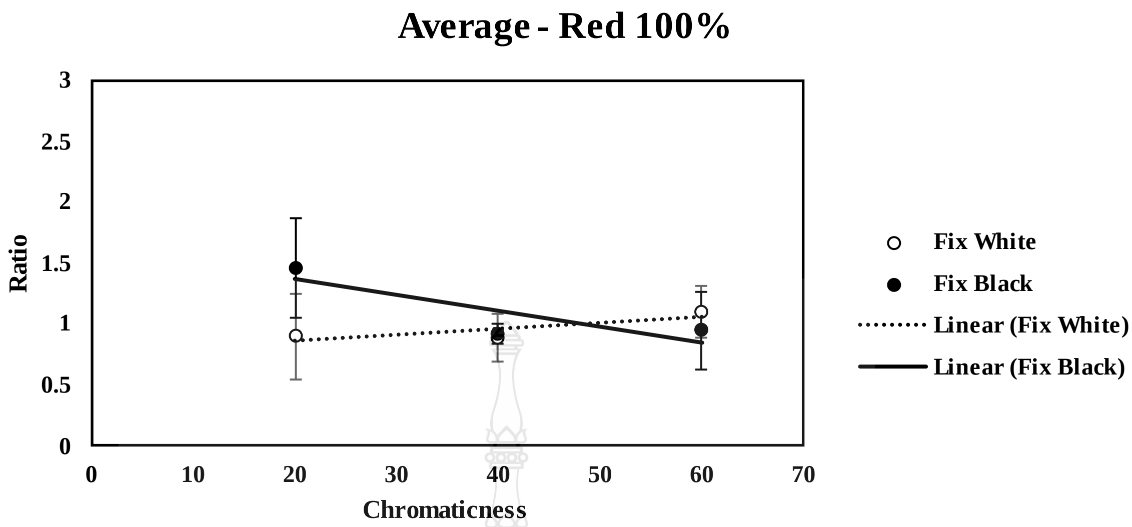



**Figure 1.1** The relation of chromaticness and the weight ratio of red at 100 %.

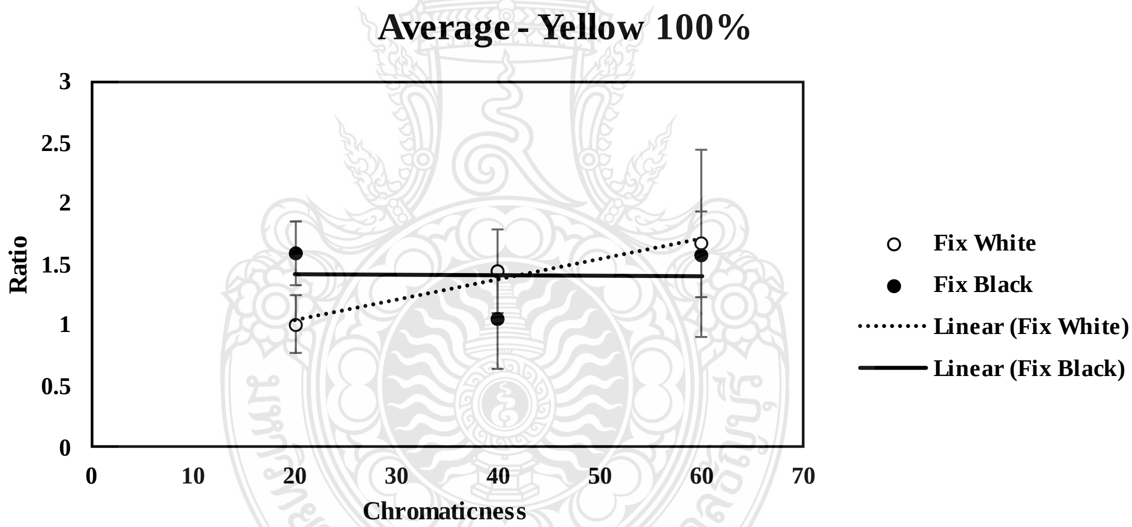



**Figure 1.2** The relation of chromaticness and the weight ratio of yellow at 100 %.

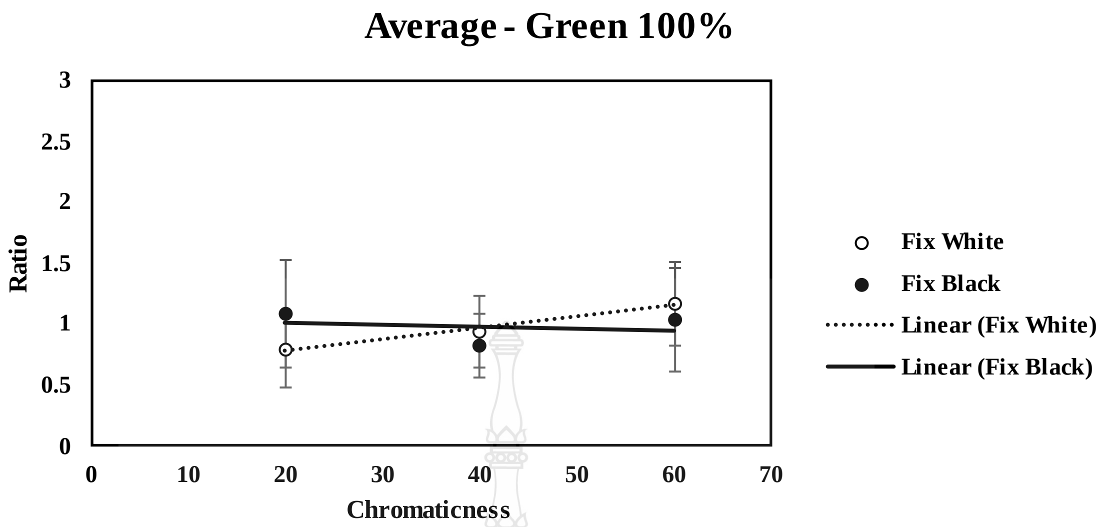



**Figure 1.3** The relation of chromaticness and the weight ratio of green at 100 %.

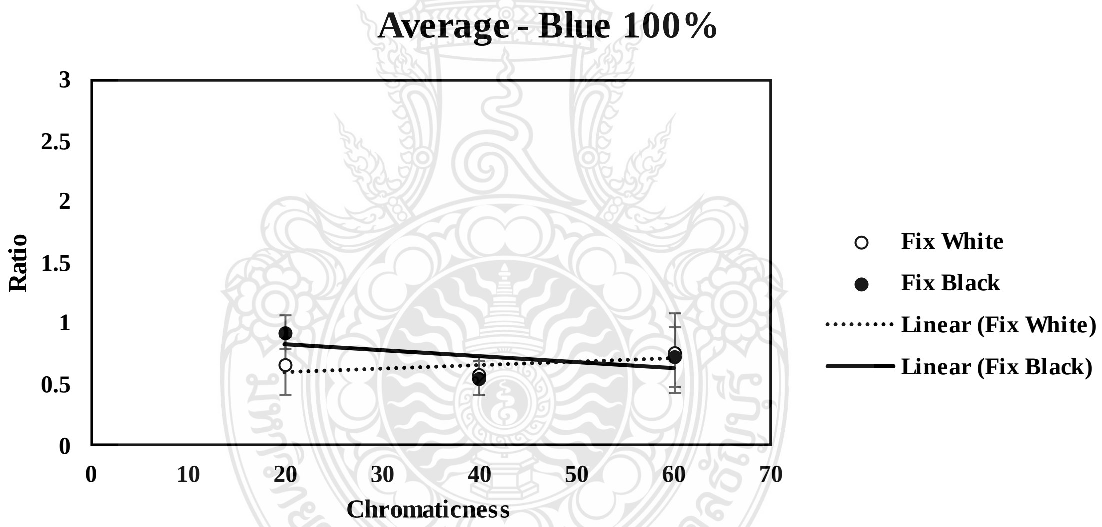



**Figure 1.4** The relation of chromaticness and the weight ratio of blue at 100 %.

# APPENDIX F

Color density and complementary relation

**Table 1.1** The color density and the complementary relation (R2)

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 3 | 0.31 | 0.57 | 0.61 | 0.45 | gb | RB | RG | - | RB | RG | - | rB | rG | Orange | Orange |
| 21 | 0.22 | 0.48 | 0.58 | 0.36 | gb | rb | RG | - | rb | RG | - | b | rG | GY | Orange |
| 30 | 0.15 | 0.77 | 1.06 | 0.41 | gb | RB | RG | - | RB | RG | - | rB | rG | Orange | Orange |
| 59 | 0.07 | 0.28 | 0.42 | 0.18 | gb | rb | rg | - | rb | rg | - | b | g | cyan | Orange |
| 71 | 0.37 | 0.56 | 0.85 | 0.49 | gb | RB | RG | - | RB | RG | - | rB | rG | Orange | Orange |
| 90 | 0.06 | 0.20 | 0.82 | 0.14 | gb | rb | RG | - | rb | RG | - | b | rG | GY | Yelllow |
| 97 | 0.32 | 0.51 | 1.27 | 0.42 | gb | RB | RG | - | RB | RG | - | rB | rG | Orange | Orange |
| 156 | 0.41 | 0.40 | 0.93 | 0.42 | gb | rb | RG | - | rb | RG | - | b | rG | GY | Yellow |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 | GB | RB | RG | gb | RB | RG | gb | rB | rG | Acromatic | Blue |
| 174 | 0.73 | 0.32 | 1.02 | 0.50 | GB | rb | RG | gb | rb | RG | gb | b | rG | Acromatic | Blue |
| 178 | 0.64 | 0.40 | 0.77 | 0.52 | GB | rb | RG | gb | rb | RG | gb | b | rG | Acromatic | Blue |
| 182 | 1.03 | 0.58 | 1.05 | 0.77 | GB | RB | RG | gb | RB | RG | gb | rB | rG | Acromatic | Blue |
| 199 | 1.12 | 0.33 | 0.48 | 0.60 | GB | rb | rg | gb | rb | rg | gb | b | g | Cyan | Blue |
| 242 | 0.63 | 0.43 | 0.46 | 0.53 | GB | rb | rg | gb | rb | rg | gb | b | g | Cyan | Blue |
| 257 | 1.20 | 0.31 | 0.20 | 0.59 | GB | rb | rg | gb | rb | rg | gb | b | g | Cyan | Blue |
| 261 | 0.70 | 0.43 | 0.27 | 0.56 | GB | rb | rg | gb | rb | rg | gb | b | g | Cyan | Blue |
| 262 | 0.72 | 0.48 | 0.23 | 0.60 | GB | rb | rg | gb | rb | rg | gb | b | g | Cyan | Blue |
| 265 | 1.36 | 0.84 | 0.47 | 1.09 | GB | RB | rg | gb | RB | rg | gb | rB | g | Blue | Blue |
| 289 | 1.25 | 1.48 | 1.22 | 1.39 | GB | RB | RG | gb | RB | RG | gb | rB | rG | Acromatic | Blue |
| 292 | 0.49 | 0.51 | 0.23 | 0.52 | gb | RB | rg | - | RB | rg | - | rB | g | Blue | Orange |
| 304 | 0.38 | 0.73 | 0.31 | 0.56 | gb | RB | rg | - | RB | rg | - | rB | g | Blue | Orange |
| 355 | 0.19 | 0.97 | 0.63 | 0.48 | gb | RB | RG | - | RB | RG | - | rB | rG | Orange | Orange |

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 359 | 0.31 | 1.49 | 1.09 | 0.66 | gb | RB | RG | - | RB | RG | - | rB | rG | Orange | Yellow |

**Table 1.2** The color density and the complementary relation (Y2)

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 3 | 0.31 | 0.57 | 0.61 | 0.45 | gb | RB | RG | g | Rb | RG | g | Rb | rg | Red | Red |
| 21 | 0.22 | 0.48 | 0.58 | 0.36 | gb | rb | RG | g | r | RG | g | r | rg | Yellow | Red |
| 30 | 0.15 | 0.77 | 1.06 | 0.41 | gb | RB | RG | g | Rb | RG | g | Rb | rg | Red | Red |
| 59 | 0.07 | 0.28 | 0.42 | 0.18 | gb | rb | rg | g | r | RG | g | r | rg | Red | Red |
| 71 | 0.37 | 0.56 | 0.85 | 0.49 | gb | RB | RG | g | Rb | RG | g | Rb | rg | Red | Red |
| 90 | 0.06 | 0.20 | 0.82 | 0.14 | gb | rb | RG | g | r | RG | g | r | rg | Yellow | Red |
| 97 | 0.32 | 0.51 | 1.27 | 0.42 | gb | RB | RG | g | Rb | RG | g | Rb | rg | Red | Red |
| 156 | 0.41 | 0.40 | 0.93 | 0.42 | gb | rb | RG | g | r | RG | g | r | rg | Red | Red |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 | GB | RB | RG | Gb | Rb | RG | Gb | Rb | rg | Acromatic | Green |
| 174 | 0.73 | 0.32 | 1.02 | 0.50 | GB | rb | RG | Gb | r | RG | Gb | r | rg | Green | Green |
| 178 | 0.64 | 0.40 | 0.77 | 0.52 | GB | rb | RG | Gb | r | RG | Gb | r | rg | Green | Green |
| 182 | 1.03 | 0.58 | 1.05 | 0.77 | GB | RB | RG | Gb | Rb | RG | Gb | Rb | rg | Acromatic | Green |
| 199 | 1.12 | 0.33 | 0.48 | 0.60 | GB | rb | rg | Gb | r | RG | Gb | r | rg | Green | Green |
| 242 | 0.63 | 0.43 | 0.46 | 0.53 | GB | rb | rg | Gb | r | RG | Gb | r | rg | Green | Green |
| 257 | 1.20 | 0.31 | 0.20 | 0.59 | GB | rb | rg | Gb | r | RG | Gb | r | rg | Green | Green |
| 261 | 0.70 | 0.43 | 0.27 | 0.56 | GB | rb | rg | Gb | r | RG | Gb | r | rg | Green | Green |
| 262 | 0.72 | 0.48 | 0.23 | 0.60 | GB | rb | rg | Gb | r | RG | Gb | r | rg | Green | Green |
| 265 | 1.36 | 0.84 | 0.47 | 1.09 | GB | RB | rg | Gb | Rb | RG | Gb | Rb | rg | Acromatic | Green |

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 289 | 1.25 | 1.48 | 1.22 | 1.39 | GB | RB | RG | Gb | Rb | RG | Gb | Rb | rg | Acromatic | Green |
| 292 | 0.49 | 0.51 | 0.23 | 0.52 | gb | RB | rg | g | Rb | RG | g | Rb | rg | Red | Green |
| 304 | 0.38 | 0.73 | 0.31 | 0.56 | gb | RB | rg | g | Rb | RG | g | Rb | rg | Red | Red |
| 355 | 0.19 | 0.97 | 0.63 | 0.48 | gb | RB | RG | g | Rb | RG | g | Rb | rg | Red | Red |
| 359 | 0.31 | 1.49 | 1.09 | 0.66 | gb | RB | RG | g | Rb | RG | g | Rb | rg | Red | Red |

**Table 1.3** The color density and the complementary relation (G2)

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 3 | 0.31 | 0.57 | 0.61 | 0.45 | gb | RB | RG | gb | rb | RG | b | rb | Rg | Red | Green |
| 21 | 0.22 | 0.48 | 0.58 | 0.36 | gb | rb | RG | gb | - | RG | b | - | Rg | Yellow | Green |
| 30 | 0.15 | 0.77 | 1.06 | 0.41 | gb | RB | RG | gb | rb | RG | b | rb | Rg | Red | Green |
| 59 | 0.07 | 0.28 | 0.42 | 0.18 | gb | rb | rg | gb | - | rg | b | - | r | Magenta | Green |
| 71 | 0.37 | 0.56 | 0.85 | 0.49 | gb | RB | RG | gb | rb | RG | b | rb | Rg | Red | Green |
| 90 | 0.06 | 0.20 | 0.82 | 0.14 | gb | rb | RG | gb | - | RG | b | - | Rg | Yellow | Green |
| 97 | 0.32 | 0.51 | 1.27 | 0.42 | gb | RB | RG | gb | rb | RG | b | rb | Rg | Red | Green |
| 156 | 0.41 | 0.40 | 0.93 | 0.42 | gb | rb | RG | gb | - | RG | b | - | Rg | Yellow | Green |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 | GB | RB | RG | GB | rb | RG | gB | rb | Rg | Acromatic | Green |
| 174 | 0.73 | 0.32 | 1.02 | 0.50 | GB | rb | RG | GB | - | RG | gB | - | Rg | Green | Green |
| 178 | 0.64 | 0.40 | 0.77 | 0.52 | GB | rb | RG | GB | - | RG | gB | - | Rg | Green | Green |
| 182 | 1.03 | 0.58 | 1.05 | 0.77 | GB | RB | RG | GB | rb | RG | gB | rb | Rg | Acromatic | Green |
| 199 | 1.12 | 0.33 | 0.48 | 0.60 | GB | rb | rg | GB | - | rg | gB | - | r | Cyan | Green |
| 242 | 0.63 | 0.43 | 0.46 | 0.53 | GB | rb | rg | GB | - | rg | gB | - | r | Cyan | Green |

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 257 | 1.20 | 0.31 | 0.20 | 0.59 | GB | rb | rg | GB | - | rg | gB | - | r | Cyan | Green |
| 261 | 0.70 | 0.43 | 0.27 | 0.56 | GB | rb | rg | GB | - | rg | gB | - | r | Cyan | Green |
| 262 | 0.72 | 0.48 | 0.23 | 0.60 | GB | rb | rg | GB | - | rg | gB | - | r | Cyan | Green |
| 265 | 1.36 | 0.84 | 0.47 | 1.09 | GB | RB | rg | GB | rb | rg | gB | rb | r | Acromatic | Green |
| 289 | 1.25 | 1.48 | 1.22 | 1.39 | GB | RB | RG | GB | rb | RG | gB | rb | Rg | Acromatic | Green |
| 292 | 0.49 | 0.51 | 0.23 | 0.52 | gb | RB | rg | gb | rb | rg | b | rb | r | Magenta | Green |
| 304 | 0.38 | 0.73 | 0.31 | 0.56 | gb | RB | rg | gb | rb | rg | b | rb | r | Magenta | Green |
| 355 | 0.19 | 0.97 | 0.63 | 0.48 | gb | RB | RG | gb | rb | RG | b | rb | Rg | Red | Green |
| 359 | 0.31 | 1.49 | 1.09 | 0.66 | gb | RB | RG | gb | rb | RG | b | rb | Rg | Red | Green |

**Table 1.4** The color density and the complementary relation (C2)

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 3 | 0.31 | 0.57 | 0.61 | 0.45 | gb | RB | RG | gb | rB | rG | - | rB | rG | Red | GY |
| 21 | 0.22 | 0.48 | 0.58 | 0.36 | gb | rb | RG | gb | b | rG | - | b | rG | Yellow | GY |
| 30 | 0.15 | 0.77 | 1.06 | 0.41 | gb | RB | RG | gb | rB | rG | - | rB | rG | Red | GY |
| 59 | 0.07 | 0.28 | 0.42 | 0.18 | gb | rb | rg | gb | b | g | - | b | g | Cyan | GY |
| 71 | 0.37 | 0.56 | 0.85 | 0.49 | gb | RB | RG | gb | rB | rG | - | rB | rG | Red | GY |
| 90 | 0.06 | 0.20 | 0.82 | 0.14 | gb | rb | RG | gb | b | rG | - | b | rG | Yellow | GY |
| 97 | 0.32 | 0.51 | 1.27 | 0.42 | gb | RB | RG | gb | rB | rG | - | rB | rG | Red | GY |
| 156 | 0.41 | 0.40 | 0.93 | 0.42 | gb | rb | RG | gb | b | rG | - | b | rG | Yellow | GY |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 | GB | RB | RG | GB | rB | rG | gb | rB | rG | Blue | GY |
| 174 | 0.73 | 0.32 | 1.02 | 0.50 | GB | rb | RG | GB | b | rG | gb | b | rG | Blue | GY |

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 178 | 0.64 | 0.40 | 0.77 | 0.52 | GB | rb | RG | GB | b | rG | gb | b | rG | Blue | GY |
| 182 | 1.03 | 0.58 | 1.05 | 0.77 | GB | RB | RG | GB | rB | rG | gb | rB | rG | Blue | GY |
| 199 | 1.12 | 0.33 | 0.48 | 0.60 | GB | rb | rg | GB | b | g | gb | b | g | Blue | GY |
| 242 | 0.63 | 0.43 | 0.46 | 0.53 | GB | rb | rg | GB | b | g | gb | b | g | Blue | Blue |
| 257 | 1.20 | 0.31 | 0.20 | 0.59 | GB | rb | rg | GB | b | g | gb | b | g | Blue | Blue |
| 261 | 0.70 | 0.43 | 0.27 | 0.56 | GB | rb | rg | GB | b | g | gb | b | g | Blue | Blue |
| 262 | 0.72 | 0.48 | 0.23 | 0.60 | GB | rb | rg | GB | b | g | gb | b | g | Blue | Blue |
| 265 | 1.36 | 0.84 | 0.47 | 1.09 | GB | RB | rg | GB | rB | g | gb | rB | g | Blue | Blue |
| 289 | 1.25 | 1.48 | 1.22 | 1.39 | GB | RB | RG | GB | rB | rG | gb | rB | rG | Blue | Blue |
| 292 | 0.49 | 0.51 | 0.23 | 0.52 | gb | RB | rg | gb | rB | g | - | rB | g | Magenta | Blue |
| 304 | 0.38 | 0.73 | 0.31 | 0.56 | gb | RB | rg | gb | rB | g | - | rB | g | Magenta | Blue |
| 355 | 0.19 | 0.97 | 0.63 | 0.48 | gb | RB | RG | gb | rB | rG | - | rB | rG | Red | GY |
| 359 | 0.31 | 1.49 | 1.09 | 0.66 | gb | RB | RG | gb | rB | rG | - | rB | rG | Red | Blue |

**Table 1.5** The color density and the complementary relation (B2)

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 3 | 0.31 | 0.57 | 0.61 | 0.45 | gb | RB | RG | gb | RB | rg | g | Rb | rg | Magenta | Blue |
| 21 | 0.22 | 0.48 | 0.58 | 0.36 | gb | rb | RG | gb | rb | rg | g | r | rg | Blue | Blue |
| 30 | 0.15 | 0.77 | 1.06 | 0.41 | gb | RB | RG | gb | RB | rg | g | Rb | rg | Magenta | Blue |
| 59 | 0.07 | 0.28 | 0.42 | 0.18 | gb | rb | rg | gb | rb | - | g | r | - | Yellow | Blue |
| 71 | 0.37 | 0.56 | 0.85 | 0.49 | gb | RB | RG | gb | RB | rg | g | Rb | rg | Magenta | Green |
| 90 | 0.06 | 0.20 | 0.82 | 0.14 | gb | rb | RG | gb | rb | rg | g | r | rg | Blue | Green |

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 97 | 0.32 | 0.51 | 1.27 | 0.42 | gb | RB | RG | gb | RB | rg | g | Rb | rg | Magenta | Green |
| 156 | 0.41 | 0.40 | 0.93 | 0.42 | gb | rb | RG | gb | rb | rg | g | r | rg | Blue | Green |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 | GB | RB | RG | GB | RB | rg | Gb | Rb | rg | Blue | Green |
| 174 | 0.73 | 0.32 | 1.02 | 0.50 | GB | rb | RG | GB | rb | rg | Gb | r | rg | Cyan | Green |
| 178 | 0.64 | 0.40 | 0.77 | 0.52 | GB | rb | RG | GB | rb | rg | Gb | r | rg | Cyan | Green |
| 182 | 1.03 | 0.58 | 1.05 | 0.77 | GB | RB | RG | GB | RB | rg | Gb | Rb | rg | Blue | Green |
| 199 | 1.12 | 0.33 | 0.48 | 0.60 | GB | rb | rg | GB | rb | - | Gb | r | - | Cyan | Blue |
| 242 | 0.63 | 0.43 | 0.46 | 0.53 | GB | rb | rg | GB | rb | - | Gb | r | - | Cyan | Blue |
| 257 | 1.20 | 0.31 | 0.20 | 0.59 | GB | rb | rg | GB | rb | - | Gb | r | - | Cyan | Blue |
| 261 | 0.70 | 0.43 | 0.27 | 0.56 | GB | rb | rg | GB | rb | - | Gb | r | - | Cyan | Blue |
| 262 | 0.72 | 0.48 | 0.23 | 0.60 | GB | rb | rg | GB | rb | - | Gb | r | - | Cyan | Blue |
| 265 | 1.36 | 0.84 | 0.47 | 1.09 | GB | RB | rg | GB | RB | - | Gb | Rb | - | Blue | Blue |
| 289 | 1.25 | 1.48 | 1.22 | 1.39 | GB | RB | RG | GB | RB | rg | Gb | Rb | rg | Blue | Blue |
| 292 | 0.49 | 0.51 | 0.23 | 0.52 | gb | RB | rg | gb | RB | - | g | Rb | - | Magenta | Blue |
| 304 | 0.38 | 0.73 | 0.31 | 0.56 | gb | RB | rg | gb | RB | - | g | Rb | - | Magenta | Blue |
| 355 | 0.19 | 0.97 | 0.63 | 0.48 | gb | RB | RG | gb | RB | rg | g | Rb | rg | Magenta | Blue |
| 359 | 0.31 | 1.49 | 1.09 | 0.66 | gb | RB | RG | gb | RB | rg | g | Rb | rg | Blue | Blue |

**Table 1.6** The color density and the complementary relation (M2)

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 3 | 0.31 | 0.57 | 0.61 | 0.45 | gb | RB | RG | b | RB | Rg | b | rb | Rg | Blue | Orange |
| 21 | 0.22 | 0.48 | 0.58 | 0.36 | gb | rb | RG | b | rb | Rg | b | - | Rg | Yellow | Orange |

| Hue(°) | Color density | | | | Additive color | | | Complementary effect | | | Light adaptation | | | Predicted | Real |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | M | Y | K | C | M | Y | C | M | Y | C | M | Y | | |
| 30 | 0.15 | 0.77 | 1.06 | 0.41 | gb | RB | RG | b | RB | Rg | b | rb | Rg | Yellow | Orange |
| 59 | 0.07 | 0.28 | 0.42 | 0.18 | gb | rb | rg | b | rb | r | b | - | r | Magenta | Orange |
| 71 | 0.37 | 0.56 | 0.85 | 0.49 | gb | RB | RG | b | RB | Rg | b | rb | Rg | Blue | Orange |
| 90 | 0.06 | 0.20 | 0.82 | 0.14 | gb | rb | RG | b | rb | Rg | b | - | Rg | Yellow | Orange |
| 97 | 0.32 | 0.51 | 1.27 | 0.42 | gb | RB | RG | b | RB | Rg | b | rb | Rg | Yellow | Orange |
| 156 | 0.41 | 0.40 | 0.93 | 0.42 | gb | rb | RG | b | rb | Rg | b | - | Rg | Yellow | Orange |
| 168 | 0.76 | 0.77 | 1.16 | 0.79 | GB | RB | RG | gB | RB | Rg | gB | rb | Rg | Blue | Orange |
| 174 | 0.73 | 0.32 | 1.02 | 0.50 | GB | rb | RG | gB | rb | Rg | gB | - | Rg | Green | Blue |
| 178 | 0.64 | 0.40 | 0.77 | 0.52 | GB | rb | RG | gB | rb | Rg | gB | - | Rg | Green | Blue |
| 182 | 1.03 | 0.58 | 1.05 | 0.77 | GB | RB | RG | gB | RB | Rg | gB | rb | Rg | Blue | Blue |
| 199 | 1.12 | 0.33 | 0.48 | 0.60 | GB | rb | rg | gB | rb | r | gB | - | r | Cyan | Blue |
| 242 | 0.63 | 0.43 | 0.46 | 0.53 | GB | rb | rg | gB | rb | r | gB | - | r | Cyan | Blue |
| 257 | 1.20 | 0.31 | 0.20 | 0.59 | GB | rb | rg | gB | rb | r | gB | - | r | Cyan | Blue |
| 261 | 0.70 | 0.43 | 0.27 | 0.56 | GB | rb | rg | gB | rb | r | gB | - | r | Cyan | Blue |
| 262 | 0.72 | 0.48 | 0.23 | 0.60 | GB | rb | rg | gB | rb | r | gB | - | r | Cyan | Blue |
| 265 | 1.36 | 0.84 | 0.47 | 1.09 | GB | RB | rg | gB | RB | r | gB | rb | r | Blue | Blue |
| 289 | 1.25 | 1.48 | 1.22 | 1.39 | GB | RB | RG | gB | RB | Rg | gB | rb | Rg | Blue | Blue |
| 292 | 0.49 | 0.51 | 0.23 | 0.52 | gb | RB | rg | b | RB | r | b | rb | r | Blue | Blue |
| 304 | 0.38 | 0.73 | 0.31 | 0.56 | gb | RB | rg | b | RB | r | b | rb | r | Blue | Blue |
| 355 | 0.19 | 0.97 | 0.63 | 0.48 | gb | RB | RG | b | RB | Rg | b | rb | Rg | Yellow | Orange |
| 359 | 0.31 | 1.49 | 1.09 | 0.66 | gb | RB | RG | b | RB | Rg | b | rb | Rg | Red | Orange |

**APPENDIX G**

Average of metamerism

**Table 1.1** The average metamerism index

| Hue (°) | R1 | R2 | Y1 | Y2 | G1 | G2 | C1 | C2 | B1 | B2 | M1 | M2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 88 | 129 | 43 | 70 | 49 | 108 | 38 | 64 | 51 | 94 | 69 | 116 |
| 21 | 93 | 139 | 46 | 76 | 50 | 110 | 39 | 71 | 48 | 89 | 73 | 125 |
| 30 | 94 | 132 | 53 | 75 | 55 | 80 | 46 | 76 | 47 | 81 | 73 | 116 |
| 59 | 104 | 162 | 50 | 86 | 57 | 129 | 42 | 81 | 52 | 104 | 80 | 145 |
| 71 | 83 | 123 | 42 | 65 | 53 | 107 | 40 | 78 | 42 | 74 | 62 | 111 |
| 90 | 94 | 148 | 52 | 76 | 65 | 124 | 52 | 112 | 47 | 68 | 67 | 131 |
| 97 | 80 | 118 | 45 | 61 | 56 | 100 | 48 | 94 | 43 | 66 | 58 | 105 |
| 156 | 70 | 115 | 45 | 61 | 64 | 116 | 48 | 94 | 40 | 65 | 49 | 105 |
| 168 | 57 | 92 | 37 | 49 | 52 | 92 | 37 | 68 | 38 | 62 | 42 | 84 |
| 174 | 69 | 80 | 45 | 57 | 75 | 110 | 62 | 97 | 51 | 64 | 59 | 81 |
| 178 | 55 | 96 | 41 | 61 | 72 | 117 | 51 | 80 | 45 | 84 | 50 | 88 |
| 182 | 57 | 76 | 39 | 50 | 68 | 97 | 52 | 71 | 43 | 73 | 49 | 72 |
| 199 | 56 | 85 | 56 | 61 | 95 | 125 | 54 | 58 | 68 | 118 | 57 | 91 |
| 242 | 57 | 103 | 37 | 59 | 72 | 123 | 38 | 55 | 64 | 113 | 52 | 94 |
| 257 | 48 | 84 | 54 | 66 | 88 | 131 | 39 | 55 | 102 | 141 | 70 | 106 |
| 261 | 56 | 97 | 36 | 54 | 71 | 125 | 35 | 52 | 86 | 133 | 58 | 100 |
| 262 | 56 | 96 | 37 | 54 | 67 | 121 | 41 | 58 | 89 | 136 | 61 | 101 |
| 265 | 48 | 80 | 34 | 48 | 59 | 109 | 39 | 53 | 79 | 116 | 56 | 87 |
| 289 | 50 | 72 | 31 | 41 | 36 | 62 | 29 | 41 | 43 | 66 | 41 | 66 |
| 292 | 75 | 111 | 40 | 58 | 58 | 120 | 43 | 64 | 85 | 136 | 63 | 107 |
| 304 | 87 | 112 | 50 | 65 | 48 | 98 | 46 | 72 | 77 | 123 | 68 | 103 |
| 355 | 104 | 137 | 68 | 87 | 50 | 84 | 50 | 82 | 63 | 97 | 90 | 127 |
| 359 | 90 | 117 | 63 | 78 | 44 | 75 | 49 | 80 | 58 | 79 | 78 | 105 |

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| | |
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