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EFFECTS OF MEMORY COLOR ON COLOR PERCEPTION OF NATURAL OBJECTS UNDER DIFFERENT ILLUMINATION

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งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาผลของสีในความทรงจำต่อการรับรู้ของวัตถุในธรรมชาติภายใต้การส่องสว่างที่ต่างกัน ผู้สังเกตจำนวน 78 คนทำการทดลองทางอินเตอร์เน็ตผ่านเว็บไซต์ (https://memorycolor.net) ในการทดลองที่ 1 ผู้สังเกตแสดงสีของวัตถุในธรรมชาติ 5 อย่างคือ บลูเบอรี่ บล็อกโคลี่ แซลมอน ดอกทานตะวัน และมะเขือเทศ ตามที่ผู้สังเกตจำได้ของวัตถุนั้น ๆ พบว่า ผู้สังเกตแต่ละคนมีสีในความทรงจำที่ต่างกัน ในการทดลองที่ 2 ผู้สังเกตมองภาพของวัตถุในธรรมชาติ และแสดงสีที่รับรู้ในภาพนั้น ภาพทดสอบที่ใช้ประกอบด้วยภาพถ่ายภายใต้แสงกลางวัน D65 และภาพที่ดัดแปลงสีเพื่อจำลองให้อยู่ภายใต้แสงสีต่าง ๆ จำนวน 4 สี ได้แก่ แสงสีแดง แสงสีเขียว แสงสีน้ำเงิน และแสงสีเหลือง จากผลการทดลองพบว่า การรับรู้สีของวัตถุภายใต้แสงสีใกล้เคียงกับสีของวัตถุภายใต้แสง D65 มากกว่าสีในความทรงจำ แสดงให้เห็นว่า ผู้สังเกตสามารถแยกสีของแหล่งแสงออกจากสีของวัตถุได้ ทำให้รับรู้สีของวัตถุได้ใกล้เคียงกับสีในภาพต้นฉบับ สีในความทรงจำส่งผลน้อยต่อการเกิดการรับรู้สีคงที่ (color constancy) ในการทดลองที่ 3 ผู้สังเกตมองภาพมอนเดรียน (Mondrian) ที่มีสีเหมือนภาพในการทดลองที่ 2 เพื่อทดสอบการรับรู้สีที่ไม่มีวัตถุธรรมชาติในภาพ พบว่า ภาพที่มีวัตถุธรรมชาติเกิดการรับรู้สีคงที่มากกว่าภาพมอนเดรียน ดัชนีความคงที่สี (color constancy index) เฉลี่ยทุกวัตถุและทุกแหล่งแสงของภาพวัตถุมีค่าเท่ากับร้อยละ 68 และร้อยละ 41 สำหรับภาพมอนเดรียน สีในความทรงจำของวัตถุที่คุ้นเคยเพียงอย่างเดียวไม่ทำให้เกิดการกำจัดสีของแหล่งแสงออกจากภาพได้

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NADOL CHEAWSOPON: EFFECTS OF MEMORY COLOR ON COLOR PERCEPTION OF NATURAL OBJECTS UNDER DIFFERENT ILLUMINATION. ADVISOR: ASST. PROF. SUCHITRA SUEEPRASAN, Ph.D., 79 pp.

This study aimed to investigate the effects of memory color on color perception of natural objects under different illuminations. A series of experiments were carried out and launched on the Internet through a website (https://memorycolor.net). Seventy-eight observers participated in the experiments. In Experiment 1, observers were asked to provide a typical color of five natural objects (blueberry, broccoli, salmon, sunflower and tomato) based on their memory. The results showed that memory colors were different for different observers. In Experiment 2, observers were shown an image of natural objects and selected the color they perceived. The experimental images of natural objects consisted of a natural object images taken under daylight simulators D65 and modified images to simulate illumination changes. Four different illuminants were tested: red, green, blue and yellow. The results showed that in almost all cases the perceived colors were closer to the match in D65 than to memory color. This indicated that observers were able to separate the illuminant color from the object and perceived the object color as close to its original image. The contribution of memory color to color constancy was weak. In Experiment 3, Mondrian images having the same colors as the images in Experiment 2 were created to investigate color perception of an image without natural objects. The results showed that the color constancy in the object images was higher than in the Mondrian images. The color constancy index averaged across objects and illuminants for the object image was 68%, and 41% for the Mondrian image. Memory color of the familiar object in the scene was not the only cue for discounting the illuminant.

Department:	Imaging and Printing Technology	Student's Signature	....
		Advisor's Signature	....
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Chapter 1
INTRODUCTION

Color perception is an individual experience. Two people looking at the same object under the same condition could perceive color differently. Taken the recently famous phenomenon The Dress as an example, an image of a striped dress initially posted on Tumblr on 26 February 2015 divided people into two groups: one perceiving it as blue/back and the other as white/gold [1]. The illumination assumption is one of mechanisms of color constancy. Cues to the illumination in the dress image are ambiguous, so they lead to different people assuming different illuminations. People who assume that the dress is under warm illumination perceive the dress as blue/back, while those who assume cool illumination perceive it as white/gold [2]. This phenomenon confirms the fact that color is a human perception. The color of an object is changeable depending on many factors including observers' experience.

Color perception depends on three factors: light from a light source, optical properties of an object and the human visual system of an observer. Light emitted from a light source hits an object. The object then absorbs some parts of the light and reflects the rest into an observer's eyes, where the human visual system interprets what color is perceived. Thus the light reflected from an object is changeable depending on lighting conditions. However, the human visual system is able to compensate for the change in the color of the light source in such a way that the perceived color of objects remains constant under varying illumination conditions. This phenomenon is called color constancy [3].

Color constancy is the phenomenon that color of an object can be the same despite illumination changes. The human visual system can adapt to the illumination changes so that the perceived color of objects is the same throughout the day. Memory color is one of the mechanisms of color constancy. Memory color refers to a typical color of an object that an observer acquires through their experience with that object [4]. For example, when we think about banana, we associate it with yellow. Therefore, we tend to perceive banana as yellow regardless of light reflected from banana entering the eyes. The influence of memory color on color constancy depends on many factors, including experiences of individuals and physical and optical properties of objects.

Some objects have unique characteristics such as shape and texture that can be recognized and give rise to the effect of memory color. In Duncker's study, he cut the same color paper into different shapes: leaf and donkey [5]. He found that observers perceived leaf's color greener than donkey. Olkkonen et al [6] used photographs of fruits under various simulated illuminations and found that observers perceived fruit stimuli slightly tinted in their typical color even when every pixel of the stimulus was achromatic. The effect depended on how realistic the stimuli were, as the stimuli with 2D outline shapes showed no effect.

Memory color occurs not only with natural objects. As mentioned earlier, memory color is acquired through experience with the objects. Hence, memory color depends on individual knowledge and experience of typical colors of familiar objects. Witzel et al [4] investigated memory color with artificial objects. The results showed that knowledge on a typical color of artificial objects could influence color appearance. Knowledge from color in memory can increase the ability to estimate color of illumination. Granzer and Gegenfurtner [7] showed that the scene with many familiar objects could increase color constancy.

This study aims to investigate the effect of memory color on color perception of natural objects under different color lights. The degree of changes in color perception due to memory color was investigated. To do so, three experiments were conducted. Firstly, memory colors of selected natural objects were collected by asking observers to display colors in their memory of the given objects. The images of the natural objects were taken and the second experiment collected the color perceptions of the natural objects in the images. Finally, the color perceptions of images without natural objects but having the same colors as the images in the second experiment were collected. If memory color has no effect on color perception, the results from the second and third experiments should be the same. When memory color induces color constancy, the color perceptions of natural objects should shift towards the colors obtained in the first experiment.

1.1 Objectives

To investigate the effects of memory color on color perception of natural objects under different illuminations.

1.2 Scope

The visual experiments were carried out on the Internet. A website (https://memorycolor.net) was created, so that observers from various backgrounds could access the experiments. The differences between displays and viewing conditions of the participants were minimized through a monitor calibration chart and gray-balance technique.

Five natural objects included in this study were; Blueberry, Broccoli, Salmon, Sunflower and Tomato. Images of each of the natural objects were taken under D65 simulators and then modified as if taken under extreme colored lights – Red, Green, Blue, and Yellow. The modification was done with Color Filter tool in Adobe Photoshop.

Mondrian images with exactly the same colors as the natural object images were created to investigate the color perception when the object was unknown to the observers.

The results were collected in terms of sRGB values and converted to CIELAB color values. The degree of changes in color perception due to memory was quantified in terms of color constancy index. The differences between color perceptions of natural objects and unknown objects were quantified by CIEDE2000.

1.3 Expected outcomes

1. The degree of changes in color perception due to memory color.
2. Color differences between color perceptions of natural objects and unknown objects.

1.4 Contents

This thesis contains five chapters. The first chapter provides the introduction to the study. Chapter 2 explains theories and literatures on the related work. Chapter 3 gives detailed explanations of experiments. Chapter 4 discusses the experimental results, and the conclusion is given in Chapter 5.

Chapter 2
THEORETICAL CONSIDERATIONS AND LITERATURE REVIEW

2.1 Theoretical considerations

Color perceptions of natural objects under various illuminations were investigated in this study. In order to understand and analyze the results, the theoretical backgrounds relating to the present study are given in this chapter. Firstly, the process of color perception is discussed in Section 2.1.1. Changes in color perception due to color constancy phenomenon are given in Section 2.1.2. Section 2.1.3 describes the effect of memory color, which is the main concern of this study. Finally, the information on HTML5 is given in Section 2.1.4 due to the fact that it was used for generating web pages for launching the experiments.

2.1.1 Color perception

Visual perception is one of human abilities to sense the surroundings. Three main factors in the process of human visual perception are the light, an object and the eye, as illustrated in Figure 2-1. Light from the light source hits the object and reflects to the eye.

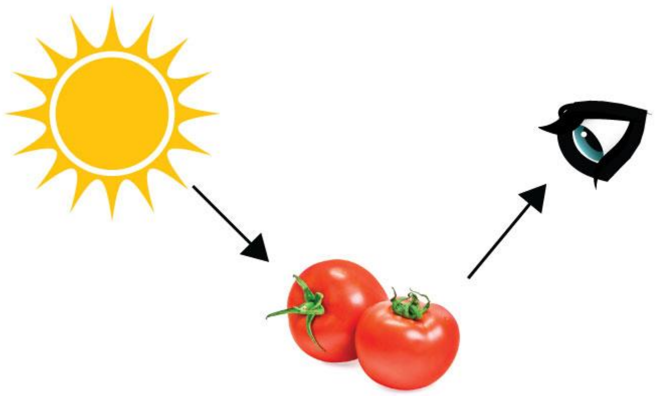

Figure 2-1: Three factors of visual perception.

The color of visible light depends on its wavelengths. White light contains all wavelengths from about 400–700 nm. Each wavelength is perceived as different colors, e.g. at 700 nm red color is perceived. In the process of color perception, light from a light source incident the object, some of the light absorbs in different amount. Then, the rest of the remaining light reflects and enters the eyes. The three types of cone cells in retinal photoreceptor: L, M and S cones convert the color light signal and send to the visual cortex causing color perception. Figure 2-2 shows spectral responsivities of the L, M and S cones [3].

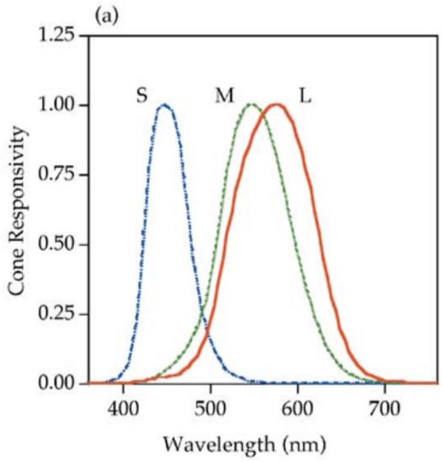

Figure 2-2: Spectral responsivities of human cones, S, M, and L types.

Figure 2-3 illustrates how a green color box is perceived. The white light falls and hits the green box, all color lights except green are absorbed. Only the green light reflects to the eyes. Then, M cones are active and send the signal to the nerve, causing the green color perception. On the other hand, black objects absorb the light in all wavelengths. For white objects, the light in all wavelengths is reflected, so the objects appear white.

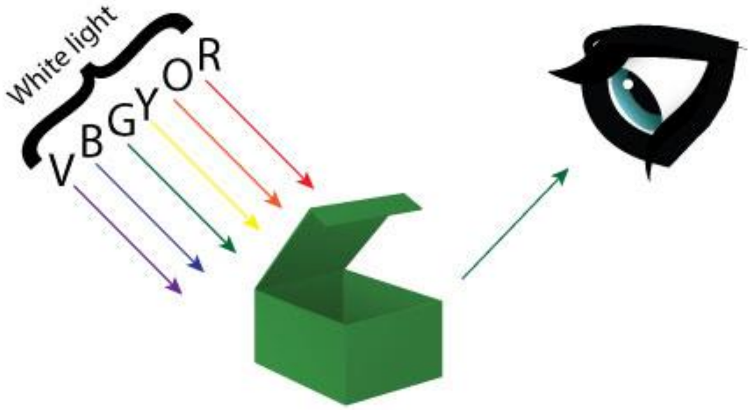

Figure 2-3: The process of color perception.

Consequently, color perception depends on these three main factors. When either a light source or an object change, the reflected light changes, leading to different amount of light stimulating the cones. When the light source and the object remain, but the observer changes, color perception could be different depending on the observer's cone sensitivities. Hence, color of an object is changeable. However, color perception is not determined only by the amount of light in each wavelength stimulating each of the three cones. The human visual system can compensate for the changes in color of a light source, in such a way that color perception remains constant under varying illuminations [3].

2.1.2 Color constancy

Color constancy refers to the phenomenon that objects appear relatively constant in color despite changes in illumination. A red apple appears red whether it is under tungsten light or in sunlight. Under different lighting conditions, the red apple reflects the different light into the eyes, but the apple still appears red. The perceived color of a surface color depends on spectral reflectance properties. The challenge for the visual system is to estimate or eliminate the effect of the illuminant [8]. The human visual system can adapt to the illumination changes so that color perception of objects is the same throughout the day. Color constancy is the perceptual phenomenon – the results of mechanism in the eye and brain [9].

Chromatic adaptation is an ability of the human visual system that can compensate the change in color of the illumination. The human visual system can adjust the sensitivities of the cones, where the sensitivities of each of the three cone types vary independently. Figure 2-5 shows conceptual illustration of the process of chromatic adaptation as the independent sensitivity regulation of the three cone responsivities [3]. When light of a certain wavelength enters the eyes relatively higher than the other wavelengths, cones adapt to be less sensitive to that light. Chromatic adaptation plays an important role in achieving color constancy. Chromatic adaptation can be considered as having two mechanisms: sensory mechanism and cognitive mechanism. Sensory mechanism alone is not capable of complete chromatic adaptation. Cognitive mechanism plays an important role in obtaining complete chromatic adaptation [10].

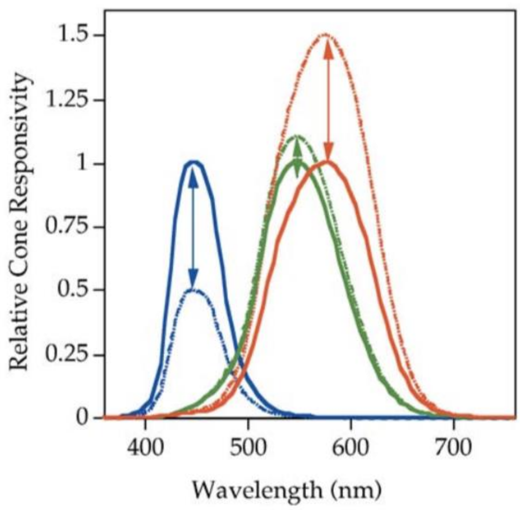

Figure 2-4: Conceptual illustration of the process of chromatic adaptation.

- Sensory mechanism

Sensory mechanism responds automatically to the stimulus energy changes. This mechanism is generally believed to be sensitivity control in the photoreceptors and neurons in the first stage in the human visual system. The concept of sensory mechanism is the normalization of cone signal [9]. The sensory mechanism of chromatic adaptation completes after 60 seconds for changes in adapting chromaticity at constant luminance [3].

- Cognitive mechanism

Cognitive mechanism responds to observers' knowledge of individual observers. The object recognition and memory may also involve in this mechanism [9]. Cognitive mechanism refers to memory color and discounting the illuminants, relying on knowledge of observer. This mechanism can be effectively instantaneous once knowledge is obtained [3].

Discounting the illuminant refers to the cognitive ability of observers to interpret the colors of objects based on the illuminated environment in which they are viewed [3]. It allows human to perceive the actual color of an object independent of changes in the illumination.

2.1.3 Memory color

Memory color is one of the mechanisms in chromatic adaptation. Memory color refers to a typical color of an object that an observer acquires through their experience with that object [10]. For example, when we think about banana, we associate it with yellow, therefore we tend to perceive banana as yellow regardless of light reflected from banana entering the eye.

The knowledge about typical color of objects can influence the color appearance [6]. Memory color could be used to estimate the color lights. For example, the color of yellow banana is less yellow than memory color, so it could be that this banana is under blue illumination. The strongly associate with typical color of objects can help to eliminate the illumination changes [8].

Many previous studies have investigated the role of memory color on color constancy. Jin and Shevell found that color constancy could improve if valid cues to the illuminant estimation increased [11]. The knowledge of a typical color could be the cue to estimate an unknown illuminant. Moreover, the knowledge of an object's typical color could affect color perception [12].

Dunker's study showed that while observers were shown a donkey and leaf cut from the same material, observers matched the color of leaf greener than a donkey. This confirmed Hering's prediction that the two identical colored patches were perceived in different colors when shaped into familiar object and unfamiliar object [5].

Olkkonen M., Hansen T. and Gegenfurtner K.R. [6] found that when presented with a simple outline, memory color effect was weak. On the other hand, memory color was more accurate and consistent for the stimuli containing more realistic features. They found a better color constancy for textured stimuli than uniform stimuli. This indicated that physical properties of natural objects, i.e. shape, texture, highlight and shadow, affected memory color and color perception.

Several researches have reported the effects of memory color on saturation and hue of object color appearance. Dunker [5] found that observers overestimated the saturation when doing a color matching. Moreover, Granzier and Gegenfurtner found that observers overestimated the amount of the typical hue in fruit stimuli [7].

The effects of memory color found not only in natural objects, but also in artificial objects, so long as observers were familiar with the objects, i.e. blue color of Smurf or yellow of UHU glue [4].

Many works have been done to investigate the role of memory color on color perception and color constancy. But it is still unclear whether memory color plays a role in achieving color constancy and how large of this effect [7].

2.1.4 HTML5

HTML5 is a markup language used for structuring and presenting content on the World Wide Web (WWW). HTML stands for Hypertext Markup Language. It cooperates between the World Wide Web Consortium (W3C) and the Web Hypertext Application Technology Working Group. With native tags for document structures such as headers, footers, figures, sections, video and audio, HTML5 allows a browser to display multi-media documents without plug-ins or custom APIs [13]. HTML5 includes detailed processing models to encourage more interoperable implementations. It extends, improves and rationalizes the markup available for documents, and introduces markup and application programming interfaces (APIs) for complex web applications [14].

On HTML5, elements and attributes are used for controlling the website, e.g. <div> is used for generic block, <Video> is used for embedding video on a webpage, or <svg> is used to define vector-based graphics for the web. The graphics is defined in xml format and do not lose any quality when zoomed or resized. Figure 2-5 shows sample for HTML5 coding.

```
<!DOCTYPE html>
<html dir="ltr" lang="en">
▶<head>…</head>
▼<body>
  ▶<viewer-pdf-toolbar id="toolbar" style="transform-origin: 50% 0px 0px; transform:
  translateY(-100%);">…</viewer-pdf-toolbar>
    <div id="sizer" style="width: 826px; height: 12892px;"></div>
  ▶<viewer-password-screen id="password-screen">…</viewer-password-screen>
  ▶<viewer-zoom-toolbar id="zoom-toolbar" style="right: 0px; bottom: 0px;">…</viewer-zoom-
  toolbar>
  ▶<viewer-page-indicator id="page-indicator" style="top: 259.975px; right: 16px; opacity: 0;
  ">…</viewer-page-indicator>
  ▶<viewer-error-screen id="error-screen">…</viewer-error-screen>
    <script src="pdf_fitting_type.js"></script>
  ▶<iron-a11y-announcer>…</iron-a11y-announcer>
    <script src="toolbar_manager.js"></script>
    <script src="viewport.js"></script>
```

Figure 2-5: HTML5 coding interface.

Colors on websites are typically specified in the sRGB color space, where each color is made up of a red, green and blue component. These three components relate to three cone types in the human eye.

On the Web, sRGB colors are specified in formats which describe the color as a 24-bit integer, where the first 8 bits provide the red value, the second 8 bits the green value, and the final 8 bits the blue value. This gives a total space of 16,777,216 unique colors, but not all displays can show these colors. It depends on color gamut and technology of each display [15].

HTML5 simplifies the description of colors with a set of three 8-bit number representing the red, green and blue components of a sRGB color. A seven-character string begins with # character, followed by six ASCII hex digits, representing the red, green and blue components [15].

The sRGB color space is set as the default color space for digital camera images, which corresponds to the color space showing in HTML5. Since the working space for digital camera images and HTML5 is the same, when embedded digital camera images on a website, the colors are the same between these two media.

Color contrast is also important when showing an image on a website. Color contrast can make the colors in images clearly visible.

2.2 Literature review

Hansen et al. [12] also investigated the effects of memory colors on color appearance. They presented digital images of the fruit objects on a uniform gray background and asked observers to adjust the fruit color until they appeared gray. The assumption was that for a fruit to appear neutral gray, observers needed to adjust its color away from the gray adaptation point in a direction opposite to the typical color of the fruit because of memory color affecting its color appearance. The results showed that natural fruit objects tended to be perceived in their typical color. Color perception is determined not only by the reflectance of an object, but also by memory color.

Olkkonen, Hansen, T. and Gegenfurtner [6] studied the effect of memory colors on color appearance of natural objects presented under various simulated illuminations. In the experiments, they asked observers to adjust the color of the stimulus (a photograph of fruit or vegetable) presented on monitor either to gray or to the fruit's (or vegetable) typical color. Three versions of stimuli were tested: original photographs (3D shapes), photographs of painted fruit (3D shapes without texture), and 2D outline shapes. The results showed that color appearance of natural objects was affected by their typical colors. The strength of the memory color effect depended on naturalness of the stimuli. The color perception was most affected with realistic photographs having the correct chromatic and luminance texture, less with stimuli without appropriate surface texture, and not at all with outline shapes. They concluded that the visual identity of an object had a measurable effect on color perception, and that this effect was robust under illuminant changes. Their findings indicate the potential significance of memory color as an additional mechanism for color constancy.

Witzel et al. [4] investigated the memory color effect for artificial, man-made objects. They conducted two experiments. The first experiment was to find suitable artificial objects to be used in the second experiment. The second experiment was the main experiment that investigated the memory color effect. The artificial objects varied in the complexity of their visual features and in the abstractness of their color characteristics. Observers adjusted the objects to their typical color and to achromatic color. If the achromatic object appeared in its typical color, then observers should adjust it to the opponent color in order to perceive it as gray. The results showed that memory color effect was also found in artificial objects. The acquired knowledge about objects modulated their color appearance.

Granzier and Gegenfurtner [7] tested whether the presence of objects with diagnostical colors within a scene influenced color constancy for unknown colored objects in the scene. Observers matched the Munsell patch placed in a scene illuminated under colored light with the Munsell book of color illuminated with D65. The Munsell patches were placed in four different scenes: one scene containing familiar objects, another containing incongruent colored object, the third with geometrical objects of the same color as the familiar objects, and the last scene containing non-diagnostically colored objects (objects that could be in any color, for example, a yellow coffee mug). The results showed that the scene with familiar objects had the highest color constancy index (46.2%), followed by the scene with incongruent colored objects (39%), the scene with geometrical colored objects (37.6%), and the scene with non-diagnostically colored objects (34.9%). The results showed the effect of memory still occurred but weak in non-diagnostical scene. The lack of information in artificial objects could affect information gained in the scene.

Chapter 3
METHODOLOGY

3.1 Apparatus

3.1.1 Digital Still Camera

Model:	Fujifilm X-T2
Lens:	Standard lens 18-55 mm

3.1.2 Light Box with D65 lamp

3.1.3 Software Application

Adobe Photoshop:	Version CC 2015
Microsoft Word:	Version 2017
Microsoft Excel:	Version 2017
MATLAB:	Version R2015b

3.2 Method

This study investigated the effect of memory color on color perception of natural objects. To this end, a series of visual experiments were conducted on a computer screen, where observers were able to display colors they memorized or perceived using a color picker tool. Firstly, observers identified colors of the given natural objects based on what they memorized. Having done so, a set of images of the said natural objects under different illumination was shown to the observers and their task was to identify the colors they perceived in each image. Lastly, observers were presented with Mondrian images containing exactly the same colors as those in the natural object images and were again asked to identify the colors they perceived. The results were recorded in terms of RGB values of the colors observers selected. The CIE color system was employed to quantify the degree of memory color effect.

The detailed descriptions of experiments are divided into three parts. Section 3.2.1 gives the details of the experimental setup, as well as how the test images were prepared. The experimental steps for an observer are given in Section 3.2.2. Finally, Section 3.2.3 explains how the experimental data were analyzed.

3.2.1 Experimental preparation

In this study, the visual experiments were carried out through web pages, so that the experiments could be done online under the usual working environment with a computer for an individual observer. The web pages were designed to serve the purpose of each of the three main experiments. Experiment 1 was to determine observers' memory colors. Experiment 2 was to obtain colors of the natural objects that observers perceived in the images with the recognizable objects. The colors perceived in the images without the recognizable objects were collected in Experiment 3. This section describes the selection of natural objects, and the preparation of web pages and test images.

3.2.1.1 Natural Objects

Five natural objects were carefully selected with an intention to cover a range of distinct colors in nature. Moreover, the objects must be well-known to most people, if not all, and well-recognized by their shapes or characteristics. The natural objects under study included tomato (red), broccoli (green), blueberry (purple), sunflower (yellow) and salmon (orange).

3.2.1.2 Web pages

In this study, web pages of experiments were created with HTML5 code to launch online. These web pages were combined with four sections: Pre-experiment section, Display calibration section, Main experiment section, and Thank you and share section (Figure 3-1).

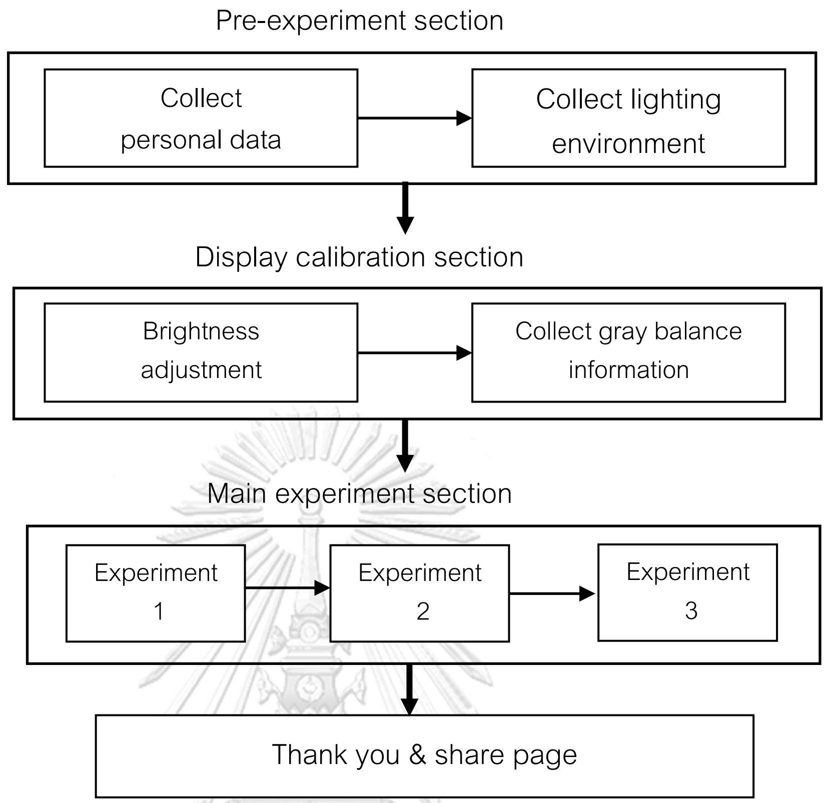

Figure 3-1: A flow of experimental web pages

1. Pre-experiment section

This section aimed to collect information that could affect the results. Since memory color depends on individual experience, observers' personal data such as gender, age and their filed of work must be included. Moreover, the experiments will be done in an uncontrolled lighting condition. The information on lighting environment must also be collected. This section thus contained two web pages: one for collecting observers' personal data and the other for collecting their lighting environment at the time of doing experiments.

2. Display calibration section

Since the experiments were carried out online, there was no control over the viewing conditions for each observer. To minimize the differences between devices and viewing environments that affect color perception, a simple calibration that can be done by an inexperienced observer must be incorporated.

Brightness of a monitor could affect contrast of the displayed image. Thus the first step was to adjust the brightness of the monitor using a gray chart with various lightness steps. When the monitor is adjusted to its appropriate brightness, observers should be able to see differences between all steps.

The monitor white point and the ambient light could affect color appearance of displayed image. When they deviate from typical white of daylight, the deviated color casts over the entire image, resulting in an imbalance of gray. Consequently, the unequal RGB values of a gray patch could be used to calibrate the data. In this step, observers must be presented with a gray patch having equal RGB values, so that their color perception of the gray can be collected.

To find the gray balance information, the layout of the webpage was designed to feature three main elements (Figure 3-2). They were Test Image box for showing the target color or the test image, Match Color box for displaying the color that observers select from a color picker to match what they see in the test image, and Color Picker Tool, which is a tool to find the wanted color. This layout was constant for the main experiments, with an instruction on top of the page. A submit button was at the bottom on the page. It was used to confirm and submit the RGB values of the match color, as well as lead to the next page.

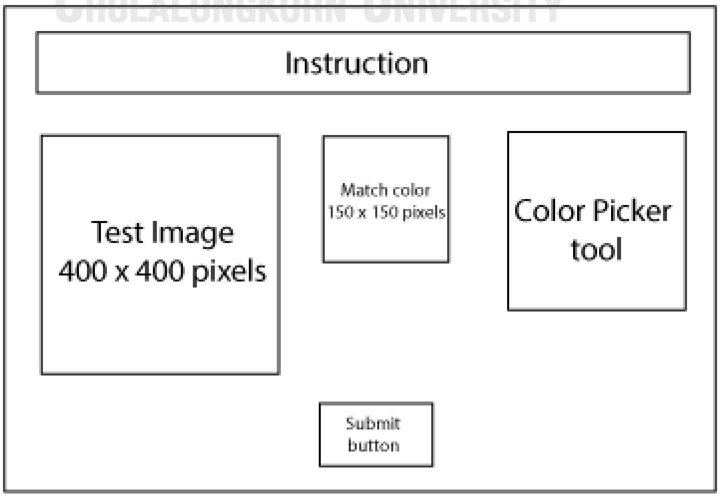

Figure 3-2: Web page layout

The background of web pages was gray (RGB = 128, 128, 128). The instruction were in English and Thai, white (RGB = 255, 255, 255), Courier New 16 points. The test image box was 400x400 pixels, placed on the left. The match color box was 150x150 pixels, placed in the middle, and the color picker tool was placed on the right of the web page. The color picker tool in JavaScript was adopted from https:eyecon.ro/colorpicker [16].

Two pages of gray balance adjustment were included. The gray patches in the two pages were different. One was for data calibration, and the other was for familiarizing observers with using the color picker tool.

3. Main experiment section

In this section, the same web page layout of gray balance adjustment section was used. This section included with three parts: Experiment 1 – Memory color of natural objects, Experiment 2 – Color perception of images with natural objects, and Experiment 3 – Color perception of images with non-natural objects. In each experiment, test images were randomly shown in a random order. Observers must do the experiments from Experiment 1 to Experiment 3, respectively. The RGB values of match colors were collected.

4. Thank you and share page

Once observers finished all parts of experiments, thank you and share page appeared in the last section. The data are saved only when this page appears, if not, the data are not saved. Observers could share the experimental web page on their personal Facebook page to expand the experiment and gain more observers. Facebook thumbnail with 1200 x 632 pixels in size was created from one of the test images, together with the website headline to attract people who saw this link.

3.2.1.3 Test images

Test images were categorized into three sets according to the three main experiments. The test images in Experiment 1 were simply a set of object names inside a square of 400 x 400 pixels. They were generated on Adobe Photoshop. The text was in white (RGB = 255, 255, 255), Arial Regular 84 points, presented against a gray background (RGB = 100, 100, 100) with the center alignment of the square. Note that the same configuration was applied to all object names except Sunflower due to its long spelling, so the word size was reduced to 60 points to fit in the same square size.

In Experiment 2, the test images were the images of the five natural objects under different illumination. The last image set was a set of Mondrian-pattern images having exactly the same colors as the image set in Experiment 2.

- Natural object images

The images of the five natural objects selected in Section 3.2.1.1 were taken under daylight simulators D65 in a light box. The setting of the digital camera was as follows: f no. 4, Shutter speed 1/400 seconds, ISO 400 and Auto White balance mode. The original images size 6000 x 4000 pixels was cropped and resized to 400 x 400 pixels using bi-cubic mode in Adobe Photoshop. The experimental images of Broccoli, Blueberry, Salmon, Sunflower and Tomato are shown in Figure 3-3.

Figure 3-3: Test images of natural objects taken under D65 simulators.

- Modified images

In addition to the natural object images under daylight, Experiment 2 contained images of the natural objects under different colored lights. In this study, the original images were modified to simulate the same scene taken under different color lighting. To do so, Color Filter function in Adobe Photoshop was applied to the entire image of each original. Four colors were selected in this study: Red (150, 0, 0), Green (0, 255, 0), Blue (0, 0, 255) and Yellow (255, 255, 0). When applying Color Filter, the opacity of each color was set to 50%. Figure 3-4 shows the examples of modified images for sunflowers. In total, 25 images (5 originals + 20 modified images) were included in Experiment 2 image set.

Figure 3-4: Examples of modified images in four different color lights: Yellow, Blue, Green and Red

- Mondrian images

In Experiment 3, color perception of an image without natural objects was investigated. Mondrian images were generated for each of the test images in Experiment 2, in which each Mondrian image had exactly the same color pixels as its corresponding natural object image. A flow chart of Mondrian image processing is illustrated in Figure 3-5.

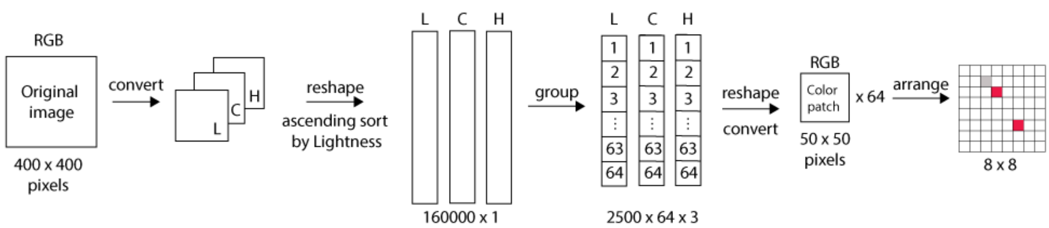

Figure 3-5: A flow chart of Mondrian image processing

The color transformation was computed in sRGB under the assumption that any camera output color image encoding is sRGB [17]. The transformation was done on a pixel-by-pixel basis in MATLAB. The first step was to convert the sRGB values of the natural object image to CIE LCH color values of lightness (L), chroma (C) and hue (H). The color data were then sorted by lightness from low to high values. When two or more colors had the same lightness, they were sorted by hue. From the image size of 400x400 pixels, the total number of pixels was 160,000 pixels. After sorting, the data were grouped into 64 groups having 2500 pixels in each group. Each data group then formed a color patch of 50x50 pixels. Sorting the color data by lightness could separate colors with different hues into different color patches. This is because the colors with different hues in the natural object images in this study had markedly different lightness.

To form a Mondrian-pattern image of 400x400 pixels in size, the resultant 64 color patches were randomly arranged into an 8x8 grid image in Adobe Photoshop. Finally, the color patch having the same color data as the natural object in the original image was marked with an arrow pointed at the bottom left corner. Note that the color data were selected from the prominent areas of the natural object in the image. In total, 25 Mondrian images were tested in Experiment 3. Figure 3-6 shows the examples of Mondrian images.

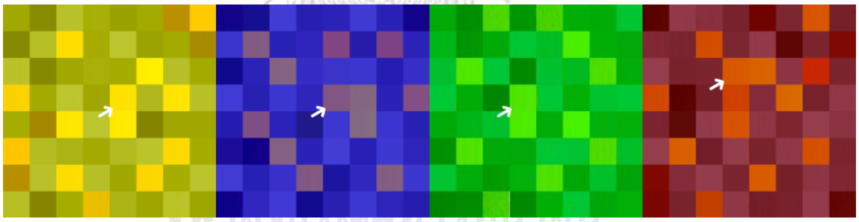

Figure 3-6: Mondrian images of the images in Figure 3-4

3.2.2 Experimental procedure

Observers participated in the visual experiments online via a website containing a series of web pages described in Section 3.2.1.2. The URL of the experimental website was https://memorycolor.net. The experimental steps are as follows.

3.2.2.1 Pre-experiment

First, observers were asked to fill in their personal data: nationality, age, occupation and gender. For occupation, they were asked only whether or not their field of work related to design or art or color. Figure 3-7 shows the interface of the personal data collection page. On the next page, the observers were asked to fill in their lighting environment. Firstly, they were given a choice of light sources in a drop-down list, including Dark (referring to no ambient light), Natural light and Office light. When Office light was selected, two more drop-down lists appeared for types of Office light: White, Yellowish or Bluish light; and its brightness: Bright or Dim.

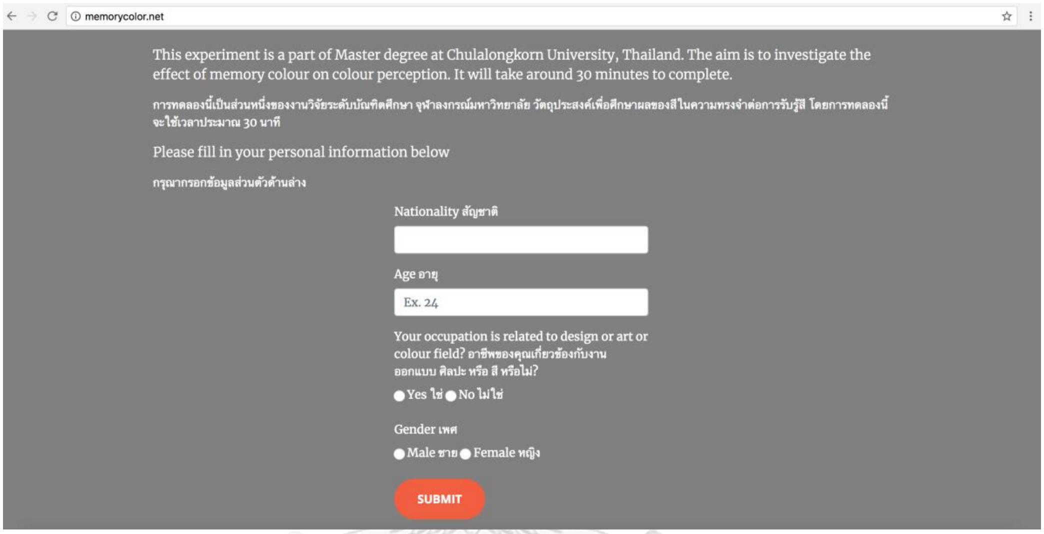

Figure 3-7: Pre-experiment interface

3.2.2.2 Display calibration

Observers were presented with three pages (one for adjusting brightness, the other two for finding gray balance) for display calibration.

- Brightness adjustment

The Monitor Calibration chart (Figure 3-8) adopted from Kris Zaklika, Jasc Software Inc. [18] was shown to observers. Their task was to adjust the brightness of their monitor so that they could distinguish between shade numbers 0, 1, and 2 on both black and white ends.

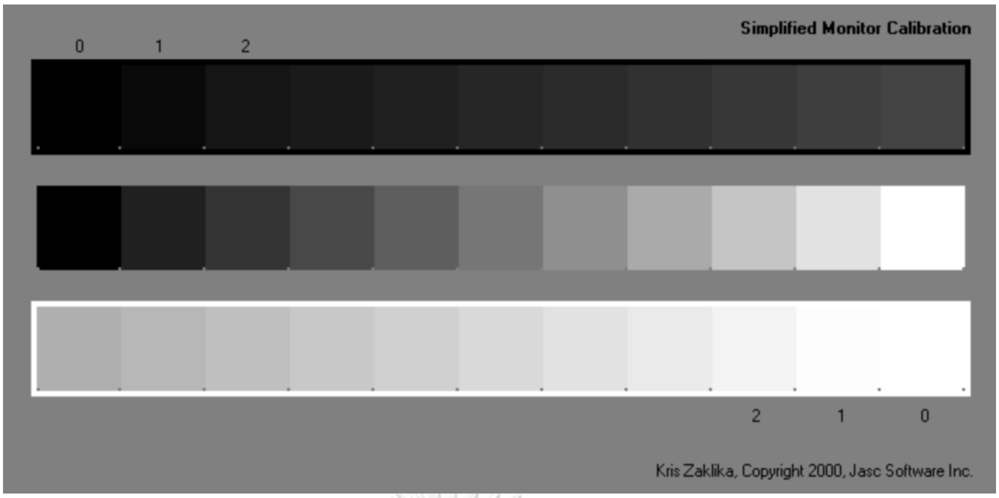

Figure 3-8: Monitor calibration chart from Kris Zaklika, Jasc Software Inc

- Gray balance

On this page, observers were shown a gray patch (RGB = 100, 100, 100) and asked to identify the color that they perceived. The interface of this page is shown in Figure 3-9. The same procedure was repeated with a lighter gray patch (RGB = 200, 200, 200) on the second page.

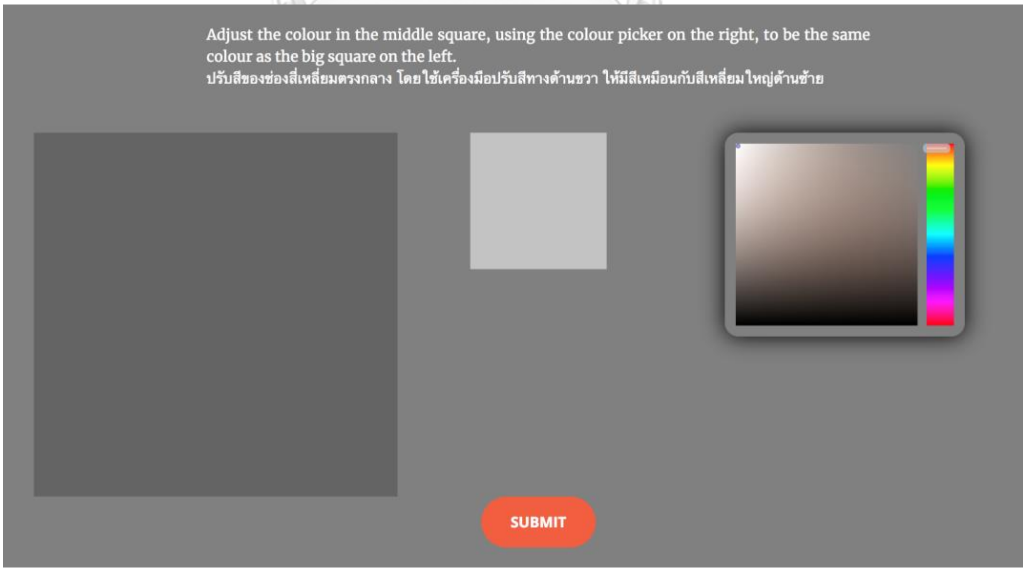

Figure 3-9: Interface to find gray balance condition.

3.2.2.3 Experiment 1 – Memory color of natural objects

The purpose of this experiment was to find the memory color of natural objects. Observers were given an object name, e.g. Tomato, and adjusted the color using the color picker to match the color of Tomato in their memory (Figure 3-10). The RGB values of the selected color were collected. Five object names were shown in turn in a random order.

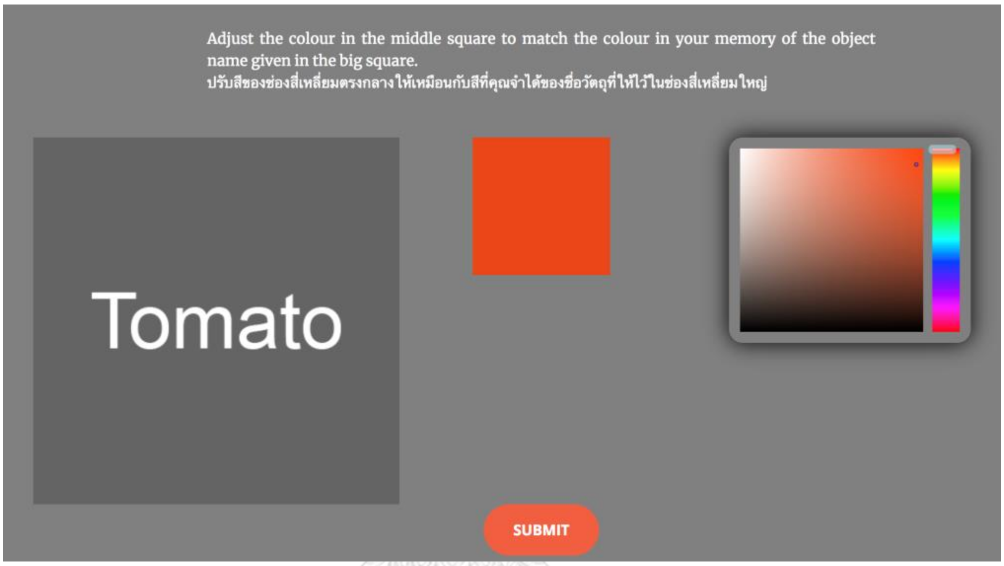

Figure 3-10: Interface of Experiment 1

3.2.2.4 Experiment 2 – Color perception of images with natural objects

Experiment 2 aimed to find the perceived color of the natural objects in the images. The images with natural objects in different colored lights were shown one after another in a random order. The first 20 images were modified images, i.e. natural objects in extreme colored light, followed by the original images under daylight. This arrangement was done to prevent the effect of color memory instead of memory color. Their task was to select a color from the color picker that matched the color of object that they perceived in the image. The RGB values of the selected colors were collected.

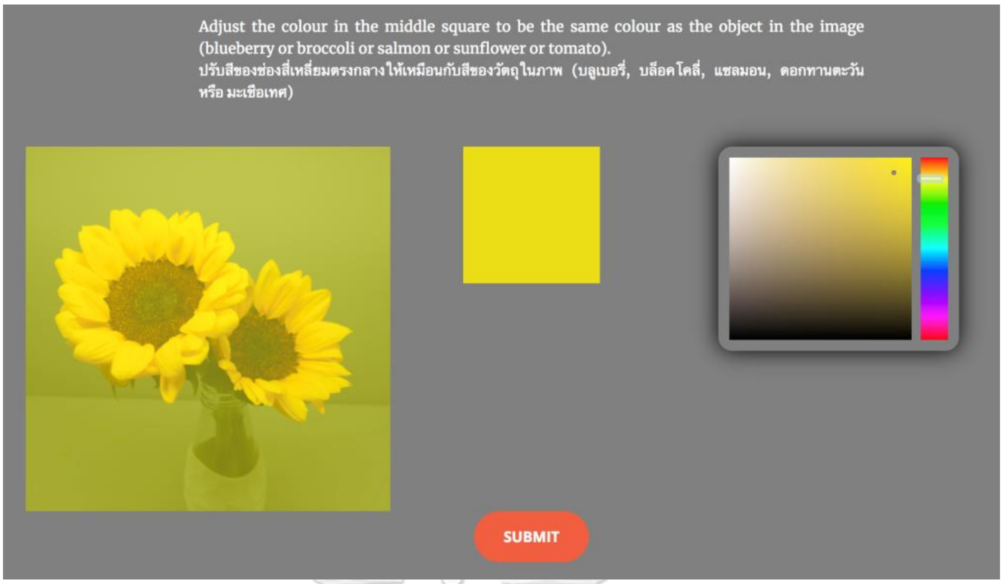

Figure 3-11: Interface of Experiment 2

3.2.2.5 Experiment 3 – Color perception of images with non-natural objects

This experiment aimed to find the perceived color in an image without natural objects. Observers were shown 25 Mondrian images one at a time and in a random order (Figure 3-12). Their task was to select a color from the color picker that matched the color that they perceived in the image where the arrow pointed. The RGB values of the selected colors were collected.

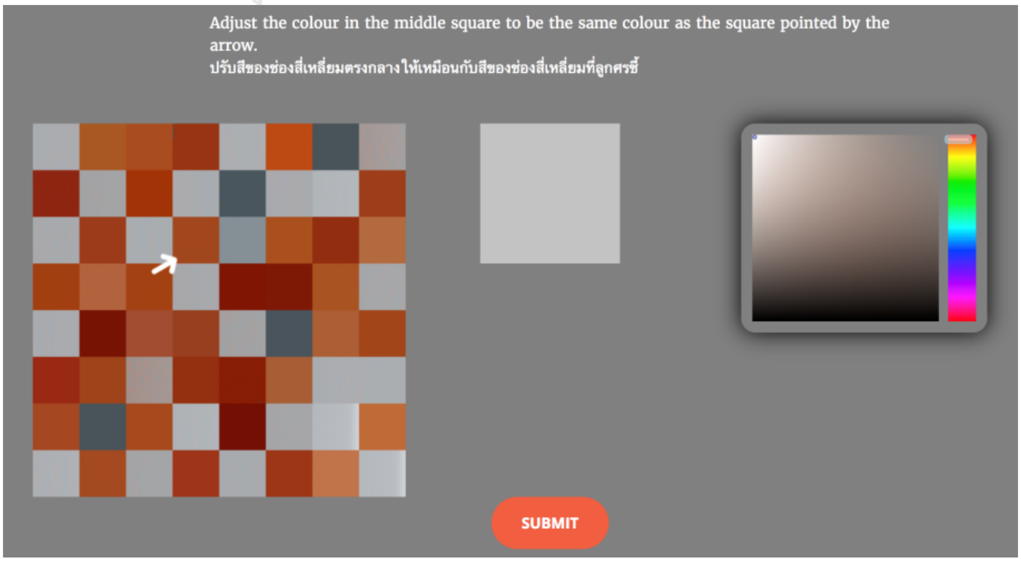

Figure 3-12: Interface of Experiment 3

3.2.3 Data analysis

1. Color correction

The test images shown to observers could have different color appearance for different observers due to variations of devices and lighting conditions. Using the gray patch (RGB = 100, 100, 100) as a calibration target, its RGB values obtained from observers' color perception were used to compute a color correction transform. The RGB values obtained from the experiments were then calculated to compensate for the color cast due to the viewing conditions (Equation 3-1).

$$R_{new} = \frac{100}{x} \times R$$
$$G_{new} = \frac{100}{y} \times G \qquad (3-1)$$
$$B_{new} = \frac{100}{z} \times B$$

Where x, y and z are the R, G and B values, respectively, of the gray patch obtained from the observer.

2. Color data

After color correction, the adjusted RGB values were transformed to CIE XYZ values following the sRGB computation [17]. The XYZ values were then converted to color attributes in CIELAB color space, including L* (lightness), a* (red-green), b* (yellow-blue), C^*_{ab} (chroma) and h_{ab} (hue-angle).

3. Color constancy index

To quantify the degree of color constancy, differences in observers' color perception and the ideal match are expressed in a chosen color space [19]. In this study, the results were presented in the a*b* plane of CIELAB color space, as illustrated in Figure 3-12. The colors of natural objects under D65 denote "Match Color", i.e. an idea match to the original image. The true colors of objects in the modified images, i.e. the colors taken directly from the images, denote “Actual Color”. These two colors serve as anchor points to determine the degree of color constancy. When the perceived colors, referred to as “Color Perception”, fall in the same position as Match Color, perfect color constancy occurs, i.e. observers perceive the same color as in the original image regardless of light entering the eyes. On the other hand, when the Color Perception falls in the same positions as Actual Color, it means zero color constancy, i.e. observers perceive the same color as the color light entering the eyes, no influence of chromatic adaptation. The color constancy index (%CC) is defined by the ratio of the distance between Actual color and Color perception (AC-CP) and the distance between Actual color and Match color (AC-MC). The end formula is multiplied by 100 to get percentages (Equation 3-2).

$$\%CC = \frac{(a*_{AC} - a*_{CP})^2 + (b*_{AC} - b*_{CP})^2}{(a*_{AC} - a*_{MC})^2 + (b*_{AC} - b*_{MC})^2} \times 100 \qquad (3-2)$$

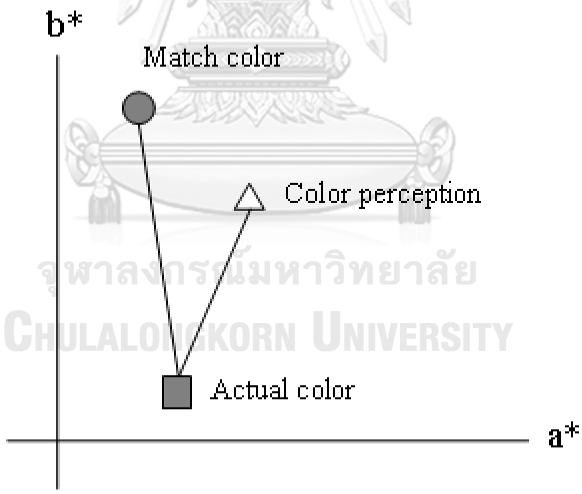

Figure 3-13: Concept of color constancy index, the a*b* values of Match color (circle; the color of natural objects under D65 – the original image), Color perception (triangle; the perceived color of natural objects under colored lights – the modified image) Actual color (square; the true color of natural objects in the modified image).

The Euclidean distance as provided in Equation 3-2 combines the differences in both chroma and hue between two colors. However, the concept of color constancy index adapted from Arend et.al. [20] and Troost and De Weert [21] comprehends the degree of color constancy in a one-dimension case, but in a two-dimension case, it does not give complete information. Given Figure 3-13 as an example, hue of Color Perception can deviate from the AC-MC line. In this case, the AC-CP distance can be the same as AC-MC, but the color constancy is not perfect. Taking the deviation into account, this study applied the same concept to calculate the color constancy index for differences in hue (ΔH^*_{ab}) and chroma (ΔC^*_{ab}), separately.

4.Color differences

Color differences were calculated in terms of CIEDE2000 [22] between:

- Color Perception and Memory Color
- Color Perception and Match Color
- Color Perception and Actual Color
- Color Perceptions of the object images and the Mondrian images

Chapter 4
RESULTS AND DISCUSSIONS

The visual experiments were conducted on a computer screen by means of color matching tasks using a color picker tool to find the matches. In Experiment 1, observers were asked to provide a typical color of the given natural objects that they memorized, and the memory color data were collected. The observers then matched the color they perceived in the images of natural objects in various illuminants, and the color perception data of natural object images were collected in Experiment 2. In Experiment 3, the observers provided the color perception data for the Experiment 2 images that all the colors were rearranged to create Mondrian images.

The results are categorized into four sections. Section 4.1 discusses about the variations of memory colors collected from the observers in this study. Section 4.2 shows the results of perceived colors in the natural object images in terms of color constancy index. Section 4.3 compares the color differences between perceived colors and memory colors, and the ideal match colors, and the actual colors in the images, to investigate the role of memory color in achieving color constancy. Finally, the comparisons of perceived colors in the natural object and Mondrian images are presented in Section 4.4, to investigate the effect of familiar objects on color perception.

4.1 Memory color

The experiments were carried out online, so that they were accessible to more people and the viewing condition was a usual working environment for an observer. There were altogether 98 participants after two weeks of launching on the Internet. After examining the experimental data, 20 participants were excluded from the list for data analysis due to errors in the data. This included those who did not finish the experiments properly, i.e. their results showed repeated data from a certain point in the experiments through the end. Some gave erroneous typical colors of the natural objects (Experiment

1), e.g. a gray for tomato. In total, the results from 78 participants were used in the data analysis.

The information that may yield differences in memory colors and color perceptions was collected. This included the observers' personal data and the viewing environment for the experiments. Figure 4-1 shows the personal data, including gender, nationality and the related field of work. There were more female (54%) than male observers (46%). The majority of the observers were Thai (94%), and the other five nationalities were Argentinean, Indian, Jordanian, Myanmar and Spanish. Regarding the field of work, the observers were asked whether their occupation was related to Arts, Design and color, to which the majority (68%) did not work in the related field. In the case of age, the average from 78 observers was 26 years old, ranging from 19–38 with a standard deviation of 3.9 years old.

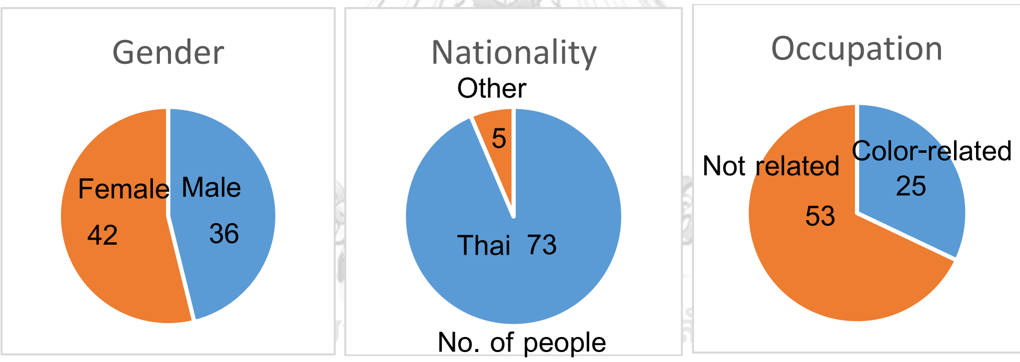

Figure 4-1: Demographic data.

Figure 4-2 shows the lighting environment at the time of experiments by each observer. The majority of the observers (65%) did the experiments in the office light while 29% in the natural light and only 6% did in the dark surround. As for the color of office light, 37 observers reported bright white light, while 10 observers worked under yellowish light.

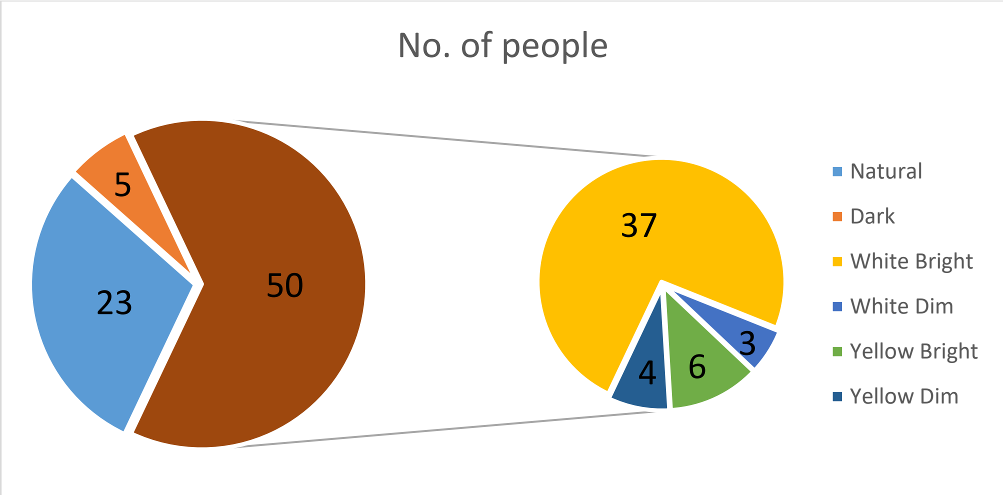

Figure 4-2: Lighting environment at the experiments.

Five natural objects were selected in this study. They were tomato, broccoli, sunflower, salmon and blueberry. Their typical colors as memorized by the observers are presented in CIELAB color space and given in Figures 4-3 (for the a*b* plot) and 4-4 (for the C^*_{ab}-L* plots). It can be seen that the memory colors of the five natural objects fall in the hue regions as follows: red for tomato, green for broccoli, yellow for sunflower, orange for salmon, and purple for blueberry. For tomato, broccoli and blueberry, their memory colors spread widely in the chroma direction but showed lesser differences in hue. On the contrary, memory colors of sunflower tended to spread more widely in the hue direction than the chroma. In the case of salmon, the distribution of memory colors scattered in both directions. The rather constant hue for tomato, broccoli and blueberry conformed to the findings by Smet et al. that observers were more tolerant toward chroma shifts than hue shifts [23].

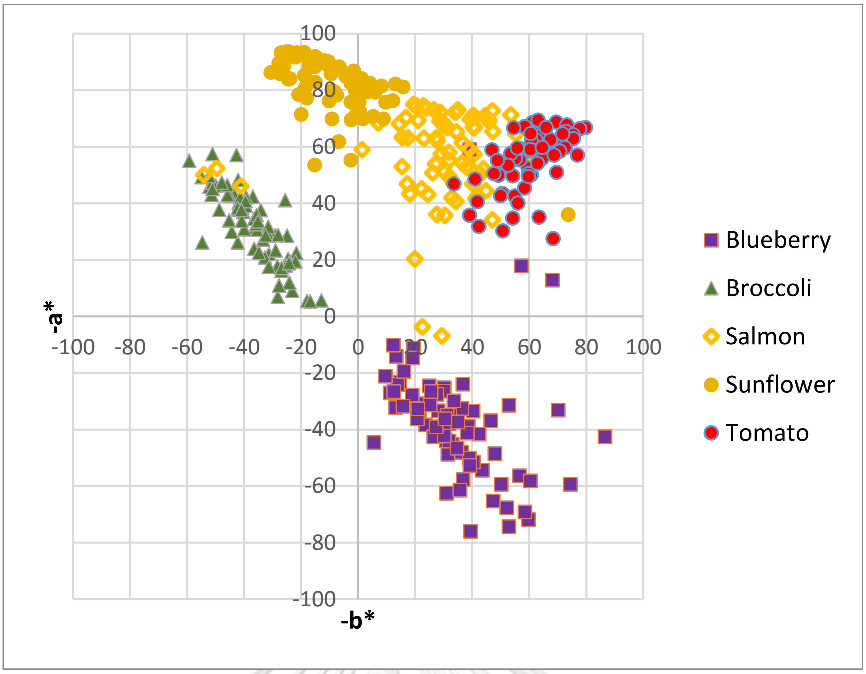

Figure 4-3: Memory colors of tomato, broccoli, sunflower, salmon and blueberry in the a*b* plot.

Bartleson found that memory colors of familiar objects tended to be more chromatic than the actual colors and not necessarily of the same hue [24]. Observers tended to shift hue toward their preference [25]. This could be the case for sunflower that varied from saturated yellow to saturated orange-yellow. The possible explanation for the large variations in memory colors of salmon is that in the experiment observers were only given the word “salmon” without further detail. So, it was up to the imagination of each individual whether it was raw or cooked salmon. In other words, different observers could think of different forms of salmon, resulting in various colors with different hue, chroma and lightness.

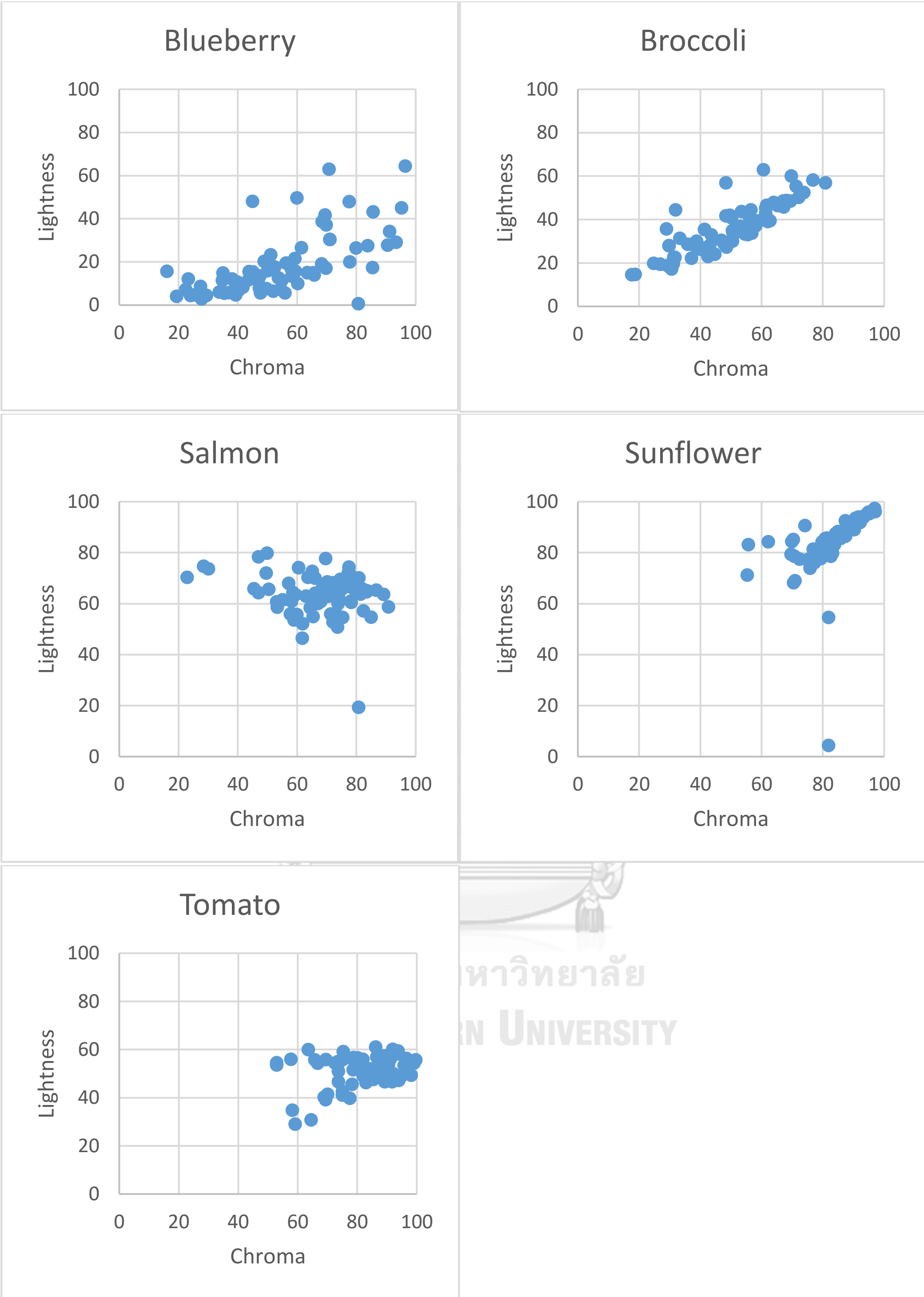

Figure 4-4: Lightness and chroma of memory colors of the five natural objects.

In the case of lightness (Figure 4-4), broccoli and blueberry seemed to spread more than the other objects. The observers tended to remember tomato as saturated red with medium lightness, while they remembered sunflower as bright, saturated color. The spreads of broccoli and blueberry were vast in both lightness and chroma, despite being rather constant for their hue. It could be because broccoli has two clearly dissimilar parts with different lightness and chroma, i.e. the flower heads usually in deep green color and the stalk usually in pale green. In the case of blueberry, it is commonly processed into various products such as jam, juice, etc. The colors of different products usually differ in lightness and chroma, and they are usually different from the fresh blueberry. Since memory color depends on individual experience with the objects, it can vary from observer to observer. Hence, for further analysis, the results were calculated for each individual observer before finding an appropriate descriptive statistic to represent the results.

4.2 Color constancy in natural object images

Color perceptions of the natural objects presented in the images were compared in terms of color constancy index that indicates how constant the color of the objects is when viewed under illuminant different from the normal daylight. Four colored illuminants (red, green, yellow and blue) were studied. The color perceptions of the original images under D65 were taken as the ideal match colors when calculating color constancy index. This is because if the observers were able to completely discount the illuminant color that casts over the entire image, they would perceive the color of the original image. When the perceived colors in the images were the same as their actual colors (the colors taken directly from the images), color constancy index would be zero. The higher the value of color constancy index, the better agreement between the perceived colors in the colored illuminant and in D65.

The results of color constancy index were calculated for each observer, for each object in each illuminant. The median value was used to represent the data obtained from all observers, as opposed to the mean value, due to the large differences in the results between observers.

4.2.1 Comparing between different objects

Figure 4-5 shows the results of color constancy indices (%CCs) for comparing between objects for each illuminant. In Red, %CCs were high for all objects, ranging from 67% (Sunflower) to 91% (Broccoli and Salmon). This indicated that observers were able to estimate the illuminant color and separate it from the object colors, so the perceived colors were close to the colors in the original images in D65. However, in Green, all objects had comparatively low %CCs, ranging from 44% (Salmon) to 61% (Broccoli and Sunflower), whereas in both Blue and Yellow, %CCs were more varied between objects, ranging from 45% (Broccoli) to 88% (Sunflower) for Blue, and from 51% (Tomato) to 95% (Sunflower) for Yellow. The results showed that some objects remained constant in color in some illuminant but poorly perceived in some, for example Salmon. Illuminant dependency of the object color constancy was further analyzed using the average %CCs and range of %CCs (differences between the max and min %CCs) of each object across illuminants (Figure 4-6).

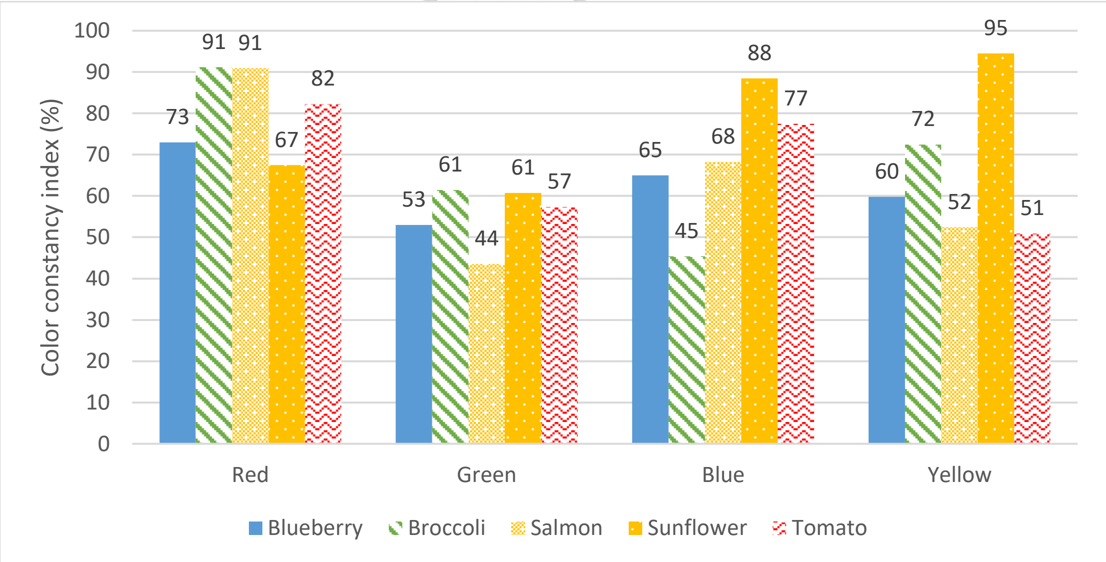

Figure 4-5: Color constancy indices compared between objects.

In Figure 4-6, the high number of the range values indicates the high illuminant dependency. It was found that the average %CCs were not much different between objects. However, their ranges in different illuminants varied more largely. Blueberry showed the least illuminant dependent, with the range of 20, meaning that observers could perceive relatively the same color of Blueberry under varying illuminants. It is possibly because the original color of Blueberry in the images was very dark, low in both lightness and chroma (see Appendix A for the distributions of color perceptions in the original images in CIELAB). Therefore, the illuminant color had little effect on the changes of the actual colors in different images (see Appendix B for the distributions of the actual colors in CIELAB). In contrast, Salmon had a high range value (47), showing that the degree of color constancy for Salmon depended on which illuminant color was cast upon the entire scene. The possible explanation is that the majority of the observers were Thai, who may not be familiar with Salmon which is not native to the Gulf of Thailand. Hence, it was hard for the observers to discard the illuminant color when it was much different from the object color, i.e. the green illuminant.

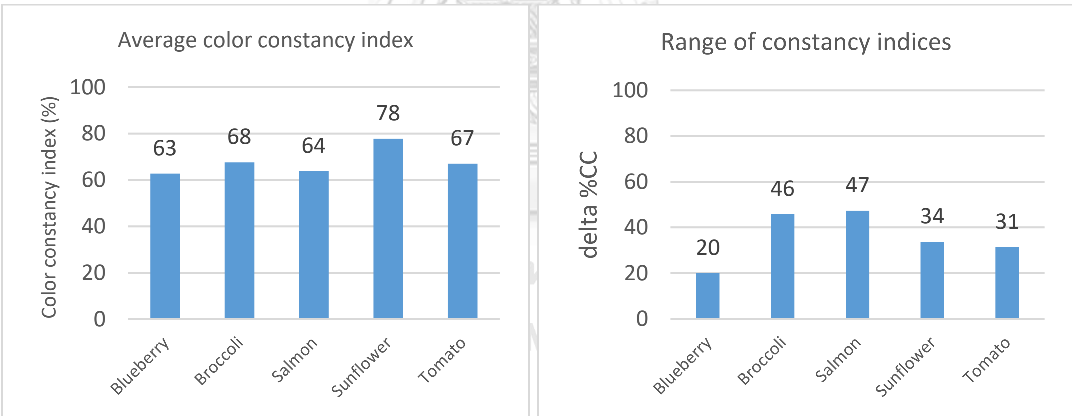

Figure 4-6: The average and range of color constancy indices across illuminants for different objects.

The color perception can vary in both hue and chroma. The notion of color constancy is to preserve the same object-color perceptions in various illuminations. The color constancy exists so long as the object color is not assigned to different hue categories when viewed under different illumination [21]. When the colored light illuminates the scene, it is expected to affect the hue of the object more than the chroma.

In this study, the color constancy indices were also calculated to investigate the constancy in hue and chroma, separately. The results are presented in Figures 4-7 and 4-8 for hue constancy, and 4-9 and 4-10 for chroma constancy.

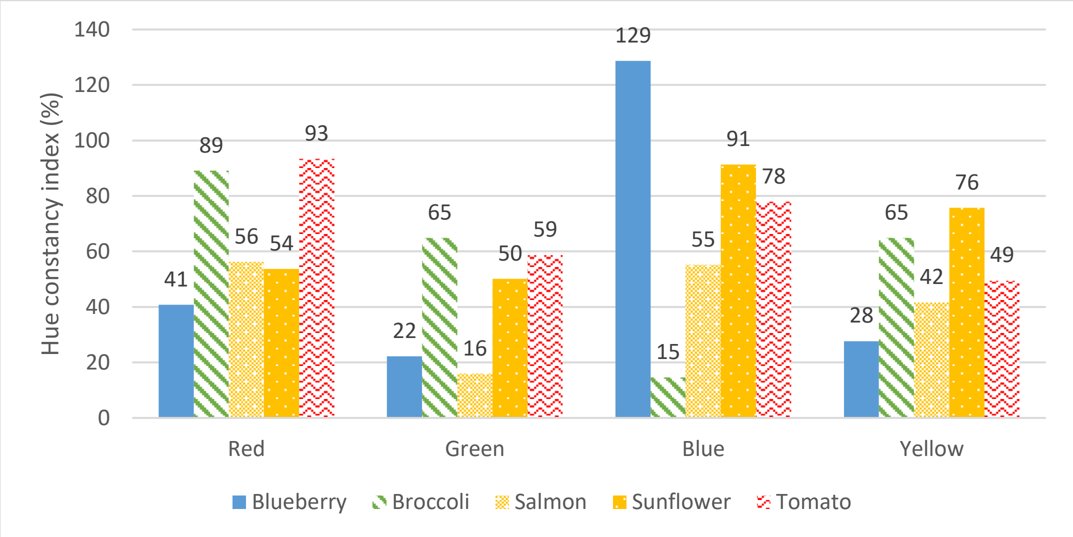

Figure 4-7: Hue constancy compared between objects.

When %CC is higher than 100%, it means that observers over-compensate the effect of illuminant color for that particular attribute. This happened in the case of Blueberry in the blue illuminant. The observers could not discount the illuminant color from the object color, resulting in the perceived color shifting in blue and being bluer than the original blueberry in D65.

In Figure 4-8, Tomato had the highest hue constancy (70%), followed closely by Sunflower (68%), and their differences between the highest and lowest %CCs were moderate. This shows that observers were able to estimate the illuminant color and identify the object colors under the unnatural colored illuminants. This could be because both Tomato and Sunflower are common in Thailand. The observers were familiar with the objects, so it was rather easy for them to separate the illuminant color and the object color.

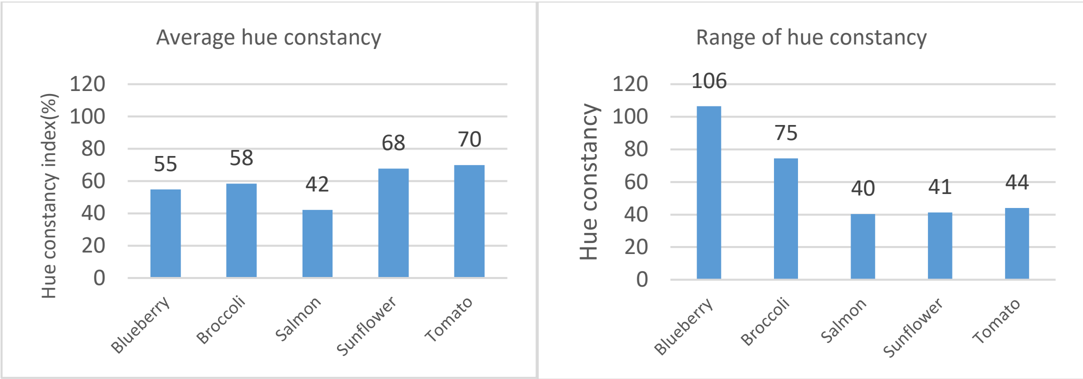

Figure 4-8: The average and range of hue constancy across illuminants for different objects.

In terms of hue constancy, Blueberry had the most illuminant dependent (106), i.e. the degree of hue constancy varied vastly from illuminant to illuminant. However, the results in Figure 4-6 showed that Blueberry had the least illuminant dependent for the color constancy combined for both hue and chroma. The similar results were found for Salmon in that it had the lowest illuminant dependency in hue constancy but the highest combined constancy. The results of chroma constancy could explain these findings.

In Figures 4-9 and 4-10, %CCs in chroma of Blueberry were relatively constant across illuminants with the smallest range of 17, while Salmon had reasonably high in the range value (87). Chroma of Blueberry was fairly constant because of its dark color in the original image, leaving little room for chroma changes in the actual colors when colored illuminant was applied. In contrast, the original color of Salmon was bright and saturated; some illuminant could increase its chroma while some could decrease its, resulting in varying degrees of chroma constancy in different illuminants.

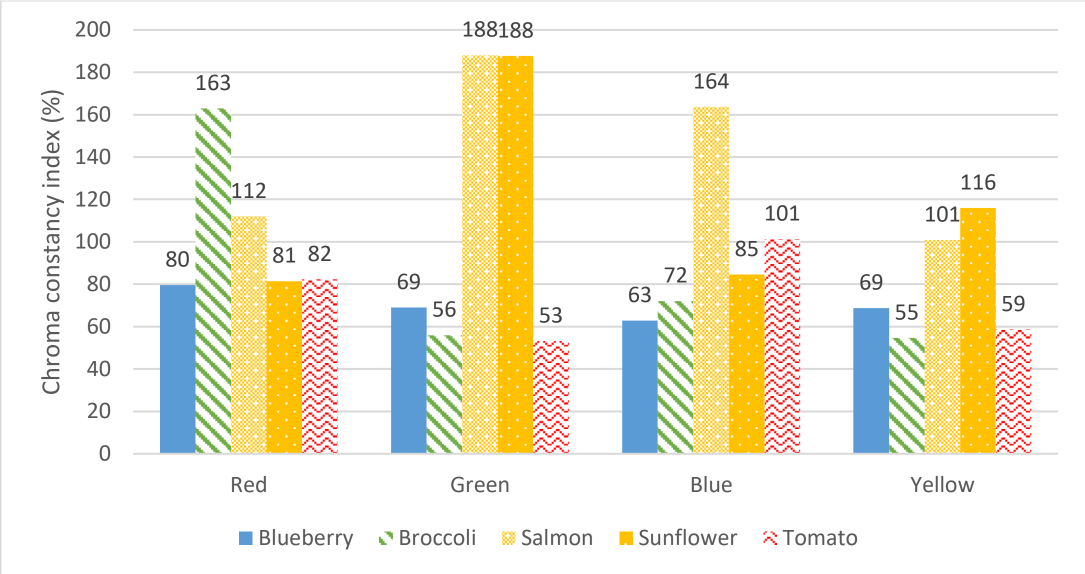

Figure 4-9: Chroma constancy compared between objects.

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The average %CCs in chroma showed that Salmon and Sunflower were over-compensated (141% and 117%, respectively), feasibly due to the bright, saturated colors in the original images in D65. The chroma constancy of Broccoli depended extensively on the illuminant (108). In other words, different illuminants gave considerably varying degrees of chroma constancy.

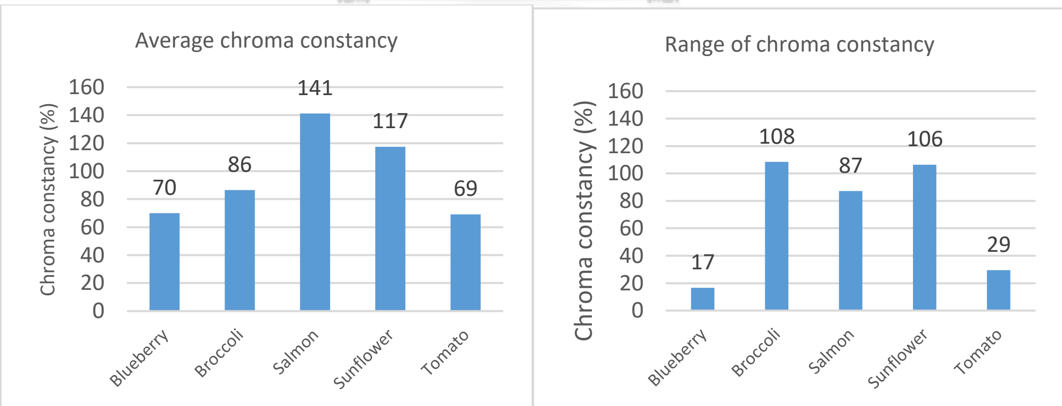

Figure 4-10: The average and range of chroma constancy across illuminants for different objects.

Comparing between hue constancy and chroma constancy, the differences between objects were smaller for hue (max-min = 28) than for chroma (71). However, it is as expected that, on average the chroma constancy was higher than hue. This is because the illuminant color directly changes the object hue to the extent that in some colored illuminant, the actual object color is void of the typical hue of that object. Therefore, it is harder to perceive the same hue as when viewed under normal lighting.

4.2.2 Comparing between different illuminants

Figure 4-11 shows the results of %CCs for comparing between illuminants for each object. It was found that for all objects with an exception of Sunflower, %CCs in Red were the highest. In the case of Sunflower, it had the highest color constancy in Yellow. It can also be seen that %CCs were high when the objects were in the illuminants having colors similar to their colors: 95% for Sunflower in Yellow, 91% for Salmon in Red, 82% for Tomato in Red, 65% for Blueberry in Blue and 61% for Broccoli in Green. Even though in the case of Blueberry and Broccoli, those %CCs were not their highest values, the color constancy index of above 60% was considered comparatively high. For Blueberry, observers associated it with purple in color, rather than blue. Since purple is the mix of red and blue, it could be taken that Blueberry also had the highest color constancy in the illuminant having similar color to it. It is possibly because when the illuminant color was similar to the object color, it made little change to the hue, but increased the chroma of the object color. Thus, the color perceptions remained relatively constant.

The color constancy indices were averaged across objects and the ranges between the highest and lowest values were calculated. The results are given in Figure 4-12. It was found that the highest color constancy was Red (81%) and the lowest was Green (55%). For Blue and Yellow, %CCs were not much different (69% and 66%, respectively). When considering the range values, Green had the lowest object dependency, meaning that regardless of the objects, Green always gave the worst color constancy. It might be because the natural light, albeit varying throughout the course of day, never has the shade of green. The sunlight could be yellowish or reddish in the morning and evening, and bluish in mid day, but never greenish. It might be harder for the human visual system to compensate for the object-color changes due to this illuminant. Red was also comparatively low in object dependency. With its high average color constancy index, it means that color constancy was high in Red regardless of objects. For Blue and Yellow, the degree of color constancy depended on the objects.

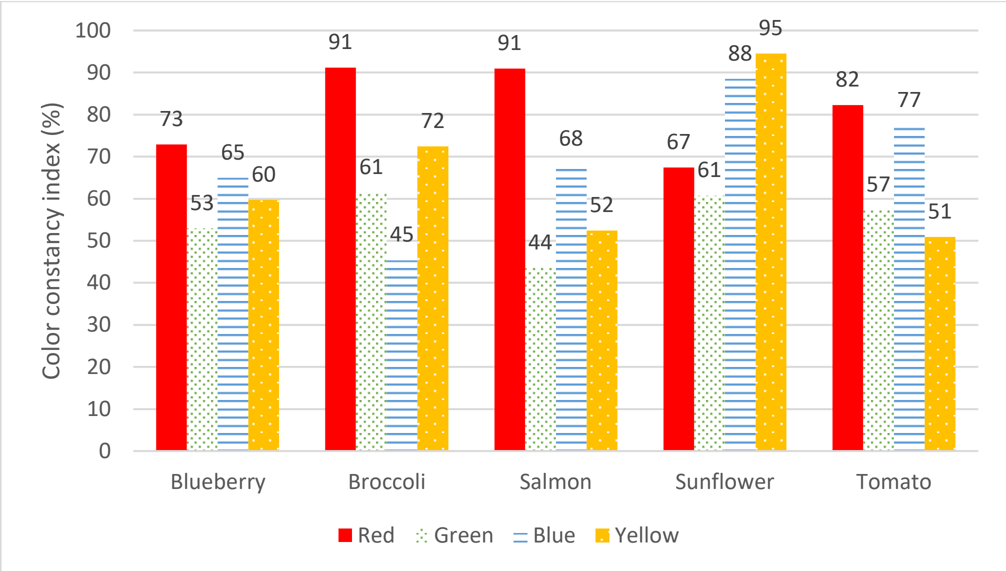

Figure 4-11: Color constancy indices compared between illuminants.

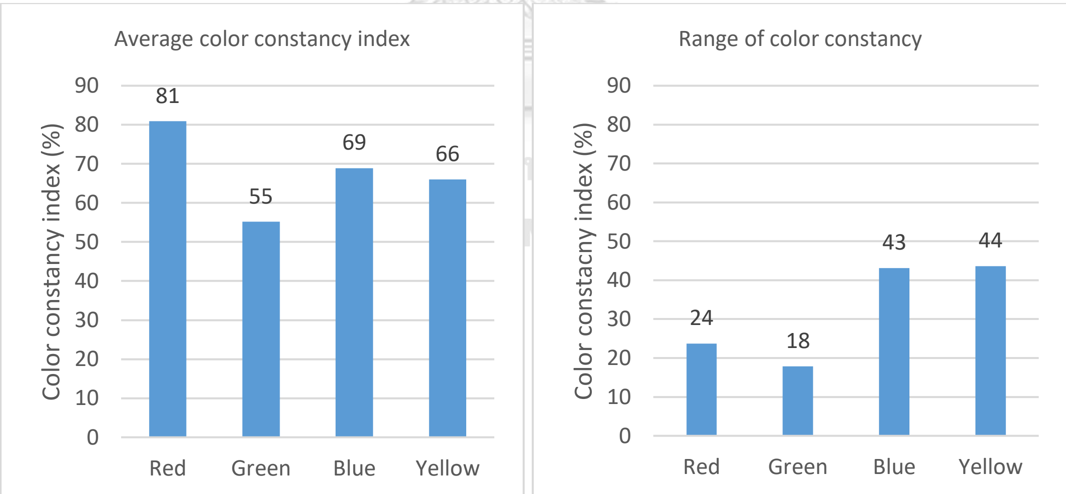

Figure 4-12: The average and range of color constancy indices across objects for different illuminants.

Figures 4-13 and 4-14 show the degree of color constancy in hue. The results showed that the highest hue constancy was Blueberry in Blue (129%), which was the only case that showed the over-compensation in hue. The possible explanation is that observers did not perceive the blue cast on the object as the illuminant color but took it as surface color due to their expectations of its typical color, so it became bluer than the original color.

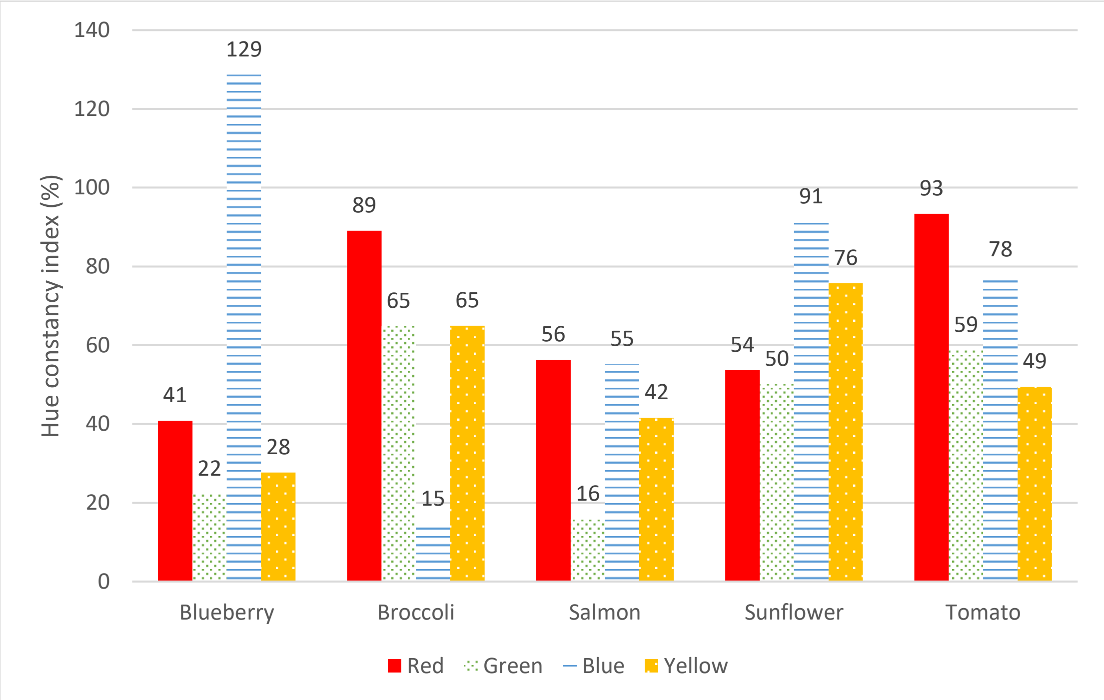

Figure 4-13: Hue constancy compared between illuminants.

In Figure 4-14, Blue had the highest hue constancy (74%) followed by Red (67%), Yellow (52%) and Green (52%). The results showed that Blue was the most object dependent for hue constancy (114). This indicates that it depended on the objects in order to achieve high hue constancy in Blue. Some objects could result in very low hue constancy. Moreover, Red, Green and Yellow illuminant were not much different in ranges of hue constancy (approximately 50). However, they were all considered reasonably high values, revealing that hue constancy in all illuminants was object dependent.

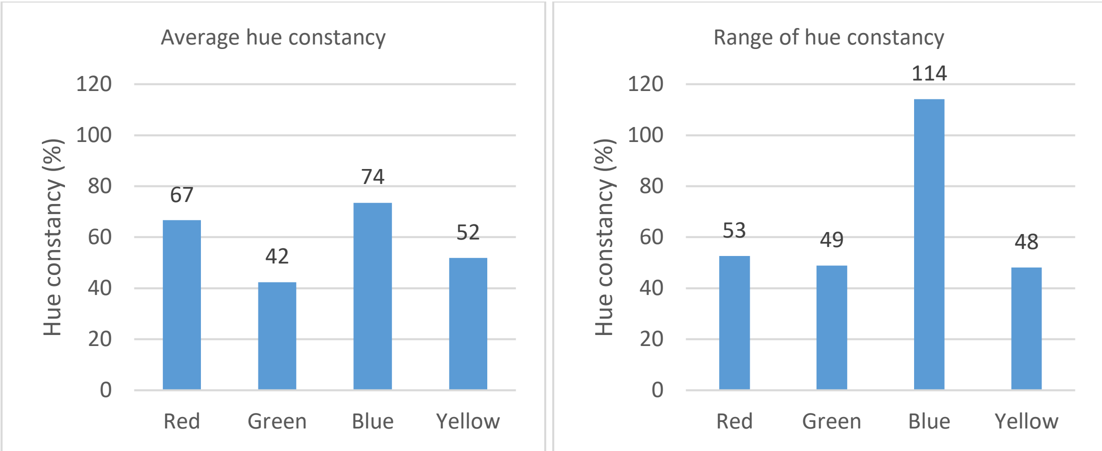

Figure 4-14: The average and range of hue constancy across objects for different illuminants.

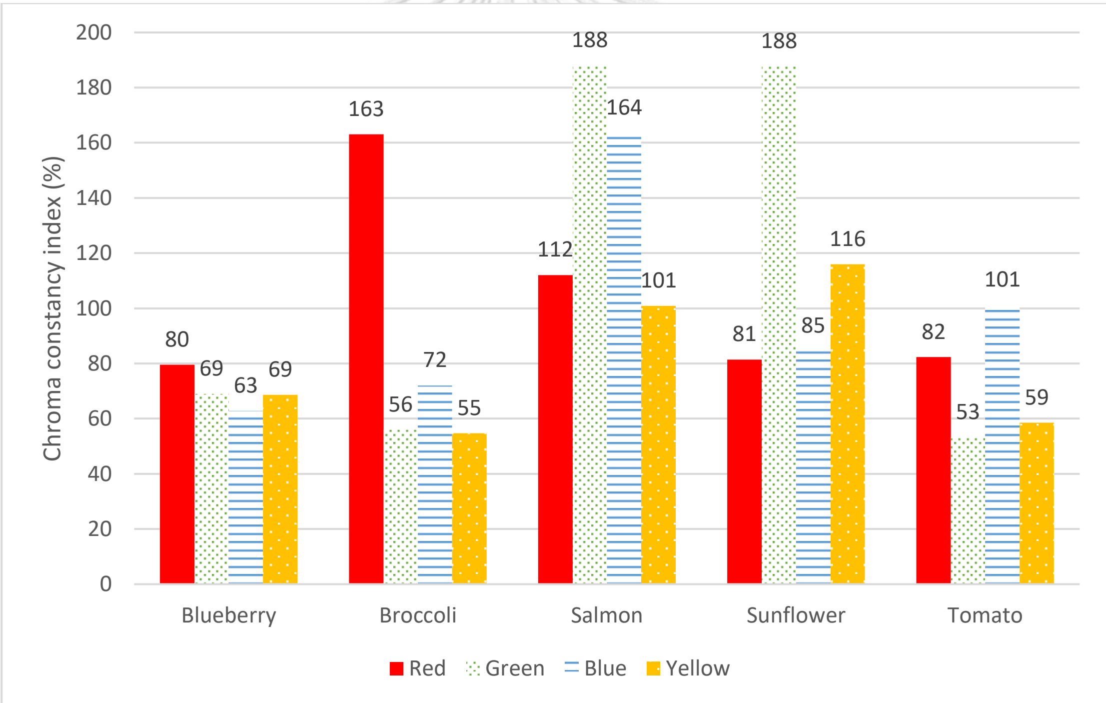

Figure 4-15: Chroma constancy compared between illuminants.

In Figure 4-15, %CCs in chroma of Salmon were over 100% in all illuminants. This means that observers over-compensated the chroma of Salmon in all illuminants. This might be because the texture and surface of Salmon made it look as if it had a semi-transparent color, which was shiny. Observers then selected high chroma colors to match that effect.

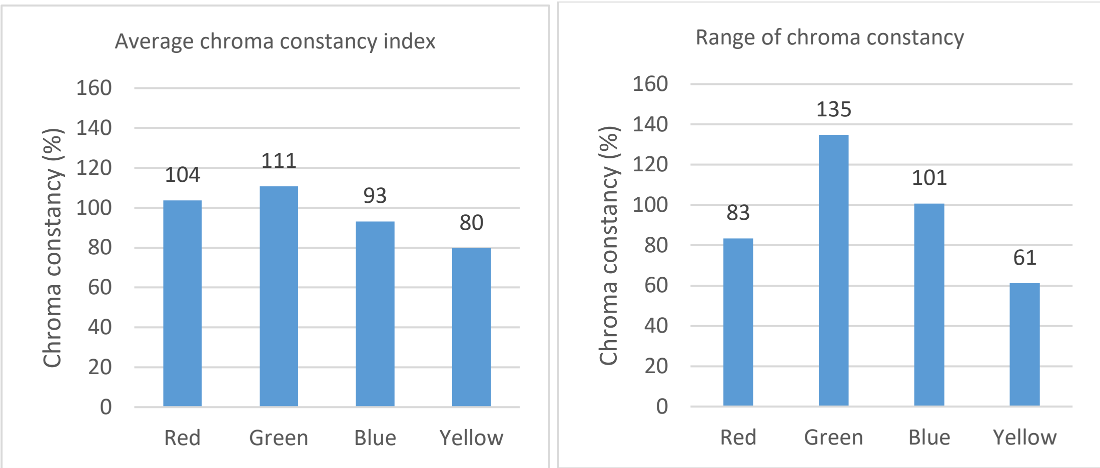

Figure 4-16: The average and range of chroma constancy across objects for different illuminants.

The average %CCs in chroma showed that the object chroma in Red and Green was over-compensated (104% and 111%, respectively). Blue and Yellow showed chroma constancy of 93% and 80%, respectively. Moreover, all illuminants were highly object dependent. Comparing between hue constancy and chroma constancy, chroma constancy was higher and also more object dependent. Different objects gave varying degrees of chroma constancy.

4.3 Comparisons between perceived color and memory color

The results from Section 4.2 showed that color constancy occurred: when the colors of the natural objects changed due to the illuminant color, the color perceptions remained close to the object colors under D65 to a certain degree. Color constancy is a fundamentally contextual phenomenon, which by no means results from a unitary mechanism [8, 19]. One of its mechanisms is chromatic adaptation, whereby photoreceptors in the eye adjust their sensitivity to compensate changes in illumination. This sensory mechanism takes time to reach a steady state. However the cognitive mechanism such as discounting-the-illuminant happens instantaneously. The cognitive mechanism requires observers' knowledge about or past experience with the scene to estimate the illuminant color and remove it from the scene. Memory color also contributes to the success of discounting the illuminant color, as it directly influences the color perception of the object [26].

To investigate the effect of memory color on color perception of the natural objects under unnatural illuminants, color differences (CIEDE2000) were calculated between perceived colors and memory colors (CP-MEM), perceived colors and the ideal match (CP-D65), and perceived colors and the actual colors (CP-AC) for each observer. The results averaged from all observers are shown in Figure 4-17. If the perceived colors are closer to memory colors than the object colors under D65 (i.e. CP-MEM color differences are lower than CP-D65), it is possible that memory color plays a more important role than other mechanisms.

For Blueberry, the perceived colors were closer to the match in D65 than to memory colors in all illuminants. As mentioned in Section 4.1, memory colors obtained from observers in this study were based on individual imaginations of the objects, with no clarification of state of form. Especially in the case of blueberry, which is not the native fruit of Thailand, fresh blueberries as used in the test images are less common than blueberry-processed products. Thus, it is not surprising that the differences between the perceived colors in the images and memory colors in observers' imaginations of Blueberry were larger than that between the perceived colors in the modified images and the perceived colors in the original image. The CP-MEM differences were even larger than the perceived colors and the actual color in the image where the color constancy is zero.

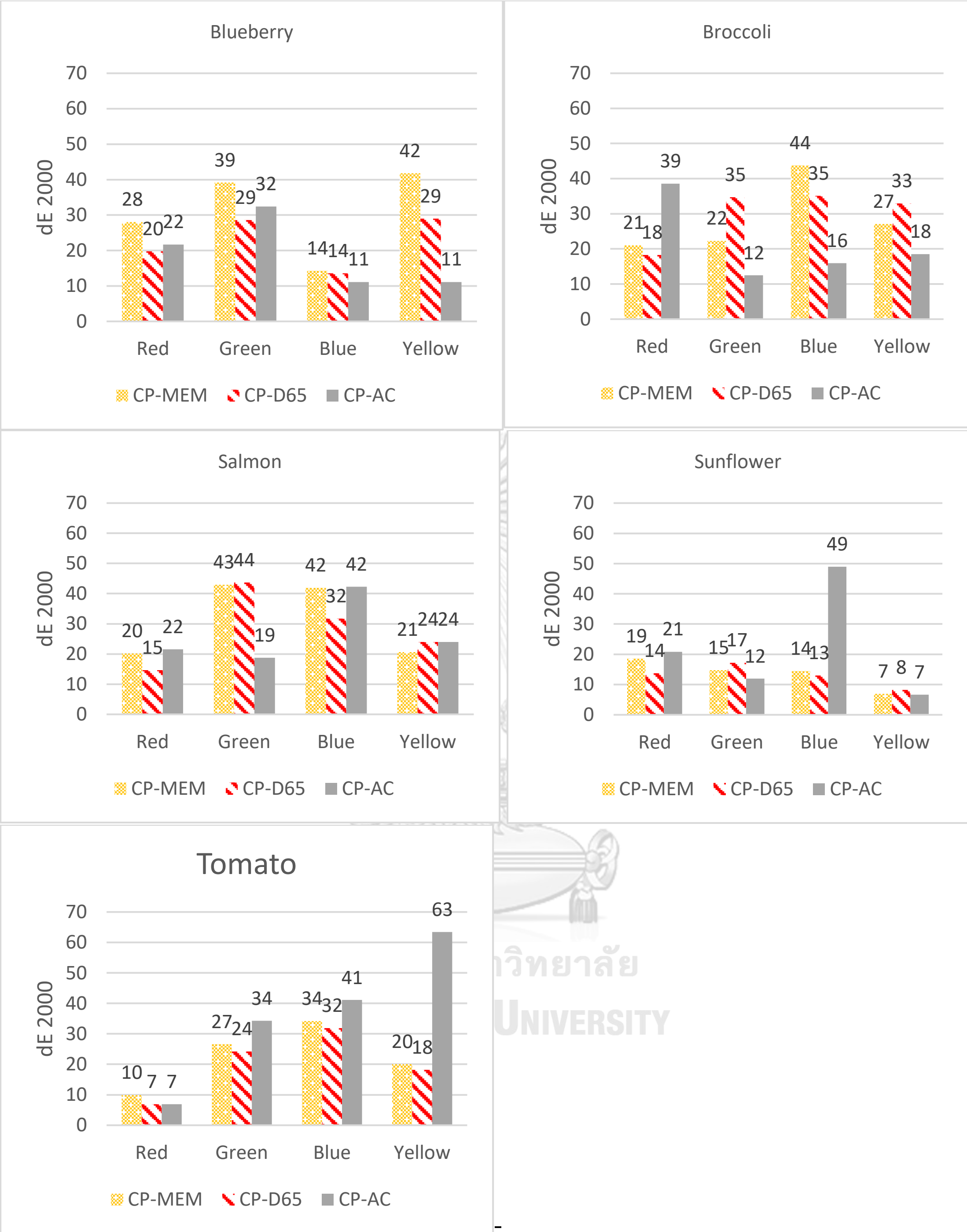

Figure 4-17: Color differences between color perception and memory color, and match color.

On average, comparing between objects, Sunflower had the lowest color differences between the perceived colors and memory colors, meaning that observers perceived the color of Sunflower closer to their memory than any other objects. It is possible that sunflowers growing in Thailand are not of many varieties, so memory colors of Sunflower were close to the sunflowers used in the test images. The CP-D65 differences of Sunflower were also lower than the other objects, indicating that the perceived colors were closer to the match in D65. On average, Sunflower showed to have the highest degree of color constancy (78%, see Figure 4-6). Observers were able to discount the illuminant color; therefore, the color perceptions remained relatively constant across illuminants. It is feasibly because Sunflower had bright, saturated color that could be easily separated from the illuminant color.

Overall, the results showed that in almost all cases the perceived colors were closer to the match in D65 than to memory colors. Observers were able to discard the illuminant color from the scene and perceived the object color as close its original image. The object-color perception shifted from the actual color toward the direction of the match color in D65, rather than the object-memory color (see Appendix C for the distributions of color perceptions in the object images in CIELAB). This reveals that the contribution of memory color to color constancy was weak.

It is worth noting that the CP-MEM differences for all objects were lower than other illuminant colors when the objects were in the illuminant colors similar to the object colors. For instance, the orange salmon had CP-MEM differences of 20 and 21 in the red and yellow illuminants, respectively, which were lower than in the green (43) and blue (42) illuminants, respectively, by a factor of two. In the case of red tomato, its CP-MEM difference was 10 in the red illuminant, whereas it was 27, 34 and 20 in the green, blue and yellow illuminants, respectively. When the illuminant color closely similar to the object color was applied to the image, it increased chroma of the object color. Since memory colors also shift toward more chromatic color than the actual colors. The color differences between the perceived colors and memory colors, thus, decreased in these cases.

4.4 Color constancy in Mondrian images

To investigate the effect of familiar object on color constancy, the differences in color perceptions between the perceived colors in the object images and in the Mondrian images were evaluated in terms of color constancy index and CIEDE2000. The median value was used to represent the results of color constancy indices, while the mean value was used for the color difference results.

4.4.1 Color constancy indices of natural object and Mondrian images

The Mondrian images had exactly the same colors as the object images; however, the colors were rearranged to form square patches. If the familiar object has no effect on color constancy, the color perceptions must be the same in both object and Mondrian images. Figure 4-18 shows the results of color constancy indices compared between the object images and Mondrian images. It was found that in all cases, the object images had higher %CCs than the Mondrian images did. This reveals that the familiar object contributed to achieve color constancy. Not only the sensory mechanism that provides a compensation when there is too much of a certain light stimulate the human visual system, but also the cognitive mechanism that is based on observers' experience work in achieving color constancy. Hence, it is as expected that the color constancy in the object images was higher than the Mondrian images.

Figure 4-18: Color constancy indices compared between natural object and Mondrian images.

The role of familiar object in achieving color constancy is that it provides a cue for observers for estimating the illuminant color in the scene [7, 27]. Hence, memory color contributes in the way that when observers recognize an object in the scene and remember its typical color, but see that the object color deviates from its usual color, observers use this information to separate the illuminant color from the object color, leading to color constancy. Without any familiar objects, observers need to rely on other cues to estimate the illuminant color.

4.4.2 Color differences between actual colors and color perceptions

Color differences between the perceived colors in the object images and their actual colors (Obj-AC), and the perceived colors in the Mondrian images and the actual colors (Mondrian-AC) were compared, as shown in Figure 4-19. It is as expected that the color differences of Mondrian-AC were lower. When there was no familiar object in the scene, observers perceived the color of the square patch as belonging to its surface, no influence of illumination. Consequently, the perceived colors were close to their actual colors (see Appendix D for the distributions of color perceptions in the Mondrian images in CIELAB). On the other hand, when the familiar object was present, observers perceived the color of the object in illumination mode, estimating the surface color by removing the illuminant color. Thus, the perceived colors shifted away from the actual colors.

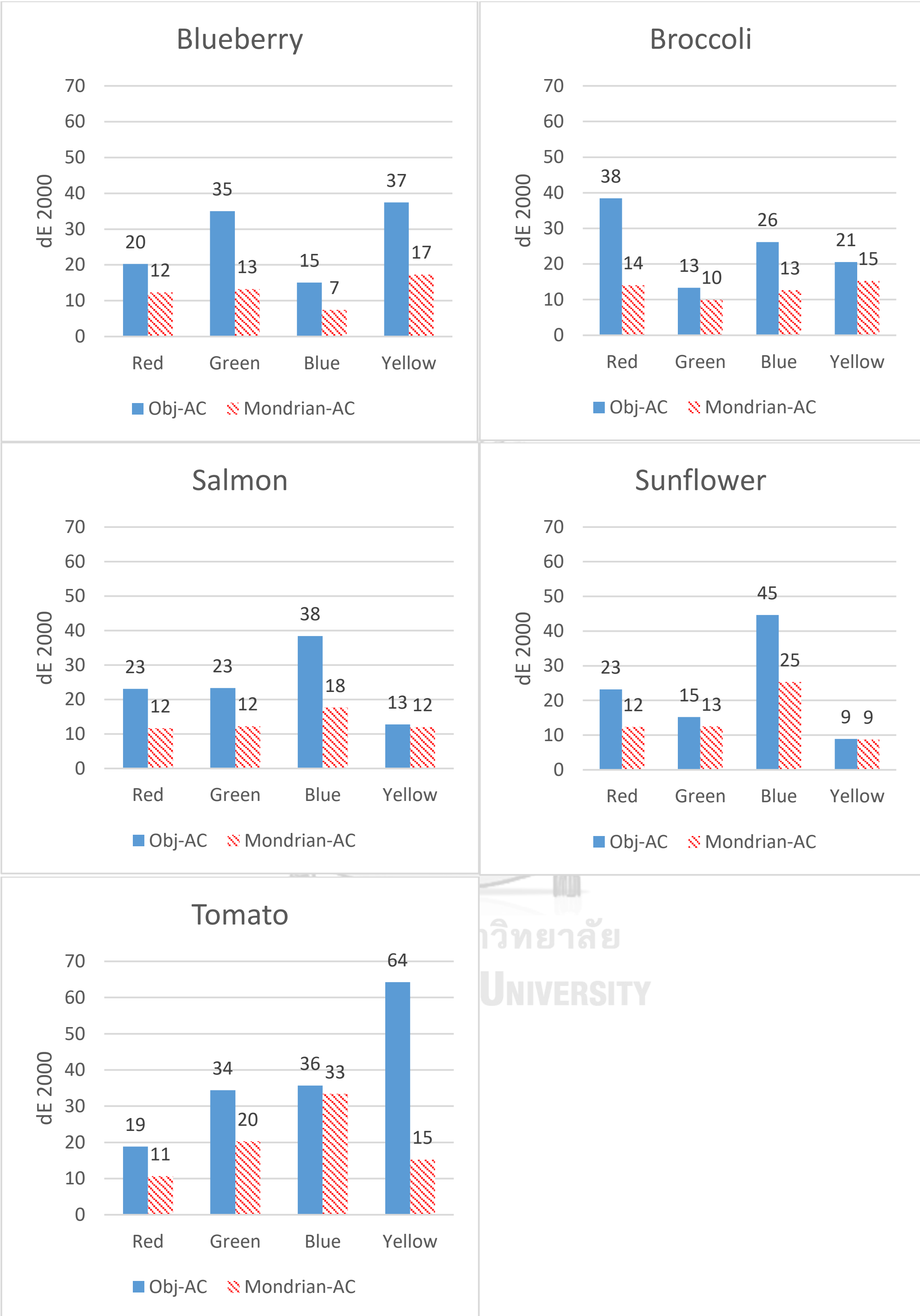

Figure 4-19: Color differences between actual color and color perceptions of object and Mondrian images.

Figure 4-20 compares the color differences between the perceived colors in the object images and in the Mondrian images. The results showed that they were clearly different, especially in the case of Broccoli in the red illuminant, where its color constancy was high (91%, see Figure 4-18). The smallest difference was found for Sunflower in the yellow illuminant. This case also showed to have the smallest differences between color perceptions and the match in D65, and the actual color (see Figure 4-17). It could be that the object color in the modified image was close to the color in the original image, leading to close match with and without the familiar object.

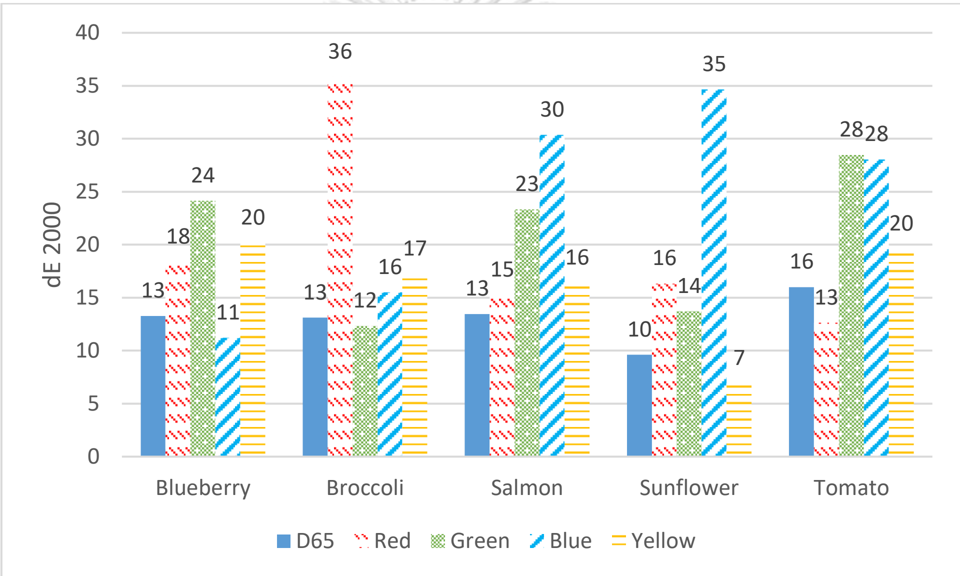

Figure 4-20: Color differences between object-color perception and Mondrian pattern perception.

The memory color effect refers to the effect that the color of a familiar object influences the color perception of the actual color of that object [26]. The memory color effect depends on observers' familiarity with the object. In this study, it could be assumed that the memory color effect happened in a way. Since color constancy in the object images was higher than in the Mondrian images, observers must have used the knowledge about the typical color of the natural objects to estimate the illuminant color. However, the effect was weak compared to other mechanisms. When the entire scene is dyed in a certain color, observers could interpret that color as the illuminant color and extract it from the scene with or without the help of familiar objects. This mechanism is called discounting-the-illuminant and it plays a stronger role in achieving color constancy.

Chapter 5
CONCLUSIONS AND SUGGESTIONS

This study investigated the observers' color perceptions of natural objects when the natural objects were presented under colored lights other than a natural white light. The perceived colors in the images where a natural object was present were compared with the perceived colors in the Mondrian images having the same colors as the object images. Memory colors were collected and the influence of memory color on color constancy was examined. The visual experiments were launched online for about two weeks with 98 people participating. However, the results were analyzed based on 78 participants, excluding those who gave erroneous experimental data. Five natural objects with well-recognized visual characteristics (tomato, broccoli, sunflower, salmon and blueberry) were tested for their color constancy in four illuminants (red, green, yellow and blue) via color matching tasks. This Chapter summarizes the major findings (Section 5.1) and provides suggestions for future work (Section 5.2).

5.1 Conclusions

The sRGB values taken from the images and those of the perceived colors were converted to CIELAB color values. Color constancy index quantifying how well the observer can perceive the same color of objects, invariant to the illuminant color was employed. It was found that the degree of color constancy was both object and illuminant dependent. In other words, the results from different objects and illuminant colors were markedly varied, revealing that whether or not the perceived color remains relatively constant depends on the type of objects and illuminant colors. Chroma constancy was higher and more object and illuminant dependent than hue constancy. The color constancy index averaged across objects and illuminants was 68%, with hue constancy of 59% and chroma constancy of 98% for the object image. The average color constancy for the Mondrian image was 41%.

5.1.1 Memory color

Memory colors of natural objects depend on individual experiences of each observer. Therefore, memory colors can be different for different observers. This study provided observers with only the object name, for example “salmon”, without any other detail. It was up to the observers what kind of salmon they thought of, for example cooked or raw. The variety of the natural object can also yield the differences. For example, tomato has many varieties with clear difference in color. Observers could be familiar with different varieties, so their memory colors will be different.

The result showed that memory colors of tomato, broccoli and blueberry spread widely in the chroma direction and lesser differences in hue. On the other hand, Sunflower showed more widely spread in the hue direction than the chroma. In the case of salmon, memory colors spread in both hue and chroma directions.

5.1.2 Effect of memory color on color perception

Memory color is the color that an observer associates with the object based on his/her experience with it. Familiarity with an object results in observers expecting the color of the object and this expectation influences the color perception of that object. It has been reported that observers over-estimate the saturation of the familiar object colors, especially when the hue corresponds to the typical color of the objects. Observers perceive the color of familiar objects to be more chromatic than it actually is. The color perception thus depends on surface reflectance of the object and the observer’s experience with it.

If memory color plays an important role in achieving color constancy, the color perception should be closer to memory color than the color in the original image. The results showed that in almost all cases the perceived colors were closer to the match in D65 than to memory colors. This indicates that observers were able to separate the illuminant color from the object and perceived the object color as close its original image. The object-color perception shifted from the actual color toward the direction of the match color in D65, rather than the object-memory color, revealing that the contribution of memory color to color constancy was weak.

5.1.3 Effect of familiar object on color constancy

Color constancy occurs when the color perceptions of the objects remain relatively constant despite the change in illumination. The sensory mechanism and cognitive mechanism work together to achieve color constancy. The cognitive mechanism requires observers' knowledge and experience to estimate the illuminant color in order to remove it from the scene. Memory color of the familiar object could be used as a cue for estimating the illuminant color. For example, when color of sunflower is away from its typical yellow, one uses this deviation to determine the illuminant color and separate it from the surface color.

The object images had the average color constancy for each object across illuminant as follows: 63% for Blueberry, 68% for Broccoli, 64% for Salmon, 78% for Sunflower and 67% for Tomato. The Mondrian images had the average color constancy for each object across illuminant as follows: 27% for Blueberry, 28% for Broccoli, 45% for Salmon, 49% for Sunflower and 55% for Tomato. It is as expected that the color constancy in the object image was higher than in the Mondrian image. However, color differences between the perceived color in the object image and the match color in D65 were lower than those between the perceived color and memory color. This means that observers were able to separate the illuminant color from the scene, so they perceived the color close to the original color when there was no color cast. Nevertheless, memory color of the familiar object in the scene was not the only cue for discounting the illuminant. The fact that the entire scene was dyed in a certain color provided a stronger cue for viewing the object color in illumination mode, rather than surface mode. Thus, color constancy could also be achieved without a familiar object in the scene.

5.2 Suggestions

1. In this study, the experiments were launched on the Internet. Therefore, observers' understanding of the experimental procedures relies on the written instruction. This means that the instruction should be highly clear. So, the accurate data can be obtained.

2. This study tested five natural objects and four illuminants, combining to 25 images in Experiment 2 and 25 images in Experiment 3. With these many images, it could take observers a long time to finish the whole experiment. Some observers gave up before it was done. Some might lose interest in the later stage. In future study, it is probably better to divide the experiments into two or more sessions, so that each session does not last long. This could keep observers' interest and maintain their concentration.

3. Mondrian images were used to represent the color of natural objects. However, Mondrian images are unlike the real scene in everyday life. Observers can only perceive the color in Mondrian images as surface color because there is no cue for illumination estimation. In the real scene, there are many cues for determining illumination. The future study could use an image with the real scene by replacing the natural object with a cube with the same color as the natural object, to investigate the effect of familiar object instead of Mondrian pattern.

4. In this study, the colors of the natural objects were simulated as if the objects were presented in the extreme colored illuminant. Thus, the illuminant color was unnatural and very different from the normal daylight. In future work, the more natural lighting such as bluish white or pinkish white that could be encountered in real life could be tested so as to gain more understanding on color constancy in real life situations.

5. In the experiment for obtaining memory color, the natural objects chosen in the present study were ambiguous, which could lead to the large differences between observers' memory color of the object the observers imagined and the real object used in the later experiment. For example, the observers might have thought of the color of blueberry jam, white fresh blueberries were used in the color perception experiment. It is

therefore recommended for future study that more common natural objects with few varieties such as carrot (to replace salmon for orange color) or plum (to replace blueberry for blue/purple color) be tested

6. The natural objects tested were fruit (blueberry and tomato), vegetable (broccoli), meat (salmon) and flower (sunflower). The future study could include only the objects of the same kind. For example, all natural objects chosen are a kind of fruits.

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APPENDICES

Appendix A

The distributions of color perceptions in the original images in CIELAB

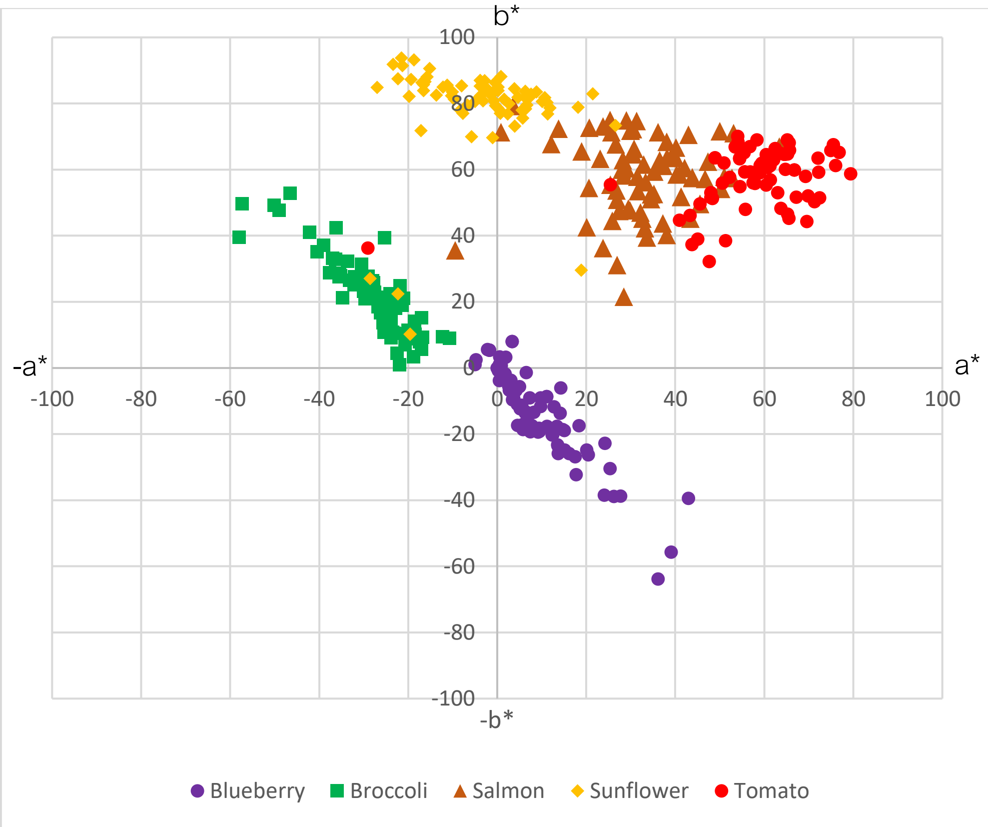


Figure A-1: Color perceptions in the original images in the a*b* plot.

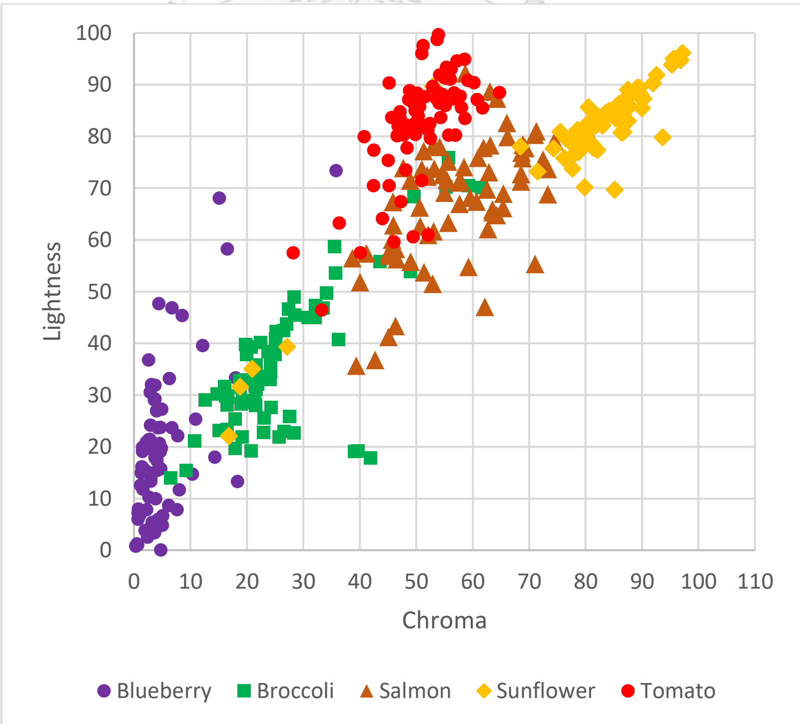


Figure A-2: Lightness and chroma of color perceptions in the original images.

Appendix B

The distributions of actual colors in CIELAB

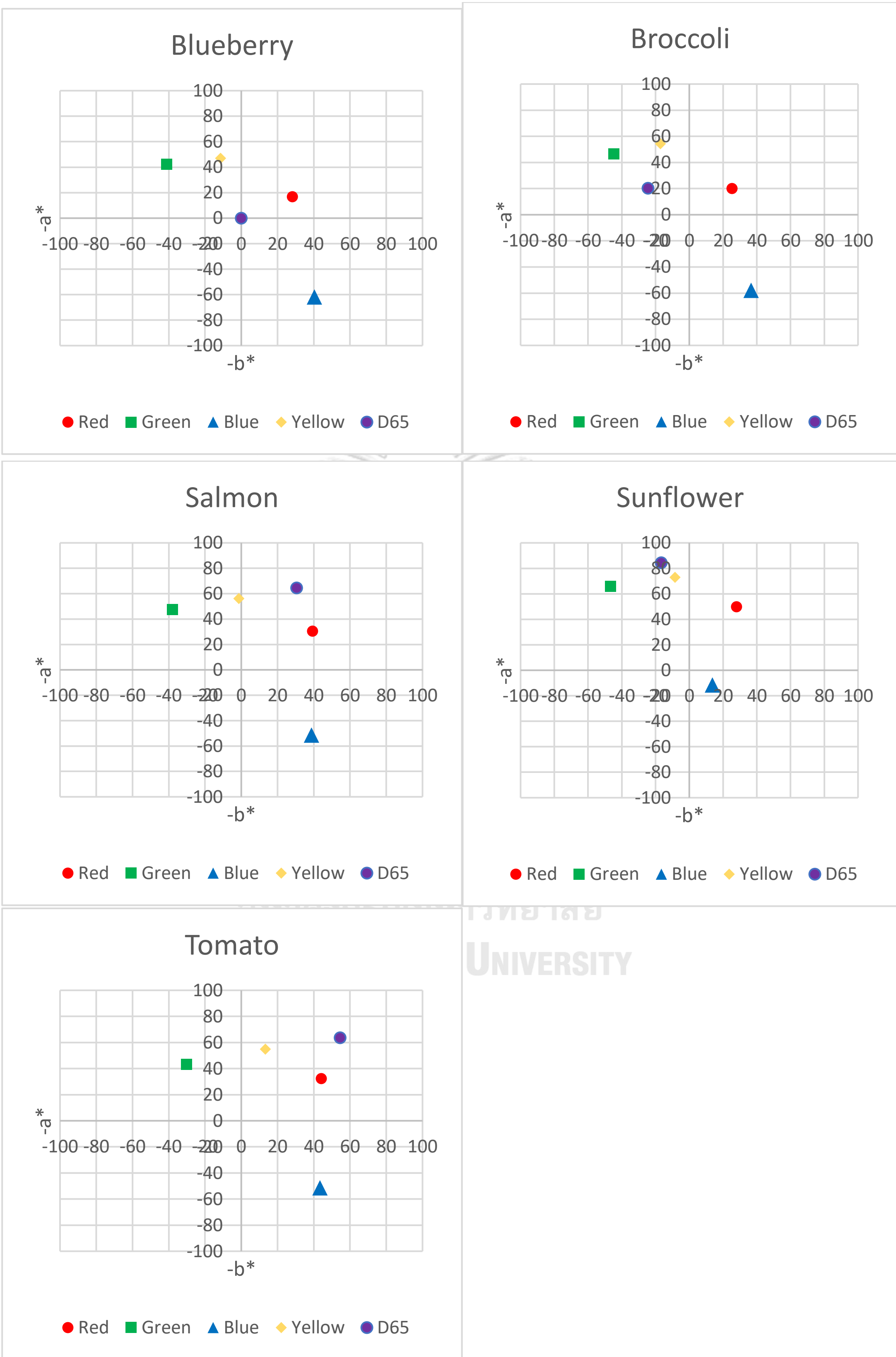


Figure B-1: The distribution of actual color of five natural objects in the a*b* plot

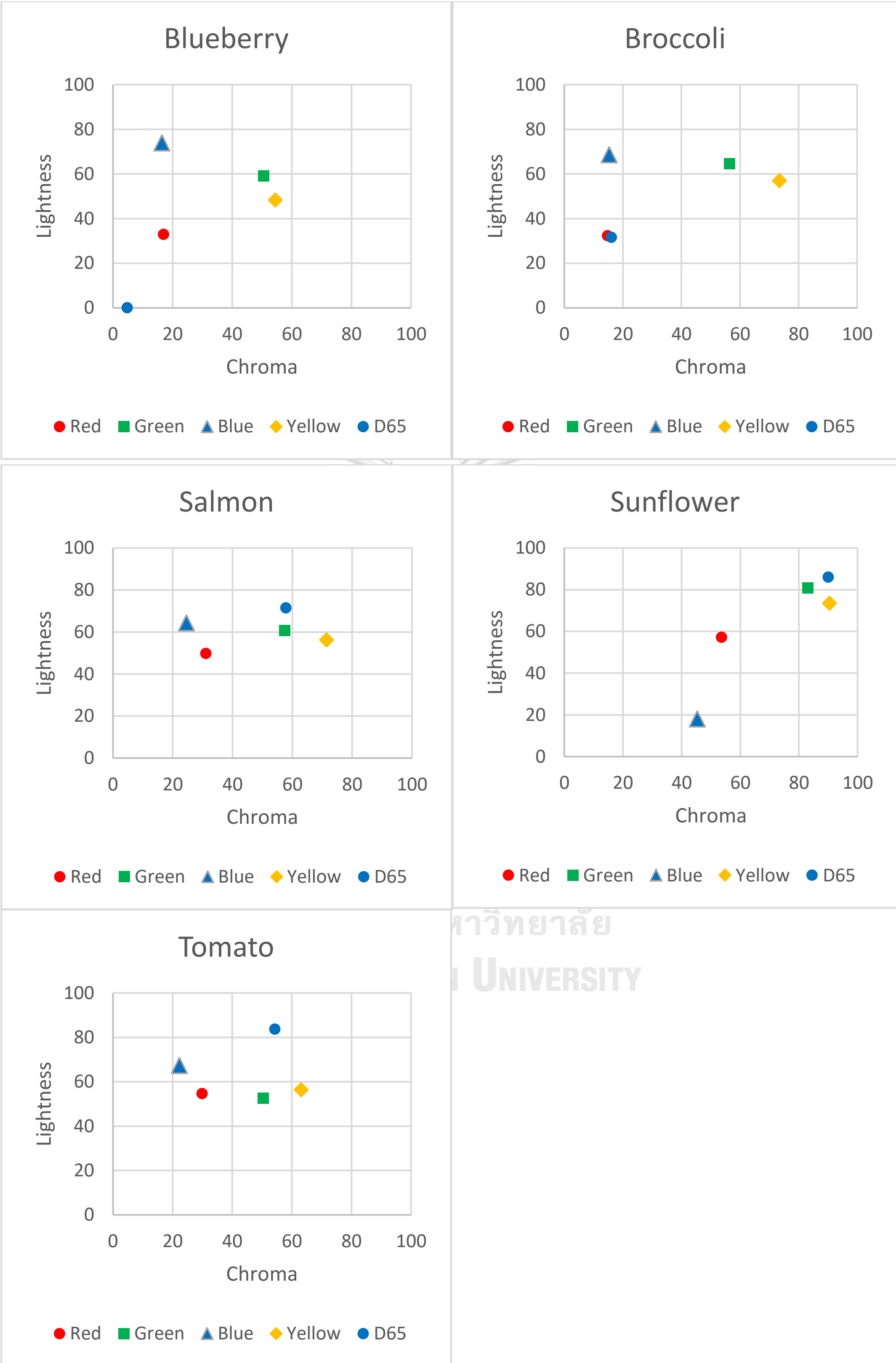


Figure B-2: Lightness and chroma of actual color in the original images.

Appendix C

The distributions of color perceptions in the object images in CIELAB

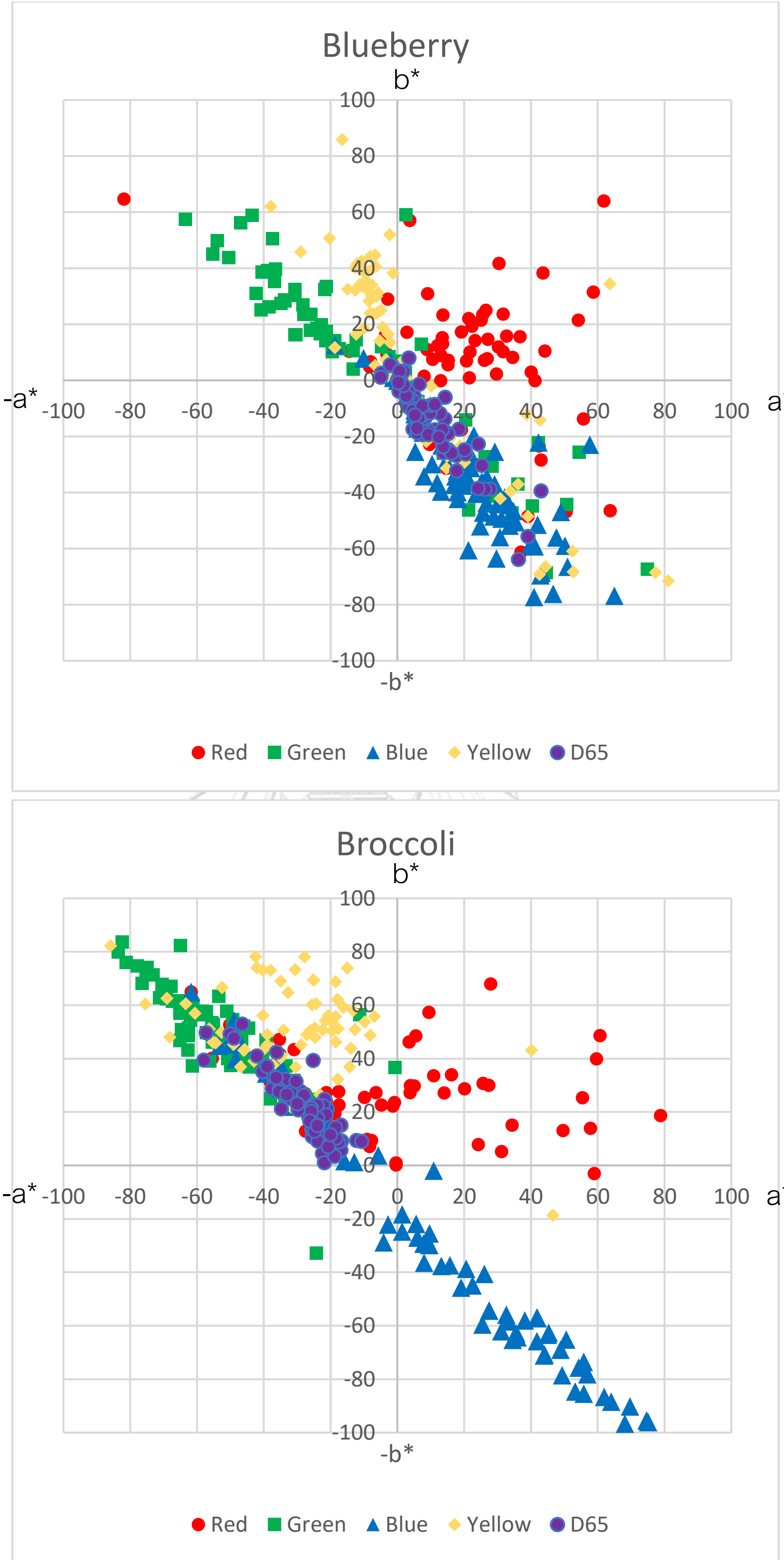
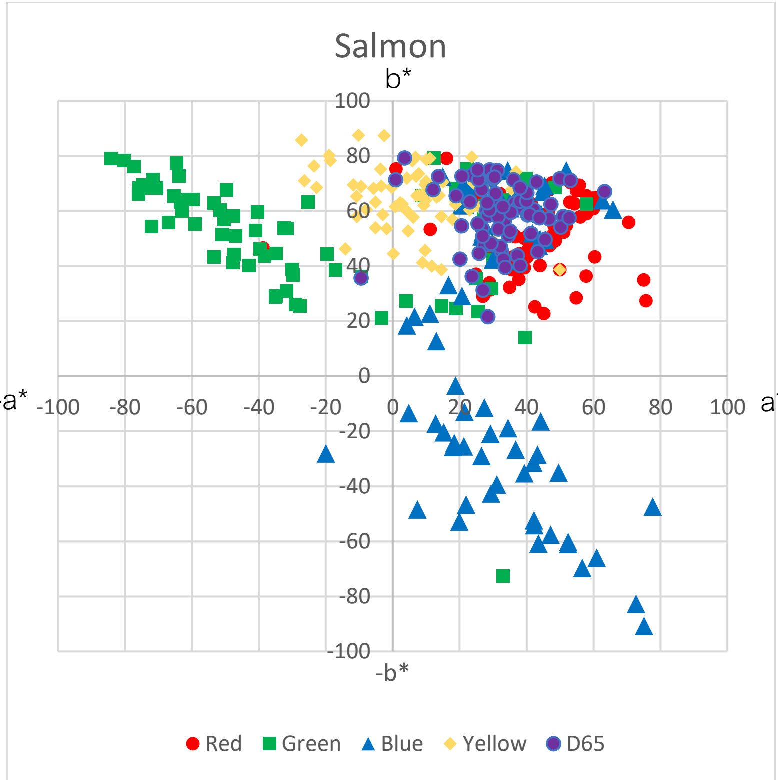


Figure C-1: The distribution of color perceptions in object images in the a*b* plot



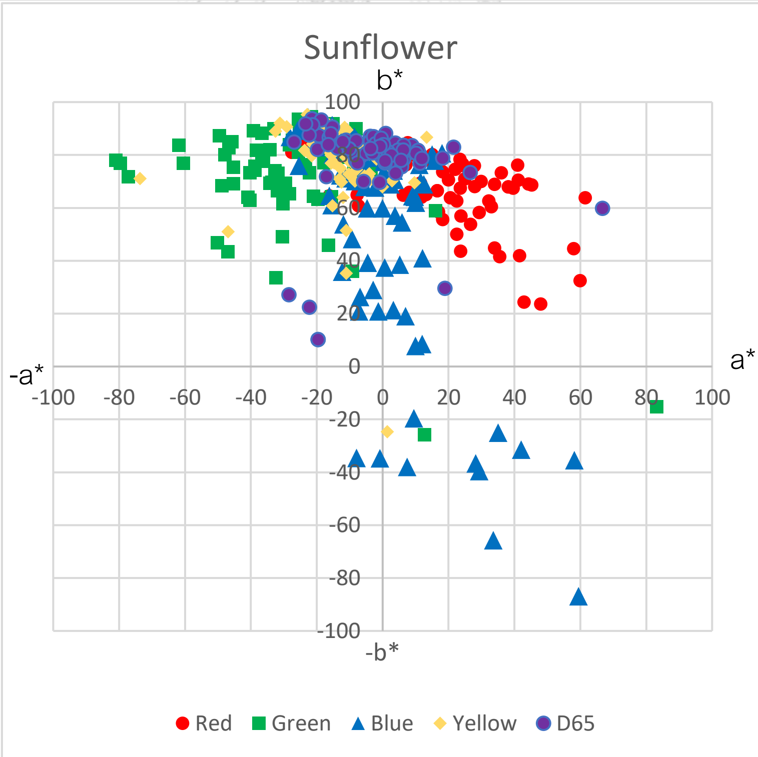


Figure C-1: (cont.)

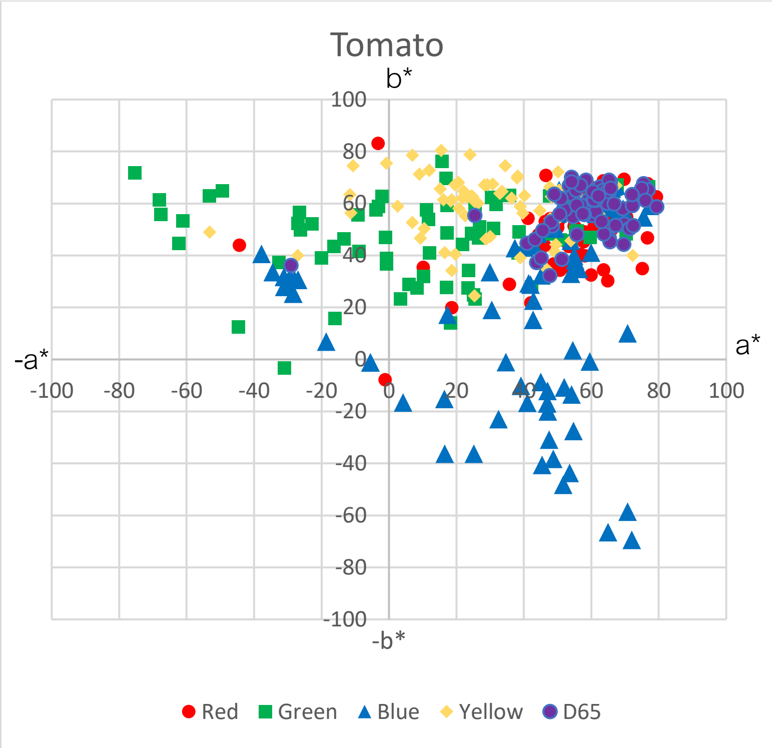


Figure C-1: (cont.)

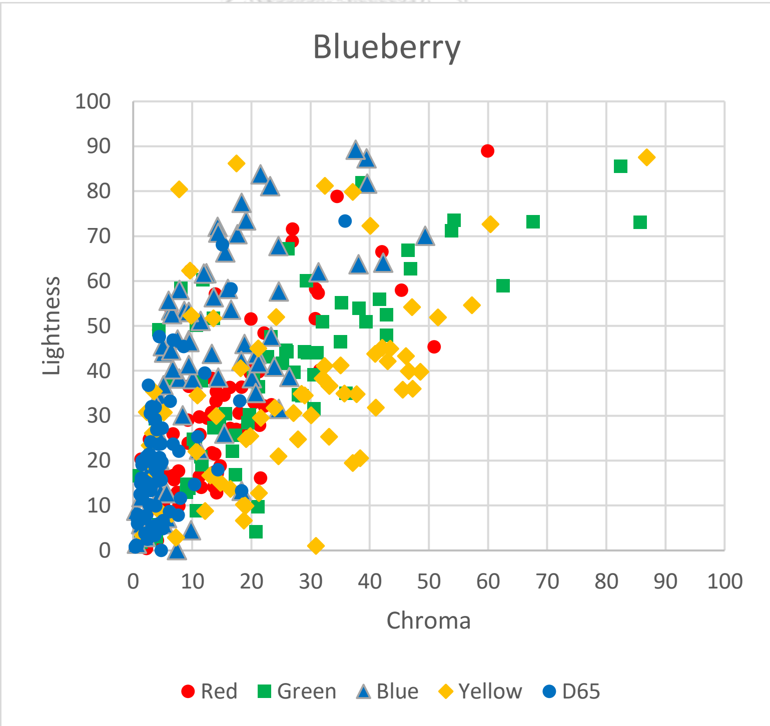
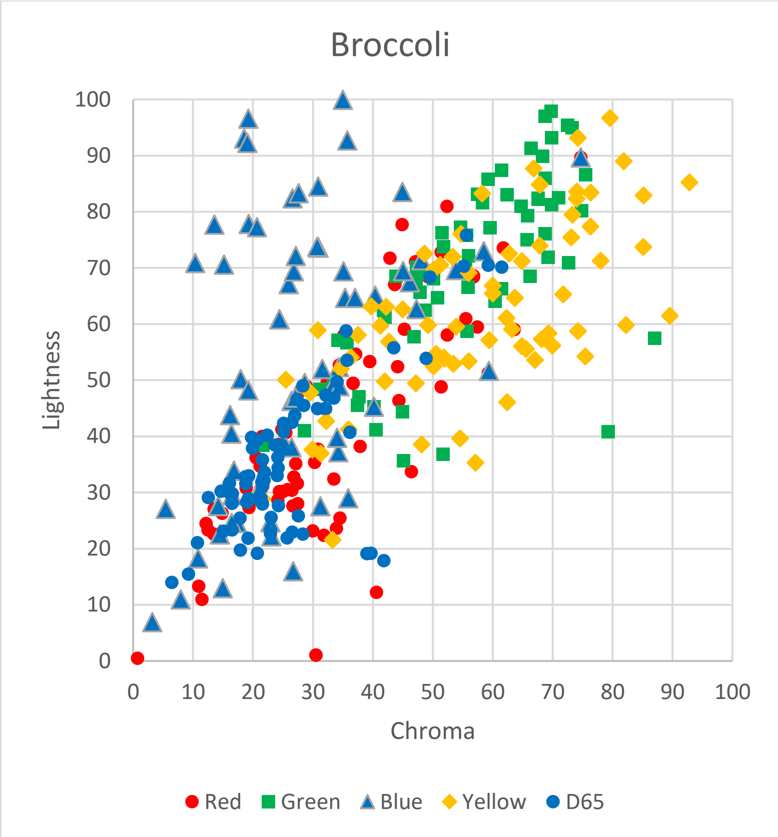


Figure C-2: Lightness and chroma of color perceptions in the original images.



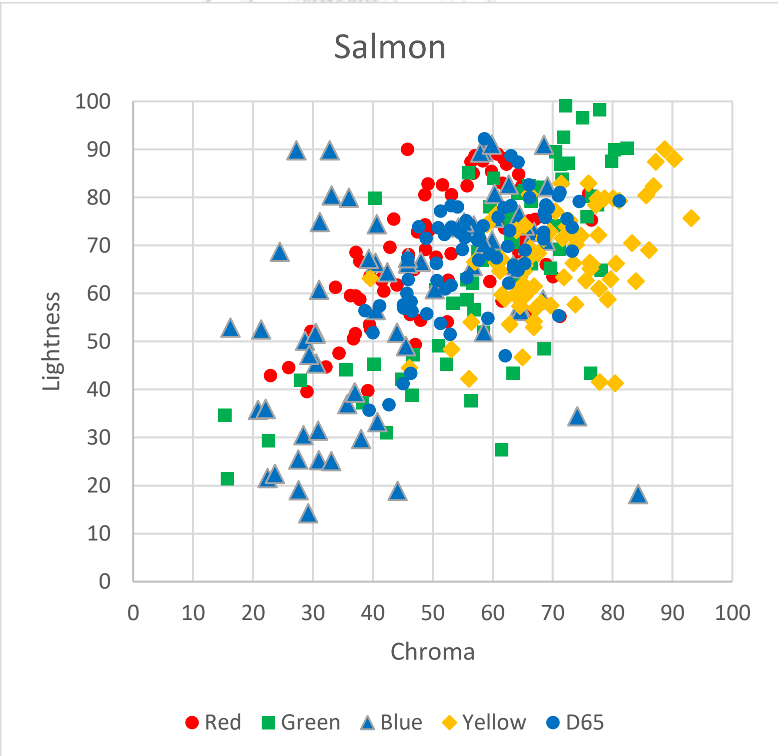


Figure C-2: (cont.)

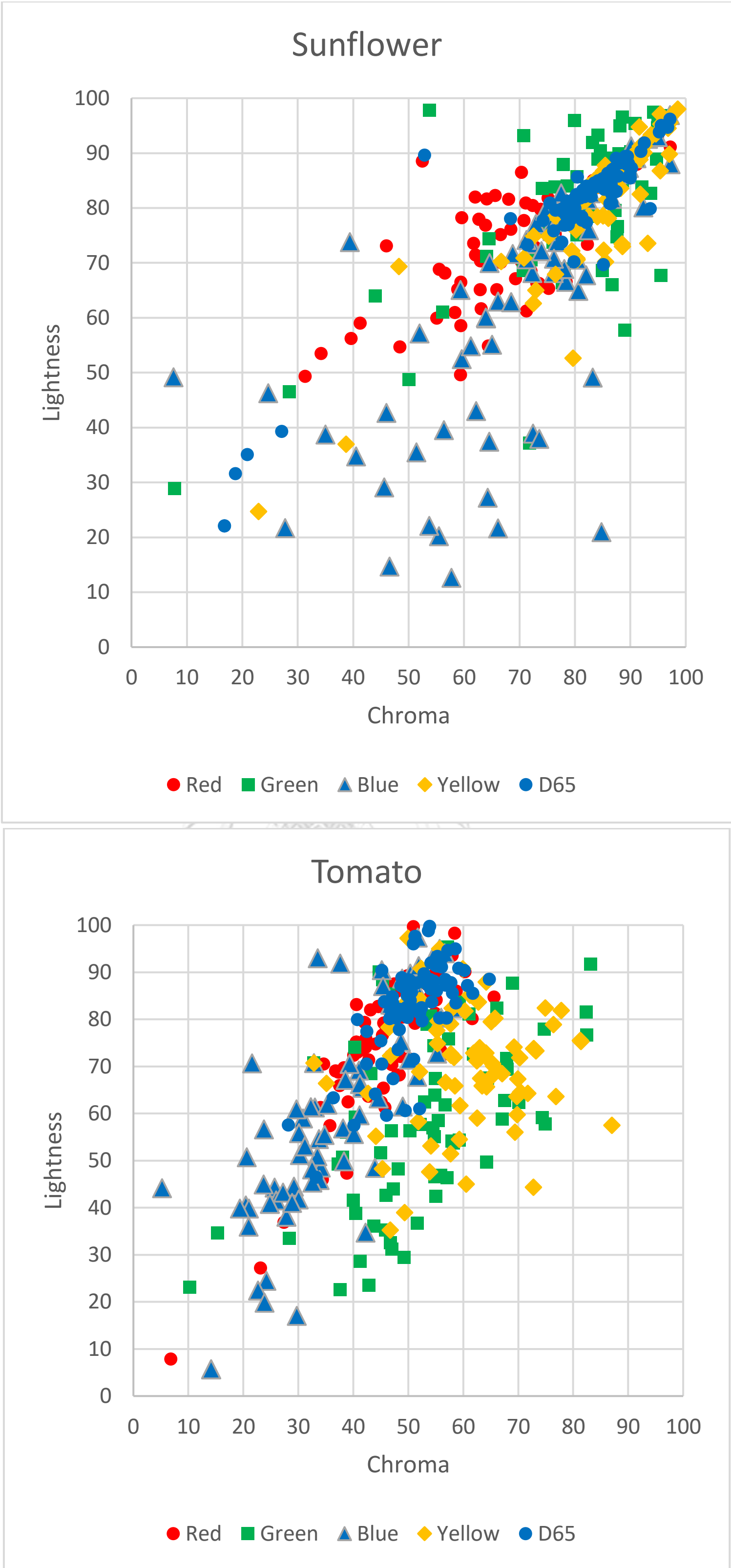


Figure C-2: (cont.)

Appendix D

The distributions of color perceptions in the Mondrian images in CIELAB

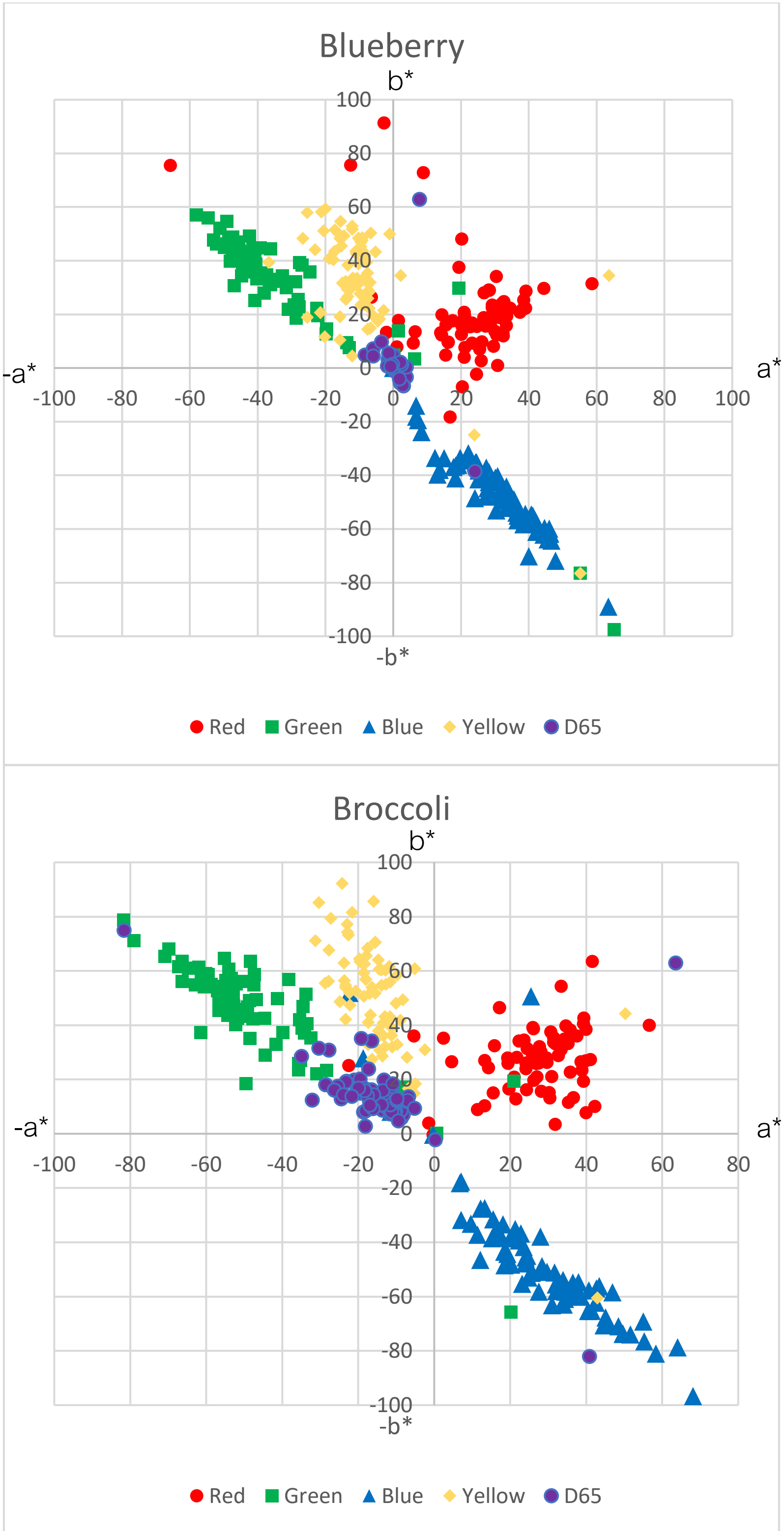
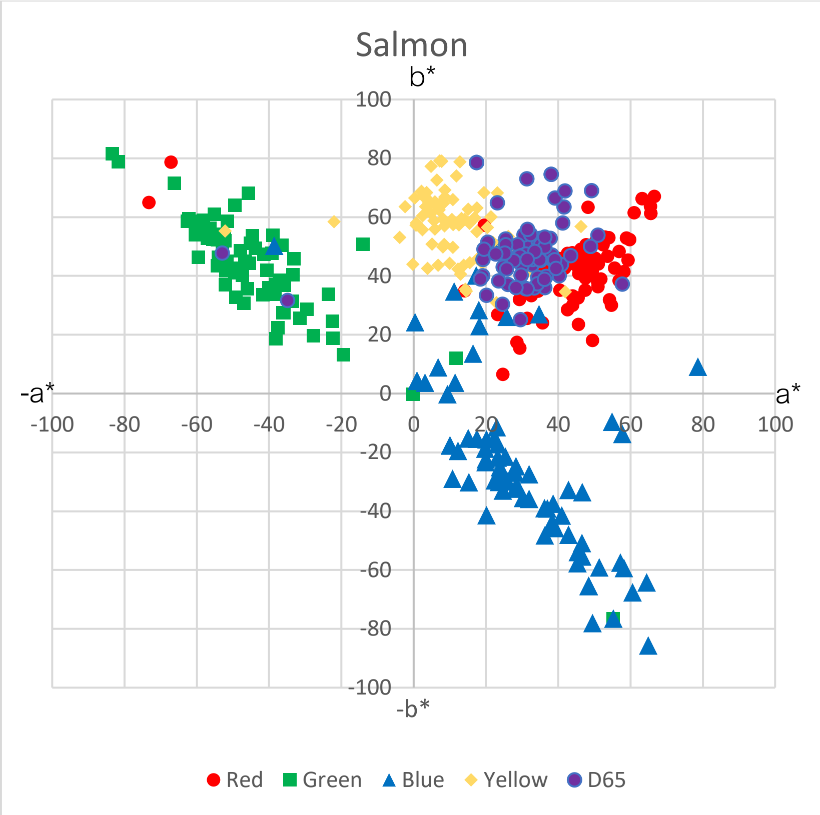


Figure D-1: The distribution of color perceptions in Mondrain images in the a*b* plot



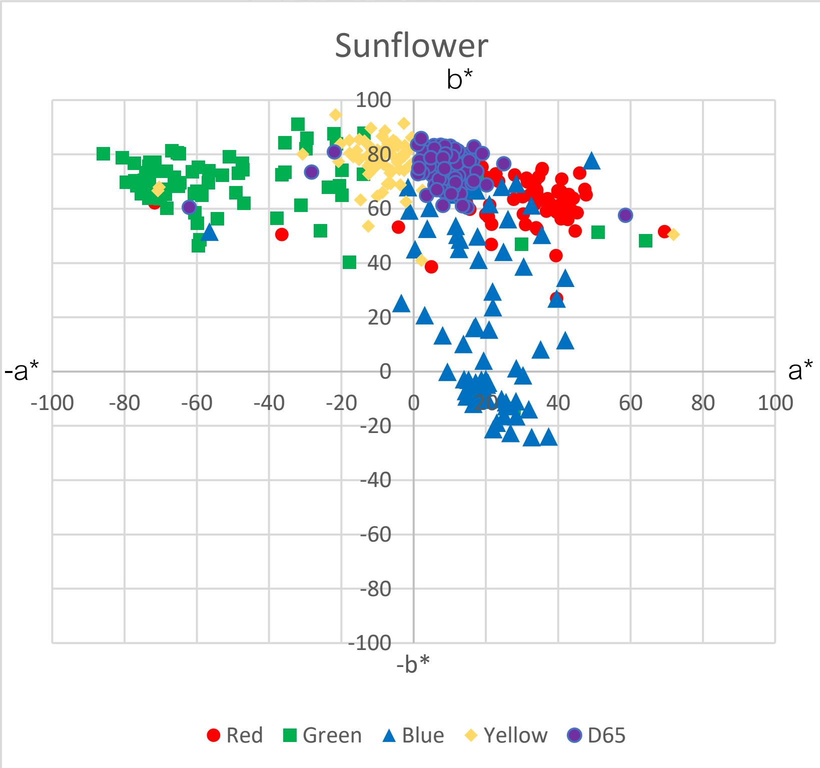


Figure D-1: (cont.)

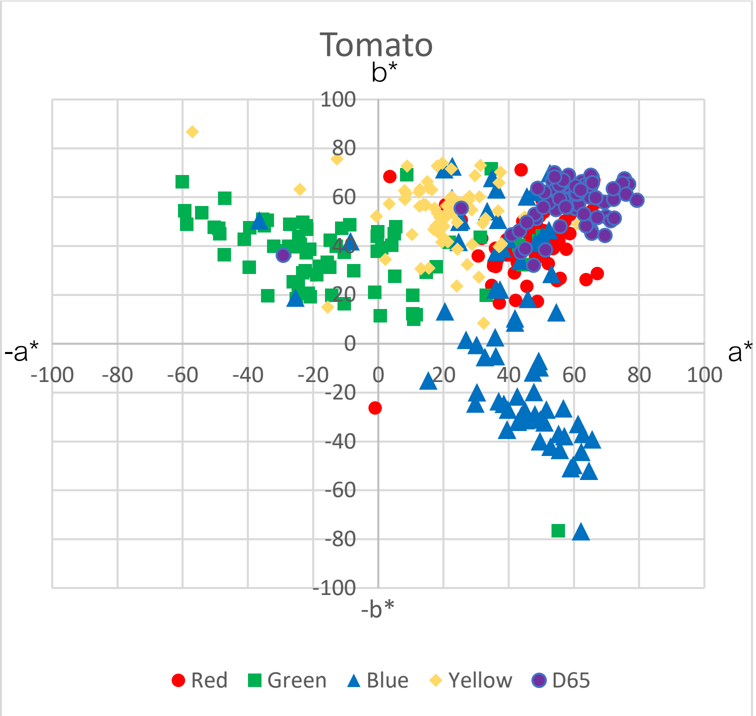


Figure D-1: (cont.)

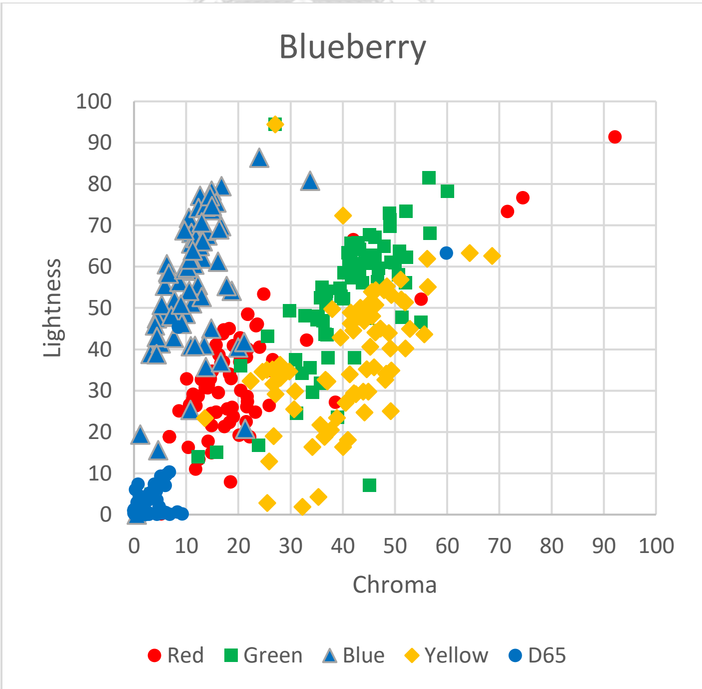
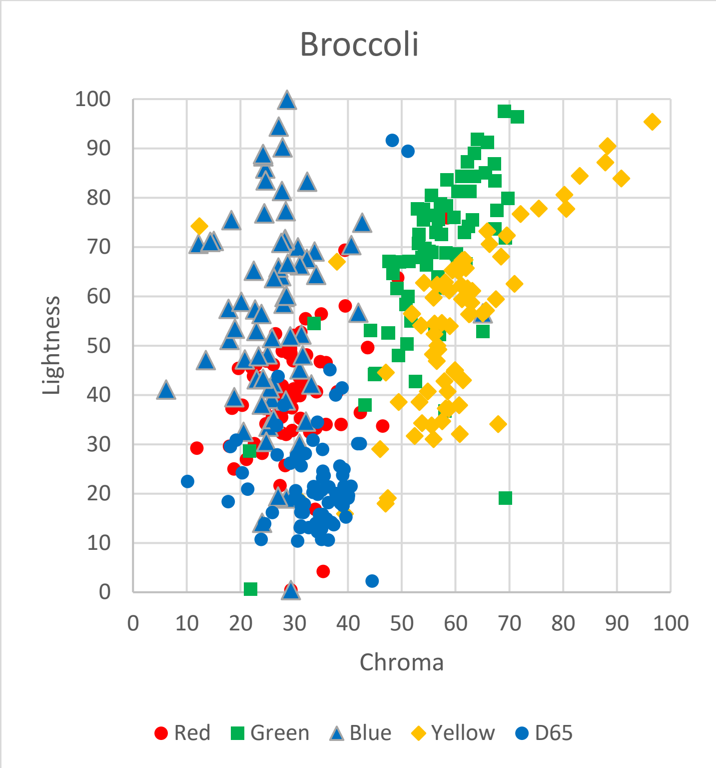


Figure D-2: Lightness and chroma of color perceptions in the Mondrian images.



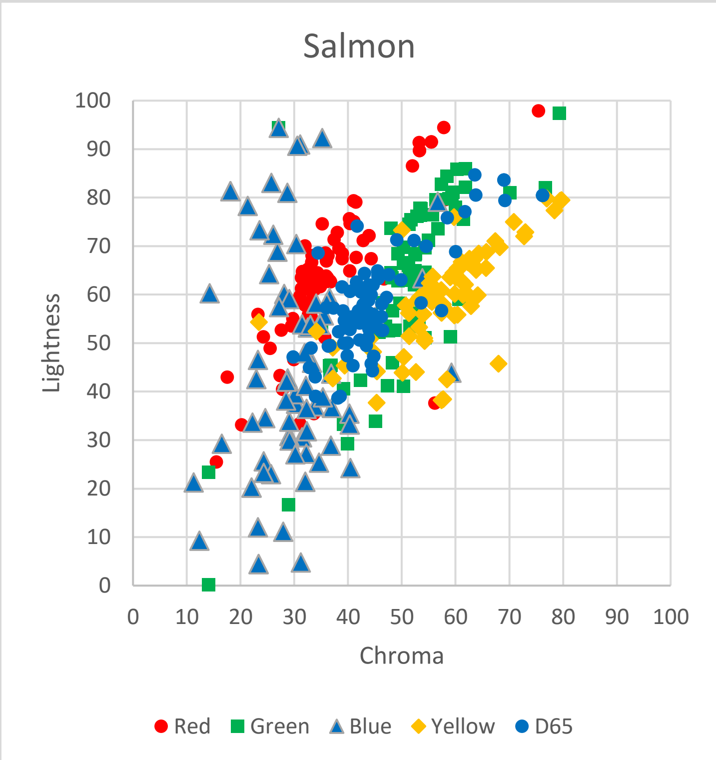
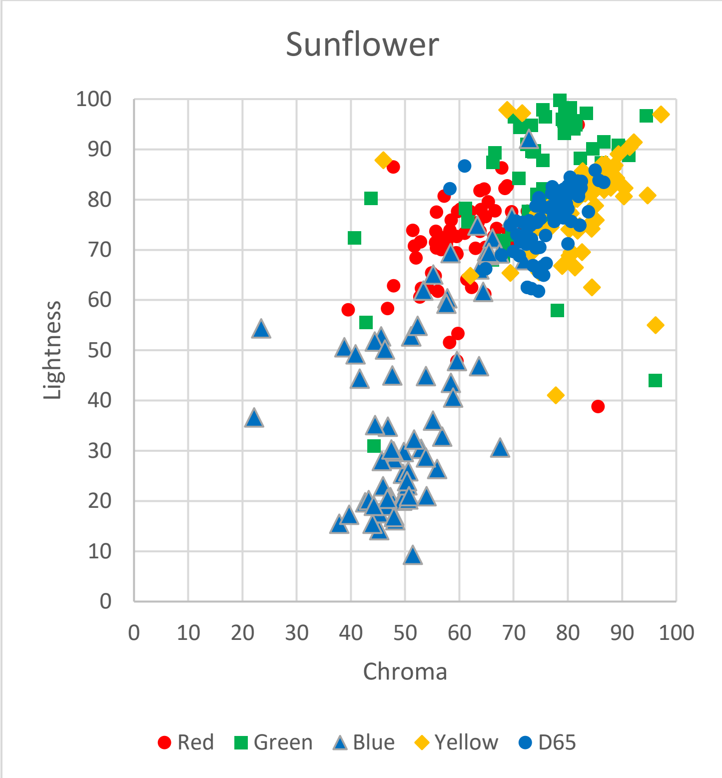


Figure D-2: (cont.)



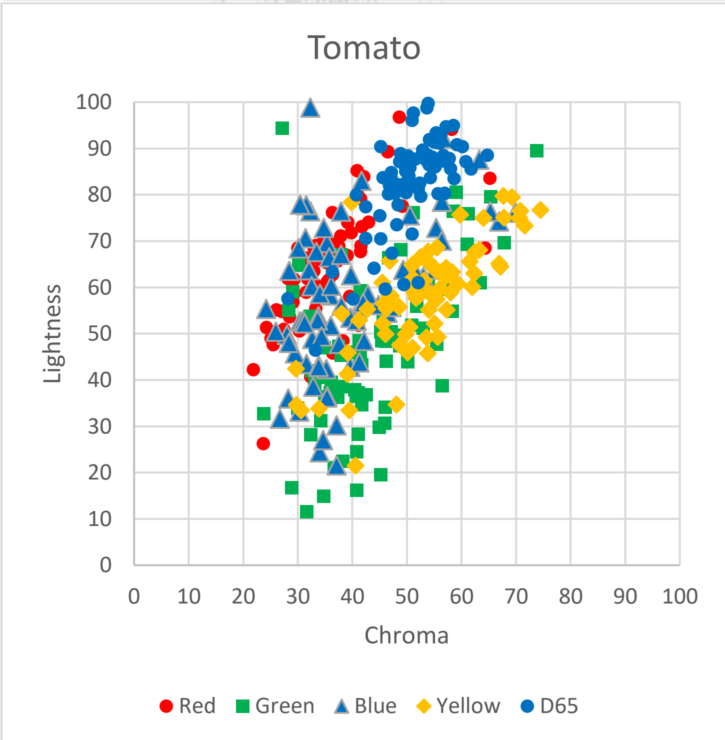


Figure D-2: (cont.)

VITA

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