The Effects of Neighboring Colors on Color Appearance

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The Effects of Neighboring Colors on Color Appearance

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ABSTRACT

Every day, people don't perceive one color independently, but perceive many neighboring colors simultaneously. Most color studies regarding color appearance were done based on a single color. There are also earlier studies conducted on neighboring colors. However, it is not sufficient to focus on the effect of neighboring colors which color attribute affect the color appearance. Therefore, the effects of neighboring colors on color appearance need to be investigated.

The research aimed to investigate how neighboring colors effect on color appearance. Color appearance experiment was carried out in the dark room by using a viewing booth. Total of 5 different neighboring color conditions were used in the experiment and those were 'Reference Condition', 'Desaturated', 'Saturated', 'Dark', and 'Light'. Total of 20 participants were invited to each neighboring color condition. Each participant evaluated Hue, Colorfulness, and Lightness of 22 test colors by using magnitude estimation method. To analyze the data, all participants' responses were averaged by using arithmetic mean. Then the experiment results were analyzed according to neighboring color conditions. Furthermore the results were compared with the estimated results of two different color appearance models, CIELAB and CIECAM02, respectively.

As for the findings of the experiment, Hue, Colorfulness, and Lightness tended to be affected by neighboring colors. First, Colorfulness was evaluated higher when neighboring colors were desaturated. Both Colorfulness and Lightness of test colors tended to be evaluated lower when neighboring colors were lighter. Hue was affected when neighboring colors were light.

The results were compared with estimated color appearance values of CIELAB and CIECAM02. In overall, CIECAM02 showed better performance than CIELAB. The performances of both models tended to be worse as the neighboring color condition became extreme in a specific color attribute, especially when estimating Colorfulness and Lightness. The degree of color appearance changes was compared between experimental results and CIECAM02 values of 'Reference Condition' and 'Light'. In the result, CIECAM02 model could not estimate the Colorfulness and Lightness changes according to neighboring color conditions sufficiently and it estimated the changes less than experimental results in both Colorfulness and Lightness.

Therefore, further research regarding color appearance should be considered more in regards to surrounding environment.

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1. Introduction

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1.1 Background

Humans live in a world which consists of various colors. People see and perceive many colors every day. There are many different circumstances when perceiving colors such as watching a television, reading a magazine, watching a traffic signal on the road, and so forth. In these situations, people commonly perceive colors as local properties of colored objects. However, color appearance is not just determined by the local light signals from each object, but instead depends on relative light signals across the visual scene (Richard and Donald, 1997). That is, people don't perceive one color independently, but perceive many neighboring colors simultaneously in most cases. This fact is very important in marketing area. For example, think about a lipstick shop. There are so many different types and colors of lipsticks. They are usually displayed together and the way how they displayed could affect the color perception of each lipstick. One surrounded with generally vivid colors might be perceived differently than the identical one surrounded with generally less colorful colors. Thus, will lead to more sales. Another example, suppose a situation seeing an object surrounded by LED spot lighting which doesn't reach the object. LED lighting is able to reproduce various colors. Perceived color of the object can be affected by adjacent color as LED lighting changes.

Color studies have been done to quantify color appearance. There are many earlier studies regarding color appearance. Most research regarding color appearance were done based on single color (Fairchild, 1995; Chenyang, 2012; Martijn, 2013). Therefore, experimental settings were similar to a single test color on mid-gray or black background. However, people perceive many colors at the same time and color appearance can be affected by neighboring colors. Therefore, earlier research results regarding color appearance might be quite different when compared to actual daily life.

There are earlier studies regarding color appearance which considered neighboring colors (Luo et al., 1991; Choi et al., 2010). The studies considered neighboring colors by presenting them in the experiment test pattern to simulate complex scene. Figure 1 shows the experiment pattern used in LUTCHI data set (Luo et al., 1991). In the Figure, neighboring colors, which were referred as decorating colors in the research, were distributed randomly along the edges of background.

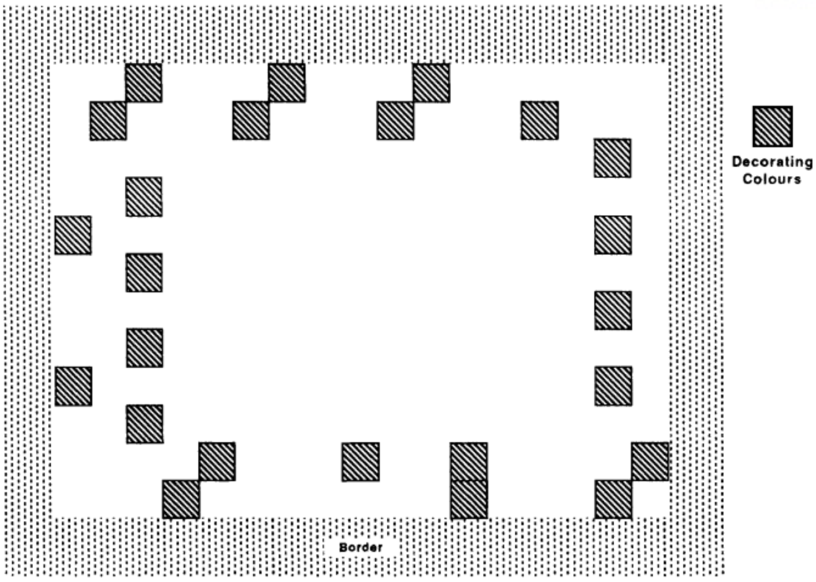

Figure 1. The Experimental Pattern Used in LUTCHI Data Set (Luo et al., 1991)

Another earlier studies show that color appearance can be affected according to neighboring colors (Richard and Donald, 1997; Oh and Kwak, 2014). In both studies, color appearance experiment was conducted with and without neighboring colors. The results illustrate that color appearance was affected according to the presence of neighboring colors. However, most previous studies handled neighboring colors as if the colors were presented or not. There are not sufficient research focusing on the effect of neighboring colors in which color attribute can affect the color appearance. Therefore, the effects of neighboring colors on color appearance need to be investigated.

1.2 Aim of the Research

The aim of this research is to investigate the effect of neighboring colors on the color appearance. The detailed aims of the study are (1) to analyze color appearance phenomena according to neighboring colors and (2) to test the performance of the color appearance models, CIELAB and CIECAM02.

1.3 Research Outline

To investigate the effect of neighboring colors on color appearance, two hypotheses were formulated as follow:

Hypothesis 1: If average Chroma of neighboring colors change, Colorfulness will change

Hypothesis 2: If average Lightness of neighboring colors change, Lightness will change

To test the hypotheses, psychophysical experiment was carried out by using 5 different neighboring color conditions. These were ‘Reference Condition’, ‘Desaturated’, ‘Saturated’, ‘Dark’, and ‘Light’. Among 5 conditions, ‘Reference Condition’ was a control group to compare the experiment results. Two conditions, ‘Desaturated’ and ‘Saturated’, consist of colors differently in Chroma to test *Hypothesis 1*. The other conditions, ‘Dark’ and ‘Light’, consist of colors differently in Lightness to test *Hypothesis 2*.

The results were compared to one another according to neighboring color conditions. Then the results were compared with the estimated color appearance values of two different color appearance models, CIELAB and CIECAM02, respectively.

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2. Literature Review

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2.1 Color Appearance Terminology

Color appearance is human perception of colors under various viewing conditions. Commission Internationale de l'Eclairage (CIE) defined color terms by publishing International Lighting Vocabulary (Commission Internationale de l'Eclairage, 1987). Following color terms are important in this research.

2.1.1 Hue

Hue is an attribute of a visual perception according to which an area appears to be similar to one, or to proportions of two, of the perceived colors red, yellow, green, and blue.

For example, hue of some fruits can be described like apple as red, banana as yellow, and grape as mixture of red and blue.

2.1.2 Brightness

Brightness is an attribute of a visual perception according to which an area appears to exhibit more or less light.

2.1.3 Lightness

Lightness is the brightness of an area judged relative to the brightness of a similarity illuminated area that appears to be white or highly transmitting.

Based on the definition, Lightness could be also represented as follow equation:

$$Lightness = \frac{\text{Brightness}}{\text{Brightness of White}}$$

2.1.4 Brightness vs. Lightness

Brightness and Lightness could be discriminated by that Brightness is the absolute value and Lightness is the relative value. Figure 2 shows the explanation of difference between Brightness and Lightness.

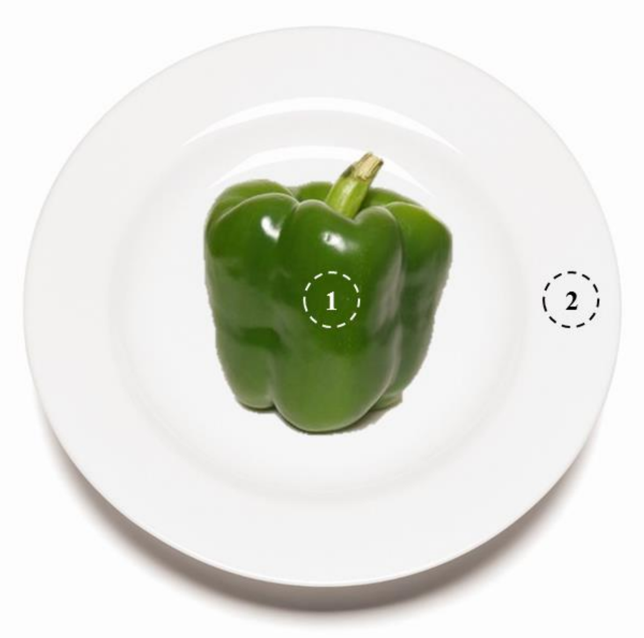


Figure 2. The Image for Explaining Brightness and Lightness

In the Figure, there is a green pepper on the white plate. There are points 1 and 2 that represent a surface of the green pepper and the white plate, respectively. For example, think about a case to define Brightness and Lightness of point 1. In case of Brightness, it could be defined as an absolute visual perception of the light coming from the point 1. On the other hand, Lightness could be defined as Brightness of point 1 relative to Brightness of point 2 which is used as a reference white.

2.1.5 Colorfulness

Colorfulness is an attribute of a visual perception according to which an area appears to exhibit more or less of its hue.

2.1.6 Chroma

Chroma is the colorfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Based on the definitions, Chroma could be represented as below equations:

$$Chroma = \frac{\text{Colorfulness}}{\text{Brightness of White}}$$

2.1.7 Saturation

Saturation is colorfulness of an area judged in proportion to its brightness.

Based on the definitions, Saturation could be represented as below equations:

$$Saturation = \frac{\text{Colorfulness}}{\text{Brightness}}$$

2.1.8 Colorfulness vs. Chroma, Saturation

Three concepts could be classified by whether it is absolute or relative value. Colorfulness is an absolute value and the others are relative values. Chroma and Saturation are both relative values, but each concept is based on different standards. Chroma is the colorfulness relative to brightness of reference white, but Saturation is the colorfulness relative to its brightness.

2.2 Color Appearance Phenomena

Color appearance phenomena are the cases where two identical colors look different according to surrounding, backgrounds, size, shape, surface, illumination, and so forth. Following instances of color appearance phenomena were mostly based on the book, 'Color Appearance Models' (Fairchild, 2013).

2.2.1 Simultaneous Contrast

Simultaneous Contrast is one of color appearance phenomena that are directly related to the spatial structure of the stimuli. Figure 3 shows an example of Simultaneous Contrast.

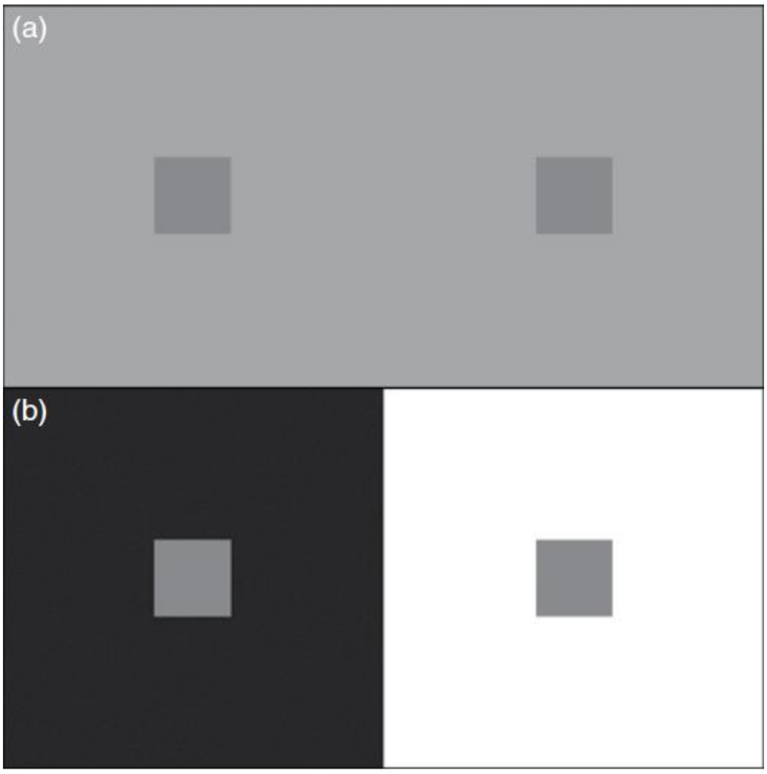


Figure 3. An Example of Simultaneous Contrast (Fairchild, 2013)

In Figure 3, the two identical gray patches are shown on different backgrounds in (a) and (b), respectively. In case of Figure 3 (a), both gray patches are presented on light gray background. In case of Figure 3 (b), one gray patch is presented on black background and the other is presented on white background. The gray patch on black background appears lighter than that on white background even though both gray patches have exactly same physical characteristics. This is Simultaneous Contrast and it causes stimuli to shift in color appearance when their surrounding or background changes. That is, black background induces the gray patch to look lighter and white background induces the same gray patch to look darker. This phenomenon can also be adapted to colored stimuli. In case of colored stimuli, background color induces stimuli, it looks more as complimentary color of the background. For instance, red background induces green, green background induces red, yellow background induces blue, and blue background induces yellow. One of earlier researches regarding Simultaneous Contrast (Albers, J., 2006), various aspects of Simultaneous Contrast were explored and used to suggest guideline for artist and designers to avoid pitfalls and take advantage of the effect.

2.2.2 Crispening Effect

Crispening Effect is a similar effect with Simultaneous Contrast and it is one of the effects that color appearance changes according to surroundings. The effect could be illustrated that when comparing two colors on a uniform background, the color appearance difference between two colors increases on the background which is similar in color with two colors. Figure 4 shows an example of Crispening Effect.

(a) (b) (c)

Figure 4. An Example of the Crispening Effect

There are two gray patches lying on the different backgrounds in each Figure 4. (a) ~ (c). The pair of gray patches are identical from (a) to (c), but the color appearance difference of two gray patches appears differently according to backgrounds. The pair on the gray background, which is shown in Figure 4. (b), appears bigger color difference than (a) and (c).

2.2.3 Hunt Effect

Color appearance of the same object changes significantly according to overall luminance levels. Suppose two situations where one is watching a tomato on a bright summer afternoon and the other is watching the same tomato on very dim place such as in a movie theater. The tomato appears more vivid and contrasty on the bright summer condition than the dim condition. This is Hunt Effect and it can be simply illustrated that Colorfulness increases with luminance. Figure 5 shows simulated images for showing Hunt Effect visually.

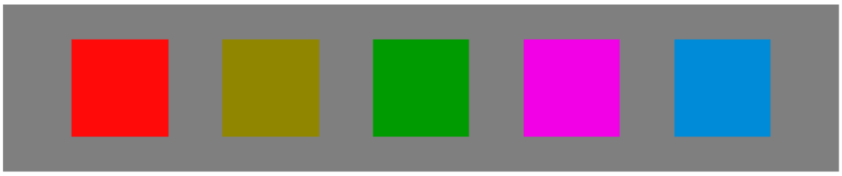
(a) (b) (c)

Figure 5. Simulated Images for Showing Hunt Effect (Fairchild, 2013)

In Figure 5, there are three images which are originally same, but different luminance. Overall luminance of the image decreases from (a) to (c). As luminance of the image decreases, it becomes darker and less vivid simultaneously from (a) to (c).

2.2.4 Helmholtz-Kohlrausch Effect

Helmholtz-Kohmrausch Effect illustrates Brightness not only dependent on luminance, but also chromaticity. That is, if the color has higher chroma value, it becomes to appear brighter. Figure 6 shows an example of Helmholtz-Kohmrausch Effect.



(a)

(b)

Figure 6. An Example of Helmholtz-Kohlrausch Effect

In Figure 6. (a), there are 5 different colors displayed on the gray background. Among 5 colors, red and magenta colors appear especially brighter than the others. However, if these colors are adjusted into the grayscale, the result will be comparable to the Figure 6. (b). In fact, the 5 colors have same luminance values, but different chroma. Red and magenta colors have higher chroma values than the others, as a result these two colors look brighter.

2.3 CIE Colorimetry

Colorimetry is literally defined as the method of measuring colors. For measuring colors accurately, there are important components for Colorimetry and those are light source, object and observer. Color measurement results could be different according to the three components.

To measure colors quantitatively and consistently, Commission Internationale de l'Eclairage (CIE) specified the standard light source, measurement geometry and observer.

2.3.1 Light Source and CIE Standard Illuminants

Light source plays a very important role in colorimetry. The measurement results of the same object could be different according to lightings. For a simple instance, suppose a red rose under a daylight. When it is seen under a very dim lighting condition such as a movie theater, its color might be perceived as brownish or almost black. Color appearance of a specific object could be totally different according to light source. Therefore, light source should be specified properly.

To reduce the complexity of the situation such as the above rose example, CIE has introduced a standardization of light sources (CIE, 2006). Standard illuminants specified by CIE could be largely divided into standard illuminant A, B, C and D. Each standard illuminant can be defined with a table of spectral power distribution and quoted with CCT (Correlated Color Temperature).

Standard illuminant A represents the spectral power distribution of tungsten filament lamp which is the most common domestic artificial light source and its CCT is 2856K. Both standard illuminant B and C represent daylight. Standard illuminant B represents sunlight which has a CCT of 4874K and Standard illuminant C represents average daylight which has a CCT of 6774K. Finally, standard illuminant D also represent the daylight, but containing region of ultra-violet. There are some series of standard illuminant D according to CCT. Among them, D65 is the most widely used which has CCT of 6504K.

2.3.2 CIE Standard Measurement Geometry

Measurement geometry is also important in colorimetry. The reflectance of an object is not just decided by the wavelength of the illumination, but also by viewing geometry. To quantify colorimetric data, the CIE recommends four standard illumination and viewing geometries for spectrophotometric reflectance measurements. These four different standard geometries are normal/45 (0/45), 45/normal (45/0), normal/diffuse (0/d) and diffuse/normal (d/0). In each designation, the first represents the illumination geometry and the second represents the viewing geometry following the slash (/). Figure 7 shows four CIE standard measurement geometries.

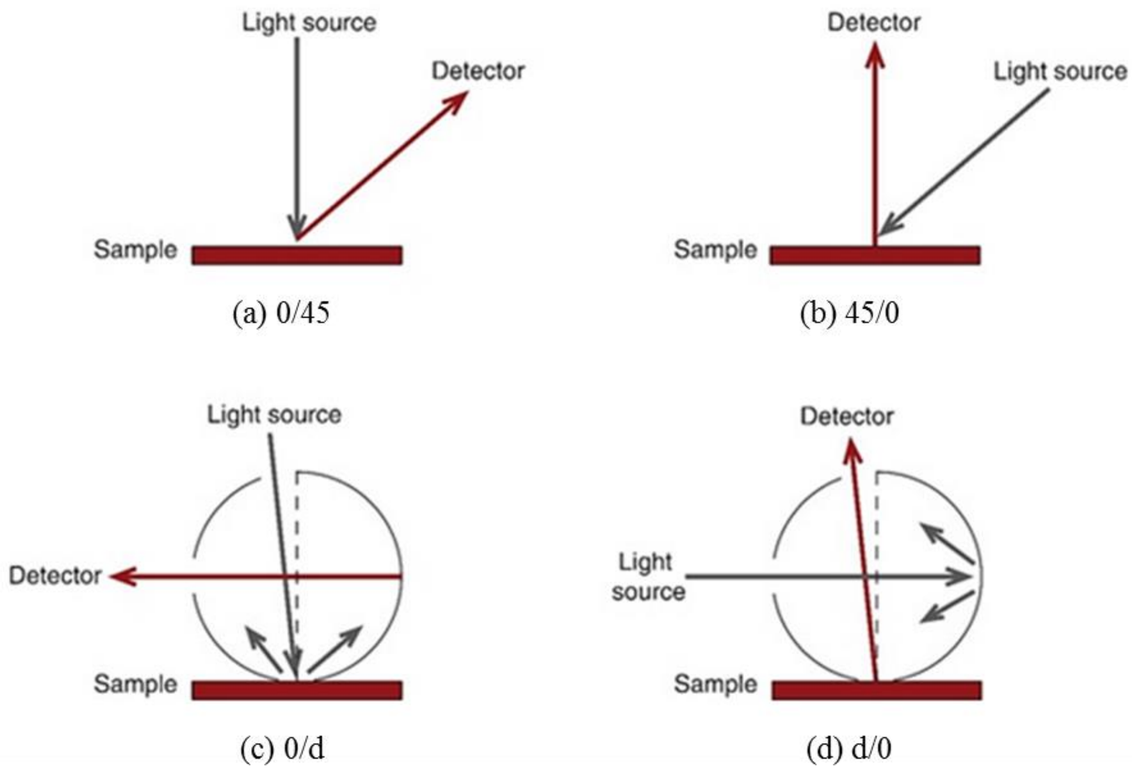


Figure 7. CIE Standard Measurement Geometries (Fairchild, 2013)

As shown in Figure 7, normal/45 (0/45) and 45/normal (45/0) could be classified as a pair. In the normal/45 geometry, the light source illuminates the surface of the object at normal and measurement is at 45° to the normal. In the 45/normal geometry, the object is illuminated by the light source at 45° to the normal and measurement was done along the normal.

Also normal/diffuse (0/d) and diffuse/normal (d/0) geometries could be classified as a pair. In both geometries, an integrating sphere was used for an object to be illuminated from all directions. In the normal/diffuse geometry, the object is illuminated at normal and reflected light is collected from all angles. In the diffuse/normal geometry, the object is illuminated from all angles and the light is measured at near normal.

In the integrating sphere of spectrophotometer, there is a gloss trap. Gloss trap can be used when including or excluding the spectral components of an object. If gloss trap is used, the spectral components are excluded, otherwise the spectral components are included.

2.3.3 CIE Standard Observer

Each person has different sensitivities of photoreceptors. To quantify color appearance, the CIE defined standard colorimetric observer and standardized the sensitivity curves of three cones based on the trichromatic color matching experiment in 1931. Figure 8 shows the experimental settings of the trichromatic color matching experiment.

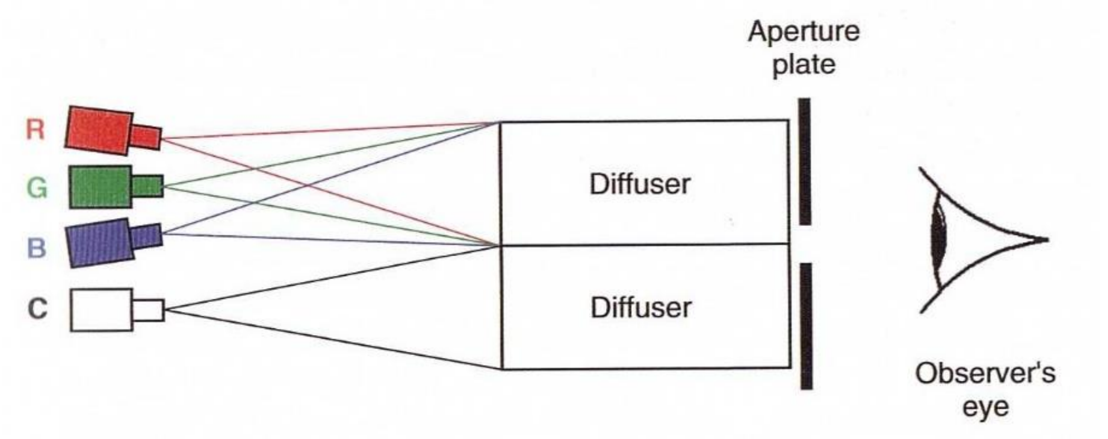


Figure 8. Experimental Settings of Trichromatic Color Matching Experiment (Hunt, 2011)

In the Figure 8, R, G and B are the monochromatic light sources of red, green and blue which have wavelengths of 700nm, 546.1nm, and 435.8nm, respectively; C is the test color which should be matched in Hue, Colorfulness and Brightness by adjusting the amounts of three sources, R, G, and B.

Based on the trichromatic color matching experiment, the CIE standardized the CIE 1931 Standard Colorimetric Observer which is often referred as the 2° observer, because a visual field of the experiment was 2°. The CIE also recommends a different color matching function, CIE 1964 Supplementary Standard Colorimetric Observer, which is also known as 10° observer. It can be used when the field size is greater than 4°.

Figure 9 shows both CIE 1931 Standard Colorimetric Observer and CIE 1964 Supplementary Standard Colorimetric Observer. In Figure 9, full lines of $\bar{x}, \bar{y}, and\ \bar{z}$ represent CIE 1931 Standard Colorimetric Observer and broken lines, $\overline{x_{10}}, \overline{y_{10}}, and\ \overline{z_{10}}$, represent CIE 1964 Supplementary Standard Colorimetric Observer.

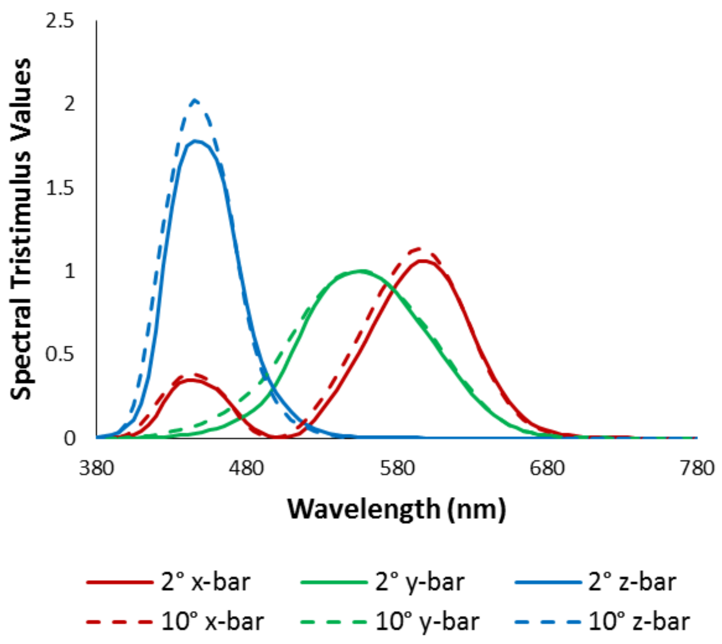


Figure 9. The CIE Color Matching Functions for the 1931 Standard Colorimetric Observer (2°), and for the 1964 Supplementary Standard Colorimetric Observer (10°)

2.3.4 CIE XYZ Tri-Stimulus Values

Color appearance is decided by three factors, light source, object and observer. Therefore, if the characteristics of three components, spectral power distribution of light source, spectral reflectance of an object and color matching function are known, every color can be quantified as tri-stimulus values. The CIE tri-stimulus values, X, Y, and Z, can be calculated with following equations.

$$\mathrm{X} = \mathrm{k}\int S\,(\lambda)\mathrm{R}(\lambda)\bar{x}(\lambda)\mathrm{d}(\lambda)$$

$$\mathrm{Y} = \mathrm{k}\int S\,(\lambda)\mathrm{R}(\lambda)\bar{y}(\lambda)\mathrm{d}(\lambda)$$

$$\mathrm{Z} = \mathrm{k}\int S\,(\lambda)\mathrm{R}(\lambda)\bar{z}(\lambda)\mathrm{d}(\lambda)$$

In the equations, S(λ) represents the spectral power distribution of a light source, R(λ) represents the spectral reflectance of an object, $\bar{x}(\lambda), \bar{y}(\lambda), and\ \bar{z}(\lambda)$ represent CIE color matching function and k is a constant.

In case of color matching function, both CIE 1931 Standard Colorimetric Observer (2°) and CIE 1964 Supplementary Standard Colorimetric Observer (10°) can be used according to the size of visual field. If the 10° observer is used, $\bar{x}(\lambda), \bar{y}(\lambda), and\ \bar{z}(\lambda)$ should be replaced by $\overline{x_{10}}(\lambda), \overline{y_{10}}(\lambda), and\ \overline{z_{10}}(\lambda)$ in the equation. When the k value is equal to 683 (lumens/watt), Y becomes the same value with the luminance, so tri-stimulus values are absolute colorimetry.

2.3.5 Chromaticity

The CIE tri-stimulus values, X, Y, and Z are not easy to represent colors intuitively, since it is represented in 3-dimensional space. In case of representations of each tri-stimulus value, Y value correlates with Brightness or more relates to Lightness, but X and Z values don't correlate with specific color appearance. Important color attributes are related to the relative magnitudes of the tri-stimulus values, not just independent tri-stimulus value itself. Therefore, Chromaticity is recommended which is able to represent relative tri-stimulus values in 2-dimensional space. The Chromaticity co-ordinates can be calculated as follows:

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

$$\mathrm{y} = \frac{Y}{X + Y + Z}$$

$$\mathrm{z} = \frac{Z}{X + Y + Z}$$

If two coordinates, x and y, are known, z can easily be calculated from 1-x-y. Therefore, it is possible to represent colors with two variables, x and y, in 2-dimensional space.

The CIE x, y Chromaticity Diagram has been widely used, but there is a problem that its color space is very non-uniform. Therefore, the CIE established a new color space called CIE 1976 Uniform Chromaticity Scale Diagram to minimize the non-uniformity. It is commonly referred as CIE u', v' chromaticity diagram, because u' and v' are used as variables rather than x and y. It can be calculated with follow equations:

$$\mathrm{u}' = \frac{4\mathrm{X}}{(X + 15Y + 3Z)}$$

$$v' = \frac{9\mathrm{Y}}{(X + 15Y + 3Z)}$$

2.3.6 Color Appearance Model

2.3.6.1 CIELAB

Chromaticity diagrams have been widely used, but they can only represent proportions of CIE tri-stimulus values. That is, they are not able to show their actual magnitudes, so they can be used when colors have same luminance and luminance factor. Generally, colors have different luminance, luminance factor, and also chromaticity. Therefore, a method of combining these variables is needed. To meet this need, CIE recommends CIELAB color space which is one of the uniform color spaces from 1976. It can be represented by plotting, along three axes at right angles to one another, the quantities can be calculated as follows:

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

$$where\ f(x) = x^{\frac{1}{3}} \text{ for } x > \left(\frac{6}{29}\right)^3$$

$$f(x) = \frac{841}{108}x + \frac{4}{29} \text{ for } x \le \left(\frac{6}{29}\right)^3$$

In the equations, X_n, Y_n, and Z_n are the CIE XYZ tri-stimulus values of appropriately chosen reference white and X, Y, and Z represent CIE XYZ tri-stimulus values of the test color.

In the CIELAB color space, correlates of Hue and Chroma are also available and can be calculated as follow:

CIE 1976 a, b hue-angle, h_{ab}

$$h_{ab} = arctan\left(\frac{b^*}{a^*}\right)$$

CIE 1976 a, b Chroma, C^*_{ab}

$$C^*_{ab} = (a^{*2} + b^{*2})^{\frac{1}{2}}$$

2.3.6.2 CIECAM02

CIECAM02 is the advanced color appearance model that the CIE designated in 2002. This model is based on the features of many previous color appearance models (Seim and Valberg, 1986; Nayatani, Takahama, and Sobagaki, 1986; Nayatani, Hoshimoto, Takahama, and Sobagaki, 1987; Nayatani, Takahama, Sobagaki, and Hashimoto, 1990; Nayatani, Sobagaki, Hashimoto, and Yano, 1997; Fairchild and Berns, 1993, Fairchild, 1996; Hunt and Pointer, 1985; Hunt, 1982, 1985, 1987, 1989, 1991, and 1994; Hunt and Luo, 1994; Luo, Lo, and Kuo, 1996). CIECAM02 can estimate Chroma, Saturation and Lightness for related colors and also Hue, Brightness and Colorfulness for both unrelated and related colors.

The steps for using the CIECAM02 model are shown as follows:

Input Data

Sample in test conditions	x	y	Y
Adopted white in test conditions	x_w	y_w	Y_w
Background in test conditions	x_b	y_b	Y_b
Reference white in reference conditions	x_{wr}=1/3	y_{wr}=1/3	Y_{wr}=100
Luminance of test adapting field (cd/m 2)	L_A		

Luminance of test adapting field, L_A, is normally set as 1/5 of the luminance of the adopted test white.

Surround Parameter

Surround parameters, c, N_c, and F, are different according to surround conditions, average, dim, and dark. Table 1 shows values of c, N_c, and F for different surrounds.

Table 1. Values of c, N_c, and F for Different Surrounds

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

First, calculate sample tri-stimulus values as follow:

$$\mathrm{X} = \frac{xY}{y}, \qquad \mathrm{Y}, \qquad \mathrm{Z} = \frac{(1-x-y)Y}{y}$$

Step 1. Convert the sample's tri-stimulus values X, Y, Z to R, G, B responses by using the matrix M_{CAT02}:

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

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

Step 2. Compute D factor, the degree of adaptation to the white point:

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

Where L_A is the luminance of the adapting field in cd/m^2

Step 3. Calculate R_c, G_c, B_c, the R, G, B values of the corresponding color:

$$R_c = D_R R \qquad D_R = \left(\frac{Y_w}{Y_{wr}}\right)\left(\frac{R_w}{R_{wr}}\right) D + (1 - D)$$

$$G_c = D_G G \qquad D_G = \left(\frac{Y_w}{Y_{wr}}\right)\left(\frac{G_w}{G_{wr}}\right) D + (1 - D)$$

$$B_c = D_B B \qquad D_B = \left(\frac{Y_w}{Y_{wr}}\right)\left(\frac{B_w}{B_{wr}}\right) D + (1 - D)$$

Step 4. Convert R_c, G_c, B_c to X_c, Y_c, Z_c by using reverse matrix M_{CAT02}:

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = M_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix}$$

$$M_{CAT02}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix}$$

Step 5. Convert X_c, Y_c, Z_c to Hunter-Pointer-Estevez cone responses:

$$\begin{bmatrix} \rho \\ \gamma \\ \beta \end{bmatrix} = M_{HPE} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix}$$

$$M_{HPE} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix}$$

Step 6. Apply luminance-level adaptation (F_L), and non-linear compression:

$$\rho_a = \left\{ \frac{\left[400\left(\frac{F_L\rho}{100}\right)^{0.42}\right]}{\left[27.13+\left(\frac{F_L\rho}{100}\right)^{0.42}\right]} \right\} + 0.1$$

$$\gamma_a = \left\{ \frac{\left[400\left(\frac{F_L\gamma}{100}\right)^{0.42}\right]}{\left[27.13+\left(\frac{F_L\gamma}{100}\right)^{0.42}\right]} \right\} + 0.1$$

$$\beta_a = \left\{ \frac{\left[400\left(\frac{F_L\beta}{100}\right)^{0.42}\right]}{\left[27.13+\left(\frac{F_L\beta}{100}\right)^{0.42}\right]} \right\} + 0.1$$

$$\text{where } F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{\frac{1}{3}}, \quad \text{k} = \frac{1}{(5L_A+1)}$$

Step 7. Calculate opponent color signals, A, a, and b:

Achromatic signal

$$\text{A} = \left[2\rho_a + \gamma_a + \left(\frac{1}{20}\right)\beta_a - 0.305\right] N_{bb}$$

$$where\ N_{bb} = N_{bc} = 0.725\left(\frac{1}{n}\right)^{0.2}, \quad n = \frac{Y_b}{Y_w}$$

Redness-Greenness

$$a = \rho_a - \frac{12\gamma_a}{11} + \frac{\beta_a}{11}$$

Yellowness-Blueness

$$\text{b} = \left(\frac{1}{9}\right)(\rho_a + \gamma_a - 2\beta_a)$$

Estimated Color Appearance

Table 2 shows the CIECAM02 equations for estimated color appearance.

Table 2. CIECAM02 Equations for Estimated Color Appearance

Color Appearance	Equation
Lightness	$\mathrm{J} = 100\left(\frac{A}{A_w}\right)^{cz}$ $\text{where z} = 1.48 + n^{0.5}\ where\ n = \frac{Y_b}{Y_w}$
Brightness	$\mathrm{Q} = \frac{4}{c}\sqrt{\frac{J}{100}}(A_w + 4)F_L^{0.25}$
Chroma	$\mathrm{C} = t^{0.9}\sqrt{\frac{J}{100}}(1.64 - 0.29^{n})^{0.73}$ $\text{where t} = \frac{\left[\left(\frac{50000}{13}\right)N_c N_{cb}\right]\left[e_t\sqrt{(a^2 + b^2)}\right]}{\rho_a + \gamma_a + \left(\frac{21}{20}\right)\beta_a}$ $e_t = \left[\frac{1}{4}\right]\left[\cos\left(\frac{h\pi}{180} + 2\right) + 3.8\right]$
Colorfulness	$\mathrm{M} = \mathrm{C}F_L^{0.25}$
Saturation	$\mathrm{s} = 100\left(\frac{M}{Q}\right)^{0.5}$
Hue angle	$\mathrm{h} = \arctan\left(\frac{b}{a}\right)$
Hue quadrature	$\mathrm{H} = H_i + \frac{\left[\frac{100\left(h^{'} - h_i\right)}{e_i}\right]}{\left[\frac{\left(h^{'} - h_i\right)}{e_i} + \frac{\left(h_{i+1} - h^{'}\right)}{e_{i+1}}\right]}$ i should be 1, 2, 3, or 4 so that $h_i \le h < h_{i+1}$

Table 3 shows CIECAM02 Hue quadrature, H, calculated from the unique Hue data.

Table 3. CIECAM02 Hue Quadrature of Unique Hue

	Red	**Yellow**	**Green**	**Blue**
i	1	2	3	4
h_i	20.14°	90.00°	164.25°	237.53°
e_i	0.8	0.7	1.0	1.2
H_i	0.0	100.0	200.0	300.0

2.4 Summary

In this chapter, related literatures were reviewed in regards to color appearance terminology, color appearance phenomena, CIE colorimetry, and color appearance models. In the psychophysical experiment of this study, color appearance was evaluated in Hue, Colorfulness, and Lightness. The experimental results were compared in Hue, Colorfulness, and Lightness, respectively, according to neighboring color conditions. Then the performance of two color appearance models, CIELAB and CIECAM02, was tested with the experimental results to investigate whether each model can estimate color appearance according to neighboring color conditions.

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3. Experimental Design

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3.1. Introduction

In this research, color appearance experiment was conducted according to 5 different neighboring color conditions. The purpose of the experiment was to investigate the effect of neighboring colors on color appearance. Total of 20 participants evaluated in each neighboring color condition. Each participant evaluated Hue, Colorfulness, and Lightness of 22 test colors by using magnitude estimation method.

3.2. Experimental Settings

The experiment was done in a dark room by using a viewing booth, Macbeth Judge 2. By using the viewing booth, color evaluation was possible under the specified lighting conditions. The size of viewing booth was 56.5 cm (Height) x 68.6 cm (Width) x 56.5 cm (Depth). The experimental lighting was fixed to Fluorescent Daylight D65, whose color temperature is 6500K, in every experimental step. As physical characteristics of D65 lighting, luminance was 1090lx and correlated color temperature was 6300K. The measurement was done on the center of the viewing booth by using illuminometer CL-200. Figure 10 shows the experimental settings.

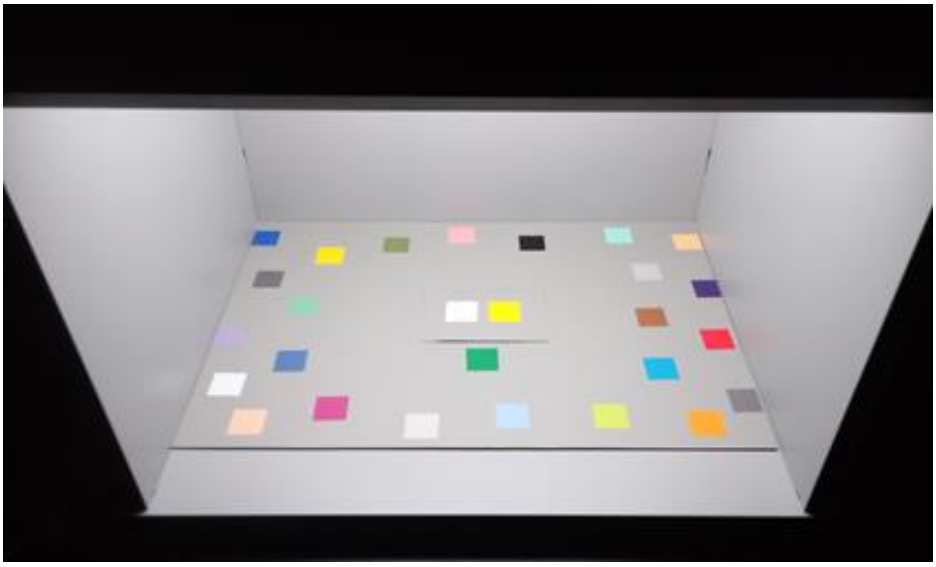


Figure 10. Experimental Settings

3.3. Test Pattern

Figure 11 shows the test pattern which was shown to each participant.

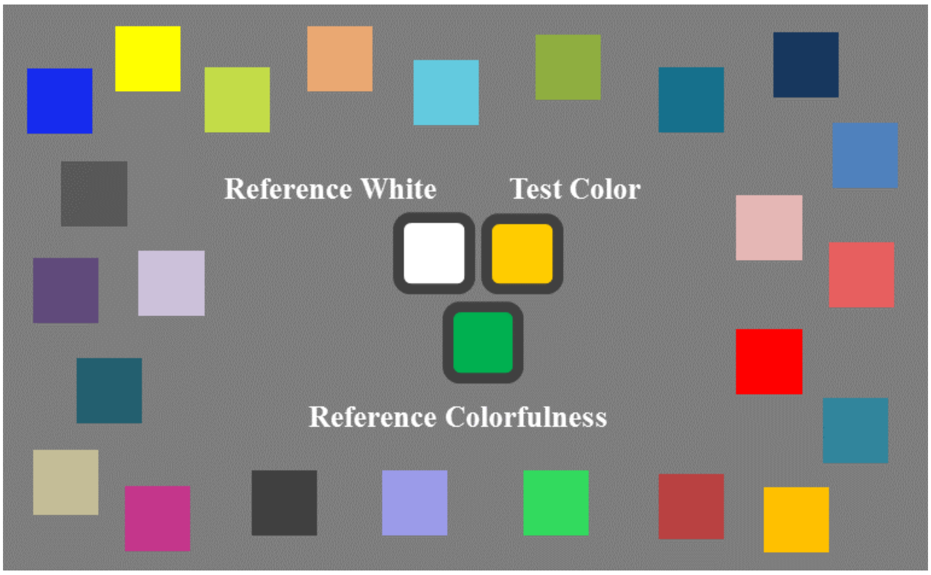


Figure 11. Experimental Settings

As shown in Figure 11, there were various color patches on gray background. The background color was set to Munsell N7 and the size of background was 61 cm (Width) x 41.5 cm (Height). Each test color was given centered right on the background side by side with reference white. There was also a reference colorfulness given for evaluating colorfulness below test color and reference white. The other 24 colors on the background are neighboring colors. The size of test color, reference white, reference colorfulness and neighboring colors was all 3.8cm square. In each neighboring color condition, 24 neighboring colors occupied 13.7% of the entire background.

3.4. Test Colors

In this experiment, test colors were selected based on 8 colors which are used to calculate CIE CRI (Color Rendering Index) and 15 colors for calculating CQS (Color Quality Scale). First, 23 colors were selected from NCS (Natural Color System) atlas which looked most similar. Among 23 selected colors, two colors were visually same, so one color was eliminated. Therefore total of 22 test colors were used in this experiment. Table 4 shows 22 test colors' NCS symbols.

Table 4. Test Colors

Patch No.	NCS	Patch No.	NCS
1	S3020-Y90R	*12*	S2040-R80B
2	S1080-Y20R	*13*	S2040-R60B
3	S0580-Y40R	*14*	S2040-R40B
4	S1070-Y60R	*15*	S3055-R50B
5	S1085-Y90R	*16*	S3555-R60B
6	S4030-Y	*17*	S7010-R90B
7	S0580-Y	*18*	S2065-R20B
8	S1070-G10Y	*19*	S2050-B40G
9	S0570-G60Y	*20*	S2050-B80G
10	S2070-G50Y	*21*	S3030-B50G
11	S3040-G10Y	*22*	S2065-B

Among 22 test colors, 8 test colors, *1*, *6*, *10*, *11*, *12*, *13*, *14*, *21* shown in the Table 4, were repeated to check each participant's inter-observer repeatability.

Each test color was measured by using tele-spectroradiometer Minolta CS-2000 (Figure 12). It is able to measure the color over the visible spectrum, from 380 nm to 780 nm, with 1nm interval. For each color measurement, Minolta CS-2000 was set as CIE standard geometry 0°/45° and measuring angle was fixed to 1°. Every measurement was done in a dark room by using a viewing booth under the D65 lighting.

Figure 12. Tele-Spectroradiometer Minolta CS-2000

Measured CIE XYZ tri-stimulus values of each test color was transformed to CIELAB values. For calculating CIELAB values of test colors, reference white was set as (X, Y, Z) = (269.8, 276.2, 342.5). Figure 13 shows how test colors are distributed in CIELAB a*b* color space and Table 5 shows the CIELAB values of test colors.

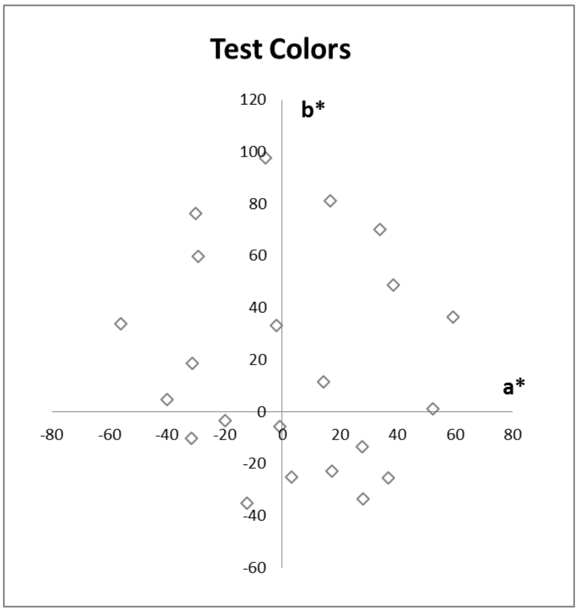


Figure 13. Color Distribution of Test Colors on CIELAB a*b* color space

Table 5. CIELAB Values of Test Colors

Patch No.	CIELAB			Patch No.	CIELAB		
	L*	a*	b*		L*	a*	b*
1	67.05	14.46	11.51	12	66.21	3.16	-25.30
2	76.33	16.61	81.21	13	65.84	17.39	-23.00
3	72.79	33.86	69.99	14	65.03	27.74	-13.53
4	66.11	38.63	48.68	15	44.78	36.88	-25.62
5	47.79	59.19	36.43	16	37.28	27.96	-33.48
6	62.39	-2.11	33.10	17	40.03	-0.74	-5.74
7	90.26	-5.89	97.57	18	44.64	52.28	1.05
8	68.65	-56.07	33.87	19	65.19	-31.43	-10.17
9	87.05	-30.05	76.43	20	67.58	-40.09	4.59
10	67.50	-29.28	59.81	21	65.89	-19.78	-3.46
11	62.70	-31.13	18.74	22	51.63	-12.31	-35.13

3.5. Neighboring Color Conditions

Total of 5 different neighboring color conditions were used in this experiment. These were ‘Reference condition’, ‘Desaturated’, ‘Saturated’, ‘Dark’ and ‘Light’. In each condition, neighboring colors were distributed on the gray background, similar to the pattern used in LUTCHI data set (Luo et al., 1991). Neighboring colors were distributed randomly along the edges of each background.

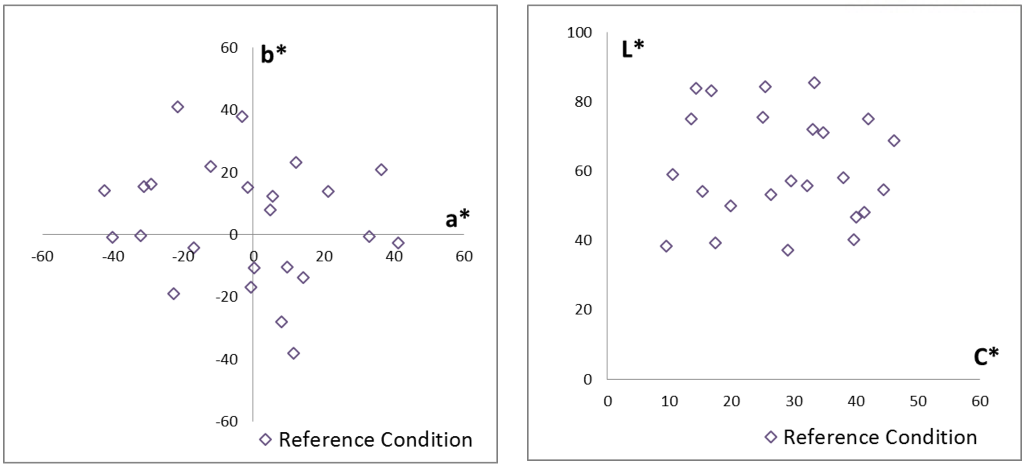
Each neighboring color was also measured by using tele-spectroradiometer Minolta CS-2000 with CIE standard geometry 0°/45° and measuring angle was fixed to 1°. Measurement was done in a dark room by using a viewing booth under the D65 lighting. Measured CIE XYZ tri-stimulus values of each neighboring color were transformed to CIELAB values based on the reference white as (X, Y, Z) = (269.8, 276.2, 342.5).

Table 6 shows the average CIELAB L* values of 24 neighboring colors and overall background considering the ratio of neighboring colors, which occupied about 13.7% of the background, and CIELAB C* values of 24 neighboring colors according to conditions. Figure 14 shows the distribution of 24 neighboring colors in CIELAB color space according to neighboring color conditions.

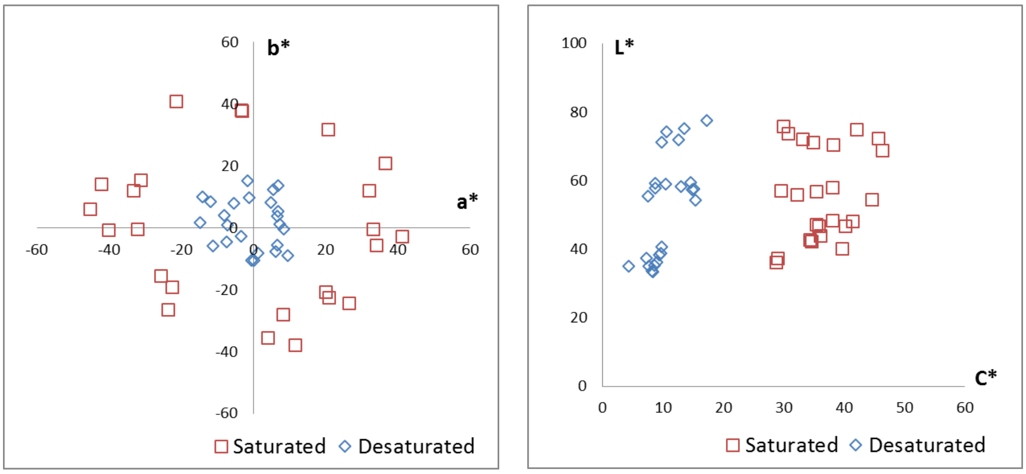
Table 6. Average CIELAB L* and C* Values of Neighboring Color Conditions

Neighboring Color Condition	CIELAB L*		CIELAB C*
	Neighboring Colors	Overall Background	Neighboring Colors
Reference Condition	61.1	67.43	28.3
Desaturated	52.2	66.41	10.6
Saturated	55.9	66.73	36.4
Dark	46.0	65.62	24.8
Light	76.9	69.30	24.5

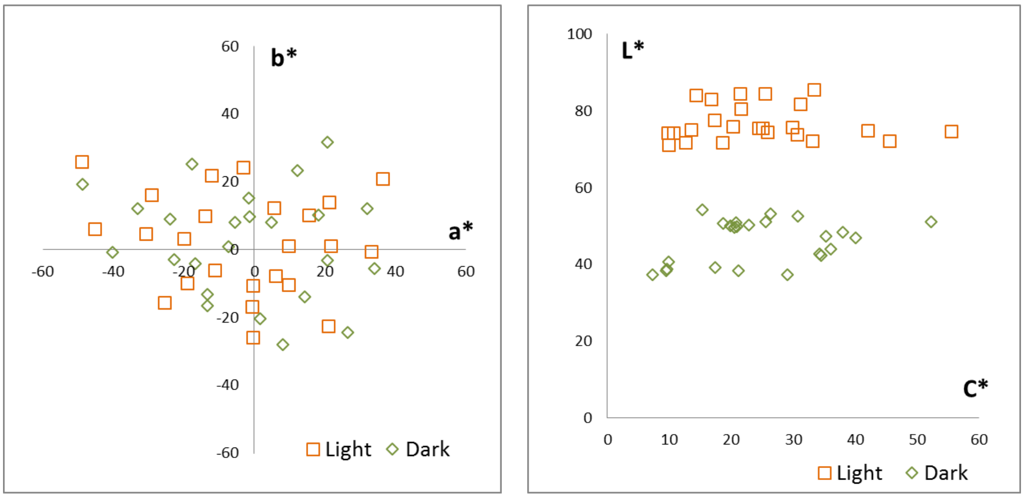
As shown in Table 6, two conditions ‘Desaturated’ and ‘Saturated’ have similar average L* values, but average C* values are different as 10.6 in ‘Desaturated’ and 36.4 in ‘Saturated’. This C* value difference was intended to see the effect of chroma of neighboring colors on color appearance. Likewise, ‘Dark’ and ‘Light’ have similar average C* values, but average L* values are different as 46.0 in ‘Dark’ and 76.9 in ‘Light’. This L* value difference was also intended to see the effect of lightness of neighboring colors on color appearance. The condition, ‘Reference Condition’, literally consists of neighboring colors which are evenly distributed on CIELAB color space and it was used as a control group.



(a) ‘Reference Condition’ on CIELAB color space



(b) ‘Desaturated’ and ‘Saturated’ on CIELAB color space



(c) ‘Dark’ and ‘Light’ on CIELAB color space

Figure 14. Color Distributions of Neighboring Color Conditions on CIELAB color space

3.6. Participants

In this experiment, total of 20 participants evaluated in each neighboring color condition. They were all Korean and university students who had a normal color vision. Among 20, 10 are male students and 10 female students. Participants for two conditions, 'Desaturated' and 'Saturated', were differently consisted from the participants who were for conditions, 'Reference Condition', 'Dark', and 'Light'. To check whether participants had a normal color vision or not, Ishihara test was conducted to each participant. Ishihara test is one of most widely used method to check normal color vision (Figure 15). If people have a normal color vision, they can read a number shown in the Ishihara test images.

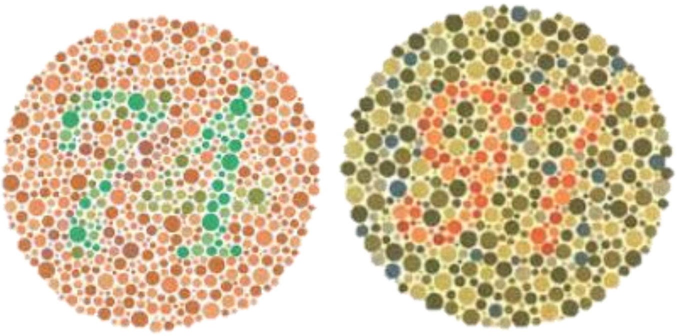
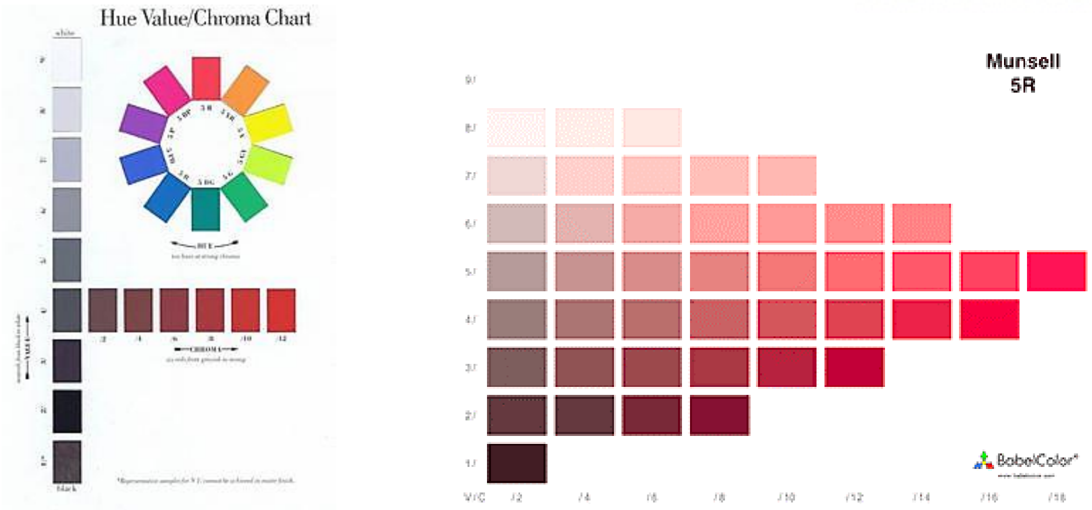


Figure 15. Ishihara test images

3.7. Psychophysical Experiment Procedure

Firstly, participants came into the experimental room and Ishihara test was given to check whether each participant has a normal color vision. After that, the experimental room became dark and D65 lighting of the viewing booth was turned on.

Before starting the experiment, a training session was done to clarify the concept of three color attributes. In the training session, each participant arranged color chips on the chart of Munsell Student's Workbook according to Hue, Colorfulness, and Lightness. Figure 16 shows Munsell Student's Workbook.



(a) HVC Chart (b) 5R Chart

Figure 16. Munsell Student's Workbook

Then, participants were asked to stare at the bottom of the viewing booth for 5 minutes to adapt to the experimental lighting. During the adaptation time, each participant was given the instructions (Appendix. 1) for experiment. The instruction contained the definitions of each color attribute enacted by CIE (Commission Internationale de l'Eclairage) and evaluation method.

In the main experiment, participants were asked to evaluate the color appearance of 22 test colors according to 5 different neighboring color conditions. The test colors were shown in a random order in each neighboring color condition. Neighboring color conditions were shown in a specific order. Three conditions, 'Reference Condition', 'Dark', and 'Light' were shown in an order and two conditions, 'Desaturated' and 'Saturated' were shown in an order. For evaluating color appearance, three color attributes, Hue, Colorfulness and Lightness, were evaluated individually by using a magnitude estimation method. Therefore, participants allocated the number to Hue, Colorfulness and Lightness, respectively. Figure 17 summarizes the overall procedure of the experiment.

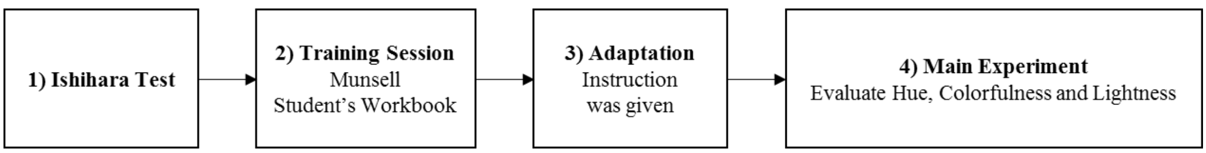


Figure 17. Overall procedure of the experiment

For evaluating Hue, participants were asked to describe the hue of each test color as a proportion of two neighboring primaries among 4 psychological primaries, red, green, yellow and blue. First of all, participants decided whether they could perceive any hue or not. If yes, participants decided on the predominant one among 4 primaries. Continuously, if participants perceived a trace of any other primaries, then they identify it. Finally, participants evaluated the proportions in which the two primaries stand. For instance, a purple color might be 60% red and 40% blue. If participants could not perceive any hue, they evaluate Hue as ‘Neutral’.

For evaluating colorfulness, participants were asked to assign a proper number to colorfulness of each test color. It was open-ended scale, so there was no maximum value for evaluation. A neutral color had no colorfulness which means zero in the scale and a reference colorfulness was given to each neighboring color condition. Reference colorfulness was selected as red, green and blue color in NCS atlas whose CIELAB C* values are similar to a possibility with the number 47.94 which is the average CIELAB C* value of 22 test colors. Reference colorfulness was differently given according to neighboring color conditions, since its hue itself could affect colorfulness evaluation. Table 7 shows NCS symbols and CIELAB C* values of selected reference colorfulness.

Table 7. Reference Colorfulness

		NCS	CIELAB C*	Neighboring Color Condition Used
Reference Colorfulness 1		S2060-R	44.72	‘Reference Condition’, ‘Desaturated’
Reference Colorfulness 2		S3060-G	51.00	‘Dark’, ‘Saturated’
Reference Colorfulness 3		S2065-B	36.65	‘Light’

As shown in Table 7, reference colorfulness 1 which is red was given in two conditions, ‘Reference Condition’ and ‘Desaturated’. Reference colorfulness 2 was given in ‘Dark’ and ‘Saturated’. Lastly, reference colorfulness 3 was given under the condition, ‘Light’. The colorfulness of reference colorfulness should be always remembered in order to evaluate the test colors relative to it. Reference colorfulness was different according to neighboring color conditions. Reference colorfulness 1 (Table 7) was given under the very first order of neighboring color conditions, ‘Desaturated’ and ‘Reference Condition’, respectively. The colorfulness of reference colorfulness 1 was assigned as 50 and participants evaluated the colorfulness of each test color related to it. Before starting the evaluation under new neighboring color condition, participants were asked to newly adapt for 5 minutes and to assign new reference colorfulness based on their memory from previous one. Then the evaluation was continued.

For evaluating Lightness, participants were asked to assign a proper number to Lightness of each test color. As an evaluation standard, the Lightness of reference white which was always given side by side with test colors was 100 and the Lightness of each participant's imaginary black was zero. Therefore, Lightness should be evaluated from zero to 100 and the assigned number would become higher if participants perceived each test color lighter.

Figure 18. Experimental Scene

To analyze the data, all participants' responses were averaged. All data were averaged by using the arithmetic mean.

3.8. Data Analysis Method

3.8.1 Coefficient of Variation (CV)

In this research, Coefficient of Variation (CV) was used to calculate the dispersion of data. The standard deviation is widely used for calculating the degree of scattering. However, it is meaningful given with the mean of the data. For instance, suppose two data groups, A and B, whose mean and standard deviation are as A ($\mu_{A,}$ σ_A) = (100, 10) and B ($\mu_{B,}$ σ_B) = (10, 5). In this case, it is hard to say that group B data is more stable than A, because the size of standard deviation is just smaller than that of A.

On the other hand, CV value is independent of the unit in which the measurement has been taken and it means CV value is dimensionless number. Therefore, CV value can be used when comparing the dispersion of various data sets which have different mean or different units.

The definition of Coefficient of Variation (CV) is the ratio of the standard deviation to the mean:

$$CV = 100 * \sigma/\mu$$

In the above equation, σ is the standard deviation and μ is the mean of the data, respectively. CV can easily be calculated dividing the standard deviation by mean of the data. Then 100 were multiplied to the result to convert CV in percentage. Therefore, if CV value is 20, it means there is about 20% variation between the data sets.

In this research, CV value was used to evaluate repeatability, reproducibility and color appearance models' performances. Repeatability is to check the consistency of each participant's responses. Reproducibility is to compare between each participant's data and average of all participants' data. To compare color appearance models' performances, CV value between participants' evaluated data and model estimation data were calculated according to color attributes, Hue, Colorfulness and Lightness.

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4. Results

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4.1 Introduction

In this research, color appearance experiment was carried out by using 5 different neighboring color conditions. Total of 20 participants evaluated in each neighboring color condition and each participant evaluated Hue, Colorfulness, and Lightness of 22 test colors by using magnitude estimation method.

Before analyzing the experimental results, observer performance was calculated by Repeatability and Reproducibility. Then color appearance changes were investigated according to neighboring color conditions. Furthermore, the experimental results were compared with the estimated results of two different color appearance models, CIELAB and CIECAM02, respectively.

4.2 Observer Performance

4.2.1 Repeatability

In this experiment, 8 test colors, *1, 6, 10, 11, 12*, *13*, *14*, *21* (Table 4), were repeated to check the repeatability of each participant's responses. That is, each participant evaluated 8 test colors, two times. The Coefficient of Variation (CV) values were calculated between each participant's evaluation results of 8 test colors according to Hue, Colorfulness and Lightness, respectively. For perfect agreement, CV value should be zero.

As a result, mean CV values of Hue, Colorfulness and Lightness were 6.8, 16.1 and 11.2, respectively. That is, there can be an individual deviation of 6.8%, 16.1% and 11.2% for evaluation of Hue, Colorfulness and Lightness, respectively. The result also means that the performance of Hue was better than the other two attributes and Colorfulness was the hardest attribute to scale.

4.2.2 Reproducibility

To check the deviation between each participant and average, the Coefficient of Variation (CV) was calculated according to Hue, Colorfulness and Lightness.

The results showed that mean CV values of Hue, Colorfulness and Lightness were 8.6, 15.9 and 12.2, respectively. All findings showed that Hue was the most consistent attribute and Colorfulness was the most difficult attribute to evaluate. There was no considerable difference between Repeatability and

Reproducibility. That is, each participant's responses were not significantly deviated from the average results.

Compared with the previous research, mean CV values of previous color appearance experiment (Luo et al., 1991) were 9, 18 and 13 for Hue, Colorfulness and Lightness, respectively. Therefore, these experimental results showed competitive with the earlier experiment.

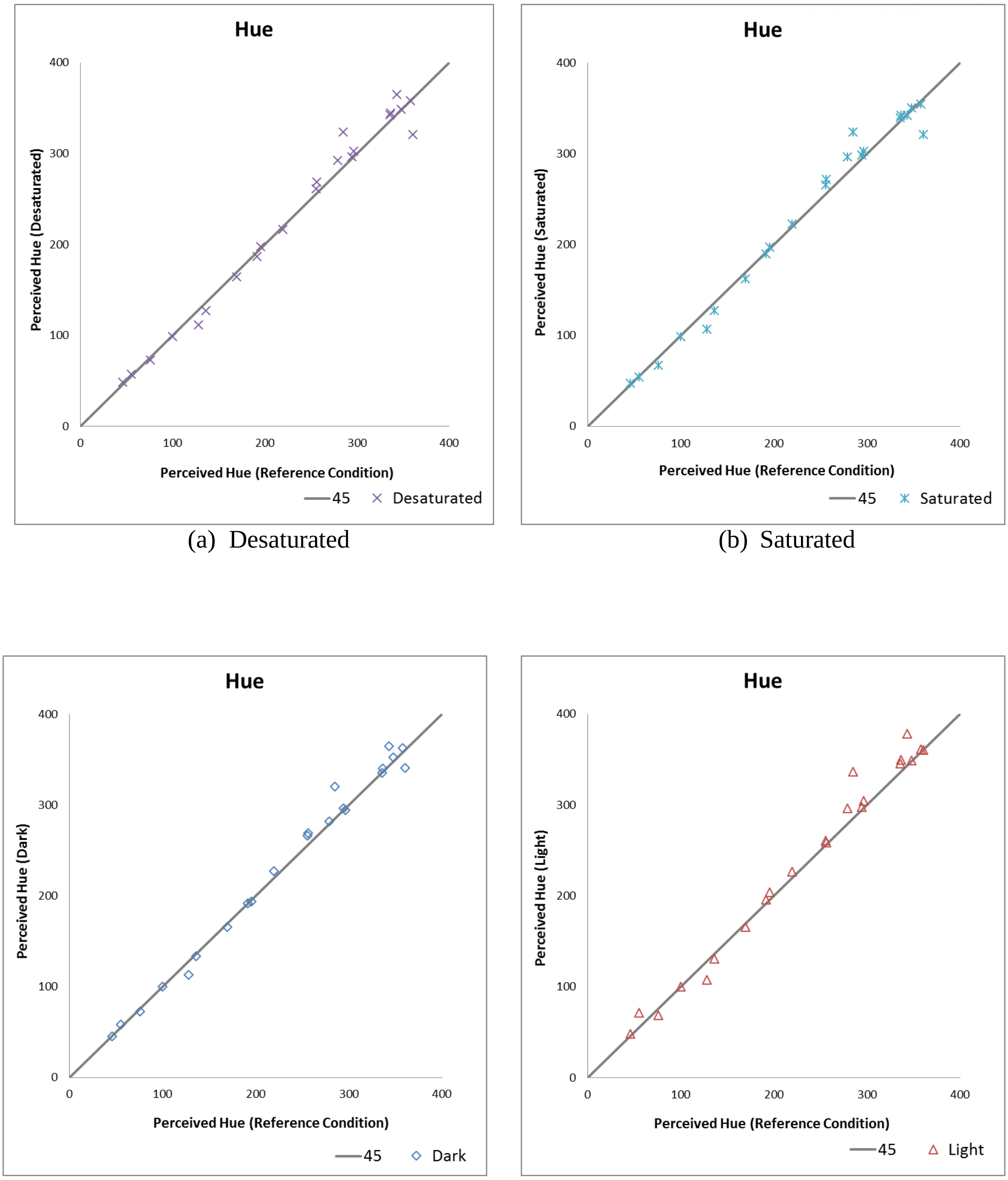
4.3 Color Appearance Change by Neighboring Color Conditions

To investigate the effect of neighboring colors on color appearance, experimental results were compared according to neighboring color conditions. The results were compared in Hue, Colorfulness, and Lightness, respectively. For a statistical analysis, paired t-test was conducted.

4.3.1 Hue

Figure 19 shows the comparison of Hue results based on 'Reference Condition' according to neighboring color conditions. In each graph of Figure 19, x-axis represents the averaged Hue response on 'Reference Condition' and y-axis means the averaged Hue response on the other conditions, 'Desaturated', 'Saturated', 'Dark' and 'Light', respectively.

As shown in Figure 19, data points were mostly distributed along the 45 degree line in all graphs. It seems that the result of 'Reference Condition' is almost similar with the results of the other neighboring color conditions.



(a) Desaturated

(b) Saturated

(c) Dark

(d) Light

Figure 19. Hue Results Comparison according to Neighboring Color Conditions

Table 8 shows t-test result of Hue between each neighboring color condition and 'Reference Condition'. If Hue is affected significantly between two conditions, p-value should be less than 0.05.

Table 8. T-test Result of Hue between Each Neighboring Color Condition and 'Reference Condition'

	Neighboring Color Condition			
	Desaturated	**Saturated**	**Dark**	**Light**
t-value	-0.611	-0.281	*-1.209*	-2.219
p	*0.548*	*0.782*	0.240	*0.038*

As shown in the table, p value showed less than 0.05 in 'Light' condition, so Hue was affected significantly comparing with 'Reference Condition'. In case of the other conditions, 'Desaturated', 'Saturated', and 'Dark', p value showed higher than 0.05, so there were no significant differences in Hue evaluation according to the conditions.

To investigate the effect of neighboring colors on Hue evaluation more in detail, two pairs of conditions were compared separately and those were 'Desaturated'-'Saturated' and 'Dark'-'Light'.

Figure 20 shows the Hue comparison results between 'Desaturated' and 'Saturated'. In the graph of Figure 20, x-axis means the averaged Hue response on 'Desaturated' and y-axis indicates the averaged Hue response on 'Saturated'. As shown in the Figure, most data point lied along the 45 degree line.

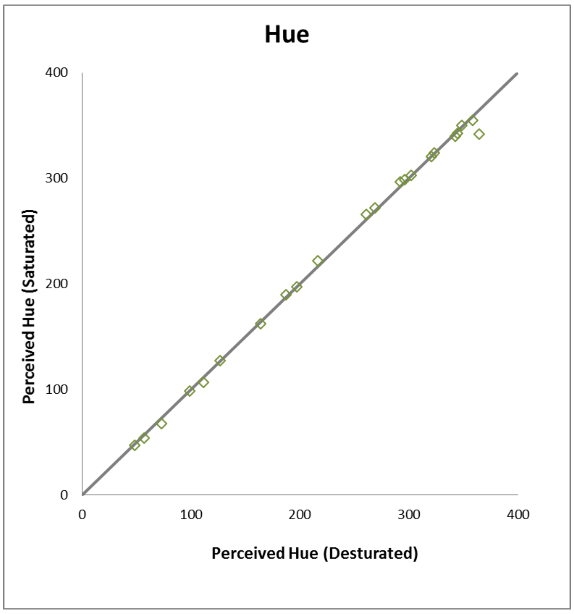


Figure 20. Hue Results Comparison between 'Desaturated' and 'Saturated'

As t-test result of Hue between 'Desaturated' and 'Saturated' conditions, t-value was 0.825 and p value was *0.419*. The p value was higher than 0.05, so there was no significant difference in Hue evaluation between two conditions, 'Desaturated' and 'Saturated'.

Figure 21 shows the Hue comparison results between ‘Dark’ and ‘Light’. In the graph of Figure 21, x-axis represents the averaged Hue response on ‘Dark’ and y-axis means the averaged Hue response on ‘Light’. As shown in the Figure, most data point lied along the 45 degree line.

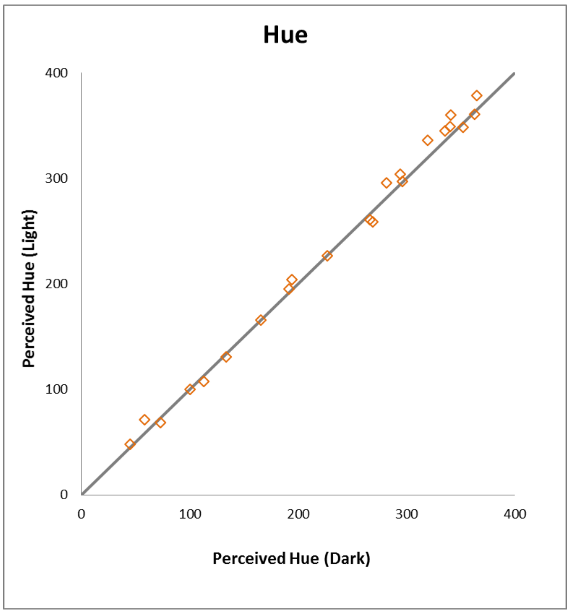
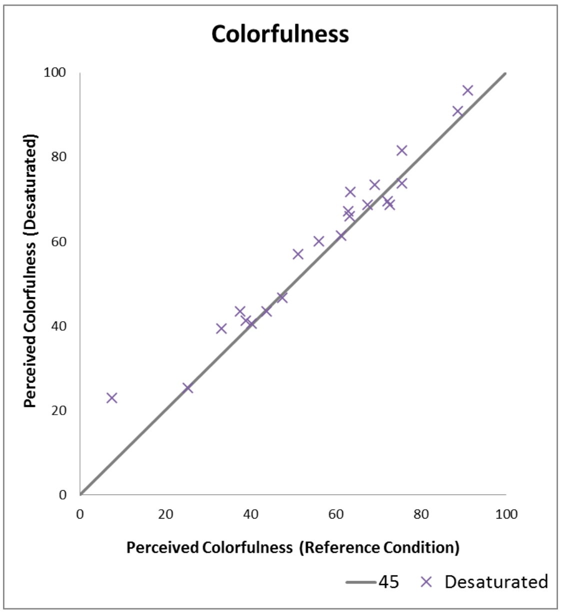


Figure 21. Hue Results Comparison between ‘Dark’ and ‘Light’

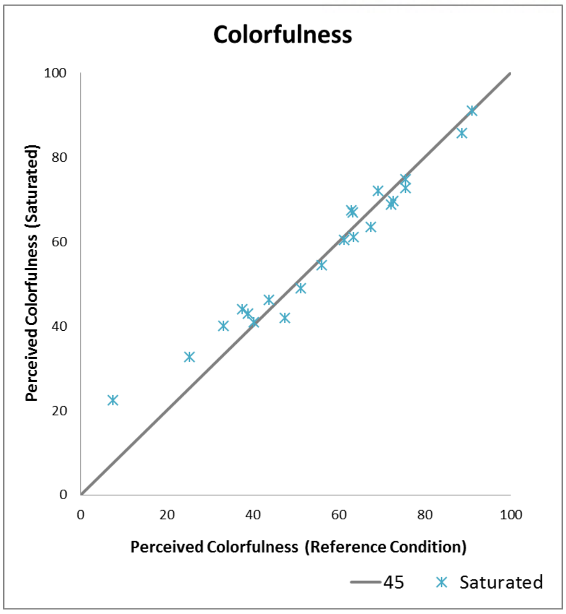
As t-test result of Hue between ‘Dark’ and ‘Light’ conditions, t-value was -2.258 and p value was *0.035*. The p value was less than 0.05, so there was significant difference in Hue evaluation between two conditions, ‘Dark’ and ‘Light’.

4.3.2 Colorfulness

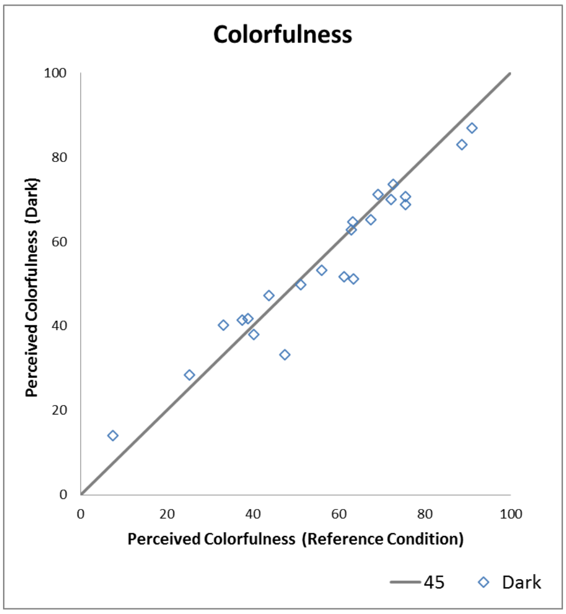
Figure 22 shows the comparison of Colorfulness results based on ‘Reference Condition’ according to neighboring color conditions. In each graph of Figure 22, x-axis represents the averaged Colorfulness response on ‘Reference Condition’ and y-axis means the averaged Colorfulness response on the other conditions, ‘Desaturated’, ‘Saturated’, ‘Dark’ and ‘Light’, respectively.



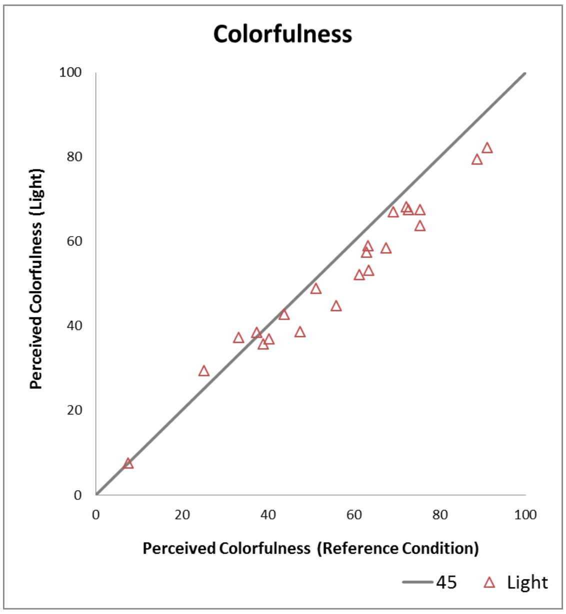
(a) Desaturated



(b) Saturated



(c) Dark



(d) Light

Figure 22. Colorfulness Results Comparison According to Neighboring Color Conditions

As shown in the graphs of Figure 22, there were some shift in Colorfulness evaluation according to neighboring color conditions. Firstly, in case of ‘Dark’ and ‘Saturated’, data points are mostly distributed along the 45 degree line. In ‘Desaturated’, data points tended to be distributed above 45 degree line. It seemed that participants tended to evaluate Colorfulness higher than ‘Reference Condition’. In ‘Light’ condition, data points tended to be distributed below 45 degree line and it suggest that Colorfulness tended to be evaluated lower than ‘Reference Condition’.

Table 9 shows t-test result of Colorfulness between each neighboring color condition and ‘Reference Condition’. If Colorfulness is affected significantly between two conditions, p-value should be less than 0.05.

Table 9. T-test Result of Colorfulness between Each Neighboring Color Condition and ‘Reference Condition’

	Neighboring Color Condition			
	Desaturated	**Saturated**	**Dark**	**Light**
t-value	-3.183	-1.068	1.407	4.899
p	*0.005*	*0.298*	*0.174*	*0*

As shown in the table, p value showed less than 0.05 in ‘Desaturated’ and ‘Light’ conditions, so Hue was affected significantly in the conditions comparing with ‘Reference Condition’. In case of the other conditions, ‘Saturated’ and ‘Dark’, p value showed higher than 0.05, so there were no significant differences in Hue evaluation according to the conditions.

To investigate the effect of neighboring colors on Colorfulness evaluation in detail, two pairs of conditions were compared separately and those were 'Desaturated'-'Saturated' and 'Dark'-'Light'.

Figure 23 shows the Colorfulness comparison results between 'Desaturated' and 'Saturated'. In the graph of Figure 23, x-axis means the averaged Colorfulness response on 'Desaturated' and y-axis means the averaged Colorfulness response on 'Saturated'.

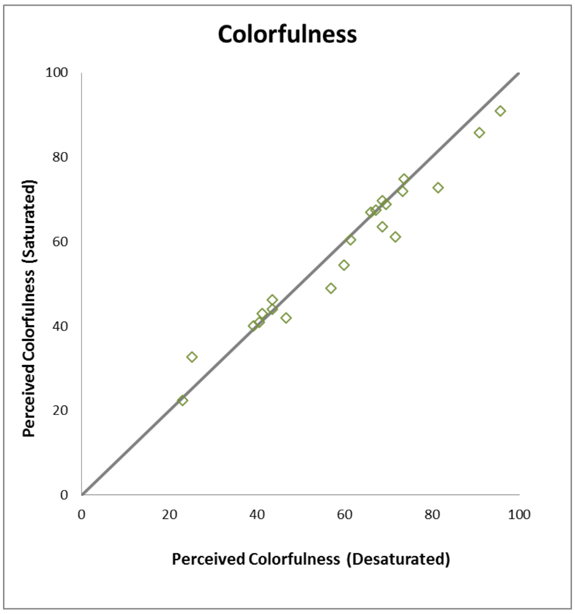
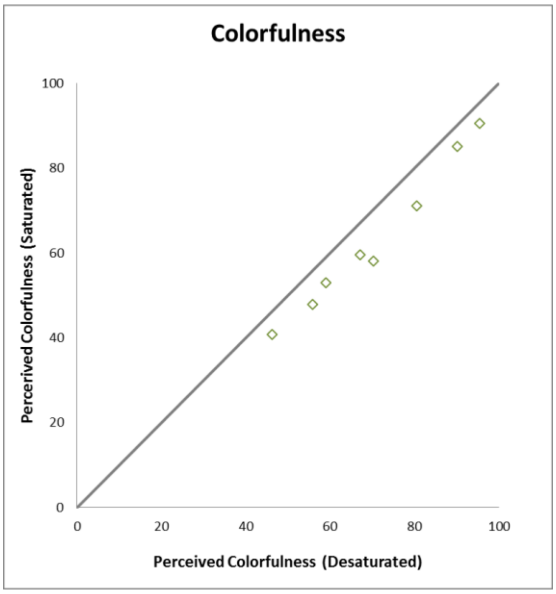


Figure 23. Colorfulness Results Comparison between 'Desaturated' and 'Saturated'

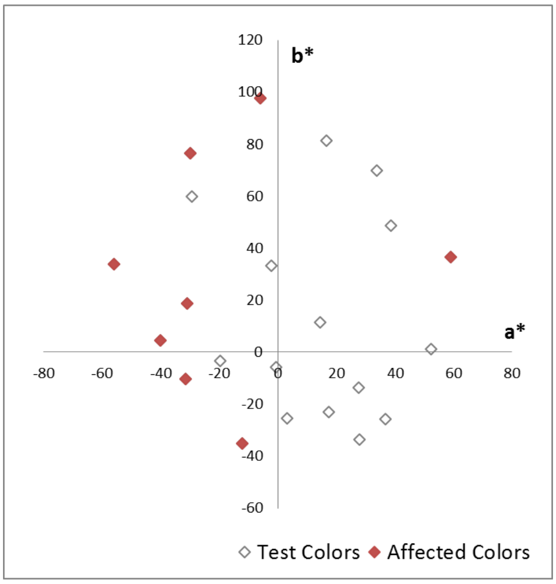
As t-test result of Colorfulness between 'Desaturated' and 'Saturated' conditions, t-value was 1.964 and p value was *0.063*. The p value was higher than 0.05, so there was no significant difference in Colorfulness evaluation between two conditions, 'Desaturated' and 'Saturated'.

However, as shown in the Figure 23, some data points are distributed below 45 degree line meaning that participants tended to evaluate Colorfulness higher in 'Desaturated' than 'Saturated'. These test colors were analyzed separately.

Figure 24 shows 8 test colors, *1*, *5*, *7*, *8*, *9*, *19*, *20*, *22* (Table 4), which were seemed to be affected in Colorfulness between 'Desaturated' and 'Saturated'. In Figure 24, graph (a) shows the Colorfulness comparison results of 8 test colors and graph (b) shows the distribution of test colors in CIELAB a*b* color space which 8 colors are highlighted as red filled.



(a) Colorfulness results of 8 test colors



(b) 8 test colors on CIELAB a*b* color space

Figure 24. Test Colors Affected in Colorfulness between 'Desaturated' and 'Saturated'

As shown in Figure 24. (b), the 8 test colors were shifted downward 45 degree line and those were mostly located outer parts of all test colors in CIELAB a*b* color space. As the data point is far from the zero point, chroma becomes higher in CIELAB a*b* color space.

Also t-test was done with 8 test colors between 'Desaturated' and 'Saturated' conditions. As a result, t-value was 2.610 and p value was *0.035*. The p value was less than 0.05, so Colorfulness of 8 test colors with high colorfulness were affected significantly in Colorfulness between 'Desaturated' and 'Saturated'.

Figure 25 shows the Colorfulness comparison results between 'Dark' and 'Light'. In the graph of Figure 25, x-axis means the averaged Colorfulness response on 'Dark' and y-axis represents the averaged Colorfulness response on 'Light'. As shown in the Figure, most data points were distributed below 45 degree line.

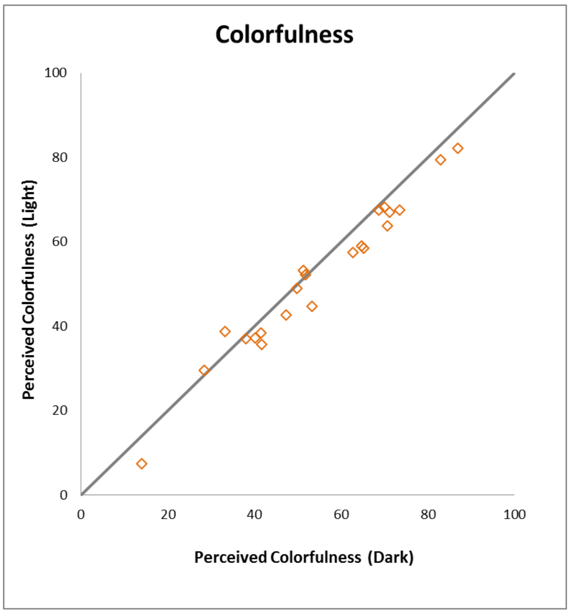
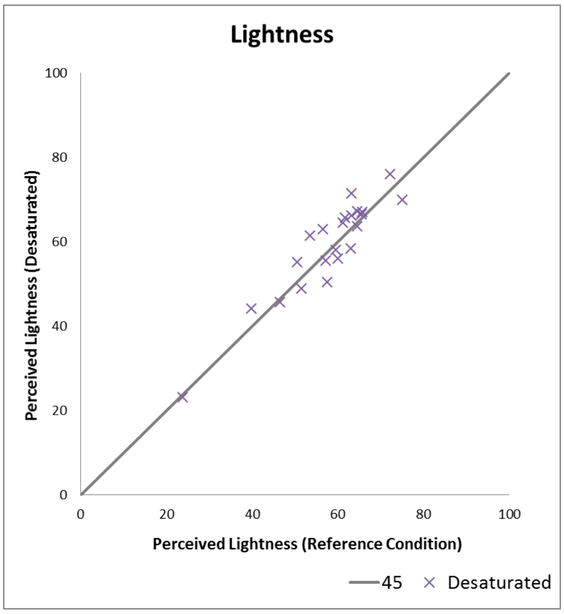


Figure 25. Colorfulness Results Comparison between 'Dark' and 'Light'

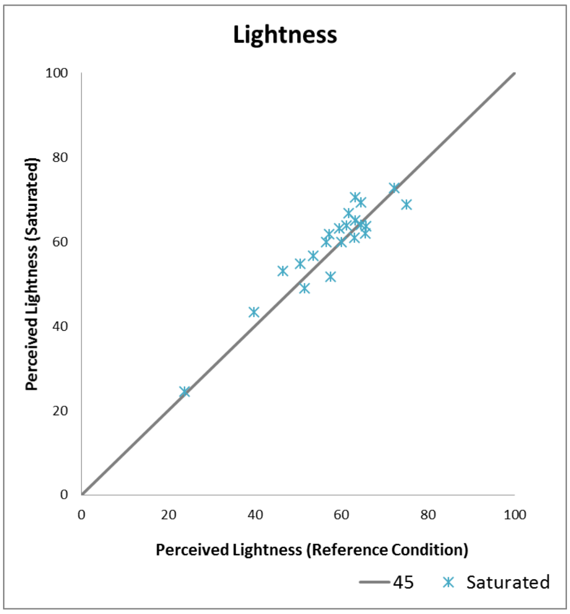
As t-test result of Colorfulness between 'Dark' and 'Light' conditions, t-value was 4.377 and p value was *0*. The p value was less than 0.05, so Colorfulness evaluation was affected significantly between 'Dark' and 'Light'.

4.3.3 Lightness

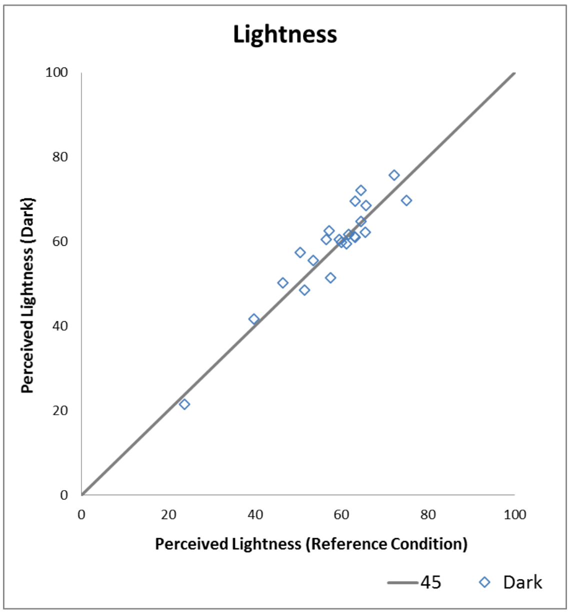
Figure 26 shows the comparison of Lightness results based on ‘Reference Condition’ according to neighboring color conditions. In each graph of Figure 26, x-axis represents the averaged Lightness response on ‘Reference Condition’ and y-axis means the averaged Lightness response on the other conditions, ‘Desaturated’, ‘Saturated’, ‘Dark’ and ‘Light’, respectively.



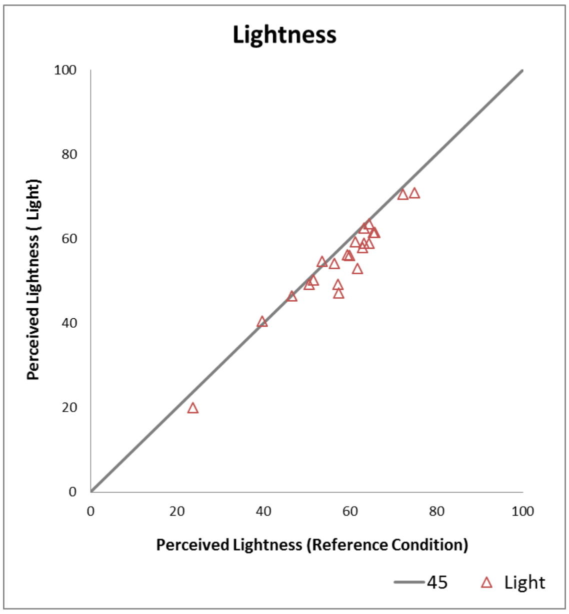
(a) Desaturated



(b) Saturated



(c) Dark



(d) Light

Figure 26. Colorfulness Results Comparison According to Neighboring Color Conditions

As shown in the Figure 26, in case of ‘Desaturated’, ‘Saturated’, and ‘Dark’, most data points were distributed along the 45 degree line. In ‘Light’ condition, most data points were distributed downward 45 degree line.

Table 10 shows t-test result of Lightness between each neighboring color condition and ‘Reference Condition’. If Lightness is affected significantly between two conditions, p-value should be less than 0.05.

Table 10. T-test Result of Lightness between Each Neighboring Color Condition and ‘Reference Condition’

	Neighboring Color Condition			
	Desaturated	**Saturated**	**Dark**	**Light**
t-value	-1.166	-1.666	-1.076	5.266
p	*0.257*	*0.111*	*0.294*	*0*

As shown in the table, p value showed higher than 0.05 in all conditions, therefore there were no significant differences in Lightness evaluation according to neighboring color conditions.

As shown in the table, p value showed less than 0.05 in ‘Light’ condition, so Lightness was affected significantly in the condition comparing with ‘Reference Condition’. In case of the other conditions, ‘Desaturated’, ‘Saturated’ and ‘Dark’, p value showed higher than 0.05, so there were no significant differences in Lightness evaluation according to the conditions.

To investigate the effect of neighboring colors on Lightness evaluation more in detail, two pairs of conditions were compared separately and those were ‘Desaturated’-‘Saturated’ and ‘Dark’-‘Light’.

Figure 27 shows the Lightness comparison results between ‘Desaturated’ and ‘Saturated’. In the graph of Figure 27, x-axis means the averaged Lightness response on ‘Desaturated’ and y-axis means the averaged Lightness response on ‘Saturated’. As shown in the Figure, almost every data point lied along the 45 degree line.

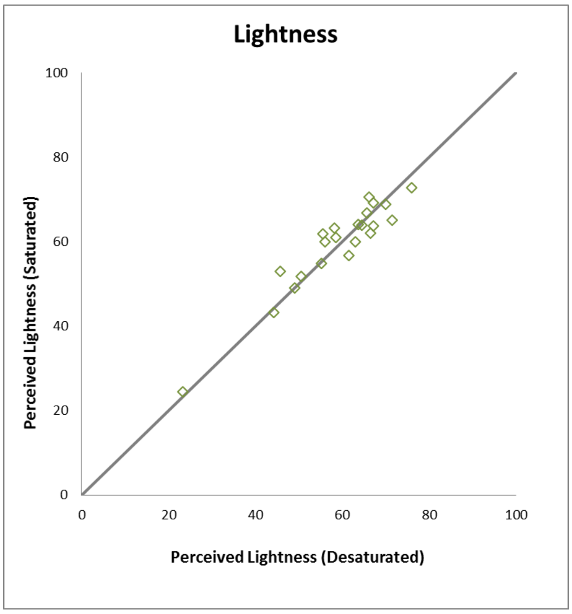


Figure 27. Lightness Results Comparison between ‘Desaturated’ and ‘Saturated’

As t-test result of Lightness between ‘Desaturated’ and ‘Saturated’ conditions, t-value was -0.372 and p value was *0.713*. The p value was higher than 0.05, so there was no significant difference in Lightness evaluation between two conditions, ‘Desaturated’ and ‘Saturated’.

Figure 28 shows the Lightness comparison results between ‘Dark’ and ‘Light’. In the graph of Figure 28, x-axis means the averaged Lightness response on ‘Dark’ and y-axis means the averaged Lightness response on ‘Light’. As shown in the Figure, most data points tended to be distributed downward 45 degree line.

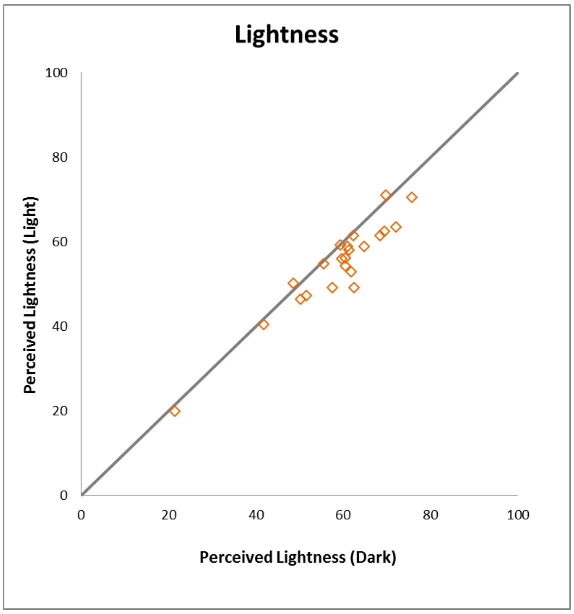


Figure 28. Lightness Results Comparison between ‘Dark’ and ‘Light’

As t-test result of Lightness between ‘Dark’ and ‘Light’ conditions, t-value was 5.339 and p value was *0*. The p value was less than 0.05, so participants evaluated Lightness significantly higher in ‘Dark’ than ‘Light’.

This result can be explained by Simultaneous Contrast effect. The effect illustrates that Lightness is affected by its surroundings or background. As intended, the average CIELAB L* values of ‘Dark’ and ‘Light’ were 46.0 and 76.9, respectively. In the condition ‘Dark’, it consisted of relatively dark neighboring colors, so test colors might be perceived relatively lighter compared to neighboring colors. In contrast, participants might evaluate Lightness of same test colors lower in ‘Light’ condition, because the condition consisted of relatively light neighboring colors, so test colors might be perceived relatively darker comparing with neighboring colors.

4.3.4 Summary

In the experiment, Hue, Colorfulness, and Lightness seemed to be affected by neighboring colors.

The experiment was designed based on two hypotheses as follow:

Hypothesis 1: If average Chroma of neighboring colors changes, Colorfulness will change

Hypothesis 2: If average Lightness of neighboring colors changes, Lightness will change

In case of *Hypothesis 1*, Colorfulness was evaluated significantly higher as neighboring colors became desaturated. Especially, 8 test colors with high colorfulness was affected in Colorfulness between ‘Desaturated’ and ‘Saturated’.

In case of *Hypothesis 2*, Lightness tended to be evaluated significantly lower as neighboring colors became lighter.

As one of unexpected results, Colorfulness also tended to be evaluated significantly lower as neighboring colors became lighter. Colorfulness evaluation tended to be affected by both Chroma and Lightness of neighboring colors. The other unexpected result, Hue evaluation was affected as neighboring colors became lighter.

4.4 Model Performance Test

In this research, two color appearance models, CIELAB and CIECAM02, were used to estimate the color appearance of the given experimental condition. The experimental results were compared with the estimated results of both models. To compare them quantitatively, Coefficient of Variation (CV) values were calculated between each model's estimated results and experimental results.

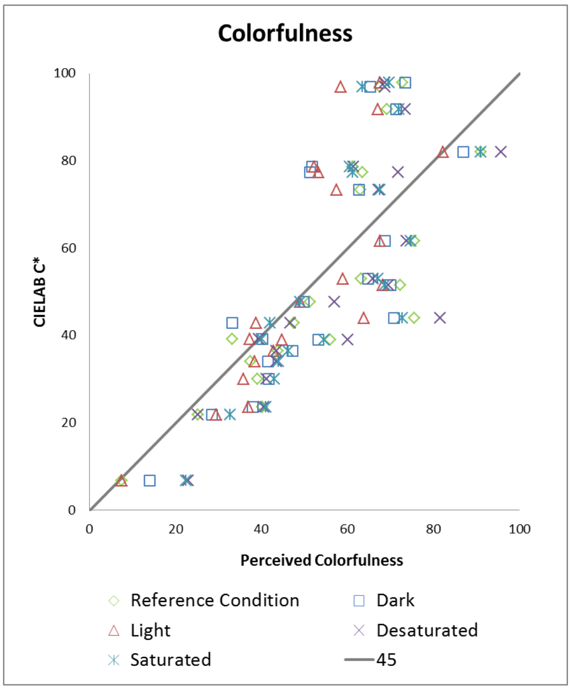
4.4.1 CIELAB

The experimental results of Colorfulness and Lightness were compared with CIELAB C* and L*, respectively. CIELAB C* value is estimated as Chroma and L* is estimated as Lightness. However Hue was excluded in comparison. Because evaluated Hue is in range from 0 to 400, but CIELAB hue-angle is in range from 0 to 360. In case of Colorfulness, there was no maximum value for evaluation. To match the scale between experimental results and CIELAB C* values, C* values were re-scaled to have same average value with the experimental results of 'Reference Condition'.

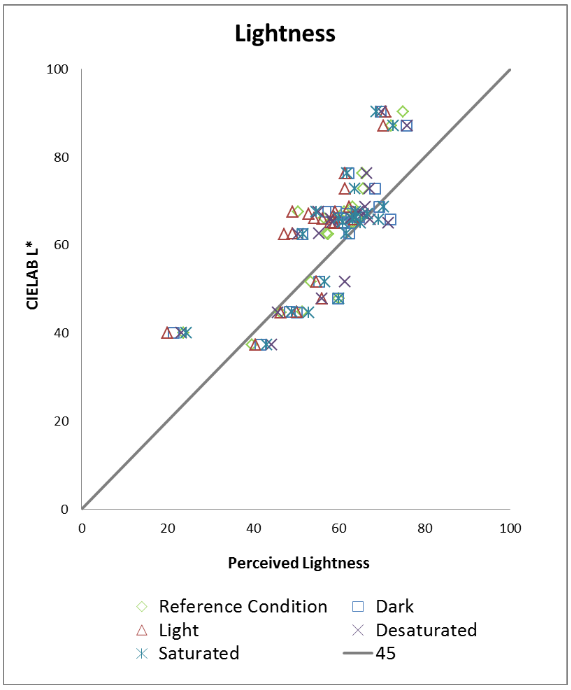
Figure 29 shows the comparison between estimated results of CIELAB and experimental results according to Colorfulness and Lightness, respectively. In each graph, x-axis represents the average of experimental results and y-axis represents the estimated CIELAB values. To explain the symbols of each graph, green diamond, blue square, red triangle, purple X and blue-green X-bar represent 'Reference Condition', 'Dark', ' Light', 'Desaturated' and 'Saturated', respectively.

Table 11 shows the Coefficient of Variation (CV) values between estimated results of CIELAB and experimental results according to neighboring color conditions. The CV values varied from 16.1 to 20.7 for Colorfulness and from 8.8 to 12.7 for Lightness. The model performances were different according to neighboring color conditions, but CIELAB model estimated each color appearance quite well overall.

Model performances were also compared according to neighboring color conditions. On average, 'Reference Condition' showed the lowest CV value as 12.6 indicating that CIELAB model estimated the color appearance most closely with the results of 'Reference Condition'. By comparing CV values of Colorfulness and Lightness, 'Reference Condition' showed the best performance among neighboring color conditions. It is seemed that the performance of CIELAB model tended to be worse when the neighboring color condition became extreme in a specific color attribute.



(a) Colorfulness



(b) Lightness

Figure 29. Comparison between Experimental Results and CIELAB Values

Table 11. Coefficient of Variation (CV) Values between Estimated Results of CIELAB and Experimental Results (unit: %)

	Neighboring Color Condition				
	Reference Condition	**Dark**	**Light**	**Desaturated**	**Saturated**
Colorfulness	16.5	19.9	16.1	19.9	20.7
Lightness	8.8	9.2	12.7	9.1	9.0
Average	12.6	14.6	14.4	14.5	14.8

4.4.2 CIECAM02

To calculate the estimated color appearance of CIECAM02, some specific input data regarding experimental condition are needed. Table 12 shows input values for calculating CIECAM02. In the Table, L_A was calculated as the Y value of reference white divided by 5, F, c, and N_c are the values under 'Dark' condition and Y_b is a relative Y value of gray background.

Table 12. CIECAM02 Input Values

	CIECAM02 Parameters				
	L_A	**F**	**c**	**N_c**	**Y_b**
Input Value	55.24	0.8	0.525	0.8	37.87

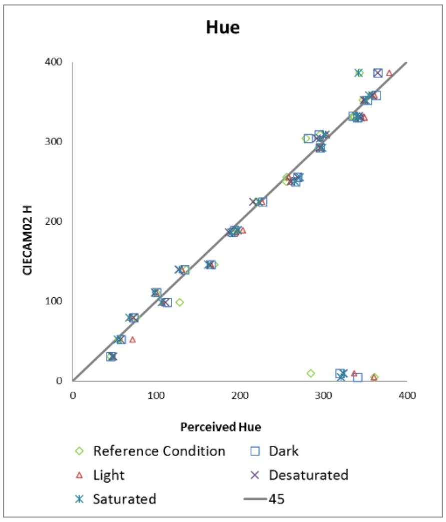
The experimental results of Hue, Colorfulness, and Lightness were compared with CIECAM02 H, M, and J, respectively. CIECAM02 H is estimated Hue, M is estimated Colorfulness, and J is estimated Lightness.

In case of Colorfulness, there was no maximum value for evaluation. To match the scale between experimental results and CIECAM02 M values, each CIECAM02 M value was re-scaled to have equal average value with the experimental results of 'Reference Condition'.

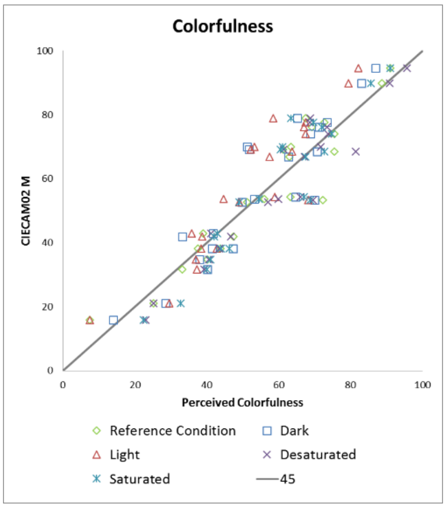
Figure 30 shows the comparison between estimated results of CIECAM02 and experimental results according to Hue, Colorfulness and Lightness. In each graph, x-axis represents the average of experimental results and y-axis represents estimated CIECAM02 values. As an explanation for symbols of each graph, green diamond, blue square, red triangle, purple X and blue-green X-bar represent 'Reference Condition', 'Dark', ' Light', 'Desaturated' and 'Saturated', respectively.

Table 13 shows the Coefficient of Variation (CV) values between estimated results of CIECAM02 and experimental results according to neighboring color conditions. The CV values for Hue varied from 12.2 to 14.4. The performance of Colorfulness was acceptable that CV value was in range from 8.4 to 12.6. In case of Lightness, CV values varied from 7.8 to 11.0.

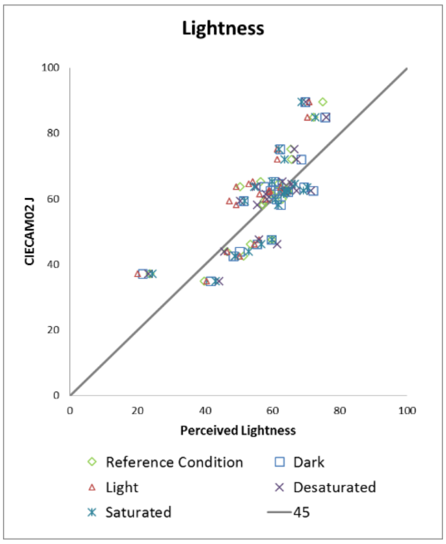
The model performance was different according to neighboring color conditions. On average, both 'Reference Condition' and 'Desaturated' showed relatively low CV values as 9.9 and 9.7, respectively, meaning that each result had quite strong correlation with the experimental results. It is also seemed that the performance of CIECAM02 model tended to be worse when the neighboring color conditions became extreme in a specific color attribute, especially estimating Colorfulness and Lightness.



(a) Hue



(b) Colorfulness



(c) Lightness

Figure 30. Comparison between Experimental Results and CIECAM02 Values

Table 13. Coefficient of Variation (CV) Values between Estimated Results of CIECAM02 and Experimental Results (unit: %)

	Neighboring Color Condition				
	Reference Condition	**Dark**	**Light**	**Desaturated**	**Saturated**
Hue	13.0	13.2	14.4	12.2	12.3
Colorfulness	8.9	9.8	12.6	8.4	9.2
Lightness	7.8	9.0	11.0	8.6	9.4
Average	9.9	10.7	12.7	9.7	10.3

Each neighboring color condition consists of different colors, so each condition has different CIECAM02 input Y_b value. Therefore, CIECAM02 performances were also compared by using different Y_b value according to the conditions. To test the model, the experimental results of ‘Reference Condition’ and ‘Light’ condition were used, because there were both Colorfulness and Lightness shift between the conditions. The degree of color appearance changes was compared with CIECAM02 value changes between ‘Reference Condition’ and ‘Light’ condition to investigate whether CIECAM02 was able to estimate color appearance shift between the conditions.

The CIECAM02 input Y_b values were set in two different methods. First, Y_b value was set based on each condition’s average Y value of 24 neighboring colors. Second, Y_b value was set based on each condition’s overall background considering the ratio of neighboring colors which occupied about 13.7% of the overall background in each condition. The results and CIECAM02 values were compared in Colorfulness and Lightness, since Hue is not affected by changing CIECAM02 Y_b value.

Table 14 shows CIECAM02 Y_b values set according to neighboring color conditions in two different methods.

Table 14. CIECAM02 Y_b Values for Testing the Model

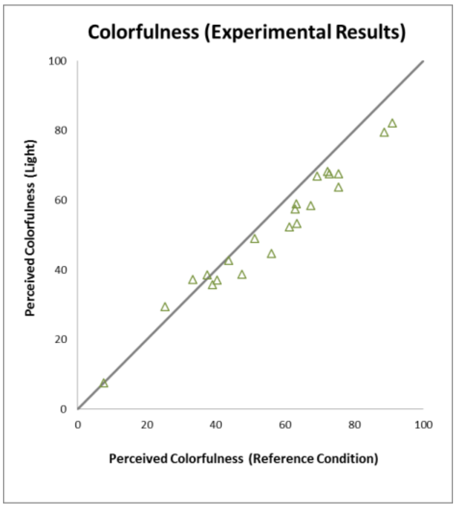
	CIECAM02 Y_b	
	(1) Y_b = Neighboring Colors	**(2) Y_b = Overall Background**
Reference Condition	32.96	37.20
Light	51.71	39.77

Figure 31 and Figure 32 show the Colorfulness and Lightness comparison results, respectively, between experimental results and CIECAM02 values of ‘Reference Condition’ and ‘Light’ according to different CIECAM02 Y_b values.

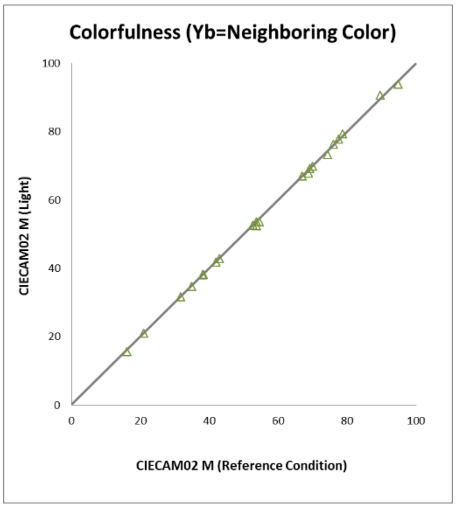
In Both Figure 31 and Figure 32, graph (a) represents the experimental result, graph (b) shows the CIECAM02 values comparison when Y_b was set based on neighboring colors and graph (c) shows the CIECAM02 values comparison when Y_b was set based on the overall background. In each graph, x-axis represent the result of ‘Reference Condition’ and y-axis represent the result of ‘Light’.

As shown in Figure 31 (a), the data points were distributed downward 45 degree line which means that participants evaluated Colorfulness lower in ‘Light’ condition than ‘Reference Condition’. In Figure 31 (b) and (c), data points were distributed slightly downward 45 degree line, but the degree of shift downward seemed much less than the experimental results. That is, the CIECAM02 model estimated the degree of Colorfulness change between ‘Reference Condition’ and ‘Light’ condition less than the experimental result.

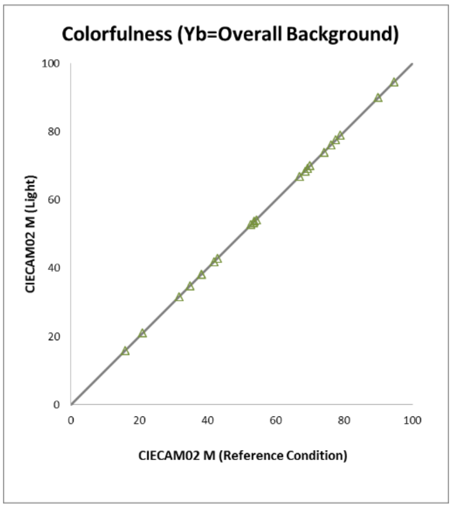
In Figure 32 (a), the data points were distributed downward 45 degree line which means that participants evaluated Lightness lower in ‘Light’ condition than ‘Reference Condition’. In Figure 32 (b) and (c), data points were distributed downward 45 degree line and the degree of data points shift seemed bigger in graph (b) than graph (c). However, the degree of shift still seemed much less than the experimental results. That is, the CIECAM02 model estimated the degree of Lightness change between ‘Reference Condition’ and ‘Light’ condition less than the experimental result.



(a) Colorfulness (Experimental)

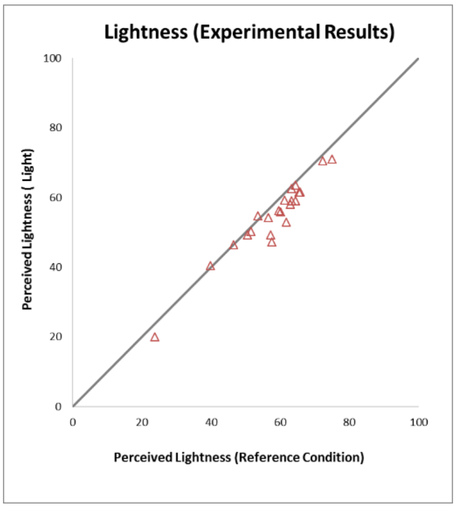


(b) CIECAM02 M (Y_b = Neighboring Colors)

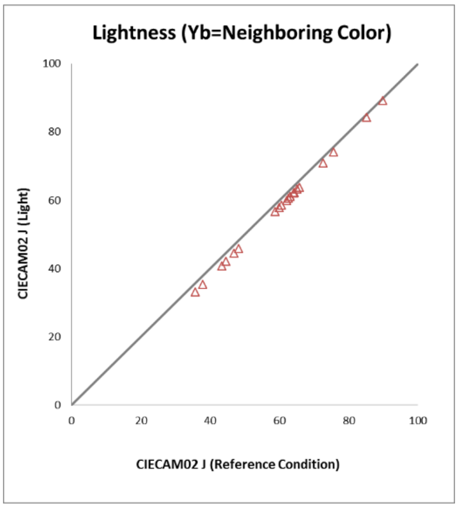


(c) CIECAM02 M (Y_b = Overall Background)

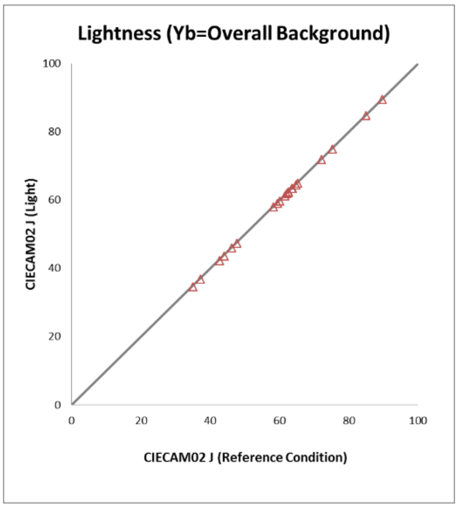
Figure 31. Comparison of Colorfulness and CIECAM02 M Difference between 'Reference Condition' and 'Light'



(a) Lightness (Experimental)



(b) CIECAM02 J (Y_b = Neighboring Colors)



(c) CIECAM02 J (Y_b = Overall Background)

Figure 32. Comparison of Lightness and CIECAM02 J Difference between 'Reference Condition' and 'Light'

4.4.3 Summary

As for the summary for model performance test, CIECAM02 showed better performance than CIELAB in overall. Both models' performances were different according to neighboring color conditions. The performance of both models tended to be worse as the neighboring color condition became extreme in a specific color attribute, especially when estimating Colorfulness and Lightness. When estimating the degree of Colorfulness and Lightness changes according to neighboring color conditions by CIECAM02, it could not estimate sufficiently in both attributes and tended to estimate the changes less than experimental results.

Based on the model performance test results, perceiving colors in Colorfulness and Lightness seemed to be affected more by colorful background colors than adjacent gray color. Also, an estimation of Colorfulness shift seemed not enough just by adjusting CIECAM02 Y_b value.

5. Conclusion and Discussion

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The purpose of the experiment was to investigate the effect of neighboring colors on color appearance. The color appearance experiment was carried out in the dark room by using a viewing booth. Total of 5 different neighboring color conditions were used in the experiment and those were 'Reference Condition', 'Desaturated', 'Saturated', 'Dark', and 'Light'. Each participant evaluated Hue, Colorfulness, and Lightness of 22 test colors by using magnitude estimation method. Total of 20 participants evaluated in each neighboring color condition. To analyze the data, all participants' responses were averaged by using arithmetic mean. Then the experimental results were analyzed according to neighboring color conditions. Furthermore the experimental results were compared with the estimated results of two different color appearance models, CIELAB and CIECAM02, respectively.

First of all, Repeatability was calculated per each participant. The result showed that the average CV values of Hue, Colorfulness and Lightness were 6.8, 16.1 and 11.2, respectively. Also Reproducibility was calculated to check the deviation between each participant's result and average of all participants' results. The results showed that CV values of Hue, Colorfulness and Lightness were 8.6, 15.9 and 12.2, respectively. Both results showed that Hue was the most consistent attribute and Colorfulness was the most difficult attribute to evaluate. The results were similar with the result of earlier color appearance experiment.

As for the findings of this experiment, Hue, Colorfulness, and Lightness tended to be affected by neighboring colors. First, Colorfulness was evaluated higher when neighboring colors were desaturated. Both Colorfulness and Lightness of test colors tended to be evaluated lower when neighboring colors were lighter. Hue evaluation was affected when neighboring colors were light.

As a comparison result of two color appearance models, CIECAM02 showed better performance than CIELAB in overall. The performances of both models tended to be worse as the neighboring color conditions became extreme in a specific color attribute, especially when estimating Colorfulness and Lightness. The degree of color appearance changes were compared between experimental results and CIECAM02 estimation values of 'Reference Condition' and 'Light'. As a result, CIECAM02 model could not estimate sufficiently the Colorfulness and Lightness changes according to neighboring color conditions and it estimated the changes less than experimental results in both Colorfulness and Lightness.

Based on the result of color appearance phenomena analysis, this research can be helpful to suggest a design guideline where color appearance matters according to neighboring colors. For example, it can be adapted in merchandise display of the store, the situation surrounded with various colors of LED spot lighting, advertisement, poster design, etc.

This research focused on the color appearance phenomena according to neighboring colors and model performance was also tested. Based on the research result, further research regarding color appearance should consider the surrounding environment.

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Appendix

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Appendix 1. Instructions for Participants

Session 1. Color Appearance Evaluation

You will be shown a series of test colors in a random order. Your task will be to tell me what lightness, colorfulness and hue you see.

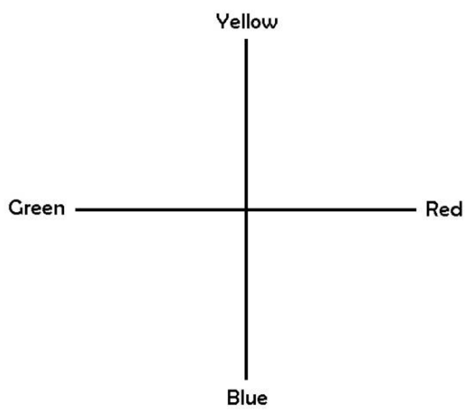
Hue is the attribute of a visual sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colors red, yellow, green, and blue.

Colorfulness is the attribute of a visual sensation according to which an area appears to exhibit more or less of its own hue.

Lightness is the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Hue scaling

There are four psychological primaries: red, yellow, green, and blue. These four colors can be arranged as points around a circle and lying at opposite ends of x and y axes. Hues lying at opposite ends of each axis cannot be sensed simultaneously. You are asked to describe a hue as a proportion of two neighboring primaries. Firstly, decide whether or not you can perceive any hue at all. If not, please reply "neutral." On the other hand, if the test colour does not appear neutral, then decide which of the four primaries is predominant. Next, decide whether or not you see a trace of any other primary hue. If so, identify it. Finally, estimate the proportions in which the two primaries stand, e.g., an orange colour may be 60% yellow and 40% red.



Colorfulness scaling

A neutral colour has no colorfulness, represented by zero on your scale. You are asked to assign a reasonable number to describe the colorfulness of the test colour. This is an open-ended scale since no top limit is set. The colorfulness of the reference colorfulness sample should always be remembered so that all subsequent test colors can be related to it. (This reference colour is also displayed in the test pattern.)

Lightness scaling

Use the reference white as a standard which has a lightness of 100 and your imaginary black has a lightness of zero. Describe the test colour by assigning a number which is in the right relationship to the reference white and the imaginary black (The reference white is displayed in the test pattern).

Appendix 2. Color Measurement Data

2.1. Test Color

Test Color	X	Y	Z
1	111.5	101.4	97.8
2	153.8	139.3	20.3
3	156.0	123.9	24.6
4	130.6	98.0	34.3
5	80.5	45.9	17.0
6	81.7	85.2	45.5
7	199.5	212.3	26.9
8	63.6	107.3	60.3
9	153.3	193.7	44.4
10	78.0	103.0	25.5
11	63.1	86.3	68.5
12	98.6	98.3	199.5
13	109.5	97.0	189.3
14	115.7	94.1	154.1
15	57.6	39.7	95.0
16	36.9	26.8	84.3
17	30.1	31.1	45.9
18	66.6	39.5	47.5
19	69.8	94.7	144.9
20	70.8	103.3	116.3
21	79.8	97.2	129.6
22	47.0	54.7	149.6

2.2. Neighboring Color

2.2.1. Reference Condition

Neighboring Color	X	Y	Z
1	88.1	108.2	50.1
2	26.5	43.9	55.6
3	147.3	185.3	171.7
4	167.5	172.3	283.1
5	68.4	72.1	31.1
6	87.9	116.8	104.7
7	64.5	58.6	37.8
8	152.0	121.1	151.5
9	38.7	62.1	53.3
10	57.7	51.0	89.2
11	121.0	135.9	107.7
12	29.1	26.8	73.6
13	46.1	65.6	82.2
14	29.6	28.5	26.9
15	69.3	46.7	62.2
16	23.4	29.9	42.2
17	35.3	31.4	104.9
18	202.2	179.2	172.5
19	58.9	61.3	50.7
20	54.2	69.3	131.0
21	184.9	177.0	261.8
22	136.8	134.1	130.3
23	170.1	133.3	107.6
24	73.1	74.6	117.1

2.2.2. Desaturated

Neighboring Color	X	Y	Z
1	22.0	23.6	32.1
2	23.8	26.8	32.3
3	25.2	23.6	25.6
4	22.1	25.3	27.3
5	67.8	64.6	77.8
6	73.9	71.0	77.2
7	26.3	28.9	27.5
8	30.9	32.1	29.0
9	29.6	28.5	26.9
10	23.3	21.2	26.7
11	68.3	75.0	103.2
12	21.5	21.6	35.2
13	25.6	24.0	35.6
14	136.8	134.1	130.3
15	119.8	116.9	168.4
16	66.6	76.2	77.5
17	73.1	74.6	117.1
18	58.9	61.3	50.7
19	73.1	70.1	62.0
20	126.9	130.3	196.9
21	107.0	119.8	166.7
22	58.9	69.7	83.1
23	127.2	144.9	148.5
24	77.4	72.6	109.9

2.2.3. Saturated

Neighboring Color	X	Y	Z
1	31.8	25.2	58.0
2	54.2	69.3	131.0
3	109.5	137.0	225.0
4	29.1	26.8	73.6
5	46.1	65.6	82.2
6	87.9	116.8	104.7
7	146.4	128.0	238.4
8	152.0	121.1	151.5
9	50.2	35.9	30.3
10	29.7	44.9	39.0
11	50.3	35.2	51.2
12	109.1	114.7	58.9
13	68.4	72.1	31.1
14	57.1	47.0	21.2
15	52.9	68.5	150.1
16	50.1	38.3	89.6
17	44.7	43.7	127.3
18	26.5	43.9	55.6
19	170.1	133.3	107.6
20	69.3	46.7	62.2
21	35.3	31.4	104.9
22	38.7	62.1	53.3
23	88.1	108.2	50.1
24	81.4	121.8	133.7

2.2.4. Dark

Neighboring Color	X	Y	Z
1	29.1	26.8	73.6
2	23.8	26.8	32.3
3	23.2	28.4	57.2
4	29.6	28.5	26.9
5	26.3	28.9	27.5
6	23.4	29.9	42.2
7	30.9	32.1	29.0
8	50.3	35.2	51.2
9	50.2	35.9	30.3
10	50.1	38.3	89.6
11	26.5	43.9	55.6
12	29.7	44.9	39.0
13	57.1	47.0	21.2
14	49.4	49.8	101.6
15	60.9	50.5	68.0
16	57.7	51.0	89.2
17	39.2	51.4	68.8
18	44.3	52.3	89.7
19	62.1	52.9	49.8
20	40.4	53.6	52.2
21	30.2	53.6	38.7
22	46.3	57.0	34.5
23	64.5	58.6	37.8
24	58.9	61.3	50.7

2.2.5. Light

Neighboring Color	X	Y	Z
1	119.8	116.9	168.4
2	132.0	119.7	120.7
3	107.0	119.8	166.7
4	152.0	121.1	151.5
5	81.4	121.8	133.7
6	146.4	128.0	238.4
7	126.9	130.3	196.9
8	137.2	130.5	158.3
9	128.1	131.5	258.1
10	86.3	132.1	95.0
11	170.1	133.3	107.6
12	136.8	134.1	130.3
13	128.9	135.3	101.7
14	121.0	135.9	107.7
15	109.5	137.0	225.0
16	115.3	137.8	160.6
17	127.2	144.9	148.5
18	180.5	158.8	193.1
19	128.5	165.2	188.4
20	167.5	172.3	283.1
21	184.9	177.0	261.8
22	202.2	179.2	172.5
23	153.9	180.3	263.6
24	147.3	185.3	171.7

Appendix 3. Color Appearance Data

3.1. Reference Condition

Test Color	Hue	Colorfulness	Lightness
1	285.3	25.3	61.8
2	76.0	72.8	65.5
3	55.0	69.3	65.8
4	45.5	63.0	56.5
5	360.8	91.0	60.0
6	128.0	33.3	57.5
7	99.8	88.8	75.0
8	191.3	63.5	63.3
9	136.0	67.5	72.3
10	169.3	61.3	50.5
11	195.5	47.5	57.3
12	296.0	39.0	64.5
13	336.3	37.5	64.5
14	357.5	43.8	63.3
15	347.5	63.3	51.5
16	336.0	72.3	39.8
17	278.9	7.5	23.8
18	343.3	75.5	46.5
19	256.3	56.0	63.0
20	219.5	51.3	61.3
21	255.3	40.3	59.5
22	294.5	75.5	53.5

3.2. Desaturated

Test Color	Hue	Colorfulness	Lightness
1	323.5	25.3	65.8
2	73.0	68.7	66.5
3	57.0	73.4	67.2
4	48.8	67.3	63.0
5	321.0	95.8	56.0
6	111.3	39.4	50.5
7	98.7	90.9	70.0
8	187.0	71.8	66.3
9	126.9	68.8	76.0
10	164.3	61.4	55.3
11	197.5	46.8	55.5
12	302.4	41.3	63.8
13	344.8	43.5	67.3
14	358.3	43.5	71.5
15	348.5	66.0	49.0
16	342.5	69.5	44.3
17	292.3	23.0	23.3
18	364.8	73.8	45.8
19	269.0	60.0	58.5
20	216.3	57.0	64.5
21	261.0	40.6	58.2
22	296.2	81.5	61.5

3.3. Saturated

Test Color	Hue	Colorfulness	Lightness
1	324.0	32.8	66.8
2	67.5	69.8	62.0
3	54.0	72.0	63.8
4	47.4	67.5	60.0
5	320.9	91.0	60.0
6	106.6	40.0	51.8
7	98.4	85.8	68.8
8	190.0	61.2	70.5
9	127.7	63.5	72.8
10	162.5	60.5	54.8
11	197.0	42.0	61.8
12	302.8	43.0	64.0
13	342.3	44.0	69.3
14	354.8	46.3	65.0
15	350.3	67.0	49.0
16	339.5	68.8	43.3
17	296.3	22.5	24.5
18	342.1	74.8	53.0
19	271.8	54.5	61.0
20	222.3	49.0	63.9
21	265.8	41.0	63.3
22	298.9	72.8	56.8

3.4. Dark

Test Color	Hue	Colorfulness	Lightness
1	320.0	28.5	61.8
2	72.8	73.5	62.3
3	58.0	71.3	68.5
4	45.3	62.8	60.5
5	341.0	87.0	59.8
6	112.8	40.3	51.5
7	100.3	83.0	69.8
8	191.5	51.3	69.5
9	133.8	65.3	75.8
10	165.5	51.8	57.5
11	194.0	33.3	62.5
12	294.5	41.8	64.8
13	340.5	41.5	72.1
14	362.8	47.3	61.0
15	352.3	64.8	48.5
16	335.5	70.0	41.8
17	281.9	14.0	21.5
18	364.8	68.8	50.3
19	269.3	53.3	61.3
20	227.3	49.8	59.4
21	266.3	38.0	60.5
22	296.3	70.8	55.5

3.5. Light

Test Color	Hue	Colorfulness	Lightness
1	336.5	29.5	53.0
2	68.5	67.5	61.5
3	71.5	67.0	61.5
4	48.0	57.5	54.3
5	360.3	82.3	56.0
6	107.3	37.3	47.3
7	100.0	79.5	71.0
8	195.5	53.3	62.5
9	130.5	58.5	70.5
10	165.8	52.3	49.3
11	203.8	38.8	49.3
12	304.3	35.8	59.0
13	349.5	38.5	63.5
14	361.0	42.8	59.0
15	348.8	59.0	50.3
16	345.3	68.3	40.5
17	296.1	7.5	20.0
18	378.5	67.5	46.5
19	258.8	44.8	58.0
20	226.8	49.0	59.3
21	260.8	37.0	56.3
22	297.5	63.8	54.8

Acknowledgements

Epilogue

Finally I am done! I feel like two years passed so fast. It has been 8 years after I started to live in Ulsan, so now I feel like here as a hometown. In UNIST, the very best thing was people! I think almost every people here are so warm and nice. Most of all, I want to say thank you very much to my advisor, professor Youngshin Kwak. I always respect you! Also I really appreciate to professor Chajoong Kim and professor Sungphil Kim for screening this paper and giving good advices. To color laboratory members, I was so happy to be with you. Yeseul nuna and Sooyeon nuna helped me in every aspect and took care of me! So thanks! Also cute Hyeyoung, you helped me a lot, too. Thank you! Finally, special thanks to my families and friends. I can laugh and be happy because of you!

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