Color Appearance and Color Connotation for Unrelated Colors

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Color Appearance and Color Connotation for Unrelated Colors

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Abstract

The purposes of this research are to identify relation between color perception and connotation of unrelated colors, and to develop mathematical models for color connotation. This research is significant in the sense that it provides fundamental data for color appearance and color connotation of unrelated colors on which there is a lack of research until now. To achieve these purposes, two psychophysical experiments were carried out.

Experiment 1: *Color perception for unrelated colors*, to investigate color perception for unrelated color using the 50 color stimuli beamed through a square hole. Twenty-two observers have answered their perceived magnitudes of three color attributes based on the magnitude estimation.

Experiment 2: *Color connotation for unrelated colors*, to examine color connotation for unrelated colors using the 50 color stimuli. Thirty-two observers have answered their connotation about each color stimulus using the 10 color connotation scales which consist of one aesthetic scale (i.e. “like – Dislike”) and nine non-aesthetic scales (i.e. “Warm – Cool,” “Heavy – Light,” “Modern – Classical,” “Clean – Dirty,” “Active – Passive,” “Hard – Soft,” Tense – Relaxed,” “Fresh – Stale,” and “Masculine – feminine”). Semantic differential method was used for measurement of color connotation scales.

The color connotation models having brightness, colorfulness and hue obtained by CAM97u and the revised CIECAM02 as input variables were developed to quantify inter-relation between the color attributes and color connotation space, and further effects of the color attributes on color connotation were visually analyzed based on conventional bubble charts.

The major findings from the experiments are summarized as follows:

In experiment 1: *Color perception for unrelated colors*, the experimental results shows that the three perceptual attributes of unrelated colors such as brightness, colorfulness and hue can be estimated by the colorimetric properties of color stimuli (i.e. luminance, excitation purity and CIE 1976 hue-angle). It is found that the estimate values of the color attributes are positively proportional to perceived magnitudes of the color attributes. The performance comparison is made of proposed estimation model with CAM97u and revised CIECAM02. The revised CIECAM02 gives the best satisfactory estimations of brightness, colorfulness and hue under photopic vision.

In experiment 2: *Color connotation for unrelated colors*, the experimental results shows that color connotation of unrelated colors has a three-dimensional space, and the three axes are “Color solidity,” “Color heat,” and “Color purity.” “Color solidity” is associated with “Hard-Soft,” “Heavy-Light,” “Tense-Relaxed,” and “Active-Passive.” “Color heat” is correlated with “Warm-Cool” and “Feminine-Masculine”, and “Color purity” has relevance to “Clean-Dirty” and “Fresh-Stale.”

In short, color connotation for unrelated colors is a function of the three color appearance attributes. All the color connotation scales are correlated with the color attributes. Four color connotation scales, “Warm-Cool,” “Heavy-Light,” “Active-Passive” and “Hard-Soft”, were modeled. The scale “Warm-Cool” is associated with hue angle and colorfulness, while significant relation between “warm-Cool” and brightness is not found. The other scales are connected with the color difference between the test color and neutral color of which brightness are varied with the color connotation scales. This implies that “Heavy-Light,” “Active-Passive” and “Hard-Soft” have relevance to colorfulness.

Furthermore, the three-dimensional color connotation space for unrelated colors is associated with the color attributes. The significant correlations between the axes of the color connotation space and color attributes are as follows: “Color solidity” with colorfulness, “Color heat” with both hue angle and colorfulness, “Color purity” with brightness.

There is room for further improvement and development in this research. (1) The data sets obtained by this research need to examine repeatability, (2) relationships of color connotations between unrelated colors and related colors is required to be analyzed, and (3) the results of this research should expend into applications in association with emotional lighting.

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Introduction

I. Introduction

I.1. Background

Studies for color have started with endeavor to quantify color. Range of research for color has been extended from color appearance to color quality. This extension of research area for color is rooted in needs of quality control for colored objects, and growth of the industries related with light source or display.

Early studies for color appearance were to investigate the way that human perceived color appearance, and to quantify the color appearance attributes, such as brightness, lightness, colorfulness, chroma, saturation and hue. The color appearance models have been developed through a number of psychophysical experiments. Representative color appearance models are CIECAM97s and CIECAM02.

Recently, researches for color quality and color psychology are actively in progress. The concepts of color quality include fidelity and preference for color reproduction. One of the representative applications associated with color quality is image quality enhancement algorithm. The studies of color connotation focused on relations between color and connotation evoked from that color. It plays important rolls in various design fields and marketing strategies.

However, early studies for color appearance and color connotation have been carried out by using color patches or colored objects on neutral color background under a specific illuminant. In other words, the mainstream of these studies was concerned with the related colors, which is color perceived to belong to an area or object seen in relation to other colors.

Contrary to the related color, an unrelated color is perceived by itself isolated, either completely or partially, from any other colors. Examples of unrelated color are signal lights, traffic lights, and street lights, viewed in a dark night. Although the colors have identical colorimetric values, color perception can vary according to viewing conditions.

Even though, recently, demand of applications associated with unrelated color has increased, there is a lack of basic research for unrelated color. Many of color appearance models have been developed for the related color. There is no agreed color appearance model connected with the unrelated color yet. In this situation, it is natural that there is also lack of researches investigating relations between color appearance attributes of unrelated color and color connotation. Figure 1 illustrates the background of this research a development process of color science by using a block diagram.

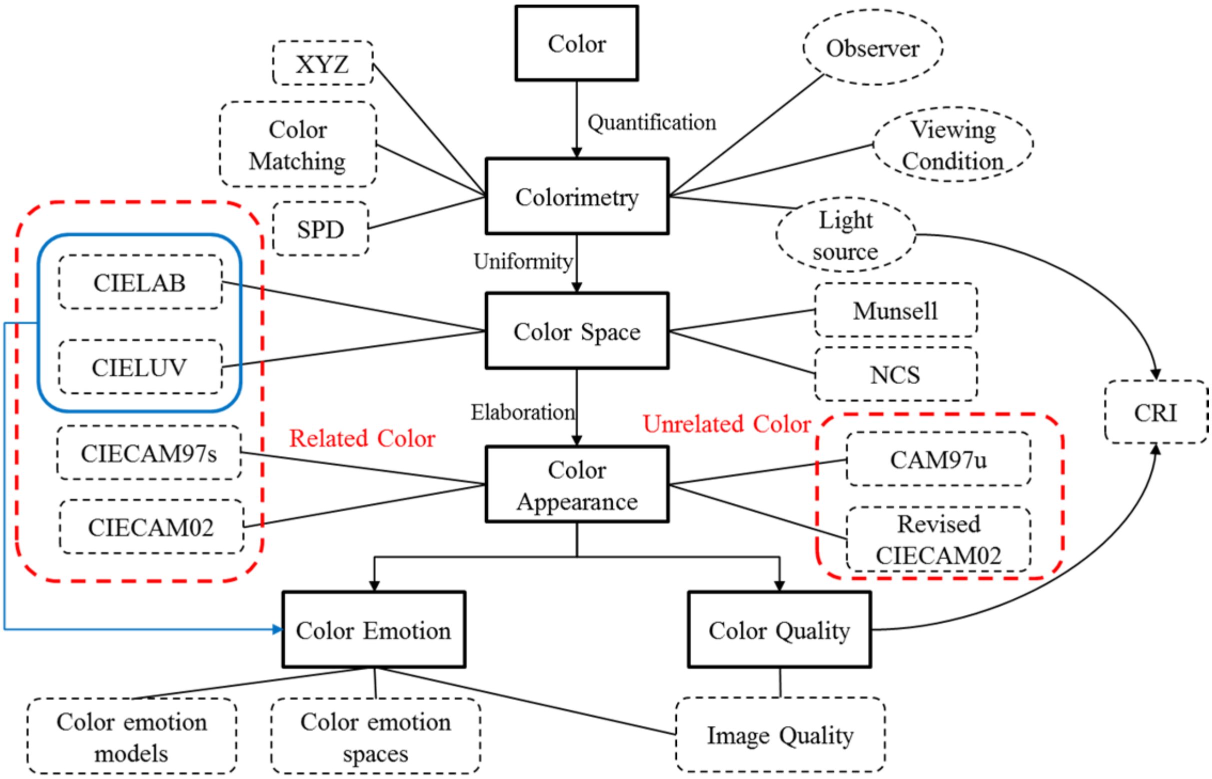


Figure 1 Background of research

I.2. Objectives of Research

The current research intends to investigate color perception, color connotation, and the relations between those in terms of the unrelated colors.

Objectives of the research for color perception were (1) to accumulate a set of color appearance data for the unrelated color, (2) to devise estimation models of color appearance for the unrelated color, (3) to test the performance of CAM97u, revised CIECAM02 for the unrelated color suggested by Fu et al. (Fu et al., 2011) and the proposed model in this research.

Purposes for color connotation were (1) to compare color connotation between different gender groups, (2) to classify color connotation scales, and (3) to develop color connotation models for the unrelated colors.

Figure 2 explains purposes of this research by using a block diagram.

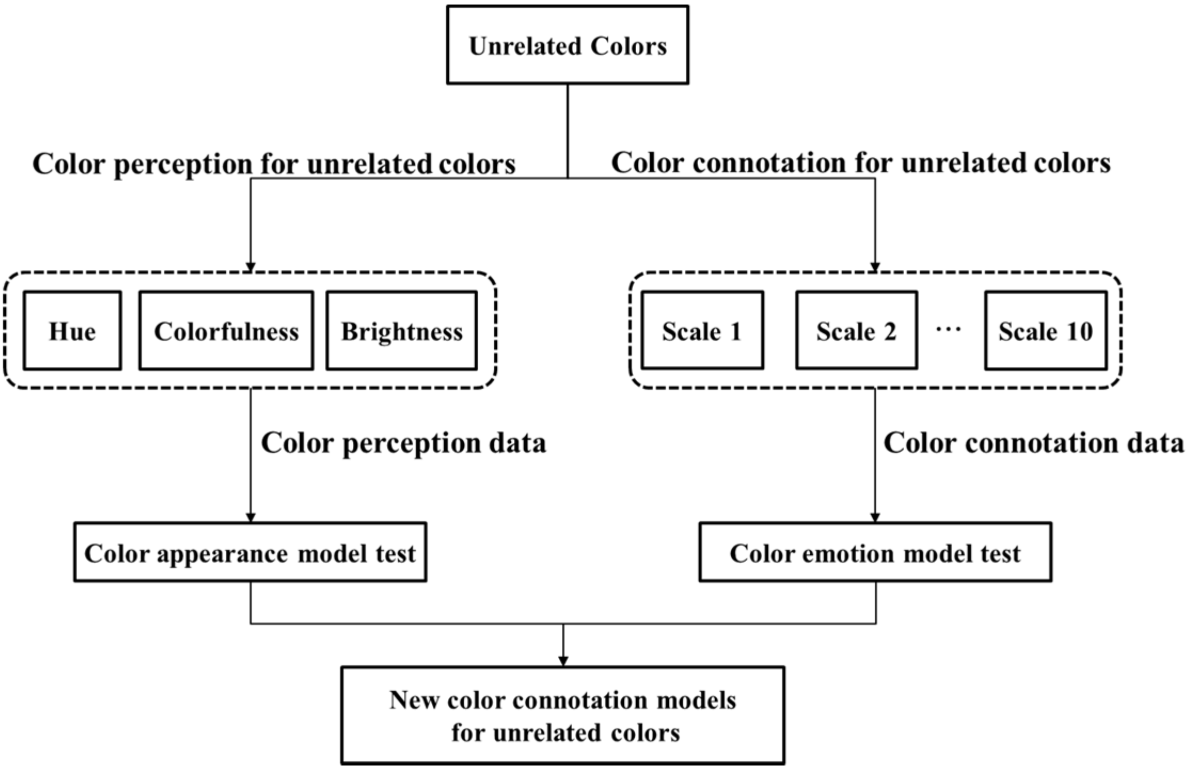


Figure 2 Objectives of research

Literature Review

II. Literature Review

II.1. Color appearance terminology and phenomena

In any scientific field, fundamental scientific concepts are defined as specific terms in order to communicate accurately, precisely and effectively. This is true in the field associated with colors. Commission International de l'Éclairage (CIE) published the International Lighting Vocabulary which includes the definitions of about 950 terms and quantities related to light and color. The definitions presented in this part are extracted from the International Lighting Vocabulary(Commission Internationale de L'Eclairage, 1987), and the second edition of Color Appearance Model(Fairchild, 2005). Following definitions is important concepts related to this research.

II.1.1. Color

Color is an attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, gray, black, etc., and qualified by bright, dim, light dark, etc., or by combinations of such names.

II.1.2. Hue

Hue is the most conspicuous perceptual attribute of colors. When most people are asked to arrange many different colors in a mess, the people tend to segregate the colors from the colors without hue first. It is easier for them to arrange the colors according to whether the color is chromatic color or not than to classify the colors depending on other perceptual attributes. The following is the definition of word "hue".

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

II.1.3. Brightness and lightness

Both brightness and lightness are associated with visual sensation according to amount of light given a color stimulus. The followings are definitions of brightness and lightness.

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

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.

By definition, lightness can be described as following equation.

$$\text{Lightness} = \frac{Brightness}{Brightness(white)}$$

The significant difference between brightness and lightness is that brightness refers to the absolute level of own perceived light of an color stimulus, while lightness can be considered as the relative brightness compared with the brightness of white or highly transmitting area close to its own color. Figure 3 illustrates the difference between brightness and lightness.

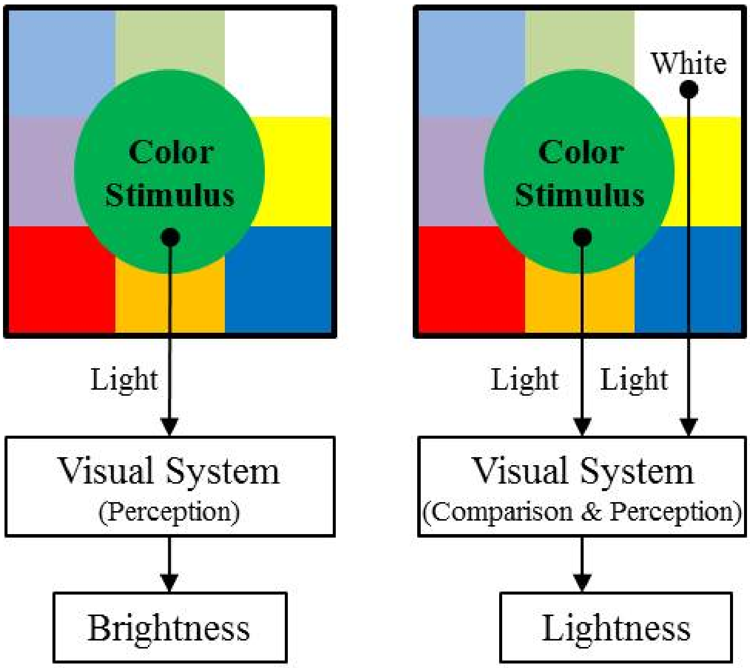


Figure 3 Brightness and Lightness

II.1.4. Colorfulness and chroma

Both colorfulness and chroma are related to visual sensation according to the density of hue given a color stimulus. Below are the definitions of colorfulness and chroma.

Colorfulness is an attribute of a visual sensation according to which the perceived color of an area appears to be more or less chromatic.

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

By definition, chroma can be expressed as following equation.

$$\text{Chroma} = \frac{Colorfulness}{Brightness(white)}$$

Neutral colors which are the colors without hue indicate zero colorfulness and chroma. When hue of the color stimulus and brightness of white or highly transmitting area around the given color stimulus are constant, as the quantity of color content increases, colorfulness and chroma rise. The relation between colorfulness and chroma is similar to the relationship between brightness and lightness. It means that colorfulness is related to the absolute perceptual quantity of the hue in given color stimulus, while chroma refers to relative colorfulness which is its own colorfulness divided by brightness of white or highly transmitting area close to given color stimulus. Figure 4 shows the difference between colorfulness and chroma.

II.1.5. Saturation

Saturation is also connected with the intensity of hue given a color stimulus. The definition of word saturation is as follows.

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

By definition, saturation is given by the ratio of chroma and lightness and it can be described in following equation.

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

Saturation is close to chroma because both saturation and chroma are relative colorfulness. Saturation, however, it is unique perceptual attribute separate from chroma and colorfulness. That is why saturation refers to as relative colorfulness compared with its own brightness of the color stimulus, while chroma is thought of as relative colorfulness judged by brightness of white or highly transmitting area around a given color stimulus. Figure 4 illustrates the definition of saturation.

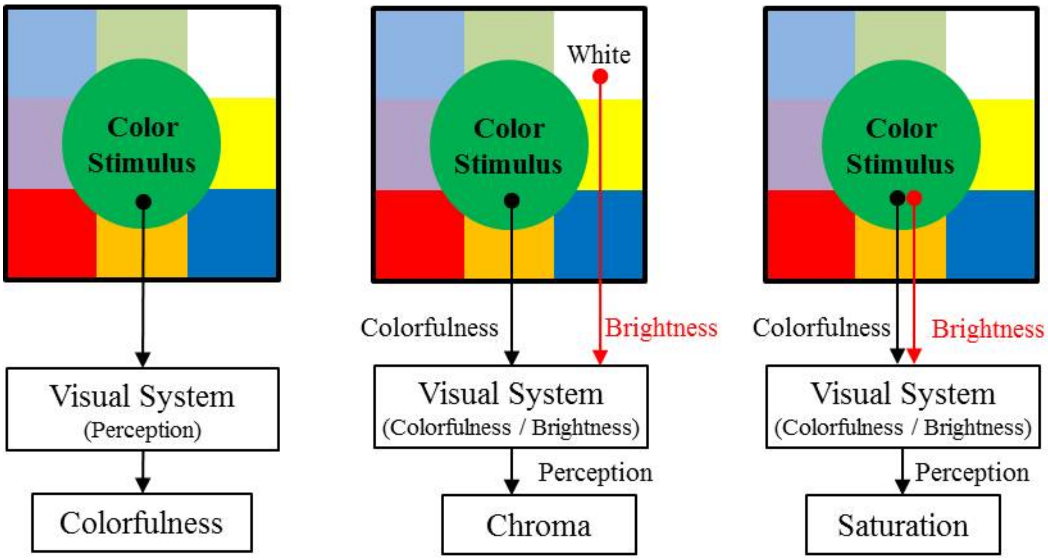


Figure 4 Colorfulness, chroma and saturation

II.1.6. Unrelated and related colors

"Unrelated" and "related" of the two terms, unrelated color and related color, are associated with the background and the surround of a color stimulus. The significant difference between related colors and unrelated colors is to whether a color stimulus is isolated from other colors or not. The definitions of terms "unrelated color" and "related color" are as follows.

Unrelated color is color perceived to belong to an area or object seen in isolation from other colors. ***Related color*** is color perceived to belong to an area or object seen in relation to other colors.

Color terminologies are applied differently to related and unrelated colors. Unrelated colors only show the color attributes of hue, brightness, colorfulness and saturation because there are no comparative colors for its own color, while related colors reveal all of the color attributes which are hue, brightness, lightness, colorfulness, chroma and saturation.

II.1.7. Adaptation Mechanisms

Human beings accommodate themselves to the environmental change in various ways in order to maintain the states of balance and stability. A notable example is that we sweat and drink fluids in hot weather. This response of a body is to stay in a safe and stable state when temperature is changed. The response called “homeostasis” is one of the processes to adapt human body to the external environment. An adaptation mechanism is a kind of these processes. There are also some adaptation mechanisms in human visual system. The important adaptation mechanisms in human visual system are “dark adaptation,” “light adaptation” and “chromatic adaptation.” Human visual system responds to the change of light condition, such as the color or intensity of illuminants.

Dark adaptation and light adaptation are concerned with the change in visual sensitivity when predominating level of illumination is decreased or increased. Dark adaptation occurs when the level of illumination is decreased, while light adaptation is inverse process of dark adaptation. The example of dark adaptation is available to be found around us. When entering darkened place from sunny spot, at first the place appears totally dark, but after a few minutes one is possible to see objects in the dark place. The inverse situation is the example of light adaptation.

Chromatic adaptation is related to the change of illuminant color. The definition is as follow.

Chromatic adaptation is visual process whereby approximate compensation is made for changes in the colors of stimuli, especially in the case of changes in illuminants.

A case of chromatic adaptation can be found when watching a white object, such as a piece of paper. Although the paper is shown under the difference types of illumination, the paper nearly retains its white appearance under all light sources. Chromatic adaptation is reflected in various color appearance models as the important process.

II.2. CIE Colorimetry

Colorimetry, synthesis of color and metrein (Greek meaning “to measure”), is methods of measuring and quantifying color appearance, so it has been widely applied to color research and color industries. The important components of colorimetry are light source, viewing condition and observer. CIE which is responsible for international standards of colorimetry and photometry has provided CIE standard colorimetry in order to maintain consistency of measuring and quantifying colors. CIE system specifies color stimuli under controlled viewing condition.

In this part, Principles of Color Technology (Billmeyer & Saltzman, 1981) and Measuring Colour (Hunt & Pointer, 2011) are used as general reference.

II.2.1. Components of Colorimetry

This part describes how these components, a light source, viewing condition and observer, are quantified and how they can be combined in order to produce colorimetric data.

Light Source and CIE Standard illuminants

Light source plays an important role in colorimetry. There is a diversity of light sources according to the methods that produce light. The methods include incandescence, gas discharges, electroluminescence, photoluminescence, cathodoluminescence and chemiluminescence. The spectral power distribution of light sources has a different shape depending on producing methods. Colorimetric values of objects are varied with the spectral power distribution of light source even if the reflectance factor of the objects is equal, and it gives raise to the difference for color perception in human visual system. For this reason, light is the most important element of color perception.

CIE has introduced some standardization into light source. Furthermore, CIE distinguishes between illuminants, which are defined in terms of spectral power distributions, and sources, which are defined as physically realizable producers of radiant power.

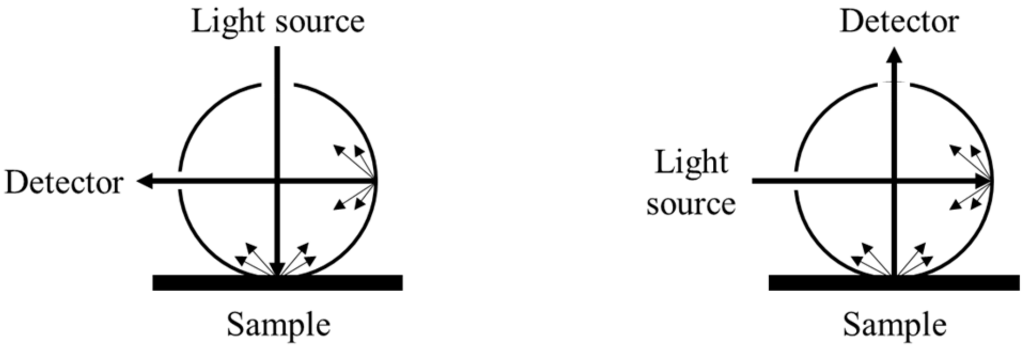
Standard illuminants designated by CIE can be separated into standard illuminant A and Standard illuminant B, C and D. Standard illuminant A represents spectral power distribution of the most common artificial light source which is tungsten filament lamp at the color temperature of 2856K. Standard illuminant B and C represent sun light and average daylight at the color temperatures of about 4874 and 6774K, respectively. A series of standard illuminant D is distinct from standard illuminant B and C because standard illuminant D contains the ultra-violet region of daylight.

CIE Geometries of Illumination and Viewing

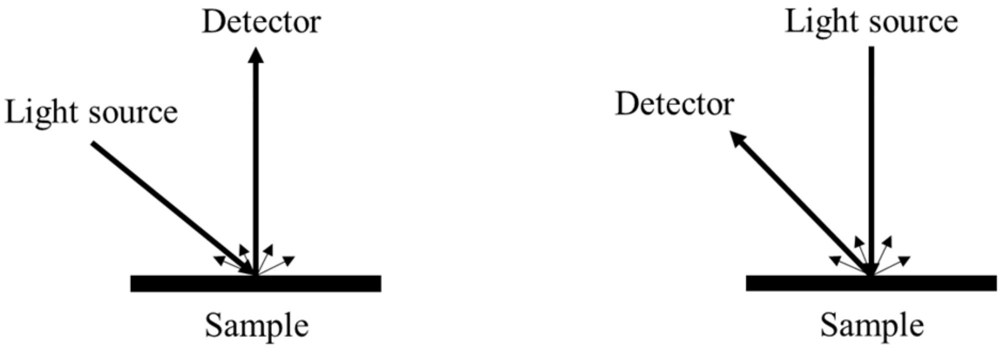
The CIE recommends four standard illuminations and viewing geometries in respect of measuring reflectance of light from an object, as shown in Figure 5.

In the normal/diffuse (0/d) geometry, the sample is illuminated from an angle near to its normal and the reflected light is collected from all angles using an integrating sphere. In the diffuse/normal geometry (d/0) which is the inverse geometry of normal/diffuse geometry, the sample is illuminated from all angles using an integrating sphere and viewed at an angle near the normal to the surface.

In 45/0 geometry, the sample is illuminated with one or more beams of light incident at an angle of 45° from the normal and measurement are made along the normal. In the 0/45 geometry, the sample is illuminated normal to its surface and measurements are made using one or more beams at a 45° angle to the normal.



(a) 0/d (b) d/0



(c) 45/0 (d)0/45

Figure 5 Measurement geometries

Standard Colorimetric Observers

CIE needed to quantify response of human visual system to a color stimulus. The quantification was realized based on color matching functions which were derived from a color matching experiment. The color matching experiment is the experiment how human eye match a colour stimulus with an additive mixture of three primaries, the monochromatic red, green and blue lights. In 1931, the CIE agreed to adopt a colour-matching system based on experimental results of Guild (Guild, 1931) and Wright (W. D. Wright, 1929). This system is called the CIE 1931 Standard Colorimetric Observer (Figure 6). It often referred to as the 2° observer, because the experiments employed the same viewing conditions, a bipartite field subtending a 2° visual angle that was surrounded by darkness.

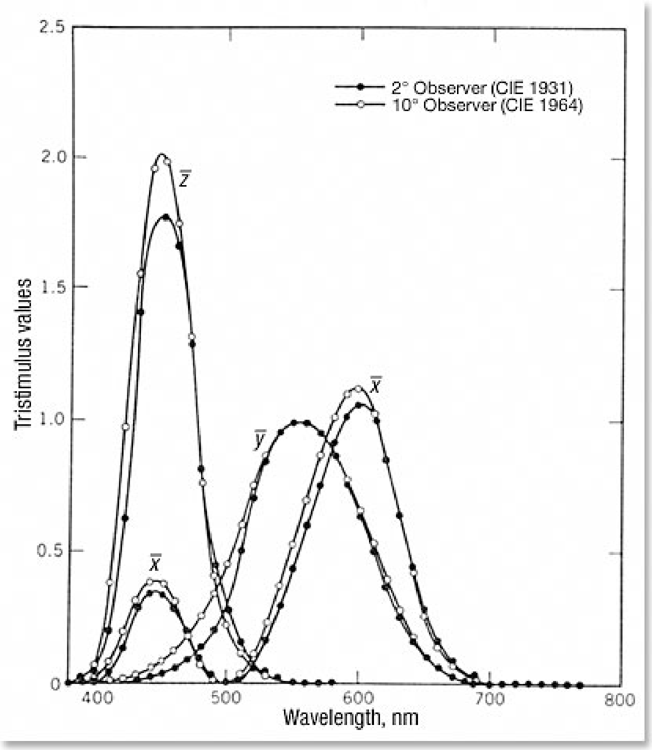


Figure 6 The CIE color matching functions for the 1931 standard colorimetric observer, and for the 1964 supplementary standard colorimetric observer

A different set of colour-matching functions was recommended in 1964 by the CIE for samples with the field size greater than 4°. These functions solve the problem that a colour match made with 2° field size does not remain a match when the field size is changed into greater than 4°. These new functions define the CIE 1964 Supplementary Standard Colorimetric Observer, often referred to as the 10° observer (Figure 6).

II.2.2. Tristimulus Values

Colors can be quantified by three values X, Y and Z called tristimulus values. For measuring self-luminous colors, the values are calculated by integrating the spectral power distribution of the self-luminous color (P_λ) and the CIE color-matching functions ($\bar{x}_\lambda$, $\bar{y}_\lambda$ and $\bar{z}_\lambda$).

$$\mathrm{X} = \mathrm{k}\int P_\lambda\,\bar{x}_\lambda \mathrm{d}\lambda$$

$$\mathrm{Y} = \mathrm{k}\int P_\lambda\,\bar{y}_\lambda \mathrm{d}\lambda$$

$$\mathrm{Z} = \mathrm{k}\int P_\lambda\,\bar{z}_\lambda \mathrm{d}\lambda$$

where k is a constant and λ is the wavelength (in unit of nm).

When colors on object's surface are measured, the term P_λ should be replaced by $S_\lambda R_\lambda$. S_λ is spectral power distribution of light source and R_λ is the spectral reflectance of the object. The tristimulus values are then determined by

$$\mathrm{X} = \mathrm{k}\int S_\lambda\, R_\lambda \bar{x}_\lambda \mathrm{d}\lambda$$

$$\mathrm{Y} = \mathrm{k}\int S_\lambda\, R_\lambda \bar{y}_\lambda \mathrm{d}\lambda$$

$$\mathrm{Z} = \mathrm{k}\int S_\lambda\, R_\lambda \bar{z}_\lambda \mathrm{d}\lambda$$

If the 10° observer is used, the color matching functions, $\bar{x}_\lambda$, $\bar{y}_\lambda$ and $\bar{z}_\lambda$, should be replaced by $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$ and $\bar{z}_{10}(\lambda)$. The unit of tristimulus value, X, Y and Z, is cd/m^2. Y tristimulus value correlates approximately with brightness or lightness. In this research, self-luminous colors are used in Experiment 1: color perception for unrelated colors and experiment 2: color connotation for unrelated colors, and the former equations are applied.

II.2.3. Chromaticity

Important color attributes are concerned with the relative magnitudes of the tristimulus values. CIE chromaticities, relative tristimulus values, are defined as follow.

$$x = \frac{\mathrm{X}}{\mathrm{X+Y+Z}}, \quad y = \frac{\mathrm{Y}}{\mathrm{X+Y+Z}} \quad \text{and} \quad z = \frac{\mathrm{Z}}{\mathrm{X+Y+Z}}$$

With two variables, such as x and y, it becomes possible to construct two-dimensional diagrams, because z can always be deduced from $1 - x - y$ if x and y are known. This diagram is called chromaticity diagram, usually referred to as CIE x, y chromaticity diagram. The CIE x, y chromaticity diagram provides a color map on which chromaticities of all colors are plotted, as shown in Figure 7. The curved line in the diagram shows where the colors of the spectrum lie and is called the spectral locus. A straight line connecting two ends of the curved line is known as the purple boundary. The area enclosed by the spectral locus and the purple boundary contains all colors. Any mixture of two spectral colors in this system is located on the line joining the two points that represent the two original spectral colors. It is important to note that the CIE chromaticity diagrams are maps of relationships between color stimuli, not between color perceptions.

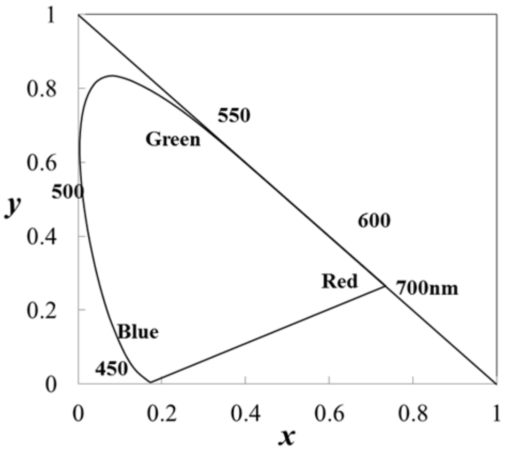


Figure 7 CIE *x, y* chromaticity diagram for the 1931 standard colorimetric observer

II.2.4. Uniform Chromaticity diagrams

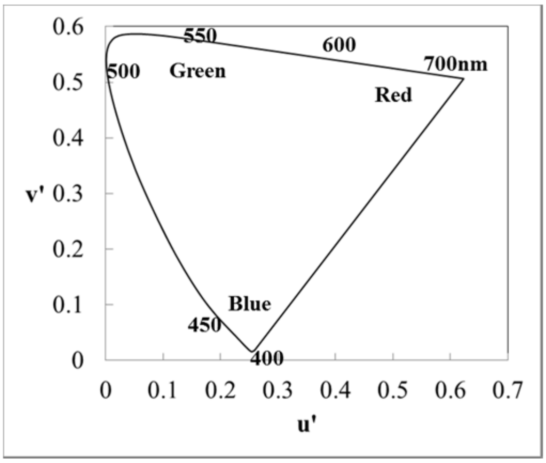


Figure 8 CIE *u’, v’* chromaticity diagram

Although the *x, y* chromaticity diagram has been widely used, it suffers from a serious disadvantage. The distribution of the colors on the diagram is non-uniform. It means that distances between two color stimuli on the diagram are not equal to perceptual color differences.

There is no chromaticity diagram that can entirely avoid the problem. However, some chromaticity diagrams are better than the CIE *x, y* chromaticity diagram. One of the chromaticity diagrams alleviating the problem is known as the CIE 1976 uniform chromaticity scale diagram or the CIE 1976 UCS diagram, commonly referred to as the *u’*, *v’* diagram (Figure 8). It is obtained by plotting *v’* against *u’*, where:

$$u' = \frac{4X}{X + 15Y + 3Z} = \frac{4x}{-2x + 12y + 3}$$
$$v' = \frac{9Y}{X + 15Y + 3Z} = \frac{9y}{-2x + 12y + 3}$$

u', v' also have the property of additive mixtures as x, y on CIE x, y chromaticity diagram. Two new measures correlating uniformly with the perception of saturation and hue have been provided based on the u', v' diagram. They are:

CIE 1976 u, v hue-angle, $h_{uv} = \tan^{-1}[(v' - v'_n)/(u' - u'_n)]$

CIE 1976 u, v saturation, $s_{uv} = 13[(u' - u'_n)^2 + (v' - v'_n)^2]^{1/2}$

II.2.5. Color Appearance Model

A color appearance model is any model that includes predictors of at least the relative color appearance attributes of lightness, chroma, and hue. Given the above definition, some simple uniform color space such as CIELAB and CIELUV color space, can be considered as a color appearance model. Later, models to estimate the color appearance attributes under a wide range of viewing conditions have been proposed by various workers. These models include some measures that are not only hue, saturation, lightness and chroma but also brightness and colorfulness. CIE has endorsed a color appearance model CIECAM97s, and a color appearance model for unrelated color, CAM97u, was also proposed at the same time.

The CIE Technical Committee 9-01, color appearance models for color management applications, has recently proposed a single set of revisions to the CIECAM97s color appearance model. This new model, called CIECAM02 (Moroney et al., 2002), is based on CIECAM97s and includes many revision and some simplifications. This agreed model, CIECAM02, is not sufficient to calculate predictors of unrelated color appearance attributes, although it is the sophisticated model. The reason is that the model was derived based on psychophysical data of related color stimuli.

Recently, Fu et al. (Fu et al., 2011) has investigated color appearance for unrelated colors under photopic vision and mesopic vision, and they proposed a new color appearance model based on CIECAM02. Using the brightness from CAM97u, the model was developed for unrelated color with parameters to reflect the effects of luminance level and stimulus size. The new color appearance model based on CIECAM02 will be referred to as revised CIECAM02 in this research.

Following sections in this part describe important formulae and calculation steps for the color appearance models above mentioned.

CIELAB

CIELAB formula employs tristimulus values, X, Y and Z, as variables. The formula is as follows.

$$L^* = 116(Y/Y_n)^{1/3} - 16 \qquad \text{for } Y/Y_n > 0.008856$$

$$L^* = 903.3(Y/Y_n) \qquad \text{for } Y/Y_n \le 0.008856$$

$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$

$$b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

where X_n, Y_n, and Z_n are the tristimulus values of the chosen reference white. If any of the ratios X/X_n, Y/Y_n or Z/Z_n is equal to or less than 0.008856, then $(X/X_n)^{1/3}$, $(Y/Y_n)^{1/3}$, or $(Z/Z_n)^{1/3}$ is replaced in the above formulae by

$$7.787\mathrm{F} + 16/116$$

where F is X/X_n, Y/Y_n or Z/Z_n. $L*$ indicates lightness of color appearance. By using $a*$ and $b*$, it is available to calculate other color appearance attributes such as hue and chroma. Hue can be presented by calculating the angle between the color stimulus and $a*$- axis with origin as center on CIELAB space, and chroma can be signified by computing Euclidean distance between origin and the color stimulus. Formulae for hue and chroma are as follows.

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

$$h_{ab} = \arctan(b^* / a^*)$$

CIE 1976 *a, b chroma*, $C*_{ab}$

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

X, Y and Z should be replaced by X_{10}, Y_{10} and Z_{10} when the samples have a viewing angle greater than 4°.

CAM97u

The following input data are required for calculating predictors of CAM97u.

	Chromaticity co-ordinates		*Photopic luminance*	*Scotopic luminance*
Sample	x	y	L	L
Adapting field	x_w	y_w	L_A	L_{AS}
Conditioning field	x_b	y_b	L_C	L_{CS}

The photopic luminance of the adapting field, LA, taken as:

$$L^{2/3}/200$$

The scotopic luminance (divided by 2.26) of the adapting field, L_{AS}, taken as:

$$L_{AS}/2.26 \;=\; (L_S/2.26)^{2/3}/200$$

The chromaticity of the adapting field is taken as that of S_E, so that x_A = 1/3, y_A = 1/3. The conditioning field is the field seen just prior to viewing the unrelated color. If there is no conditioning field, the values of x_c, y_c, L_c, L_{cs} are taken to be the same as those of the adapting field.

Step 1 Calculate X_L, Y_L, Z_L for the sample, and for the conditioning field

$$X_L \;=\; x\mathrm{L}/y \qquad Y_L \;=\; \mathrm{L} \qquad Z_L \;=\; (1-x-y)\mathrm{L}/y$$

$$X_c \;=\; x\mathrm{L}/y \qquad Y_c \;=\; \mathrm{L} \qquad Z_c \;=\; (1-x-y)\mathrm{L}/y$$

Step 2 Calculate *R, G, B* for the sample, and for the conditioning field

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} \;=\; M_H \begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} \quad \text{where} \quad M_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix}$$

Similarly from X_c,Y_c, Z_c calculate R_c, G_c, B_c

Step 3 Calculate:

$$\mathrm{W} = [(1/3)(R + G + B)]^{1/2}$$

Step4 Calculate F_L

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

Step 5 Calculate F_R, F_G, F_B

$$h_R = 3_{Rc}/(R_c + G_c + B_c)$$

$$h_G = 3_{Gc}/(R_c + G_c + B_c)$$

$$h_B = 3_{Bc}/(R_c + G_c + B_c)$$

$$F_R = (1 + L_A^{1/3} + h_R)/(1 + L_A^{1/3} + 1/h_R)$$

$$F_G = (1 + L_A^{1/3} + h_G)/(1 + L_A^{1/3} + 1/h_G)$$

$$F_B = (1 + L_A^{1/3} + h_B)/(1 + L_A^{1/3} + 1/h_B)$$

If there is no conditioning field, $h_R = h_G = h_B = 1$, and $F_R = F_G = F_B = 1$.

Step 6 Calculate, R_a, G_a, B_a

$$R_a = B_{Ru}\{f_n[F_L F_R (L_A/L_C)^c R/W]\} + 1$$

$$G_a = B_{Gu}\{f_n[F_L F_G (L_A/L_C)^c G/W]\} + 1$$

$$B_a = B_{Bu}\{f_n[F_L F_B (L_A/L_C)^c B/W]\} + 1$$

where

$$B_{Ru} = 10^7/[10^7 + (5L_A)3R_c/(R_c + G_c + B_c)]$$

$$B_{Gu} = 10^7/[10^7 + (5L_A)3G_c/(R_c + G_c + B_c)]$$

$$B_{Bu} = 10^7/[10^7 + (5L_A)3B_c/(R_c + G_c + B_c)]$$

and R_c, G_c, B_c are the values of R, G, B for the conditioning field, and

$$f_n[I] = 40[I^{0.73}/(I^{0.73}+2)]$$

A typical value for c is 0.2. If there is no conditioning field, $R_c = R_a$, $G_c = G_a$ and $B_c = B_a$ (and, since $R_a = G_a = B_a$, the ratios that follow $5L_A$ in the equations for B_{Ru}, B_{Gu} and B_{Bu} reduce to unity).

Step 7 Calculate A_a, C_1, C_2, a, b

$$\mathrm{A} = [2R'_a + G'_a + (1/20)B'_a - 0.305] + 1$$

$$C_1 = R_a - G_a$$

$$C_2 = G_a - B_a$$

$$C_3 = B_a - R_a$$

$$a = C_1 - C_2/11$$

$$b = 1/2(C_2 - C_3)/4.5$$

Step 8 Calculate hue angle *h* and hue quadrature *H*

$$\mathrm{h} = \arctan(b/a)$$

Step 9 Calculate hue quadrature *H*

$$\mathrm{H} = H_i + \frac{100(h-h_1)/e_1}{(h-h_1)/e_1 + (h_2-h)/e_2}$$

where H_i is 0, 100, 200, or 300 according to whether red, yellow, green, or blue, respectively, is the hue having the nearest lower value of *h*. The values of *h* and *e* for the four unique hues are:

	h	e_i
Red	20.14	0.8
Yellow	90.00	$0.7[L/(L+10)] + 0.3[10/(L+10)]$

Green	164.25	1.0
Blue	237.53	$1.2[L/(L+10)]+0.2[10/(L+10)]$

e_1 and h_1 are the values of e_i and h, respectively, for the unique hue having the nearest lower value of h ; and e_2 and h_2 are these values for the unique hue having the nearest higher value of h.

Step 10 Calculate *e*:

$$e = e_1 + (e_2 - e_1)(h - h_1)/(h_2 - h_1)$$

where e_1 and h_1 are the values of e and h, respectively, for the unique hue having the nearest lower value of h; and e_2 and h_2 are these values for the unique hue having the nearest higher value of h.

Step 11 Calculate F_{tu} and b_{tu}

$$F_{tu} = L/(L+0.1) \text{ and } b_{tu} = bF_{tu}$$

Step 12 Calculate the saturation, s, and the colorfulness, M

$$\mathrm{s} = 50(a^2 + b_{tu}^2)^{1/2}100e(10/13)N_c/[R_a + G_a + (21/20)B_a]$$

$$\mathrm{M} = \mathrm{s}F_L^{0.15}$$

where N_c is chromatic surround induction factor. N_c is 0.5 for unrelated colors.

Step 13 Calculate F_{LS}:

$$F_{LS} = 3800j^2 5L_{AS}/2.26 + 0.2(1-j^2)^4(5L_{AS}/2.26)^{1/6}$$

where $j = 0.00001/(5L_{AS}/2.26 + 0.00001)$

Step 14 Calculate A_S

$$A_S = B_{Su}(3.05)\{f_n[F_{LS}(L_{AS}/L_{CS})^2(L_S/2.26)^{1/2}]\} + 0.3$$

where

$$B_{Su} = 0.5/\{1 + 0.3[(5L_{AS}/2.26)(L_S/2.26)^{1/2}]^{0.3} + 0.5/\{1 + 5[5L_{AS}/2.26]\}$$

and $f_n[I] = 40[I^{0.73}/(I^{0.73} + 2)$

A typical value for c is 0.2.

Step 15 Calculate A

$$\mathrm{A} = A_a + A_S - 2.31$$

Step 16 Calculate the brightness, Q

$$\mathrm{Q} = \{[1.1][\mathrm{A} + (\mathrm{M}/100)]\}^{0.9}$$

CIECAM02

Starting data for computing the CIECAM02 model is as follows.

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		

L_A is normally taken as 1/5 of the luminance of the adopted test white.

Surround parameters are as follows.

Surround	F	c	N_c
Average	1.0	0.69	1.0
Dim	0.9	0.59	0.95
Dark	0.8	0.525	0.8

The value of F_L can be calculated using following equations.

$$\mathrm{k} = 1/5(5L_A + 1)$$

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

Background parameters:

$$\mathrm{n} = Y_b \,/\, Y_w$$

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

$$\mathrm{z} = 1.48 + \sqrt{n}$$

The value *n* is a function of the luminance factor of the background, and the value of *n* ranges from 0 for a background luminance factor of zero to 1 for a background luminance factor equal to the luminance factor of the adopted white point.

Step 1 For the sample, calculate:

$$\mathrm{X} = x\mathrm{Y}/y \qquad \mathrm{Y} \qquad \mathrm{Z} = (1-x-y)\mathrm{Y}/y \text{ and}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad \text{where} \qquad M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

Similarly from x_w, y_w, Y_w calculate R_w, G_w, B_w

Step 2 Calculate the degree of chromatic adaptation, D:

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

D factor could range from 0 for no adaptation to the adopted white point to 1 for complete adaptation to the adopted white point.

Step 3 From *R, G, B* calculate for the reference conditions the corresponding tristimulus values R_c, G_c, B_c, for the sample:

$$R_c = [(Y_w D/R_w) + (1 - D)]R$$

$$G_c = [(Y_w D/G_w) + (1 - D)]G$$

$$B_c = [(Y_w D/B_w) + (1 - D)]B$$

Similarly calculate R_{wc}, G_{wc}, B_{wc} from R_w, G_w, B_w.

Step 4 Calculate:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_H M_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} R_w{}' \\ G_w{}' \\ B_w{}' \end{bmatrix} = M_H M_{CAT02}^{-1} \begin{bmatrix} R_{wc} \\ G_{wc} \\ B_{wc} \end{bmatrix}$$

where $$\mathrm{M}_{CAT02}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 0.1082745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix}$$

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

Step 5 Calculate:

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

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

$$\mathrm{B}'_a = \frac{400(F_L B'/100)^{0.42}}{[27.13 + (F_L B/100)^{0.42}} + 0.1$$

Similarly calculate R'_{aw}, G'_{aw}, B'_{aw} from R'_w, G'_w, B'_w

Step 6 Calculate hue angle *h*:

Redness-Greenness	$\mathrm{a} = \mathrm{R}'_a - 12G'_a/11 - B'_a/11$
Yellowness-Blueness	$\mathrm{b} = (1/9)(R'_a + G'_a - 2B'_a)$
Hue angle	$\mathrm{h} = \arctan(b/a)$

Step 7 Calculate hue quadrature H by using the following unique hue data

	Red	Yellow	Green	Blue
h	20.14	90.00	164.25	237.53
e	0.8	0.7	1.0	1.2

Calculate

$$e = \left(\frac{12500}{13} N_c N_{cb}\right)\left[\cos\left(h\frac{\pi}{180} + 2\right) + 3.8\right]$$

where e_1 and h_1 are the values of e and h, respectively, for the unique hues having the nearest lower value of h; and e_2 and h_2 are the values of e and h, respectively for the unique hues having the nearest higher value of h.

$$\mathrm{H} = H_i + \frac{100(h - h_1)/e_1}{(h - h_1)/e_1 + (h_2 - h)/e_2}$$

where H_i is 0, 100, 200, or 300 according to whether red, yellow, green, or blue, respectively, is the hue having the nearest lower value of h.

Step 8 Calculate achromatic response:

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

$$\mathrm{A}_w = [2R'_{aw} + G'_{aw} + (1/20)B'_{aw} - 0.305]N_{bb}$$

Step 9 Calculate lightness J and brightness Q:

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

$$\mathrm{Q} = (4/\mathrm{c})\sqrt{J/100}(A_w + 4)F_L^{0.25}$$

Step 10 Calculate chroma C, colorfulness M, and saturation s:

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

$$\mathrm{M} = \mathrm{C}F_L^{0.25}$$

$$\mathrm{s} = 100\sqrt{M/Q}$$

II.3. Color Psychology

Many studies of color psychology have been achieved, and results of the studies have been used in various areas which are not only architecture, art and design but also business and therapy. For example, in architecture, the color of illuminants and interior & exterior colors varied with usage of the space. The selection of product's color has an effect on sales of the products in business area. These applications and studies have been developed by assuming that color can stimulate emotional reactions of people.

II.3.1. General Methodologies of Color Psychology

Although researchers have done a lot of work to measure emotional reactions, it is difficult to measure human emotions and to quantify emotional reaction up to this time. There are recently numerous attempts to measure emotional reaction by using device based on bio-signals such as heart rate, electromyogram (EMG) and electroencephalogram (EEG). These measurements still have a long way to go before measuring more accurately and estimating more meaningfully. General measurement of color psychology is to inquire of subjects about their emotional reaction, and the psychophysical data is processed by using statistical analysis such as principal component analysis (PCA).

One of the psychophysical measurements is semantic differential method proposed by Osgood. This is the measurement method for connotative meaning of an object (Osgood, Suci, & Tannenbaum, 1957). Connotative meaning represents an idea or mental image of an object rather than the thing its meaning. General steps of semantic differential method for color psychology are as follows. (1) Mental image or emotional words related with a color object are collected. (2) The words are selected according to relevance to the object by brainstorming or reflecting experts' opinions. (3) Selected words are transformed into evaluation word pairs which have opposite meanings. (4) In an experiment, subject should determine one word of the word pair and evaluate degree according to relation between words and the object.

The results of semantic differential data are processed by PCA. Degree of relations between the objet and word pairs is calculated, and correlations between word pairs are analyzed by PCA. By using the PCA results, dimensions of color connotations are derived. Color connotation of the object could be quantified, and estimation models for color connotations could be designed.

II.3.2. Classification of Color Connotation Scales

Early Studies on color connotation were typically associated with how to reduce a large number of color connotation scales into a smaller number of categories or component by using principal component analysis or factor analysis.

Wright and Rainwater (B. Wright & Rainwater, 1962) assorted 48 color emotion scales into six categories. The categories were “happiness,” “showiness,” “forcefulness,” “warmth,” “elegance” and “calmness.” In their studies, these categories were connected with the three color appearance attributes, i.e. hue, lightness and chroma. The results indicated that lightness and chroma have more influence than hue on color emotion.

Hogg (Hogg, 1969) categorized 12 color emotion scales into four components: “impact,” “usualness,” “evaluation,” and “warmth.” The results represented that components “impact” and “Warmth” were associated with chroma and hue, respectively. The other component had complicated relationships with the three color appearance attributes.

Kobayashi (Kobayashi, 1981) classified 23 color image scales into three factors by using factor analysis. These three factors consisted of independent dimension of color emotion. The three independent dimensions were “warm–cool”, “soft –hard” and “clear – greyish”. The three dimensions were also concerned with the color appearance attributes which are hue, lightness and chroma.

Sato et al.(Sato, Kahiwara, Xin, Hansuebsai, & Nobbs, 2000) suggested three dimensions corresponded to three independent dimensions proposed by Kobayashi: “warm – cool”, “potency” and “activity.” These dimensions were also found in connection with the three color appearance attributes of related colors, hue, lightness and chroma, respectively.

Ou et al. (Ou, Luo, Woodcock, & Wright, 2004) suggested universal dimensions of color emotion as investigating the classifications of color emotion scales using principal component analysis. In his studies, 10 emotion word pairs selected. He categorized 10 color emotion scales into three principal components: “Color weight,” “Color activity,” and “Color heat.” The results indicated that there was significant connection between these components and the three color appearance attributes, i.e. hue, lightness and chroma.

Gao (Gao & Xin, 2006) classified 12 color emotion scales into two orthogonal factors and one correlative factor by using factor analysis. Two orthogonal factors were assigned as “activity index” and “potency index,” and one correlative factor was assigned as “definition index.” The results indicated that activity index was related with chroma, the potency index was associated with lightness, and definition index was concerned with both chroma and lightness. On the other hand, the influence of hue on emotional response was not significant.

II.3.3. Color Connotation Models

The quantification for color connotation scales is one of the major subjects in color emotion research. Most color connotation models were developed by using the empirical data obtained by psychophysical experiments. Color appearance attributes are used as variables for predicting color emotion values in color emotion models.

Sato et al. (Sato, Kajiwara, Hoshino, & Nakamura, 2000) were developed a set of color emotion equations**.** The study included 12 emotional word pairs, and it was expressed by ellipsoid-shape equation. The foundational idea was that for each color emotion scale, there is a color having emotional value ranging from "weakest" to "strongest". Emotion values were determined by Euclidean distance between test color and reference color in CIELAB color space. The colors presenting the weakest color emotion came to be the reference colors. This idea can be represented by using axes of CIELAB color space, as follows:

$$CE = \{k_L(L^* - L_0^*)^2 + k_a(a^* - a_0^*)^2 + k_b(b^* - b_0^*)^2\}^{1/2} + k_M$$

where CE is the predicted value for a color emotion; L^*, a^*, and b^* are CIELAB co-ordinates of the test color; L_0^*, a_0^*, and b_0^* are CIELAB co-ordinates of the reference color; k_L, k_A, k_B and k_M are constants.

Sato et al. (Sato, Kajiwara, Xin, Hansuebsai, & Nobbs, 2003) also developed an alternative form of the equation as using chroma C^* of CIELAB instead of a^* and b^*, as follows:

$$CE = \{k_L(L^* - L_0^*)^2 + k_c(C^* - C_0^*)^2\}^{1/2} + k_M$$

where L^* and C^* are CIELAB lightness and chroma for test color; L_0^* and $C_0^*$are CIELAB lightness and chroma for reference color; k_L, k_A, k_M are constants.

Hue-related variables, such as $(1 - |h - h_0|/360°)$, were added into the C^* term of above equation because the equation did not reflect the contribution of hue difference. h is CIELAB hue angle of the test color and h_0 is CIELAB hue angle of the reference color. Table 1 shows examples of their color emotion equations, where B is Dyer's brightness.

Table 1 Sato's models

Color emotion	Color emotion equations proposed by Sato
Warm – Cool	$WC = 3.5\{cos(h - 50°) + 1\}B - 80$
Heavy – Light	$HL = -3.5L^* * +190$
Active – Passive	$DYP = [0.6(L^* - 50)^2 + \{4.6(1 - \Delta h_{290}/360)C^*\}^2]^{\frac{1}{2}} - 115$
Soft – Hard	$SH = [(3.2L^*)^2 + \{2.4(1 - \Delta h_{290}/360)C^*\}^2]^{\frac{1}{2}} - 180$

Xin and Cheng (Cheng, 2002) assumed that color emotion values are linearly correlated with each of the three color appearance attributes which are lightness, chroma and hue angle. Predictive equations based on their assumption were developed for single-color emotion of related color. Predictive equations were in the following form:

$$CE = k_L L^* + k_c C^* + k_h h + k_M$$

where CE is the predicted value of a color emotion; L^*, C^* and h are CIELAB lightness, chroma and hue angle for the test color; k_L, k_C, k_h, k_M are constants. Since for some scales chroma has curvilinear correlation with color emotion values, an exponent was added into the term C^* such as $C^{*(0.372)}$. Examples of their emotion equations are given in Table 2.

Table 2 Xin-Cheng's models

Color emotion	Color emotion equations proposed by Xin and Cheng
Warm – Cool	$WC_{0°\leq h\leq 180°} = 0.154L^* + 39.378C^{*(0.372)} - 0.303h + 113.855$
	$WC_{180°\leq h\leq 360°} = 0.335L^* + 23.476C^{*(0.429)} - 0.159(360° - h) + 105.710$
Heavy – Light	$HL_{0°\leq h\leq 180°} = -3.340L^* + 0.476C^* - 0.037h + 175.467$
	$HL_{180°\leq h\leq 360°} = -3.477L^* + 0.476C^* - 0.037h + 175.467$
Active – Passive	$DyPa_{0°\leq h\leq 180°} = -0.296L^* + 3.162C^{*(0.931)} - 0.073h - 68.835$
	$DyPa_{180°\leq h\leq 360°} = -0.120L^* + 4.385C^{*(0.864)} - 0.032(360° - h) - 84.791$
Soft - Hard	$SH_{0°\leq h\leq 180°} = 2.900L^* - 0.510C^* - 0.037h - 146.700$
	$SH_{180°\leq h\leq 360°} = 2.953L^* + 0.424C^* - 0.020(360° - h) - 159.795$

Each of the equations covers only 180° in the range of hue angles, and accordingly each color emotion scale requires a pair of equations for the entire range of hue angle.

Another researcher, Ou et al. (Ou et al., 2004), also developed color emotion equations for single color of related colors. Ou’s color models were affected by Sato’s models and Xin-Cheng’s models. Ou’s study included 10 connotation scales which are nine nonesthetic connotation scales and an esthetic connotation scale (Like – Dislike). He elaborated not only estimation models of each emotion scales but also those of the three color emotion components of color emotion space. Ou’s color emotion equations are summarized in Table 3.

Table 3 Ou’s models

Color emotion		Color emotion equations proposed by Sato
Color connotations	Warm – Cool	$WC = -0.5 + 0.02(C^*)^{1.07} cos(h - 50°)$
	Heavy – Light	$HL = -2.1 + 0.05(100 - L^*)$
	Active – Passive	$AP = -1.1 + \left\{(\Delta C^*_{N5})^2 + \left(\frac{\Delta L^*_{N5}}{1.5}\right)^2\right\}^{\frac{1}{2}}$
	Hard - Soft	$SH = [(3.2L^*)^2 + \{2.4(1 - \Delta h_{290}/360)C^*\}^2]^{\frac{1}{2}} - 180$
Color factors	Color activity	Color activity $= -2.1 + 0.06\left\{(L^* - 50)^2 + (a^* - 3)^2 + \left(\frac{b^* - 17}{1.4}\right)^2\right\}^{1/2}$
	Color weight	Color weight $= -1.8 + 0.04(100 - L^*) + 0.45\cos(h - 100°)$
	Color heat	Color heat $= -0.5 + 0.02(C^*)^2 \cos(h - 50°)$

Experimental Design

III. Experimental Design

The aim of experiments was to clarify the relation between color perception and color connotation of unrelated colors, and to develop models for color connotation based on color science. To achieve these objectives, two psychophysical experiments were carried out.

In experiment 1: *color perception for unrelated colors*, color perception of unrelated colors was investigated by using LED (light-emitting-diode) as color stimuli. Magnitude estimation method was used to obtain the intensities of the color attributes such as hue, colorfulness and brightness. 50 stimuli were given to an observer one by one, and the observer was asked to determine the magnitude of color attributes for each stimulus in comparison to anchor stimulus. The perceptual data was used to derive new estimation models and to examine the performance of color appearance models. Experiment 2: *color connotation for unrelated colors*, has the same experimental condition as that used in Experiment 1. Semantic differential method was used to obtain the predominant color connotation for each color stimulus. The psychophysical data was transformed into z-scores, and then z-scores data was analyzed by principal components analysis in order to construct color connotation dimension for unrelated colors.

III.1. Experimental Settings

III.1.1. Color Measuring Instrument

The accuracy of colorimetric data depends on the performance of color measuring instruments such as colorimeters, spectrophotometers, spectroradiometers, and tele-spectroradiometers. The present research used a Minolta CS-2000 tele-spectroradiometer to measure colors. It was used to determine the tristimulus data of the color stimuli for each experiment.

The Minolta CS-2000, shown in Figure 9, is one of the most widely used tele-spectroradiometers for color measurement. The instrument is capable of measuring both self-luminous and surface colors. As with other tele-spectroradiometers, the CS-2000 is composed of three key components: a telescope, monochromator, and detector.

The manufacturer states that the measurements are made over the visible spectrum from 380 to 780 nm with fixed intervals of 5 nm. It also has measurement accuracies of ±2%, ±0.0015, and ±0.0010 for the luminance, x chromaticity, and y chromaticity, respectively. The measurement repeatability values for the luminance, x chromaticity, and y chromaticity are ±0.15%, ±0.0004, and ±0.0004, respectively. Table 4 summarizes the specifications of the CS-2000.

In this research, for each measurement, the CS-2000 was set up at the same position as occupied by an observer’s eyes and directed at the color stimuli in order to obtain tristimulus values that accurately represent each color stimulus seen by the observer in the experiment. Measurement angle was set up at 1°.

Table 5 gives the CS-2000 positioning data for each experiment.

Figure 9 Minolta CS 2000 tele-spectroradiometer

Table 4 Specifications of Minolta CS-2000 tele-spectroradiometer

Spatial range	380~780 nm		
Wavelength resolution	0.9 nm/pixel		
Spectral bandwidth	5 nm or less		
Spectral accuracy	± 0.3 nm (under standard illuminant A)		
Measurement angle	1°	0.2°	0.1°
Luminance range (cd/m^2) (under standard illuminant A)	0.003~5,000 cd/m^2	0.075~125,000 cd/m^2	0.3~500,000 cd/m^2
Measurement accuracy (under standard illuminant A)	Luminance: ± 2% Chromaticity: x: ±0.0015, y: ±0.0010		
Measurement repeatability (under standard illuminant A)	Luminance: ± 0.15% Chromaticity: x: ±0.0004, y: ±0.0004		
Polarization error	2% or less (400~780 nm)	3% or less (400~780 nm)	3% or less (400~780 nm)

Table 5 Positioning data for CS-2000 and color stimuli in experiments.

	Type of Color stimuli	Height of CS-2000	Height of Color stimuli	Distance between CS-2000 and Color stimuli
Experiment 1 Experiment 2	Self-luminous (LED colors)	115 cm	115 cm	110 cm

III.1.2. *Experimental environment*

The observations had to be carried out in a totally dark environment. Figure 10 illustrates the experimental environment. Experiment 1 and experiment 2 had identical experimental environments. An observer was seated in a chair in a blackout system. The distance between the observer and color stimulus was approximately 110 cm. Two experimenters filled the roles of lighting controller and data recorder. The experimenter performing the lighting control used a computer to control the lighting cabinet, which provided a color stimulus to the observer through a square hole; this experimenter also controlled a black board to block out light at the back of the square hole.

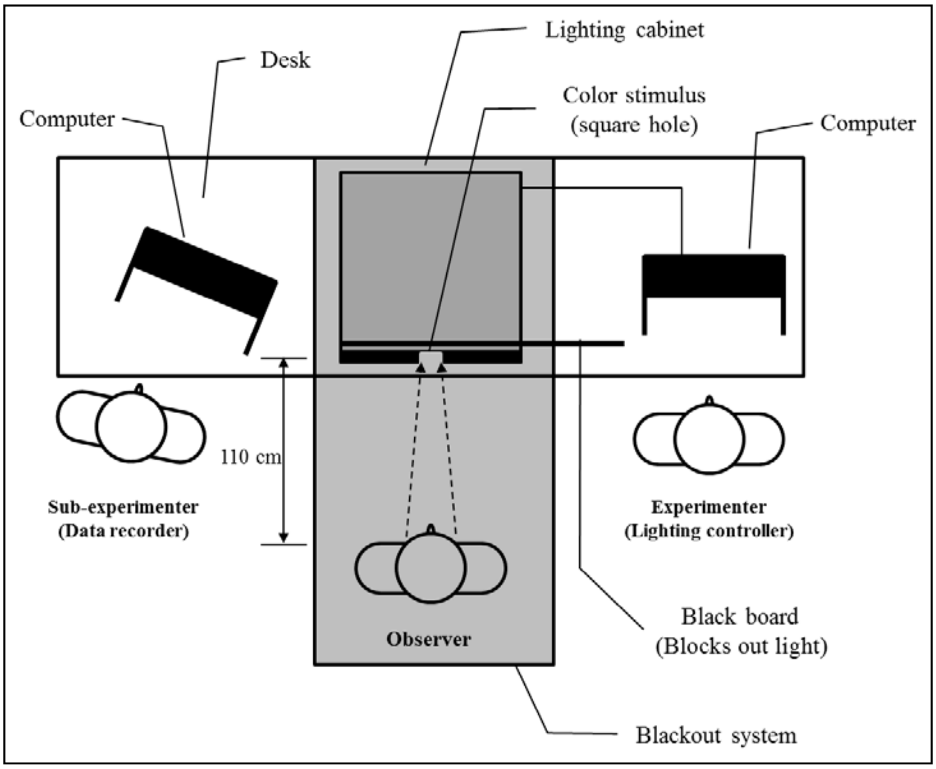


Figure 10 Experimental environment

Lighting cabinet

A custom-built lighting cabinet was used for the experiments. Figure 11 shows the front of this lighting cabinet, along with the lighting modules arranged at the top of it. The inside of the lighting cabinet was painted grey, which had CIELAB values of 97.48, –0.17, and 2.14 for L*, a*, and b*, respectively, under standard illuminant D65, measured by CR-400. The light cabinet consisted of red, green, blue, warm white, and cool white LED modules. Each module could be operated independently. Figure 12 illustrates the spectral power distributions of the light emitted by the LED modules. While the spectral power distributions of the primary light beamed from the red, green, and blue LED modules consisted of one spectral line with a narrow band width, those of both the warm and cool white modules were composed of broader spectrum throughout the spectrum with peaks at 459nm and 448nm, respectively. The illuminant level of each module was controlled by software provided by the manufacturer, Posan Industry. In the experiments, only 3 modules were used, the red, green, and blue LED modules.

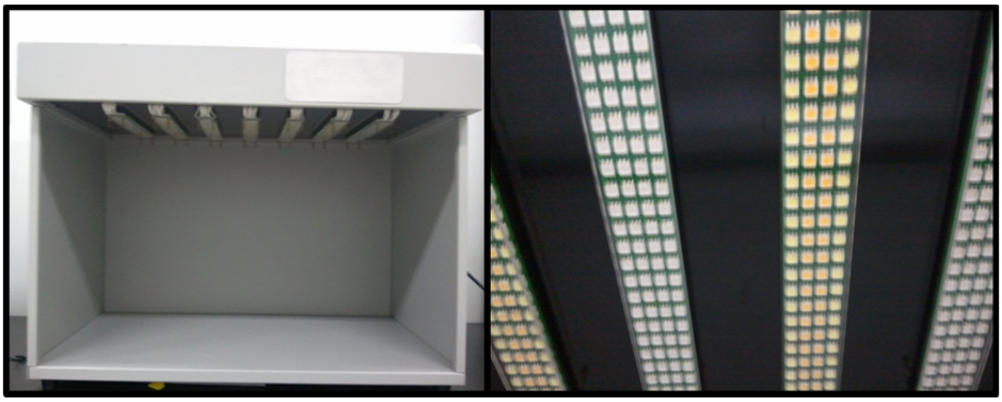


Figure 11 LED lighting cabinet and lighting modules

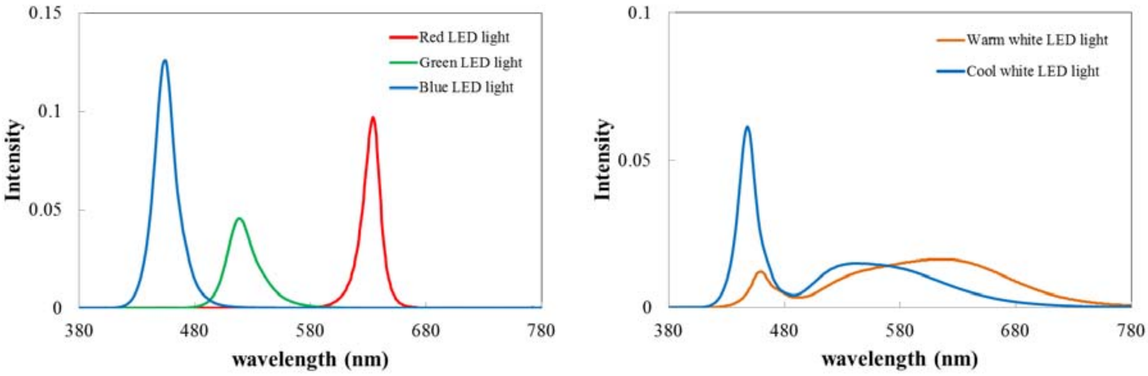


Figure 12 Spectral power distributions of each lighting module

Blackout system

In experiment 1 and experiment 2, all of the colored objects in the laboratory, excluding the LED light beamed through the square hole, were masked to display unrelated colors. The dark system consisted of two key parts: the lighting part and blackout part. The lighting part consisted of the viewing cabinet with the LED light modules and a piece of black hardboard with a square hole in the middle. The size of the square hole is 3 by 3 centimeters, and viewing angle is about 2 degree at subject's position from the square hole. The blackout part had a structure consisting of blackout curtains and a cuboid frame to block out the light from the laboratory. The blackout curtains covered all of the faces of the cuboid frame. The blackout part was 2 m long, 1.4 m wide and 1.6 m tall.

The CIELAB values of the black hardboard, measured by CR-400, were 18.14, 0.29 and 1.68 for L*, a*, and b*, respectively, under standard illuminant D65. It blocked out everything except the colored light beamed through the hole.

Figure 13 Outside (left) and inside (right) of blackout system

III.1.3. Observers

Twenty-two observers, including 11 males and 11 females, participated in experiment 1. Thirty-two observers (16 males and 16 females) took part in experiment 2. The twenty-two observers in experiment 1 also participated in experiment 2. The ages of the observers ranged from 20 to 28 years, and all of the observers were Korean. All of the observers were screened for normal color vision by means of the Ishihara test and Farnsworth-Munsell 100 Hue test. Most of the observers had average discrimination ability according to the results of the Farnsworth-Munsell 100 Hue test. Table 6 provides a summary of the characteristics of the observers in the experiments.

Table 6 Summary of characteristics of observers in experiments

	Experiment 1		**Experiment 2**	
	Female	Male	Female	Male
The number of observers	11	11	16	16
Ages	20~28 years old			
Color vision	Normal color vision (at least average color discrimination ability)			

III.1.4. Stimuli

In the experiments, fifty of the stimuli were selected, reasonably covering the entire range of hue, brightness, and colorfulness in the CAM97u. These included nine of high colorfulness colors and high brightness color at gamut boundary. The chromaticities of the 50 stimuli are shown Figure 14.

The colorimetric values of the 50 stimuli are given in Table 7, which were measured using the Minolta CS-2000 tele-spectroradiometer. The values in Table 7 are the arithmetic means of the illuminant level and chromaticity coordinates for each stimulus, which was measured fifteen times during the experiments at random intervals. The coefficient of variation (CV) was used to investigate the stability of the emitting performance because it was important for the stimuli to maintain constant colorimetric values. CV is a normalized measure of dispersion, and it is defined at the ratio of the standard deviation to the mean. Figure 15 illustrates the CV of each stimulus. Overall, the CVs of illuminant level and chromaticity coordinates were less than 0.02. This indicated that these were appropriate to use in the experiments as stimuli.

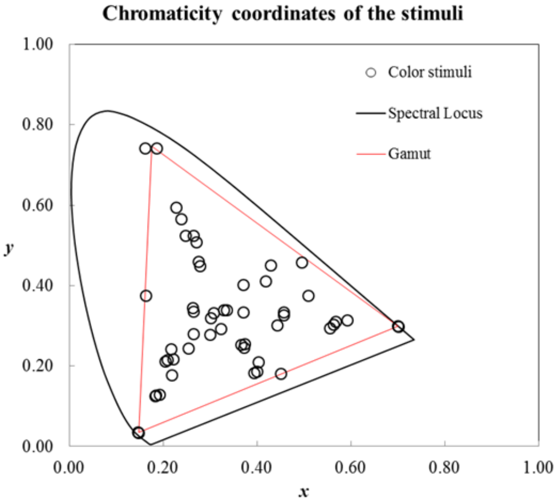


Figure 14 x, y chromaticities of 50 stimuli

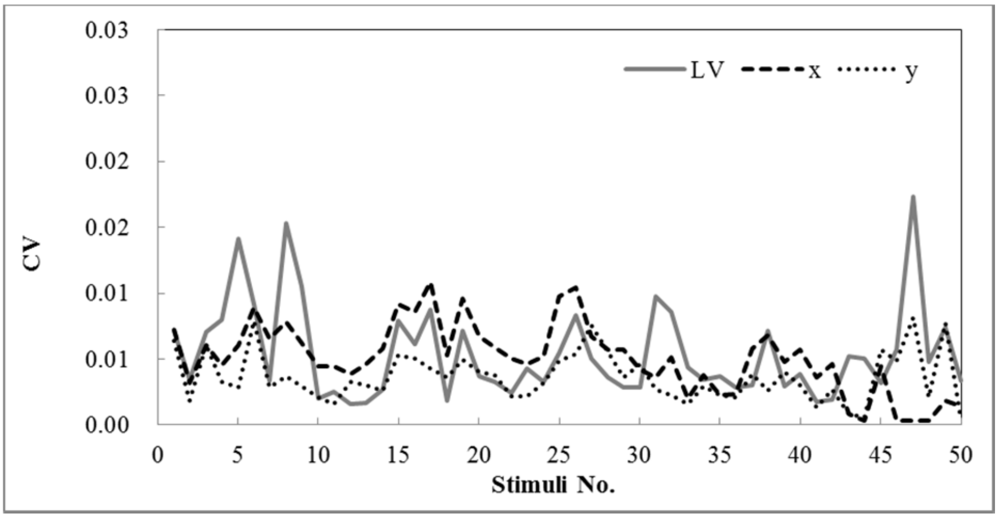


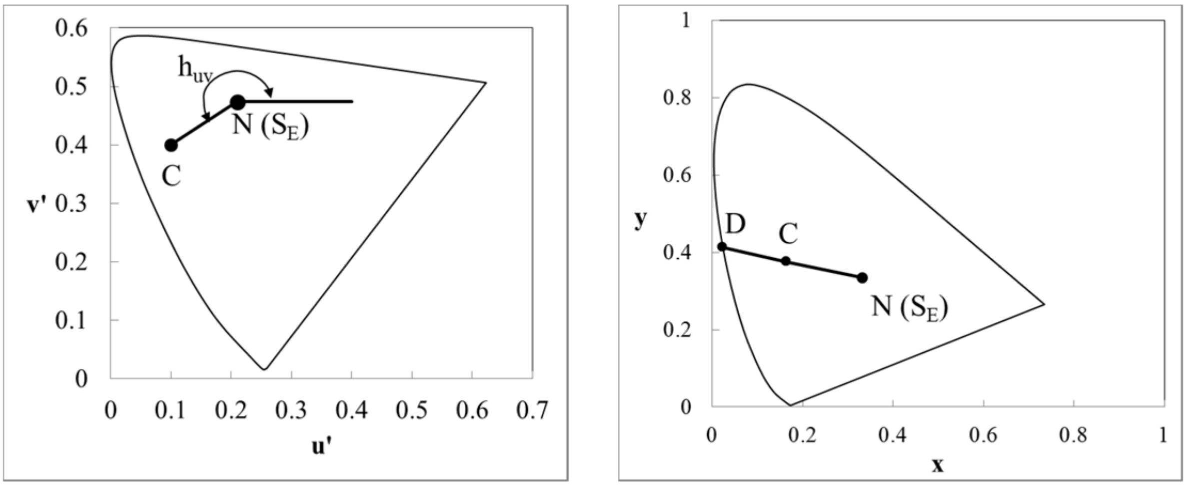
Figure 15 CV (coefficient of variation) of 50 stimuli measured by CS-2000

Table 7 Colorimetric values of 50 stimuli

Stimulus	Mean values			Stimulus	Mean values		
	Lv(cd/m^2)	x	y		Lv(cd/m^2)	x	y
1	62.88	0.5928	0.3141	26	55.73	0.2782	0.4488
2	298.62	0.4962	0.4581	27	110.44	0.2381	0.5642
3	120.89	0.2757	0.4595	28	109.50	0.2706	0.5083
4	70.81	0.2170	0.2414	29	160.60	0.2280	0.5930
5	36.84	0.2189	0.1760	30	160.08	0.2646	0.5241
6	51.10	0.5096	0.3749	31	53.05	0.1923	0.1290
7	109.58	0.4301	0.4505	32	53.29	0.2222	0.2159
8	34.49	0.2645	0.2800	33	106.40	0.1854	0.1270
9	47.08	0.2533	0.2437	34	107.34	0.2093	0.2152
10	285.27	0.3713	0.3332	35	158.65	0.1836	0.1256
11	331.64	0.4188	0.4103	36	160.24	0.2045	0.2117
12	229.99	0.2646	0.3341	37	68.70	0.4041	0.2089
13	201.74	0.2997	0.2782	38	52.16	0.3726	0.2460
14	140.16	0.3715	0.4008	39	101.89	0.4004	0.1866
15	62.34	0.2626	0.3443	40	104.23	0.3741	0.2539
16	74.33	0.3230	0.2917	41	150.04	0.3934	0.1827
17	52.48	0.3360	0.3378	42	156.97	0.3664	0.2524
18	186.85	0.3297	0.3394	43	40.03	0.7004	0.2987
19	51.90	0.4440	0.3014	44	99.38	0.7017	0.2976
20	69.14	0.5562	0.2946	45	43.87	0.4505	0.1796
21	105.23	0.4566	0.3258	46	79.37	0.1631	0.3754
22	102.83	0.5630	0.3027	47	7.31	0.1464	0.0357
23	157.89	0.4577	0.3332	48	40.71	0.1481	0.0331
24	151.52	0.5679	0.3099	49	55.40	0.1856	0.7408
25	75.10	0.2472	0.5244	50	230.74	0.1620	0.7407

III.2. Variables

III.2.1. Independent Variables



(a) The derivation in the *u'*, *v'* diagram of hue-angle, h_{uv}

(b) The derivation on the *x*, *y* diagram of excitation purity, *Pe*

Figure 16 Geometrical meanings of h_{uv} and *Pe*

The independent variables for experiments 1: color perception for unrelated colors and experiment 2: color connotation for unrelated colors were CIE 1976 hue-angle, excitation purity, and luminance. The definitions of these, as given by CIE, are as follows. Hue is an 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. Levels of independent variable "hue" are reasonably selected to cover the entire range of CIE 1976 hue-angle. CIE 1976 hue-angle is correlate of hue in the CIELUV color space. The CIE 1976 hue-angle is calculated as follows.

$$h_{uv} = \arctan[(v' - v'_n)/(u' - u'_n)]$$

v'_n and u'_n are the values of v' and u' for a suitably chosen reference white. In this research, v'_n and u'_n are assigned (1/3, 1/3) which is coordinate of equi-energy stimulus because there is no reference white when the color is the unrelated color.

Excitation purity is quantity defined by the ratio NC/ND of two collinear distances on the x, y chromaticity diagram. NC is the distance between the point C representing the color stimulus considered and the point N representing the specified achromatic stimulus; ND is the distance between the point N and the point D on the spectral locus at the dominant wavelength of the color stimulus considered. In the case of purple stimuli, the point on the spectral locus is replaced by a point on the purple boundary. The excitation purity of the stimuli has a range of 2.21 to 97.74%. In Figure 16, the geometrical meanings of CIE 1976 hue-angle and excitation purity can be seen. There is a difference of the color space between CIE1976 hue-angle and excitation purity. CIE1976 hue-angle is a measure in u', v' diagram, and excitation purity is a measure in x, y diagram. In x, y diagram, there is no measure about hue. Therefore, CIE1976 hue-angle is used as an independent variable in experiment 1:color perception for unrelated colors because CIE1976 hue-angle could be simply calculated by using x, y in x, y diagram, as written in section II.2.4. Furthermore, the measure correlates uniformly with the perception of and hue.

Luminance is the luminous intensity per unit projected area in a given direction at a point in the path of a beam, and the unit of luminance is cd/m^2. Luminance values of the stimuli range between 7.31 and 331.64 cd/m^2. The independent variables and their levels in experiment 2 were identical to those of experiment 1.

III.2.2. Dependent Variables

In experiment 1: color perceptions for unrelated colors, the dependent variables were the magnitude of the perceptual hue, brightness and colorfulness for each stimulus. To estimate magnitude of the perceptual brightness and colorfulness, stimulus 13, (Lv, x, y) = (201.74, 0.2997, 0.2782), was selected as an anchor stimulus called modulus, and the brightness and colorfulness of the modulus were assigned as 45 and 30, respectively. Finally, subsequent stimuli were evaluated in comparison to the modulus. Hue of the color stimuli was estimated by asking observers to describe the hue as a proportion of two neighboring primaries which are red, yellow, green and blue. Observers decided a predominant color, then they decided whether any other primary hue was observed or not. The measure of hue is called hue quadrature. Finally, they estimated the proportion in the two primaries stand. In the experiment, unique colors, red, yellow, green, and blue, were assigned hue quadrature values of 0, 100, 200, and 300, respectively.

In experiment 2: color connotations for unrelated colors, the dependent variables were the relative values for the color connotation indicated by the z-scores (III.4.4) of the word pairs for each stimulus. Table 8 shows the dependent variables of the experiments. In experiment 2, 10 word pairs were used to measure color connotation responses. These word pairs were adopted from the study of Ou et al.(Ou et al., 2004). According to Ou et al., the word pairs were selected using the following criteria. First, the word pairs had to have been used in various countries. Second, the word pairs had to have been used in connection with color. Third, the word pairs had to have no direct relationship with color attributes such as hue, brightness, and colorfulness. Finally, the word pairs were covered evenly, according to their literal meanings, by Osgood's three primary factors of semantics, i.e., "evaluative," "potency," and "activity"(Osgood et al., 1957).

Table 8 Dependent variables of experiments

Experiment 1	Experiment 2
The magnitude of color perception (Hue, Brightness, Colorfulness)	The relative value of color connotation (z-scores of the word pairs for each stimulus)

III.3. Experimental Procedure

III.3.1. Experiment 1: Color perception for unrelated colors

Experiment 1: color perception for colors was divided into two sessions according to similarity of measurement methods. The magnitudes of perceived brightness and colorfulness were estimated in session 1, and the magnitude of perceived hue was evaluated in session 2. The reason was that measurement methods for perceptual brightness and colorfulness should make use of an anchor stimulus while there was no need to use an anchor stimulus for evaluating perceptual hue. All subjects have participated in both sessions.

Before the experiment 1, each observer was given instructions (Appendix - A.1.) for the experiment and the definitions of the color attributes. These were formulated by referring to the definitions enacted by CIE (Commission Internationale de l'Eclairage). The observations were performed in a totally dark environment. In this study, 15 min were allowed for adaptation before starting the experiments. In the experiment, magnitude estimation was used for data collection.

Before showing the test stimuli in sessions 1, the anchor stimulus, stimulus 13, was given to an observer, and after that it was presented every 10 test stimuli during the section 1. Each test stimulus was given to the observer for 5s, followed by dark periods of about 10s. Each observer was asked to determine perceived brightness and colorfulness of the stimulus in comparison to the anchor stimulus during the dark periods. It means that subjects should respond the magnitudes of perceived brightness and colorfulness by presenting a next color stimulus.

The procedure of session 2 was similar to that of session 1. Each test stimulus was given to the observer for 5s, followed by dark periods of about 10s. Each observer was asked to evaluate perceived hue of the stimulus during the dark periods. It means that subjects should answer the magnitudes of perceived hue by presenting a next color stimulus.

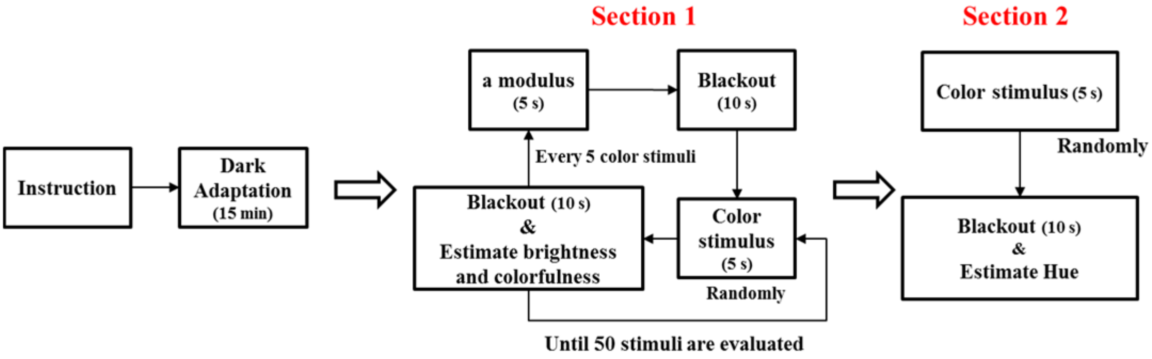


Figure 17 Procedure of the experiment 1

III.3.2. Experiment 2 : Color connotation for unrelated colors

Experiment 2 was also divided into two sessions in order to allow subjects to evaluate the ten word pairs in limited response time without difficulty. All of the word pairs were separated into two groups, and each group of the word pairs was used in different sessions.

Before the experiment 2, each observer was given instructions (Appendix – A.2.) for the experiment and the definitions of the 10 word pairs. These definitions were formulated by referring to the Cambridge Advanced Learner’s Dictionary (Appendix – A.3.).

The observations were carried out in a totally dark environment. In this experiment, 15 min was also allowed for adaptation before starting the experiments. Each stimulus was given to the observer for 5s, followed by dark periods of about 10s. 5 word pairs of the group were given in random order against each of the 50 stimuli. During the each dark period, the observer could choose one of the word pair i.e. active or passive, and the observer should evaluate 5 word pairs about each stimulus in one session.

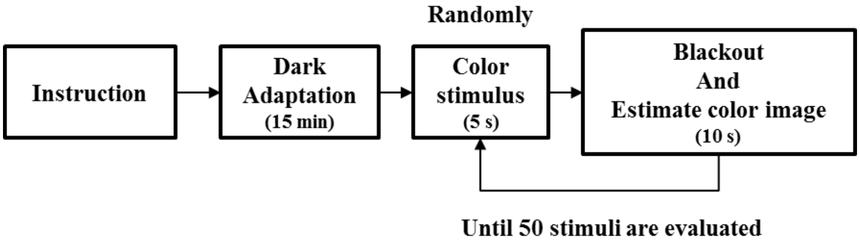


Figure 18 Procedure of the experiment 2

III.4. Data Analysis Methods

Kansei/Affective Engineering(Nagamachi, 2010) Applied Regression Analysis(Draper, Smith, & Pownell, 1966) are used as general reference.

III.4.1. *Coefficient of Variation (CV)*

Standard deviation is widely used in explaining dispersion of a population. However, standard deviation indicates absolute value of dispersion, so it is difficult to present meaningful information about dispersion according to size of data scales. For example, it has a problem with deciding more stable data according to values of standard deviation when there are two data sets, $(\mu_1, \sigma_1) = (100, 10), (\mu_2,\ \sigma_2) = (85, 8)$.

Coefficient of variation (CV) is also used to describe dispersion of a probability distribution, and it shows the extent of variability in relation to mean of the population. CV is a normalized measure and it is possible to minimize scaling problem. The coefficient of variation should be computed only for ratio scale data, and population could only take non-negative values. CV doesn't have any meaning for interval scale data. The coefficient of variation (CV) is defined as the ratio of the standard deviation to the mean value of population:

$$C_v = {}^{\sigma}/_{\mu}$$

In this formula, μ and σ are mean value and standard deviation of population, respectively. When μ and σ are geometric mean and geometric standard deviation in the formula, CV is called as geometric coefficient of variation (GCV).

In this research, CV is used in evaluating stability of the device used for generating color stimuli, and it is used for estimating observer variation about color appearance attributes in experiment 1: color perception for unrelated colors.

III.4.2. *Correlation Coefficient (r)*

Correlation coefficient is defined as the covariance of the two variables divided by the product of their standard deviations. It is also known as r, R. It is a measure of the extent and direction of the linear relation between two variables. It is defined in terms of the covariance of the variables divided by product moment of their standard deviations:

$$\rho_{X,Y} = {cov(X,Y)}/{\sigma_X \sigma_Y}$$

The correlation coefficient ranges from −1 to 1. A value of 1.0 indicates a positive linear relationship between two variables perfectly, and all data points lie on a line for which the values (X) of one variable increases as the values (Y) of another variable increases. On the other hand, a value of −1 implies a negative linear relationship between two variables perfectly, and all data points lie on a line for which the values (X) of one variable decreases as the values (Y) of another variable increases. A value of 0 indicates no linear correlation between the variables.

In this research, correlation coefficient is used in all experiments. In experiment 1: color perception for unrelated colors, it is applied to evaluate linear relationships between perceptual data and predicted data calculated by new models and color appearance models such as CAM97u and revised CIECAM02. In experiment 2: color connotation for unrelated colors, it is applied to examine gender difference for observer accuracy.

III.4.3. Coefficient of Determination (r^2)

In statistics, the coefficient of determination, denoted r^2, is used to describe how well a regression line fits a set of data. Coefficient of determination ranges from 0 to 1. A value of 1.0 indicates that a regression line perfectly fits the data, while an r^2 closer to 0 implies that a regression line does not fit the data very well. It is the proportion of variability in a data set. The variability of the data set is measured through different sum of squares:

$$SST = SSE + SSR$$

$$SST = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

$$SSR = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2$$

$$r^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST}$$

In these formulae, the values y_i are called the observed values and the values $\hat{y}_i$ are modeled values. $\bar{y}$ is the mean value of the observed values.

In this research, coefficient of determination is used in all experiments. In experiment 1: color perception for unrelated colors, it is applied to evaluate how well the estimation models and color appearance models fit a set of perceptual data obtain by the psychological experiments. In experiment 2: color connotation for unrelated colors, it is applied to examine how well the estimation models for color connotation of unrelated colors fit a set of emotional data.

III.4.4. z-Scores

In statistics, a z-score indicates how many standard deviations an element is from the mean. It is derived by dividing the difference between population mean and an element by the population standard deviation. A z-score could be calculated from following equation.

$$\mathrm{z} = {}^{(x-\mu)}/_{\sigma}$$

where z is z-score, x is the value of the element, μ is the population mean, and σ is the standard deviation. A z-score less than 0 represents an element less than the mean, a z-score greater than 0 represents an element greater than mean, and a z-score equal to 0 represent an element equal to the mean.

z-score is used in experiment 2: color connotation for unrelated colors. Test statistics z for a single population proportion is applied because raw data in experiment 2 is a nominal scale. For calculating z-score, frequency of elements is converted into proportion, and then the proportion is transformed into the z-score by using following equation.

$$\mathrm{z} = \frac{\hat{p} - p_0}{\sqrt{p_0(1 - p_0)/n}}$$

where $\hat{p}$ is a proportion of an element, p_0 is a test value, and *n* is a sample size. In this research p_0 is assigned as 0.5 because 0.5 indicates that there is no dominant color connotation.

III.4.5. Correct Decision (CD)

Correct decision is a measure of data dispersion on nominal scales while coefficient of variation is a measure of data dispersion on ratio scales. Correct decision implies how well individual data agree with the majority. A CD value is defined by:

$$\mathrm{CD} = \frac{\sum_i c_i}{N}$$

where c_i is the proportion of subjects of whose responses agree with the majority decision of the group for stimulus i and N is the number of stimuli. Majority decision is the mean value of 1-or0 responses for each stimulus when original responses of each subject assigned as either 1 or 0 such as "like" (1) dislike (0). If the majority decision is greater than 0.5, the majority of subjects agree that the stimulus is concerned with "like," whereas if the majority decision is less than 0.5, the majority agree with "dislike." When a subject response to a stimulus is 1 and the majority decision is greater than 0.5, the subject agrees with the majority decision. On the other hand when a subject response to a stimulus is 0 and the majority decision less than 0.5, the subject agrees with the majority.

The CD is applied to examine observer accuracy in experiment 2: color connotation for unrelated colors because obtained data are nominal scales such as emotional adjective.

III.4.6. Principal Component Analysis (PCA)

Principal component analysis (PCA) is a mathematical procedure for reducing a large data set of possibly correlated variables into a small data set of linearly uncorrelated variables called principal components. The number of principal components is less than or equal to the number of original variables. Principal components are guaranteed to be independent.

Orthogonal transformation is used in PCA, and the determination of eigenvectors and eigenvalues of a covariance matrix are essential notions. Eigenvectors and eigenvalues are defined as the solution of below equation:

$$\mathrm{AI} = \lambda \mathrm{I}\ (\mathrm{I} \neq 0)$$

where A and λ are eigenvector and eigenvalue, respectively. The condition $\mathrm{I} \neq 0$ means that I is not the null vector. PCA is used in experiment 2: color connotation for unrelated colors. In experiment 2, A is the covariance matrix of experimental data (z-scores) for color connotation responses. The results of color connotation scales are classified in terms of component loadings. Component loadings are the correlation coefficients between experimental data (z-scores) and principal components derived.

Results of Experiments

IV. Results of Experiments

IV.1. Experiment 1 : Color Perception for unrelated colors

Experiment 1: *color perception for unrelated colors* was carried out for several purposes. The first purpose was to collect perceptual magnitude data of color attributes concerned with unrelated colors. The second was to investigate relationships between color appearance attributes and characteristics of stimuli, and to derive estimation models of color appearance attributes based on the relationships. The third is to evaluate performance of CAM97u and revised CIECAM02 based on the visual data. Finally, the estimation models and color appearance models, CAM97u and revised CIECAM02, were compared in terms of performance for estimating brightness, colorfulness and hue.

The visual results were recorded in terms of the magnitude estimations of the brightness, colorfulness, and hue. Following the methods recommended by Fu et al. (Fu et al., 2011), the brightness and colorfulness attributes were calculated using a geometric mean, and the hue attribute was averaged using an arithmetic mean.

IV.1.1. Observer Variation

The magnitude-estimation data were collected, and the coefficient of variation (CV) was used to indicate the agreement between any two sets of data. For the hue attributes, CV values were calculated between each individual observer’s perception results and the average results for all of the observers, to represent the observer accuracy. In terms of the brightness and colorfulness, the geometric coefficient of variation (GCV) was applied because the geometric mean was calculated to average the two sets of perception data. For perfect agreement, the CV value should be zero. A CV of 15 roughly indicates a variation of 15% between two datasets.

The mean CV values for observer accuracy were 40, 27, and 12 for the brightness, colorfulness, and hue, respectively. This implies that when assessing the color appearance of unrelated colors, the observer performance for hue was better than that for the brightness and colorfulness. These results were similar to those found in earlier experiments (Luo et al., 2007) for investigating related colors.

IV.1.2. Brightness

Relationship between Luminance and Perceptual Brightness

In this section, stimulus 13 (*Lv* = 201.74cd/m^2) was employed as an anchor stimulus, and the brightness of the modulus were assigned as 45. Figure 19 illustrates the relationship between the luminance levels of unrelated color stimuli and the perceived brightness. The horizontal axis of the graph represents the luminance values of the stimuli, which ranged between 7.31 and 331.64 cd/m^2 under a photopic luminance condition. The vertical axis of the figure shows the magnitude of the perceived brightness. Overall, it appears that the magnitude of the perceptual brightness increased as the luminance level of the stimuli rose. However, it is clear that there is no linear relation between the luminance level of the stimuli and perceived brightness. The perceived brightness rose rapidly until it reached approximately 40 at a luminance level of 50 cd/m^2. It then increased slowly at values greater than 50 cd/m^2. This indicates that there is a compressive nonlinear relationship between the intensity of the luminance and the perceived magnitude of the brightness, which illustrates a decreasing sensitivity with increasing stimulus intensity.

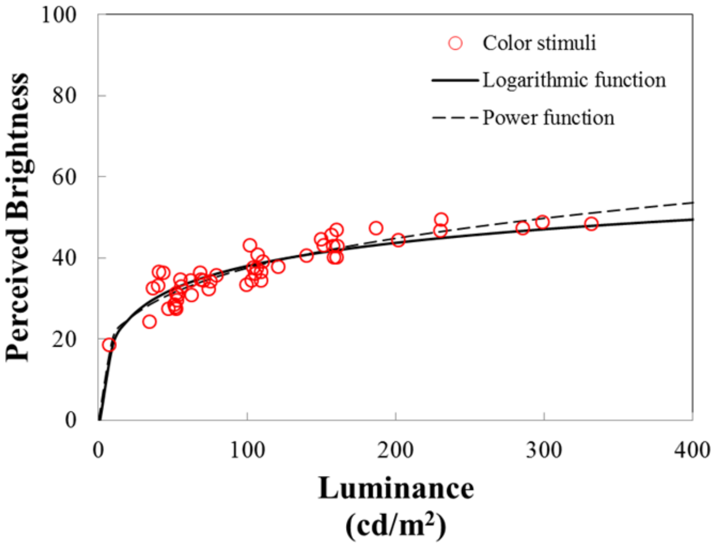


Figure 19 Relationship between luminance and perceptual brightness

In terms of the relationship between the physical intensity and perceptual magnitude, many previous studies have derived a transformation of the physical stimulus intensity scale to a perceptual magnitude scale. Fechner's law (Fechner, 1966) states that the perceived magnitude of a stimulus is proportional to the logarithm of the physical stimulus intensity. Stevens' power law (Stevens, 1961) indicates that the relationship between the perceptual magnitude and stimulus intensity follows a power law with various exponents for different perceptions. The solid curve in Figure 19 presents a logarithmic function for the luminance, while the broken curve represents the power function of the luminance when the exponent is less than unity. The constants used for the functions were derived using the least square method. These two lines seem to have similar shapes and fit the perceptual brightness data well.

The following formula can be used for the logarithmic function explaining the relation between the luminance of the stimuli and perceived brightness.

$$\text{Brightness} = a_1 \cdot \ln(luminance) + a_0$$

In this formula, a_1 and a_0 are constants with values of 8.25 and zero, respectively. The correlation coefficient (r) between the perceived brightness and logarithmic function was 0.90, indicating good correlation between these two scales. Furthermore, the coefficient of determination (r^2), which provides a measure of how well outcomes are likely to be estimated by the model, was 0.81 and the adjusted r^2 was 0.80. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 199.83). As the p-value is much less than 0.05, the logarithmic function fit the perceived brightness data well in terms of linear regression. Figure 20 plots the relationship between the values estimated by the logarithmic function and the perceived brightness.

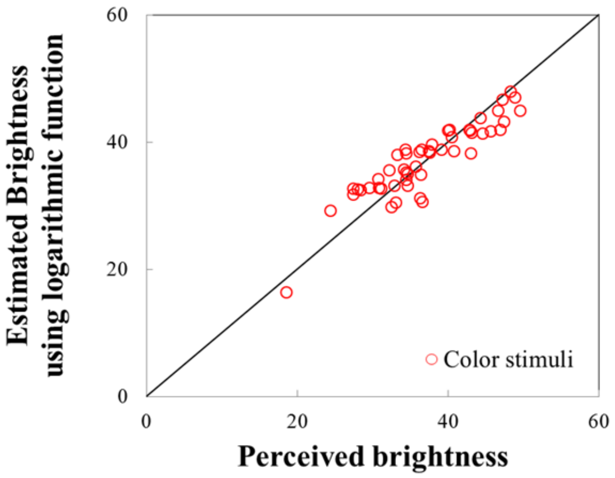


Figure 20 Comparison between brightness visual results and estimated data derived by logarithmic function depending on luminance

A power function could also be used to explain the relationship between the luminance and perceived brightness, as follows:

$$\text{Brightness} = a_0 \cdot (luminance)^n$$

In this function, a_0 and n are constants with values of about 12.45 and 0.26, respectively. n is the exponent of the function. The correlation coefficient between the magnitude of the perceptual brightness and the values estimated by the power function was 0.91, which implied a good correlation between these two scales. The coefficient of determination (r^2) was 0.83 and the adjusted r^2 was 0.82. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 225.84). As the p-value is much less than 0.05, the estimation function derived by the power function appropriately matched the perceptual data well in terms of linear regression. Figure 21 illustrates the relationship between the values estimated by the power function and the perceptual brightness data.

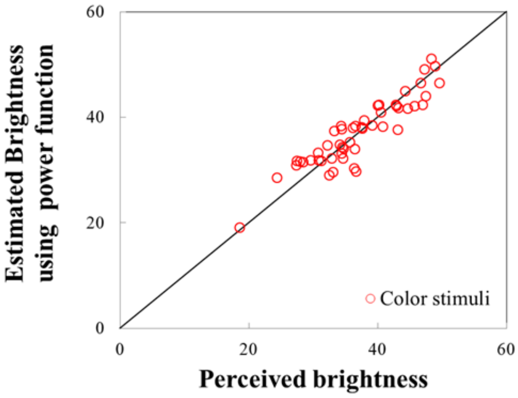


Figure 21 Comparison between brightness visual results and estimated data derived by power function depending on luminance

Performance of CAM97u for Brightness

Figure 22 illustrates the relation between the brightness perception data and brightness Q of the CAM97u model. The horizontal axis of the graph represents the perceived magnitude of the brightness, while the vertical axis of the figure presents the Q values of CAM97u for the 50 stimuli. The correlation coefficient between the magnitude of the perceptual brightness and the brightness Q estimated by CAM97u was 0.84, which implied a good correlation between these two scales. The coefficient of determination (r^2) was 0.71 and the adjusted r^2 was 0.70. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 117.33). As the p-value is much less than 0.05, the brightness Q of CAM97u fit the perceptual data well. However, the performance of the model was worse than those of the above models derived by the logarithmic and power functions using the observer data.

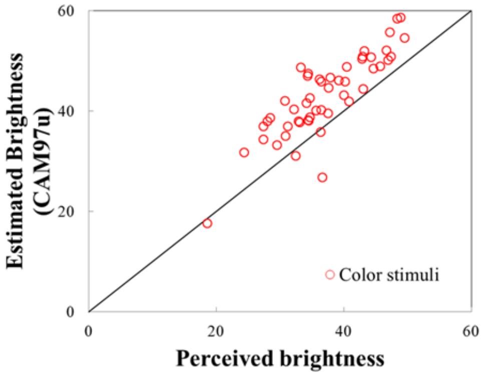


Figure 22 Comparison between perceived brightness and estimated brightness derived by CAM97u

Performance of Revised CIECAM02 for Brightness

Figure 23 illustrates the relation between the perceived brightness and brightness Q of the revised CIECAM02 model. The horizontal axis of the graph represents the perceived brightness, while the vertical axis of the figure presents the Q values of revised CIECAM02 for the 50 stimuli. The correlation coefficient between the magnitude of the perceived brightness and the brightness Q estimated by CIECAM02 was 0.91, which implied a good correlation between these two scales. The coefficient of determination (r^2) was 0.82 and the adjusted r^2 was 0.82. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 224.51). As the p-value is much less than 0.05, there is a significant relationship between the brightness Q of revised CIECAM02 and the perceptual data. The performance of the model was better than those of the above derived two models and CAM97u.

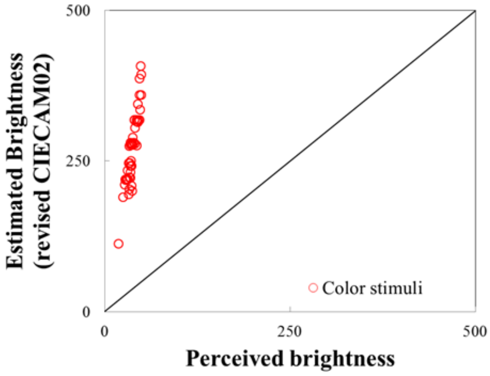


Figure 23 Comparison between perceived brightness and estimated brightness derived by revised CIECAM02 model

IV.1.3. Colorfulness

Relationship between Excitation purity and Perceptual Colorfulness

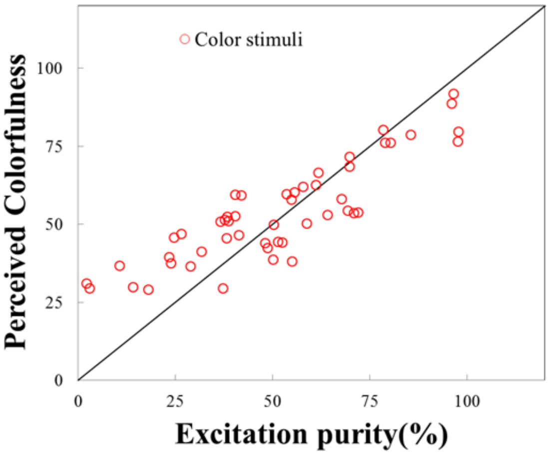


Figure 24 Relationship between excitation purity and perceptual colorfulness

Figure 24 illustrates the relationship between the excitation purity of unrelated color stimuli and the magnitude of the perceptual colorfulness attribute. The horizontal axis of the figure indicates the excitation purity of the stimuli, which had a range of 2.21 to 97.74%. The vertical axis of the plot presents the magnitude of the perceptual colorfulness. Overall, it seems that the magnitude of the perceptual colorfulness increased as the percentage of the excitation purity for the stimuli rose. Furthermore, it appears that there is a linear relation between the excitation purity percentages of the stimuli and the perceived colorfulness. The correlation coefficient between the magnitude of the perceptual colorfulness and excitation purity was 0.87, which implied a good correlation between these two scales. The coefficient of determination (r^2) was 0.76 and the adjusted r^2 was 0.76. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 153.06). As the p-value is much less than 0.05, the excitation purity fit the perceptual colorfulness data well in terms of linear regression. Therefore, the perceptual colorfulness could be presented as a linear function depending on the excitation purity.

However, as shown in Figure 24, the intercept of the vertical axis was not zero. This means the observers did not perceive the low purity colors as neutral colors. There are several reasons for this. First, the colorfulness value of the anchor stimulus was likely to be unsuitable as a modulus. The magnitude estimation was used in experiment 1. To apply the magnitude estimation, the anchor stimulus was set at a certain value. In the case of experiment 1, the colorfulness of the anchor stimulus assigned in the experiment was 30, which accounted for 18.14% of the excitation purity. For this reason, the observers regarded a colorfulness value of 30 as the colorfulness value of neutral colors. Actually, the lowest colorfulness among the stimuli was just under 30. Second, it is possible to assume that it was hard for the observers to determine the criteria for a colorfulness of zero, because there was no white reference near the presented stimulus.

To derive an estimation model for the relationship between the perceptual colorfulness and excitation purity using a linear function, a scaling factor was calculated using the gradient of a best-fit straight line that passed through the origin as a neutral colorfulness. To correct the values of perceptual colorfulness, the linear function was derived as follows:

$$Colorfulness_{CP} = 1.85 \times Colorfulness_{OP} - 53.74$$

In this formula, $\mathrm{Colorfulness_{OP}}$ and $\mathrm{Colorfulness_{CP}}$ were original perceptual value of colorfulness and corrected perceptual colorfulness.

Figure 24 shows that there is linear relationship between perceived colorfulness and excitation purity. Therefore, it is possible to derive an estimation model for colorfulness by using linear fitting. The estimation model for colorfulness is shown in the following formula.

$$\mathrm{Colorfulness}_{CP} = a_1 \cdot P_e + a_0$$

In this formula, P_e is the excitation purity and a_0 and a_1 are constants of zero and 0.9256, respectively. Figure 25 illustrates the relationship between the corrected perceptual colorfulness and excitation purity.

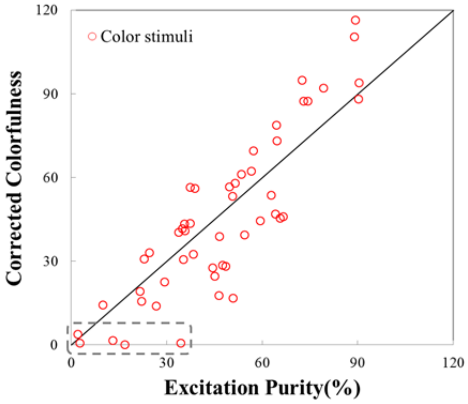


Figure 25 Relationship between corrected perceptual colorfulness and excitation purity

In Figure 25, the 5 stimuli in the broken line area were regarded as neutral color stimuli. Although several stimuli had relatively high excitation purities, the observers perceived these stimuli as belonging to the neutral area. The colorimetric values of the 5 stimuli are summarized in Table 9.

Table 9 Colorimetric values of presumed neutral colors

Color stimulus	Lv	x	y	Pe (%)
13	201.74	0.30	0.28	18.14
18	186.85	0.33	0.34	3.05
9	47.08	0.25	0.24	37.22
16	74.33	0.32	0.29	14.22
17	52.48	0.34	0.34	2.21

To further investigate neutral colors of unrelated colors, the 5 stimuli were presented on a CIE x, y chromaticity diagram in Figure 26. Two of the stimuli (17 and 18), were located close to an equi-energy stimulus consisting of equal amounts of power throughout the spectrum. Furthermore, it appears that the others tended to lie toward the blue area of the dominant wavelength.

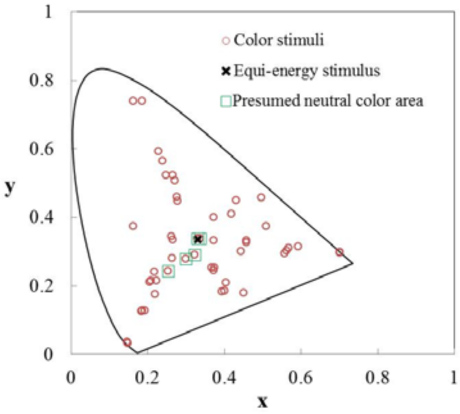


Figure 26 Presumed neutral color area on CIE x, y chromaticity diagram

Performance of CAM97u for Colorfulness

Figure 27 illustrates the relation between the corrected perceptual colorfulness data and colorfulness M of the CAM97u model. The horizontal axis of the figure represents the perceived magnitude of the colorfulness, and the vertical axis of the figure presents the M values of CAM97u. The correlation coefficient between the magnitude of the perceived colorfulness and the colorfulness M value estimated by CAM97u was 0.87, which implied a good correlation between these two scales. The coefficient of determination (r^2) was 0.76 and the adjusted r^2 was 0.76. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 152.47). As the p-value is much less than 0.05, the colorfulness M of CAM97u fit the perceptual data well, but the performance of the model was similar to that of the above model derived using the excitation purity.

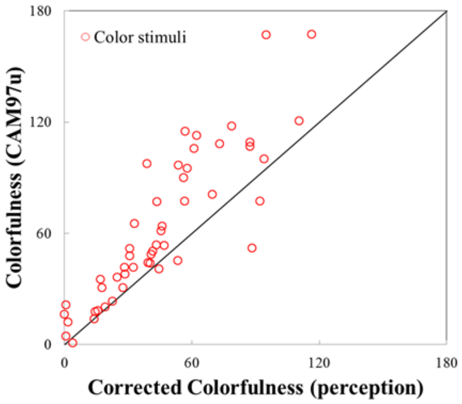


Figure 27 Comparison between perceptual colorfulness and estimated colorfulness derived by CAM97u

Performance of revised CIECAM02 for Colorfulness

Figure 28 illustrates the relation between the visual data of colorfulness and colorfulness M of revised CIECAM02 model. The horizontal axis of the figure represents the perceived colorfulness, and the vertical axis of the figure presents the M of revised CIECAM02. The correlation coefficient between the perceived colorfulness of the color stimuli and the colorfulness M estimated by CIECAM02 was 0.91, which implied an excellent correlation between these two scales. The coefficient of determination (r^2) was 0.84 and the adjusted r^2 was 0.83 (P-value = 0.00). This indicated that the colorfulness M of revised CIECAM02 fit the perceptual data well, and the performance of the model was superior to that of the above derived models and CAM97u.

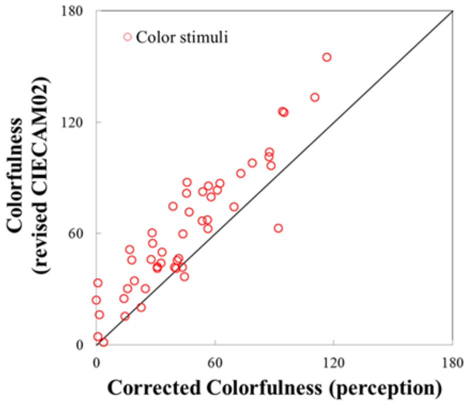


Figure 28 Comparison between perceptual colorfulness and estimated colorfulness derived by revised CIECAM02

IV.1.4. Hue

Relationship between hue angle and perceptual hue

Figure 29 illustrates the relationship between the CIE 1976 *u'*, *v'* hue-angle and the perceived hue quadrature. The horizontal axis of the graph presents the perceived hue quadrature. The vertical axis of the graph presents the CIE 1976 *u'*, *v'* hue-angle, which ranges from 0 to 360 degrees. Overall, it appears that there is a linear relation between the CIE 1976 *u'*, *v'* hue-angle and perceptual hue quadrature. The correlation coefficient between the perceptual hue quadrature and CIE 1976 *u'*, *v'* hue-angle was 0.99, which implied a good correlation between these two scales. The coefficient of determination (r^2) was 0.97 and the adjusted r^2 was 0.97. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 1723.75). As the p-value is much less than 0.05, the CIE 1976 *u'*, *v'* hue-angle fit the perceptual hue quadrature well in terms of linear regression. Therefore, it is possible to explain the perceived hue quadrature using a linear function depending on the CIE 1976 *u'*, *v'* hue-angle.

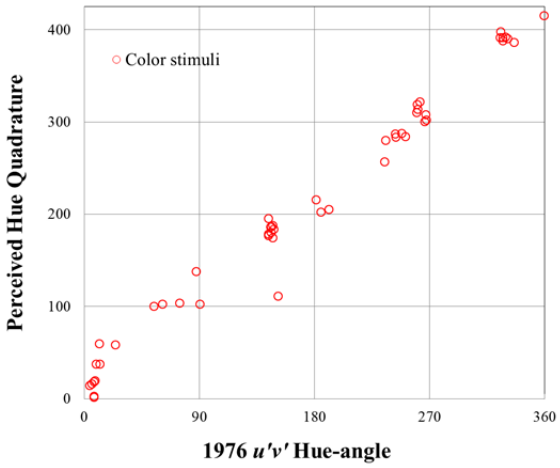


Figure 29 Comparison between hue angle on CIE uniform chromaticity scale (UCS) diagram and perceived hue quadrature

Estimation model for the perceptual hue was derived by calculating to minimize the sum of the errors between the hue-angle and perceptual hue quadrature data through a linear function. This linear function is as follows:

$$H_q = a_1 \cdot (hue\ angle) + a_0$$

where a_1 and a_0 are constants with values of 1.14 and 14.44, respectively.

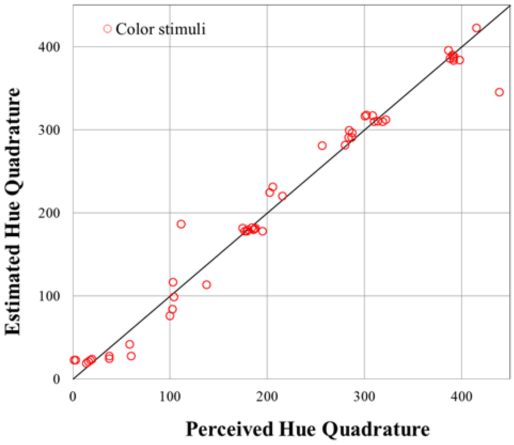


Figure 30 Relationship between perceptual hue quadrature and estimated hue quadrature

Performance of CAM97u for Hue

Figure 31 illustrates the relation between the perceived hue quadrature and hue quadrature H of the CAM97u model. The vertical axis represents the H values of CAM97u, and the horizontal axis indicates the perceived hue quadrature. The correlation coefficient between the data was 0.98, which implied a good correlation between these two scales. The coefficient of determination was 0.95 and the adjusted r^2 was 0.95. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 1723.75). As the p-value is much less than 0.05, the hue quadrature H of CAM97u fit the perceptual data in terms of linearity. Therefore, the performance of CAM97u is good enough for estimating the perceptual hue quadrature.

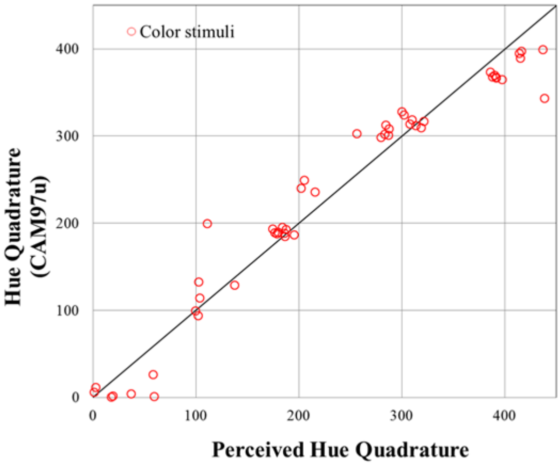


Figure 31 Relationship between perceptual hue quadrature and H of CAM97u

Performance of Revised CIECAM02 for Hue

Figure 32 illustrates the relation between the perceptual hue quadrature and hue quadrature H of the revised CIECAM02. The vertical axis represents the perceived hue quadrature, and the horizontal axis indicates H values of revised CIECAM02. The correlation coefficient between the data was 0.97, which implied a good correlation between these two scales. The coefficient of determination was 0.95 and the adjusted r^2 was 0.95. F-test was performed at significance level 0.05, and p-value was 0.00 (F = 869.57). As the p-value is much less than 0.05, the hue quadrature H of revised CIECAM02 fit the perceptual data in terms of linearity. Therefore, the performance of revised CIECAM02 is good for estimating the perceptual hue quadrature.

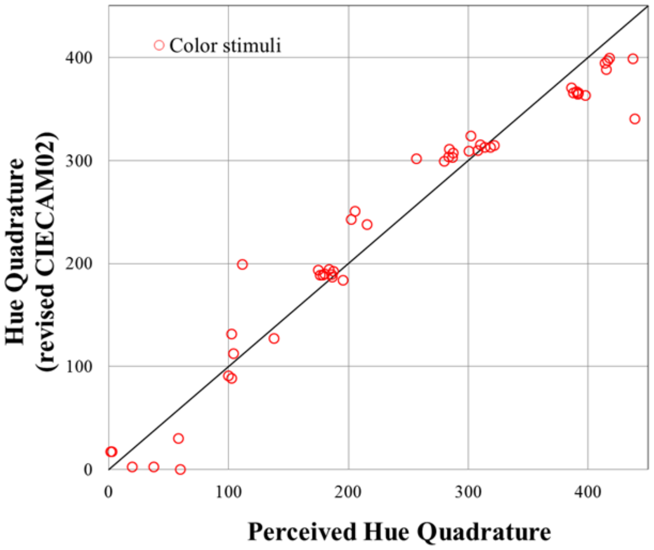


Figure 32 Relationship between perceptual hue quadrature and H of revised CIECAM02

IV.1.5. Summary

The purpose of Experiment 1 was to investigate relationships between perceptual magnitude of color appearance attributes and quantitative measures of color stimuli. Specific objectives include: (1) collection of perceptual data associated with unrelated colors, (2) deduction of relationships between color appearance attributes of unrelated colors and quantitative measures, (3) evaluations of estimation models derived by this research, CAM97u and revised CIECAM02.

The observer variation was compared between color appearance attributes. The three perceptual attributes were found to have different observer variations. The observer variations were 40, 27, and 12 for the brightness, colorfulness, and hue, respectively. The observer variation for hue was found smaller than that of the brightness and colorfulness. These results were similar to those found in earlier experiments for investigating related colors.

Brightness had a compressive nonlinear relationship with a quantitative measure "luminance," while colorfulness and hue had linear relationships with "excitation purity" and "1976 hue-angle," respectively. Estimation models were derived from these relationships, and the correlation coefficients of the models for perceived brightness, colorfulness and hue were 0.91, 0.87 and 0.99, respectively. The performances of estimation models were estimated by using a coefficient of determination. The coefficient of determinations (r^2) for brightness, colorfulness and hue were 0.83, 0.78 and 0.97, respectively.

The performances of CAM97u and revised CIECAM02 were also evaluated. The coefficients of determination between the predictors of CAM97u and perceptual results were 0.71, 0.76 and 0.95 for brightness, colorfulness and hue, respectively. In the case of revised CIECAM02, the coefficients of determination were 0.82, 0.84 and 0.95 for brightness, colorfulness and hue, respectively. CAM97u and derived estimation models showed similar performance, and colorfulness estimated by both models presented worse performance than brightness and hue calculated by both models. R^2 values of revised CIECAM02 for color appearance attributes were greater than those of other models. This indicated that the predictors of revised CIECAM02 show the best performance.

IV.2. Experiment 2 : Color connotation for unrelated colors

The aim of this experiment was to develop dimensions of color connotation. The experimental data collected by using a semantic differential method is transformed into z-scores. The z-scores were determined from female, male and all observers. Finally, dimensions of color connotation are developed by principal component analysis.

IV.2.1. Observer Accuracy

The observer accuracy indicates how well individual observers agreed with the majority of the group. The observer accuracy values were determined by correct decisions (III.4.5). Table 10 summarizes the observer accuracy in experiment 2. The accuracy values ranged from 0.5 to 1.0, where 0.5 indicated the poorest accuracy and 1.0 was the best. Table 10 shows the accuracy values for the two observer groups, in which the female group (with a mean CD value of 0.74) had significantly better accuracy than the male group (0.71), at a significance level of 0.05.

In general, "Warm-Cool" showed the highest accuracy, with a CD value of 0.80, and "Fresh-Stale" showed the lowest accuracy, with a CD value of 0.64. For both groups, "Warm-Cool," "Hard-Soft," "Feminine-Masculine," "Heavy-Light," and "Tense-Relaxed" showed high observer accuracies, whereas "Fresh-Stale," "Modern-Classical," "Like-Dislike," "Active-Passive," and "Clean-Dirty" presented low observer accuracies. The overall accuracy value is 0.73.

Table 10 Observer Accuracy (Correct Decision) in Experiment 2

	Active Passive	Clean Dirty	Feminine Masculine	Fresh Stale	Hard Soft	Heavy Light	Like Dislike	Modern Classical	Tense Relaxed	Warm Cool	**Mean**
Female	0.72	0.73	0.82	0.64	0.81	0.81	0.64	0.65	0.75	0.83	0.74
Male	0.68	0.70	0.75	0.64	0.77	0.73	0.69	0.65	0.74	0.77	0.71
Mean	0.70	0.72	0.78	0.64	0.79	0.77	0.66	0.65	0.75	0.80	0.73

IV.2.2. Gender Difference

Pearson’s product-moment correlation coefficient was used in this experiment as a measure of the gender difference in the images of unrelated colors.

This coefficient ranges from –1 to 1, where –1 represents a perfect negative correlation and 1 is a perfect positive correlation. A coefficient of zero indicates a completely nonlinear relationship between two variables. A comparison was made between the results of the male and female observers for the ten images of unrelated colors (z-scores).

Figure 33 and Table 11 show the results of this comparison, indicating high correlation coefficients for most of the scales. The two data sets agreed best on “Warm-Cool” (with a correlation coefficient of 0.94), followed by “Feminine-Masculine” (0.86), “Hard-Soft” (0.85), and “Tense-Relaxed” (0.85). This indicates that there was little difference for the color connotations of unrelated colors between the two observer groups, although “Clean-Dirty,” “Like-Dislike,” and “Modern-Classical” were found to have relatively low correlation coefficients (0.50, 0.56, and 0.57, respectively). The biggest deviation for “Clean-Dirty” involved stimulus 2, which had z-scores of 2.11 for female observers and 0.49 for males. Stimulus 40 was found to have the biggest deviation for “Like-Dislike.” It had z-scores of 1.46 for male observers and 0.32 for females.

Table 11 Summaries of correlation coefficients between male and female observers

	Warm Cool	Feminine Masculine	Hard Soft	Tense Relaxed	Heavy Light	Active Passive	Fresh Stale	Modern Classical	Like Dislike	Clean Dirty
Correlation coefficient	0.92	0.86	0.85	0.85	0.82	0.82	0.68	0.57	0.56	0.50

To further investigate the gender difference for color connotations of unrelated colors between the female and male groups, the experimental data from each group were classified using the principal component analysis (PCA).

The PCA could clarify the interrelationships between the connotation scales for each of the two observer groups (i.e., female and male). Then, by comparing the interrelationships of the connotation scales between these two groups, the gender effect on the color connotation scales could be determined.

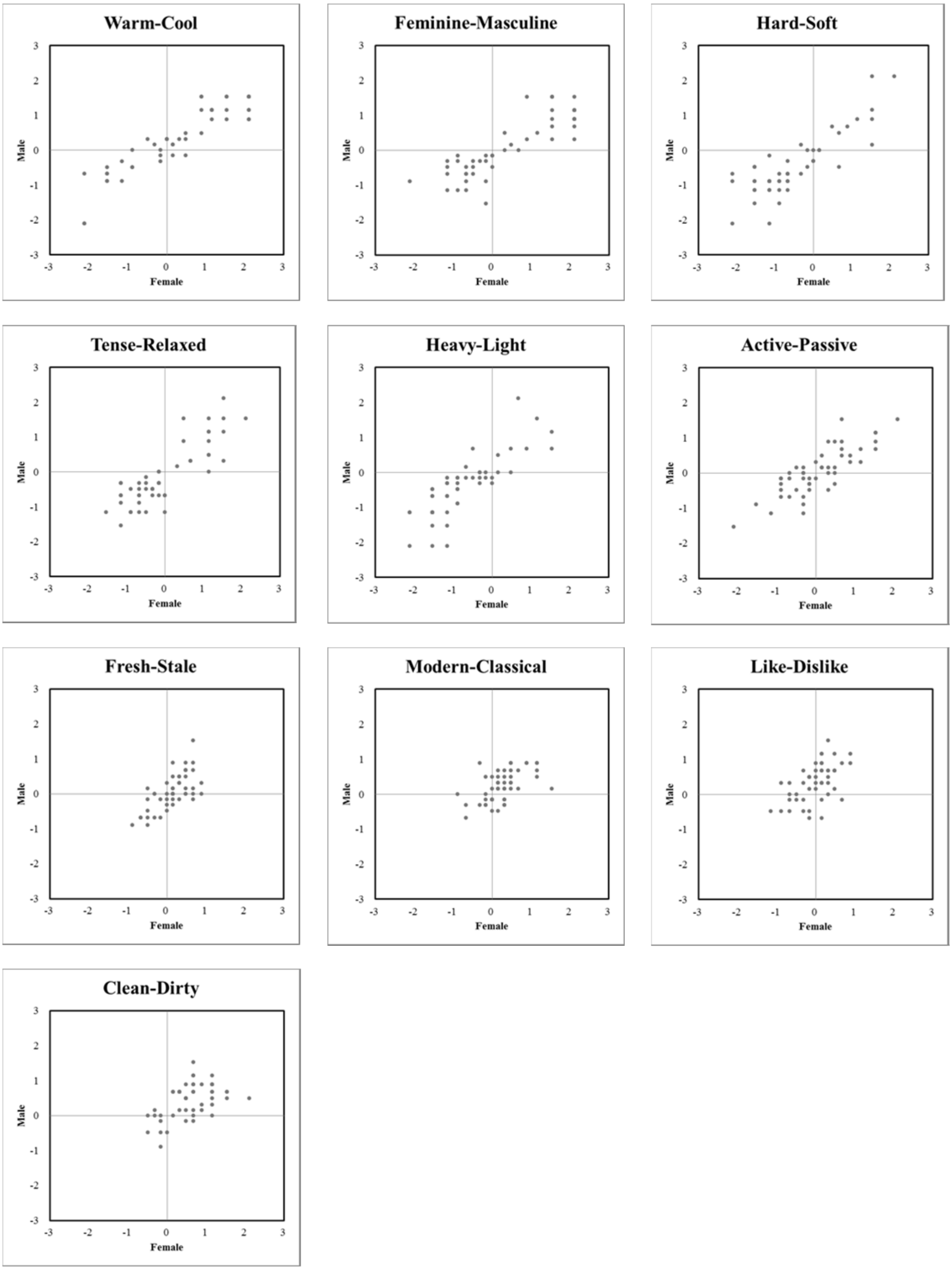


Figure 33 Comparisons of color emotion responses between female and male observers

As a result, in the female group, three principal components were extracted, accounting for 88.3% of the total variance. These were labeled as C_f 1, 2, and 3, as summarized in Table 12. In the male group, three components were extracted and were also labeled C_m 1, 2, and 3, as illustrated in Table 13. These three components accounted for 86.2% of the total variance.

Table 12 Principal component loadings of color connotations for female group

	C_f 1	C_f 2	C_f 3
Percentage of Variance	41.6%	38.9%	7.8%
Warm-Cool	**0.89**	–0.38	–0.08
Feminine-Masculine	**0.82**	–0.49	0.01
Hard-Soft	0.33	**0.90**	–0.02
Heavy-Light	0.32	**0.84**	–0.32
Tense-Relaxed	0.58	**0.76**	0.00
Like-Dislike	–0.14	**–0.65**	0.51
Active-Passive	0.60	**0.62**	0.32
Modern-Classical	0.08	**0.49**	0.29
Clean-Dirty	0.24	0.15	**0.87**
Fresh-Stale	0.08	0.30	**0.81**

The three components for the female group were compared with those of the male group by examining the principal component loadings for each principal component. A principal component loading is a correlation between the principal component score and the original variable. The values in Table 12 and Table 13 represent correlation coefficients between the z-scores of each word pair and each component. The Female group had high component loadings on "Warm-Cool" and "Feminine-Masculine" for C_f 1; "Hard-Soft," "Heavy-Light," "Tense-Relaxed," "Active-Passive," "Modern-Classical," and "Like-Dislike" for C_f 2; and "Clean-Dirty" and "Fresh-Stale" for C_f 3. The color connotation that best represented the nature of C_f 1 was "Warm-Cool," which had a value of 0.89. The principal component loading of "Hard-Soft" for C_f 2 was 0.90, while that of "Heavy-Light" was 0.84. This indicated that both word pairs had a large effect on C_f 2. For C_f 1 and C_f 2, "Active-Passive" had values of approximately 0.6 (0.60 and 0.62, respectively). Although "Modern-Classical" was involved in C_f 2, all of the values related to the components were lower than 0.5. It appeared that "Modern-Classical" was barely suitable for representing any component. The nature of C_f 3 was best described by "Clean-Dirty," which had a value of 0.87.

The male group had high component loadings on "Hard-Soft," "Heavy-Light," "Tense-Relaxed," "Active-Passive," and "Modern-Classical" for C_m 1; "Warm-Cool" and "Feminine-Masculine" for C_m 2; and "Clean-Dirty," "Fresh-Stale," and "Like-Dislike" for C_m 3. The word pairs that were the most closely connected with C_m 1 and C_f 2 were almost the same, excepting "Like-Dislike," and the color connotation scales that were the most closely related to C_m 2 and C_f 1 were the same, "Warm-Cool" and "Feminine-Masculine." In the male group, the principal component loading of "Hard-Soft" for C_m 1 was 0.95, and that of "Tense-Relaxed" was 0.92. This showed that both word pairs had a large effect on C_m 1. "Modern-Classical" presented approximately the same value of 0.45 for C_m 1 and C_m 3 (0.45 and 0.43, respectively). This showed that, independently, "Modern-Classical" could not be considered typical of any component. The word pair that best explained the nature of C_m 3 was "Clean-Dirty," which had a value of 0.90.

Table 13 Principal component loadings of color connotations for male group

	C_m 1	C_m 2	C_m 3
Percentage of Variance	42.4%	30.2%	13.6%
Hard-Soft	**0.95**	0.02	–0.08
Tense-Relaxed	**0.92**	0.14	0.22
Heavy-Light	**0.88**	–0.11	–0.34
Active-Passive	**0.67**	0.54	0.39
Modern-Classical	**0.45**	–0.22	0.43
Warm-Cool	–0.08	**0.94**	–0.17
Feminine-Masculine	–0.12	**0.92**	–0.06
Clean-Dirty	–0.01	0.07	**0.90**
Fresh-Stale	0.10	–0.01	**0.85**
Like-Dislike	–0.50	0.29	**0.53**

Further comparisons were made on the underlying color connotation structures between the male and female groups. A three-dimensional component graph was made for each group. In graphs, the 10 color connotation words, "Warm," "Active," "Like," "Modern," "Fresh," "Clean," "Hard," "Feminine," "Tense," and "Heavy," were located in a three-dimensional space determined by the three principal components. There was no need to place both adjectives of a word pair onto the graph, e.g., "Hard" and "Soft," because for each pair, the locations of the two words are diagonally opposite to each other in the graph. The results are shown in Figure 34 and Figure 35 for the female and male groups, respectively. The axes of the graphs represent principal component loadings. Positions of the word pairs on the graph indicate the relationships between word pairs and correlation between word pairs and components.

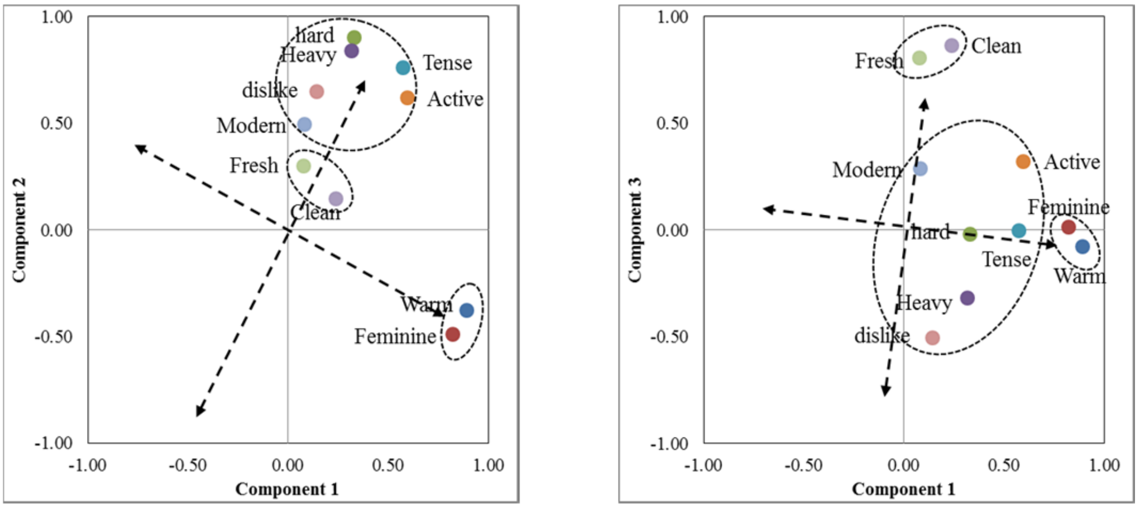


Figure 34 Component graph for color connotations for female group.

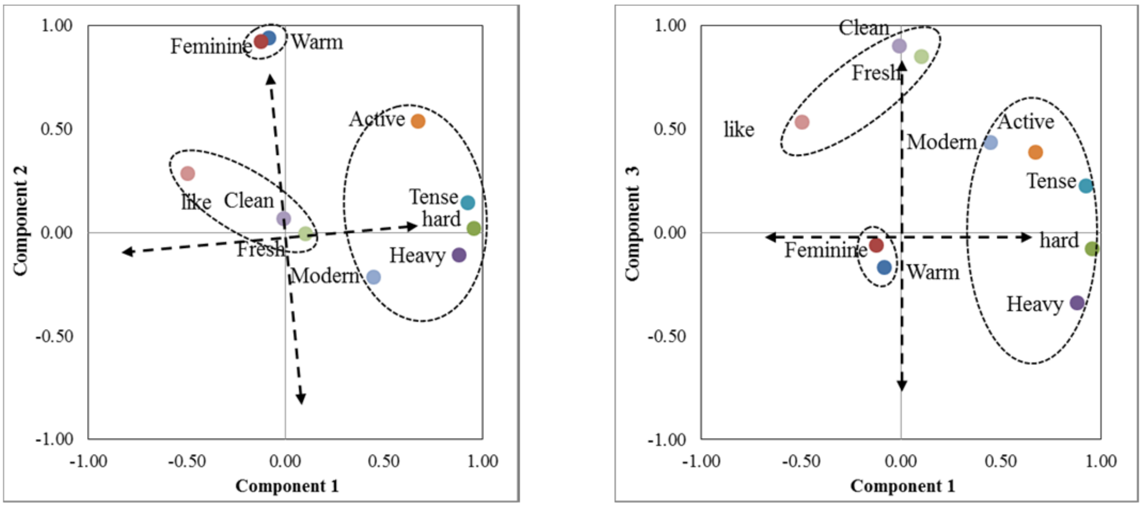


Figure 35 Component graph for color connotations for male group

In the comparison between the two graphs, every color connotation word (except "Like-Dislike") was found located at similar positions in the two graphs. In the graphs of female group, "Dislike," opposite to "Like," is located close to "Hard," "Heavy," "Tense," "Active," and "Modern." In the graphs of male group, however, "Like" is located near "Clean" and "Fresh." This indicates that the female observers tended to prefer "Soft," "Light," "Relaxed," "Passive," and "Modern," while the male observers tended to prefer colors that were associated with the feelings of "Clean" and "Fresh."

IV.2.3. Structure of Color connotation

From the results obtained above, it appeared that there is common color connotation structure across the observer groups. This structure can be established in the form of a multidimensional space, using the principal component analysis method. In developing this color space, it is inappropriate to include both aesthetic and non-aesthetic color connotation scales. There is a reason that these two types of color connotation scales have different natures. Thus, it was decided that this color space would include only non-aesthetic color connotation scales. The following two steps were taken to develop this color connotation space: component extraction and coordinate determination.

Component Extraction

The z-scores of all the observers' data were used to investigate the structure of the color connotations of unrelated colors. Two color connotation scales were excluded, "Modern-Classical" and "Like-Dislike," for the following reasons. First, "Like-Dislike" was an aesthetic color connotation scale in this research. Second, "Like-dislike" and "Modern-Classical" had small values of observer accuracy (0.66 and 0.65, respectively). Third, "Modern-Classical" had no significant relation to any of the principal components of the two observer groups. Before component extraction was applied to the all observers' data, it had been applied to each group in order to see whether differences of color connotation structure between female and male group occurred. For female group and male group, Table 14 and Table 15 illustrate principal component loadings of color connotations excluding "Like-Dislike" and "Modern-Classical", respectively. As appears by these results, there were no evident difference between the color connotation structure of female group and that of male group. Therefore, these two scales were excluded from the extraction procedure. Three principal components, accounting for 85.5% of the total variance, were extracted from the remaining color connotations by applying the principal component analysis. The results are summarized in Table 16.

Table 14 Principal component loadings of color connotations for female groups

	Component 1	Component 2	Component 3
Percentage of Variance	44.1%	39.4%	7.5%
Warm-Cool	**0.92**	-0.30	-0.05
Feminine-Masculine	**0.86**	-0.42	-0.02
hard-Soft	0.25	**0.93**	-0.03
Heavy-Light	0.25	**0.86**	-0.35
Tense-Relaxed	0.51	**0.80**	-0.04
Active-Passive	0.55	**0.67**	0.33
Clean-Dirty	0.23	0.18	**0.86**
Fresh-Stale	0.06	0.32	**0.82**

Table 15 Principal component loadings of color connotations for male groups

	Component 1	Component 2	Component 3
Percentage of Variance	44.1%	39.4%	7.5%
Hard – Soft	**0.95**	-0.07	-0.09
Tense – Relaxed	**0.94**	0.05	0.22
Heavy – Light	**0.86**	-0.18	-0.39
Active – Passive	**0.72**	0.47	0.39
Warm – Cool	0.00	**0.95**	-0.14
Feminine – Masculine	-0.04	**0.93**	-0.05
Clean – Dirty	0.02	0.04	**0.89**
Fresh – Stale	0.12	-0.04	**0.87**

Table 16 Principal component loadings of color connotations

	Component 1	Component 2	Component 3
Percentage of Variance	45.0%	30.9%	9.6%
Tense-Relaxed	**0.95**	–0.16	0.11
Hard-Soft	**0.91**	–0.35	–0.08
Active-Passive	**0.88**	0.12	0.36
Heavy-Light	**0.83**	–0.35	–0.39
Feminine-Masculine	0.22	**0.93**	–0.02
Warm-Cool	0.29	**0.93**	–0.08
Clean-Dirty	0.18	0.05	**0.93**
Fresh-Stale	0.21	–0.14	**0.89**

All the observer group had high component loadings for “Tense-Relaxed,” “Hard-Soft,” “Active-Passive,” and “Heavy-Light” for component 1, accounting for 45.0% of the total variance; “Feminine-Masculine” and “Warm-Cool” for component 2, accounting for 30.9% of the total variance; and “Clean-Dirty” and “Fresh-Stale” for component 3, accounting for about 10% of the total variance. Figure 36 illustrates the relationships between the three types of components. Supposing that color is an object, components are responses to properties of an object. The properties of an object are corporeality, energy and condition of surface. Corporeality is bodily or material nature substance; physical existence. Component 1 including “Hard-Soft,” “Heavy-Light,” “Tense-Relaxed” and “Active-Passive,” is associated with corporeality. Component 2 including “warm-cool” and “feminine-masculine” is concerned with energy of an object, and component 3 including “clean-dirty” and “fresh-stale” is related closely to surface condition of the object.

The three components were regarded as the three axes of the color space. These three axes of the color space were finally determined as follows:

Dimension 1, labeled *color solidity*, comprises the original color connotation scales “Tense-Relaxed,” “Hard-Soft,” “Active-Passive,” and “Heavy-Light.”

Dimension 2, labeled *color heat*, comprises “Feminine-Masculine” and “Warm-Cool.”

Dimension 3, labeled *color purity*, is defined by “Clean-Dirty” and “Fresh-Stale.”

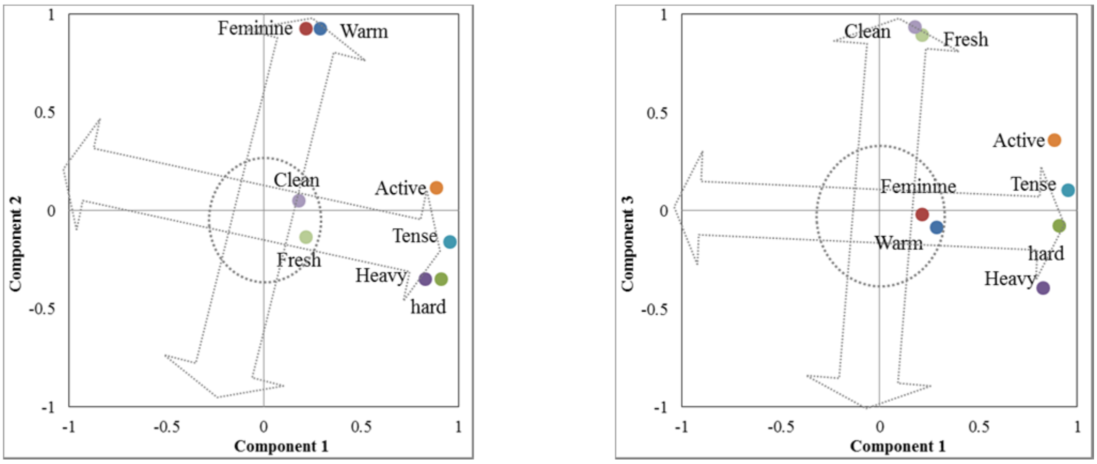
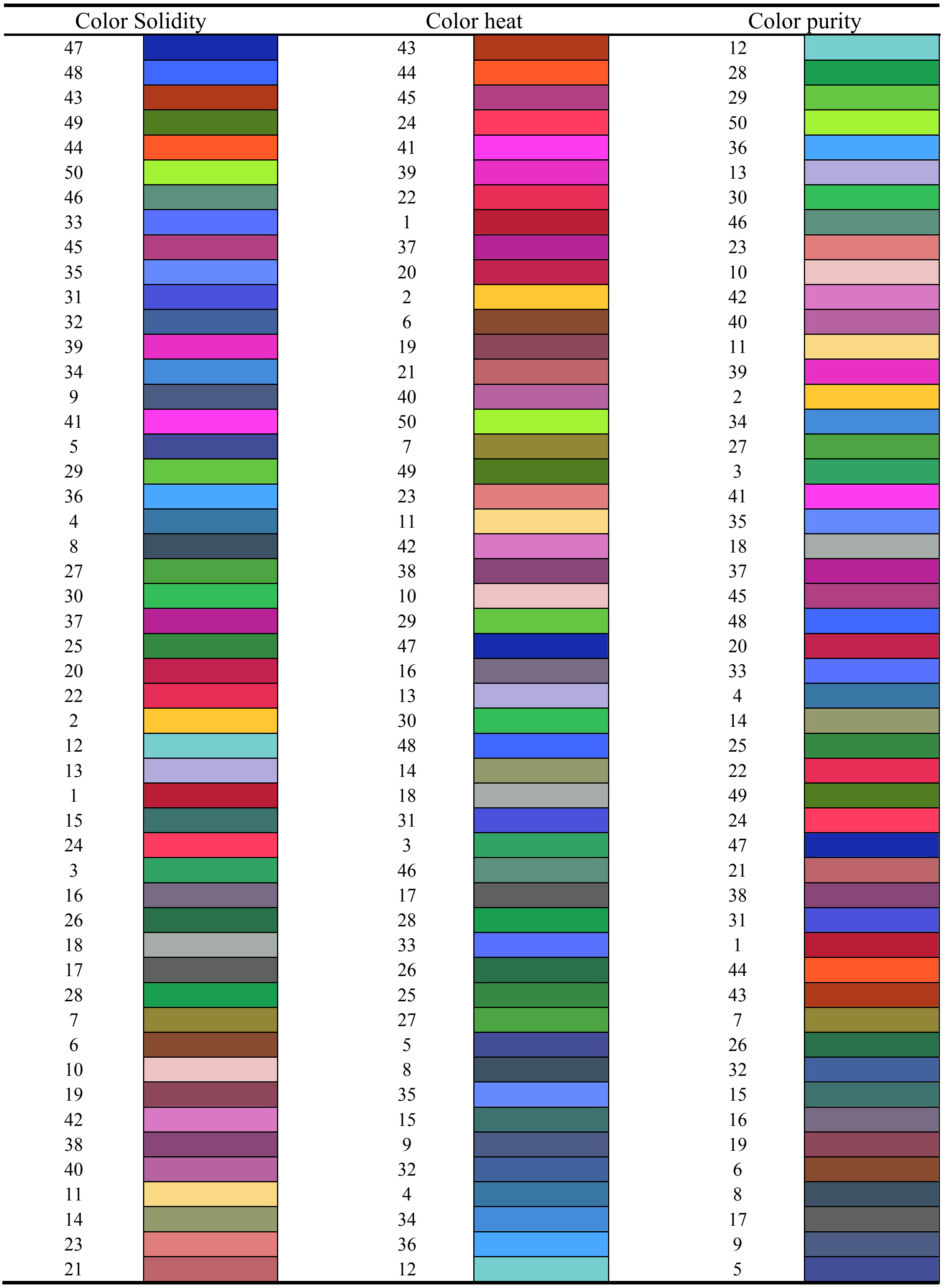


Figure 36 Components graph of color connotations across observer groups

Coordinate Determination

In Table 17, the 50 color stimuli are ranked along the three dimensions. In “Color Solidity” dimension, the colors at the high position were associated with the connotations “Hard,” “Active,” “heavy” and “tense,” while the colors at the low position were associated with “Soft,” “Passive,” “Light” and “Relaxed.” In “Color Heat” dimension, the colors at the high position were associated with the connotations “Warm” and “Feminine,” while the colors at the low position were associated with “Cool” and “Masculine.” In “Color Purity” dimension, the colors at the high position were associated with the connotations “Clean” and “Fresh,” while the colors at the low position were associated with “Dirty” and “Stale.” The colors in the middle lack a significant amount of color connotation. The coordinates of the test colors in this color connotation space were determined using the principal component scores (PCS). The PCS indicates where the color stimulus is placed along the principal component. The PCS were obtained by multiplying an eigenvectors matrix with an average deviation matrix. The eigenvectors matrix is a set of eigenvectors calculated from variance-covariance matrix of original data. The average deviation matrix is obtained by substituting the mean values of z-scores from original z-scores data. The results of this coordinate determination are shown in Figure 37 and Figure 38.

Table 17 50 color stimuli ranked along three dimensions: color solidity, color heat, and color purity



Color Solidity	Color heat	Color purity
47	43	12
48	44	28
43	45	29
49	24	50
44	41	36
50	39	13
46	22	30
33	1	46
45	37	23
35	20	10
31	2	42
32	6	40
39	19	11
34	21	39
9	40	2
41	50	34
5	7	27
29	49	3
36	23	41
4	11	35
8	42	18
27	38	37
30	10	45
37	29	48
25	47	20
20	16	33
22	13	4
2	30	14
12	48	25
13	14	22
1	18	49
15	31	24
24	3	47
3	46	21
16	17	38
26	28	31
18	33	1
17	26	44
28	25	43
7	27	7
6	5	26
10	8	32
19	35	15
42	15	16
38	9	19
40	32	6
11	4	8
14	34	17
23	36	9
21	12	5

By combining the three dimensions, a three-dimensional color connotation space was developed, as shown in Figure 37 and Figure 38. In this space, the colors in the central area were associated with weak color connotations, while those located at the outer layer were associated with strong color connotations.

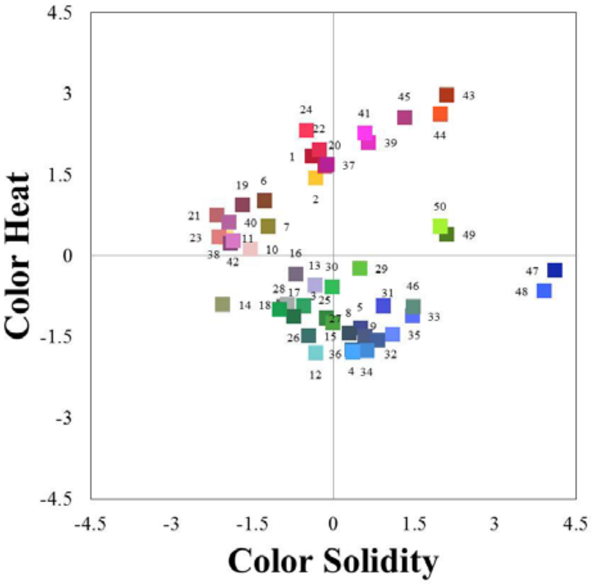
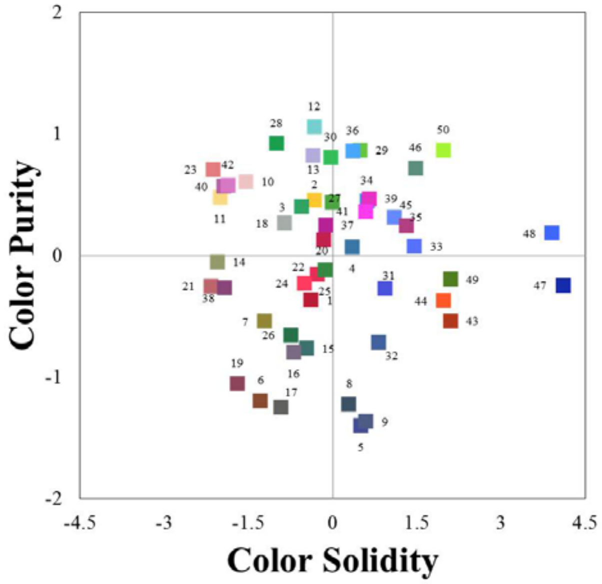


Figure 37 Two dimensions, color solidity and color heat, of three-dimensional color connotation space with 50 unrelated color stimuli



9

Figure 38 Two dimensions, color solidity and color purity, of three-dimensional color connotation space with 50 unrelated color stimuli

IV.2.4. Summary

The purpose of Experiment 2 is to develop color connotation space of unrelated colors. Specific objective include: (1) Comparisons of color connotation between genders, (2) classification of color connotation scales, and (3) development of a color connotation space.

The observer accuracy was compared between female group and male group. The two gender groups were found to have similar observer accuracy (female group: 0.74, male group: 0.71).

The Pearson correlation coefficients between the experimental data show little difference in color connotation between two gender groups, although some connotation scales, "Like-Dislike" and "Clean-Dirty," were found to have relatively low correlation coefficients (0.56 and 0.50, respectively).

The principal component analysis was applied to investigate the underlying structure of color connotation for male and female groups. As a result the two groups had similar color connotation structures for all the scales except "like-dislike". Female observers tended to prefer "Soft," "Light," "Relaxed," "Passive," and "Modern," while the male observers tended to prefer colors that were associated with the feelings of "Clean" and "Fresh."

A three-dimensional color connotation space was developed with the three axes "Color solidity," "Color heat," and "Color purity." "Color solidity" was closely correlated with "Hard-Soft," "Heavy-Light," "Tense-Relaxed," and "Active-Passive." "Color heat" was closely correlated with "Warm-Cool" and "Feminine-Masculine". "Color purity" was intimately correlated with "Clean-Dirty" and "Fresh-Stale."

IV.3. Modeling Color connotation

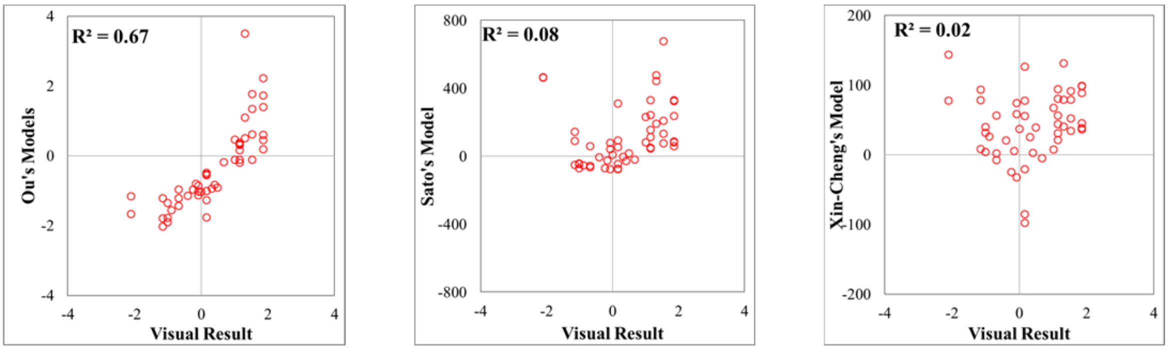
The overall goal of this research was to develop a color connotation model of unrelated colors. In this chapter, the four color connotation models “Warm-Cool,” “Heavy-Light,” “Active-Passive” and “Hard-Soft” were developed and compared with the existing color connotation models, including those by Ou et al. (Ou et al., 2004), by Sato et al. (Sato, Kajiwara, et al., 2000) and by Xin and Cheng (Cheng, 2002). The modeling was based on the color appearance attributes of CAM97u and revised CIECAM02, including hue, brightness, and colorfulness. In the present study, the bubble chart method was used in the modeling as an essential tool for observing color connotation phenomena.

IV.3.1. Performance of Existing Color Emotion Formulae

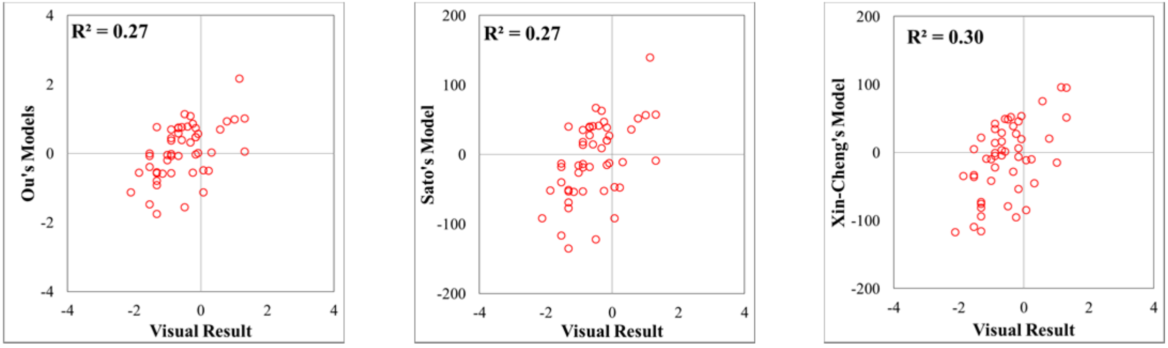
Ou et al.(Ou et al., 2004) developed a number of color emotion formulae for single colors, including the four scales “Warm-Cool,”, “Heavy-Light,” “Active-Passive” and “Hard-Soft”, as summarized in Table 3. These four models had good performance for the visual data of own experiment of Ou et al., with an R^2 of 0.74 for “Warm-Cool”, 0.76 for “heavy-Light,” 0.75 for “Active-Passive” and 0.73 for “Hard-Soft”. Sato et al.(Sato, Kajiwara, et al., 2000) and Xin and Cheng(Cheng, 2002) also developed color emotion equations, including “Warm-Cool,”, “Heavy-Light,” “Active-Passive” and “Hard-Soft”, as summarized in Table 1 and Table 2, respectively. The four models developed by Sato et al. and Xin and Cheng had good performance for the visual data of their own experiment The R^2 of Sato’s models were 0.82 for “Warm-Cool”, 0.90 for “heavy-Light,” 0.87 for “Active-Passive” and 0.82 for “Hard-Soft,” and those of Xin and Cheng’s models were an 0.77 for “Warm-Cool”, 0.95 for “Heavy-Light”, 0.95 for “Active-Passive” and 0.92 for “Soft-Hard”.

The three sets of models were tested using the current experimental data. Table 18 illustrates the test results, and Figure 39 shows the relationships between visual results of the current research and the three sets of models. Overall, the tree sets of models had bad performance when the current experimental data were used. “Active-Passive” of the three sets has better performance than other color connotation scales (mean of $R^2 = 0.44$). “Hard-Soft” of the three sets has the worst performance of four color connotation scales (mean of $R^2 = 0.09$). The test results of Ou’s models show that “Warm-Cool” has the best performance of estimation, with an R^2 of 0.67, and “Hard-Soft” has the worst performance of estimation with an R^2 of 0.00. In the case of Sato’s models, “Active-Passive” has the best performance of estimation, with an R^2 of 0.32, and “Warm-Cool” has the worst performance of estimation with an R^2 of 0.08. As regards Xin and Cheng’s models, “Active-Passive” has the best performance of estimation, with an R^2 of 0.50, and “Warm-Cool” has the worst performance of estimation with an R^2 of 0.02.

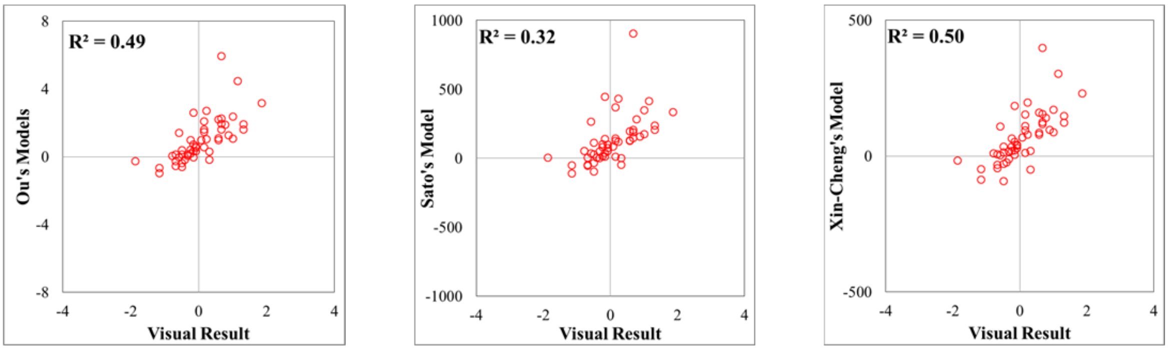
Warm-Cool



Heavy-Light



Active-Passive



Hard-Soft

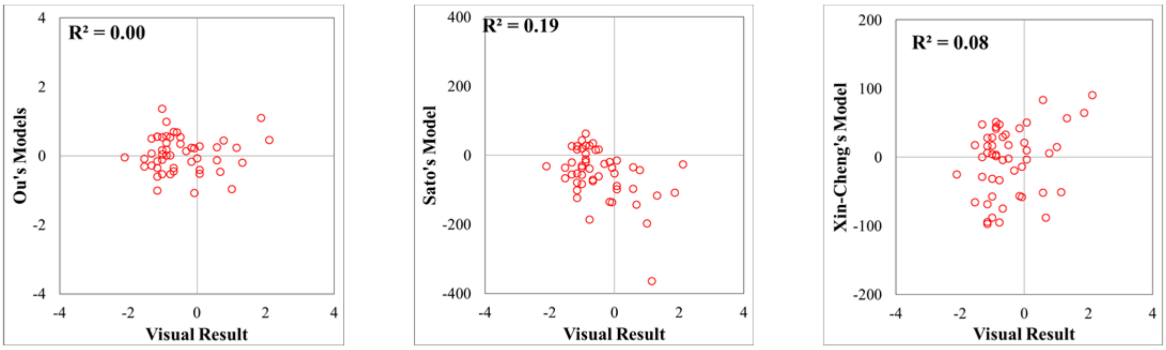


Figure 39 the relationships between visual results of the current research and color connotation models developed by Ou et al., Sato et al, Xin and Cheng

Table 18 Performance of color connotation models developed by Ou et al., Sato et al., Xin and Cheng, in respect of visual results of the current research

	Active-passive	Heavy-Light	Hard-Soft	Warm-Cool	**Mean**
Ou et al.	0.49	0.27	0.00	0.67	0.36
Sato et al.	0.32	0.27	0.19	0.08	0.22
Xin-Cheng	0.50	0.30	0.08	0.02	0.23
Mean	0.44	0.28	0.09	0.26	0.27

The models tested above do not show particularly good performance to estimate color connotations. The reason is as follows. Firstly, the existing models were derived by making use of color connotation results which used the related color as color stimuli, but unrelated colors were used as color stimuli in the current experiment. The second, a color space to derive the three set of models was CIELAB color space. CIELAB color space is uniform color space reflecting color attributes of related colors. The color appearance of the related and the unrelated color stimulus varies, although color stimuli have identical absolute tristimulus values. It has an effect on color connotation of stimulus because color appearance attributes are directly related with color connotation. Lastly, the number of color stimuli used in earlier studies was not enough to cover the whole of color gamut which includes colors of high colorfulness and high brightness. The color stimuli used in this research had colorfulness and brightness in comparison to color stimuli used in the existing studies. Therefore, the colors will be out of linear trend when the colors of high colorfulness and high brightness are put in the models. Table 19 shows the performances of the three set of models using visual data of the current research excluding color stimuli that has high colorfulness or high brightness. The models show better performance than above cases excepting “Hard-Soft” color connotation. Figure 40 shows the relationships between the three sets of models and visual results of the current research, excluding the color stimuli which have high colorfulness or brightness.

However, it is hard to estimate color connotations of unrelated colors by using existing models developed by related color data. Therefore, new color connotation estimating models need to reflect color appearance attributes of unrelated colors and to cover wide color gamut which includes high colorfulness and brightness.

Table 19 Performance of existing color connotation models in respect of visual results of the current research, excluding color stimuli which have high colorfulness and brightness

	Active-passive	Heavy-Light	Hard-Soft	Warm-Cool	**Mean**
Ou et al.	0.61	0.39	0.02	0.81	0.46
Sato et al.	0.52	0.39	0.00	0.61	0.38
Xin-Cheng	0.55	0.42	0.06	0.22	0.31
Mean	0.56	0.40	0.03	0.55	0.38

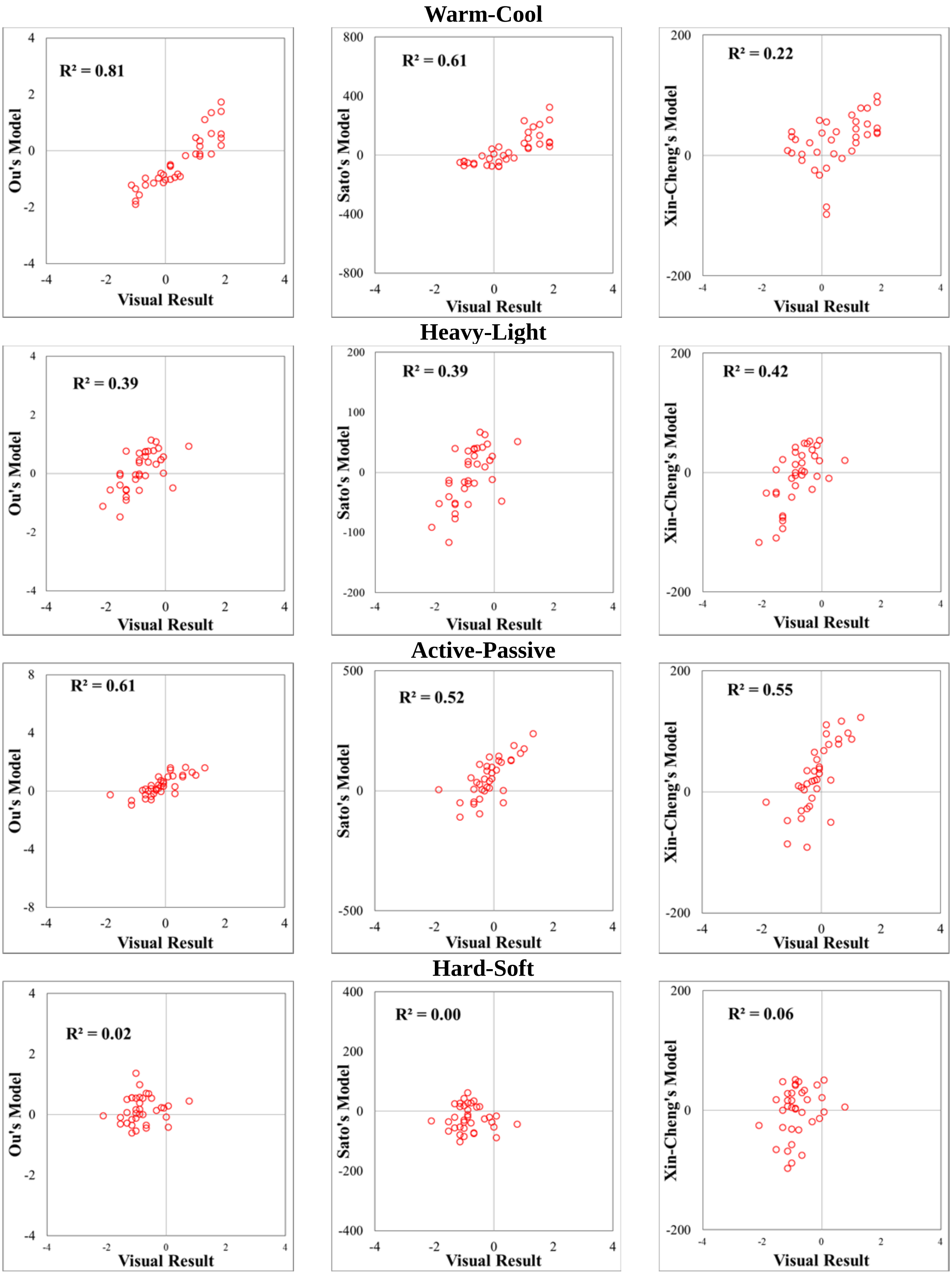
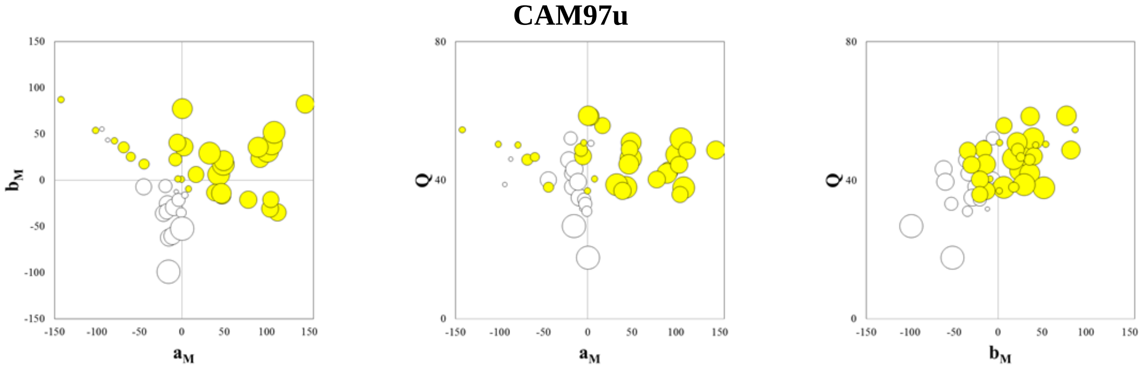


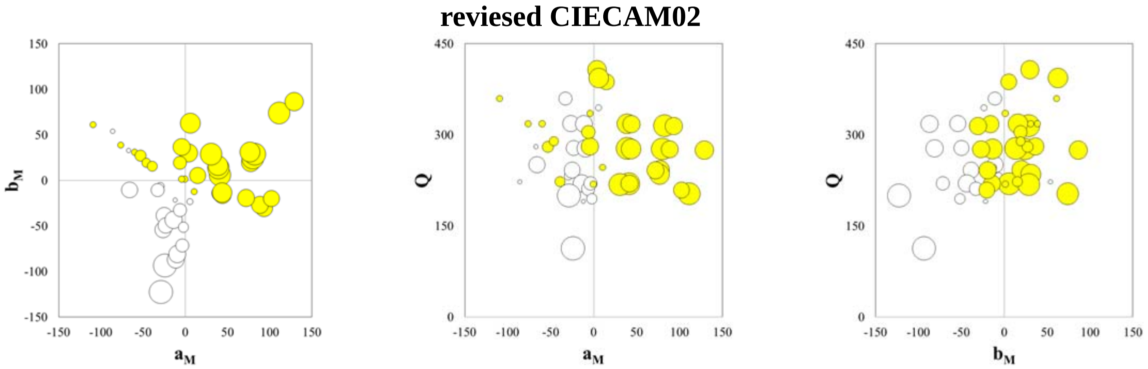
Figure 40 relationships between visual results of the current research and existing color connotation models, excluding color stimuli which have high colorfulness and brightness

IV.3.2. Color connotation scales

Warm-Cool


CAM97u

(a) a_M-b_M diagram (b) a_M-Q diagram (c) b_M-Q diagram


reviesed CIECAM02

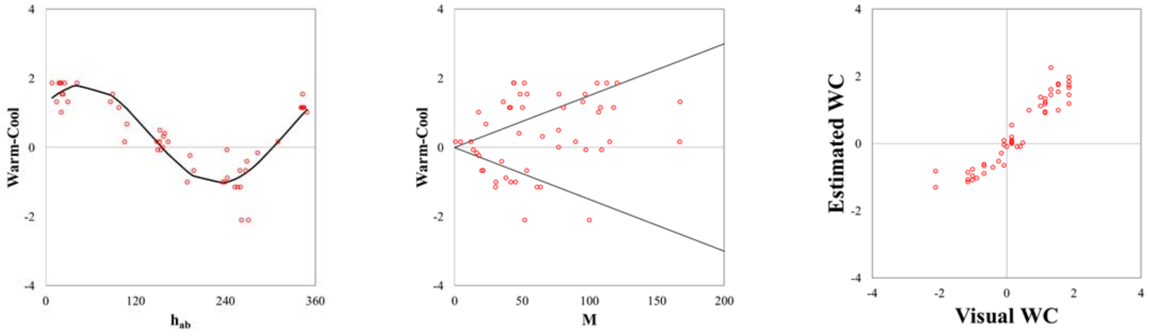
(d) a_M-b_M diagram (e) a_M-Q diagram (f) b_M-Q diagram

Figure 41 Bubble chart of "Warm-Cool" in CAM97u and revised CIECAM02

Figure 41 (a) to (f) show bubble charts for "Warm-Cool" of the 50 color stimuli in CAM97u and CIECAM02 space. The yellow bubbles represent "Warm" colors and the white bubbles represent "Cool" colors. As shown in these chart, the yellow are allocated in the red-orange-yellow region; the white bubbles are in the green-blue-purple hue region. This suggests a connection between the "warm-cool" and the hue angle - the colors at the red-orange-yellow hue angle are warm and those at the green-blue-purple hue angle are cool, as shown in Figure 41 (a) and (d). This trend is illustrated by the curve shown in Figure 42 (a) and (d).

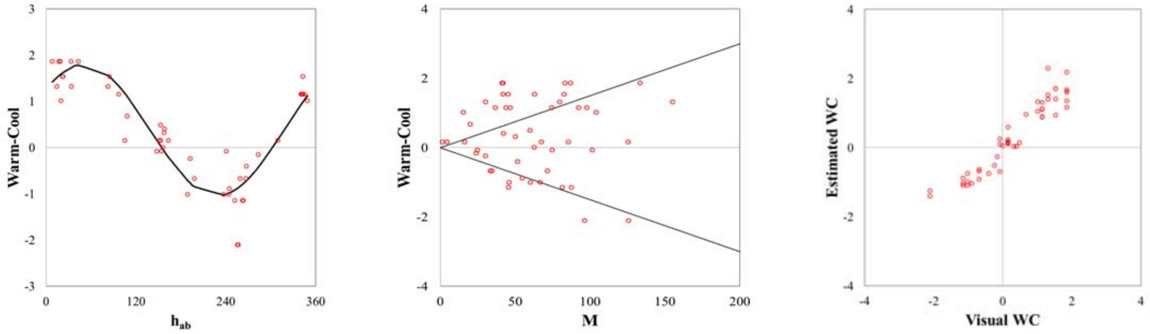
In addition to the hue angle, Figure 41 (a) and (d) also show a tendency that the bubble size becomes larger as the distance between the bubble and the neutral color increases. This tendency was found on both yellow bubbles and white bubbles. This suggests a connection between "Warm-Cool" and colorfulness – a warm color becomes warmer as its colorfulness increases; and a cool color becomes cooler as colorfulness increases. This tendency was added into the model by multiplying the cosine with a colorfulness value.

CAM97u



(a) (b) (c)

reviesed CIECAM02



(d) (e) (f)

Figure 42 Relations of “Warm-Cool” (visual result) with color appearance attributes and the final model which combines the hue angle and the colorfulness

Figure 41 (b), (c), (e) and (f) shows that the experimental data did not show clear connection between brightness and “Warm-Cool.” Brightness was not included as a variable. Following equation reflects the relationships between “Warm-Cool” and color appearance attributes.

$$\mathrm{WC} = k_0 + k_1 (M)^n \cos(k_h h - k_2)$$

where M is CAM97u colorfulness and h is CAM97u hue angle. Above equation and variables can be also derived from revised CIECAM02. Coefficients depend on color appearance models (CAM97u or revised CIECAM02). All the coefficients in the equation were optimized to fit the experimental data, and Table 20 describes the coefficients for “Warm-Cool” color connotation scale.

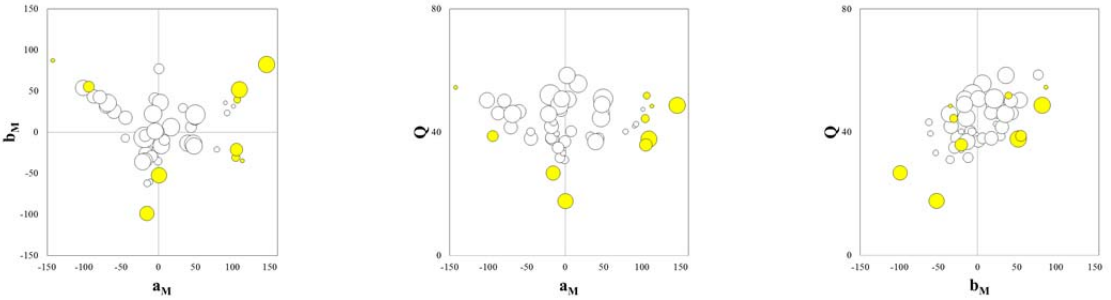
As shown in Figure 42 (c) and (f), this model shows good performance with 89% ($R^2 = 0.89$, p-value = 0.00 at significance level 0.05) and 90% ($R^2 = 0.90$, p-value = 0.00 at significance level 0.05) likelihood in CAM97u and revised CIECAM02, respectively.

Table 20 Coefficients of “Warm-Cool” color connotation equation

Models	Coefficients				
	k_0	*k_1*	*k_2*	*k_h*	*n*
CAM97u	0.29	0.39	60	1.04	0.34
CIECAM02	0.36	0.32	60	1.04	0.38

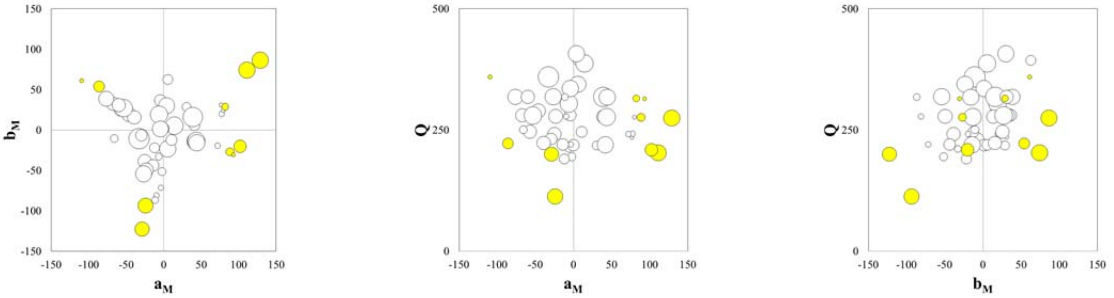
Heavy-Light

CAM97u



(a) a_M-b_M diagram (b) a_M-Q diagram (c) b_M-Q diagram

reviesed CIECAM02



(d) a_M-b_M diagram (e) a_M-Q diagram (f) b_M-Q diagram

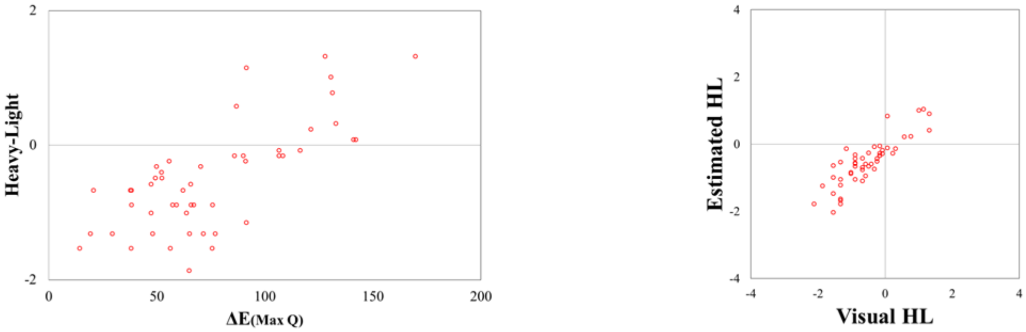
Figure 43 Bubble charts of “Heavy-Light” in CAM97u and revised CIECAM02

The method of bubble chart was also used for modeling “Heavy-Light”. As shown in Figure 43 (a) to (f), yellow bubbles represent “heavy” colors and white bubbles “light” color in CAM97u and revised CIECAM02. The colors in the outer part of the CAM97u and revised CIECAM02 tended to be heavier than those in the central area, and the color connotation of the stimuli became heavier as brightness decreases. These tendencies were reflected in the model, as shown in following equation.

$$HL = k_0 + k_D\left[k_Q(Q - Q_0)^2 + k_a(a_M - a_0)^2 + k_b(b_M - b_0)^2\right]^{\frac{1}{2}}$$

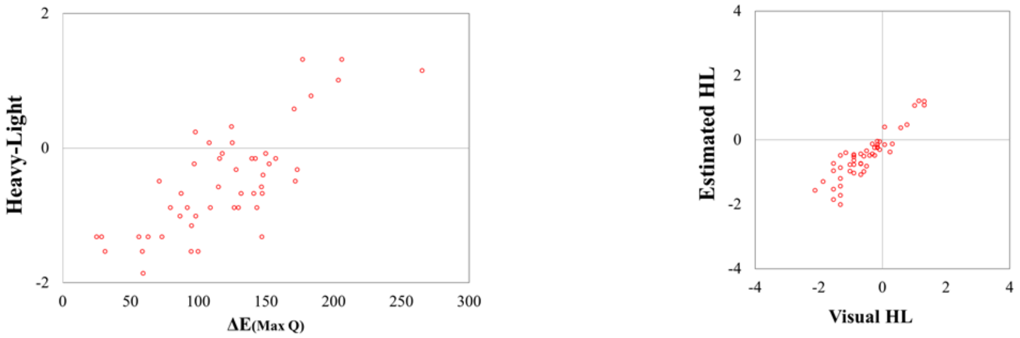
where Q is CAM97u brightness and a_M and b_M are related to hue and colorfulness in CAM97u. Above equation and variables can be also used in CIECAM02. Coefficients depend on color appearance models (CAM97u or revised CIECAM02). All the coefficients in the equation were optimized to fit the experimental data, and Table 21 describes the coefficients of equation for "Heavy-Light" color connotation scale. As shown in Figure 44 (b) and (d), this model was found to determine the experimental data of "Heavy-Light" to the likelihood of 74% (R^2 = 0.74, p-value = 0.00 at significance level 0.05) and 81% (R^2 = 0.81, p-value = 0.00 at significance level 0.05) in CAM97u and revised CIECAM02, respectively.

CAM97u



(a) (b)

reviesed CIECAM02



(c) (d)

Figure 44 Relations of "Heavy-Light" (visual result) with (a), (c) color difference between the color stimuli and the brightest neutral color and (b), (d) the final model

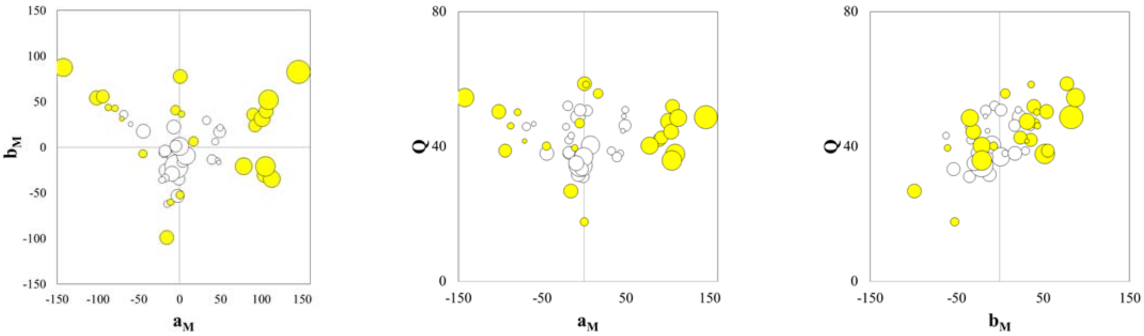
The coefficients (Q_0, a_0, b_0) are a coordinate of the brightest color stimulus in CAM97u and revised CIECAM02. Figure 44 (a) and (c) show linear relationship between "Heavy-Light" and the color difference between the color stimuli and the brightest neutral color at Q = 60 and 360 in CAM97u and revised CIECAM02, respectively. This color difference value is called $\Delta E_{\max Q}$ in the current research, where $\Delta E_{\max Q} = [(Q - Q_0)^2 + (a_M - a_0)^2 + (b_M - b_0)^2]^{1/2}$.

Table 21 Coefficients of “Heavy-Light” color connotation equation

Models	Coefficients							
	k_0	k_D	k_Q	k_a	k_b	Q_0	a_0	b_0
CAM97u	-2.50	0.08	0.87	0.05	0.08	60	0	0
CIECAM02	-2.30	0.03	0.11	0.41	0.48	360	0	0

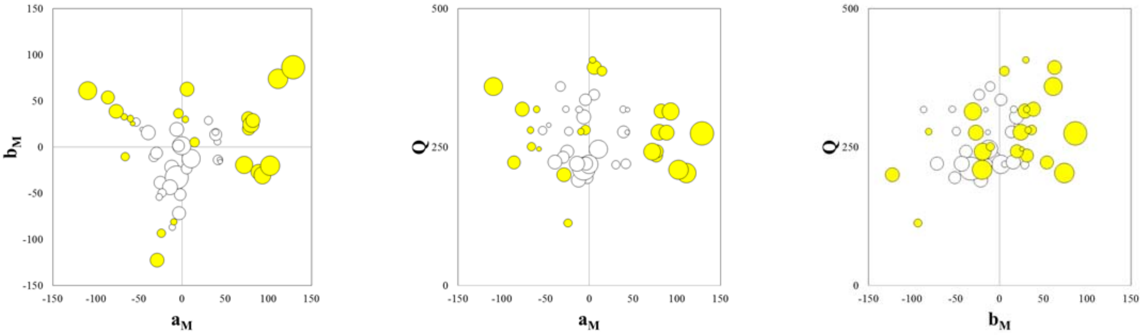
Active-Passive

CAM97u



(a) a_M-b_M diagram (b) a_M-Q diagram (c) b_M-Q diagram

reviesed CIECAM02



(d) a_M-b_M diagram (e) a_M-Q diagram (f) b_M-Q diagram

Figure 45 Bubble charts of “Active-Passive” in CAM97u and revised CIECAM02

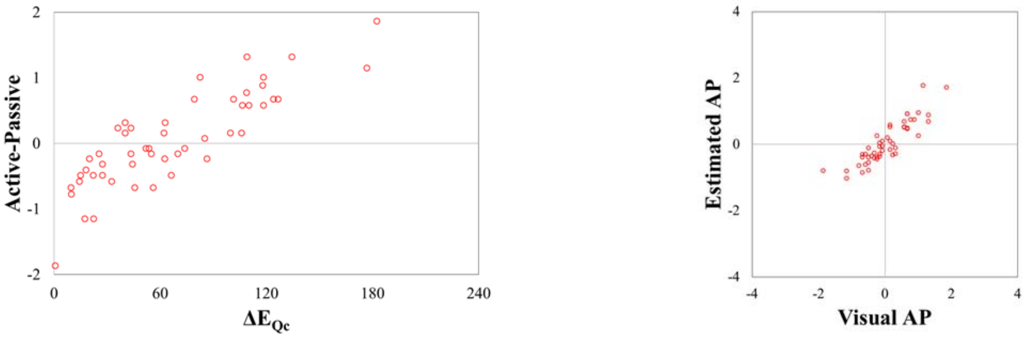
As Presented in Figure 45 (a) to (f), yellow bubbles represent “active” colors and white bubbles “passive” colors. “Active-Passive” shows the similar trend with “heavy-Light.” The colors in the outer part of color space tended to be “more active” than those in the central area. The trends were reflected in “Active-Passive” connotation model as shown in following equation.

$$AP = k_0 + k_D\left[k_Q(Q-Q_0)^2 + k_a(a_M-a_0)^2 + k_b(b_M-b_0)^2\right]^{\frac{1}{2}}$$

where Q is CAM97u brightness and a_M and b_M are related to hue and colorfulness in CAM97u. Above equation and variables can be also used in CIECAM02. All the coefficients in the equation were optimized to fit the experimental data, and Table 22 describes the coefficients of equation for “Active-Passive” color connotation scale. This “Active-Passive” model show the 78% likelihood ($R^2 = 0.78$, p-value = 0.00 at significance level 0.05) in CAM97u and 83% ($R^2 = 0.83$, p-value = 0.00 at significance level 0.05) in revised CIECAM02.

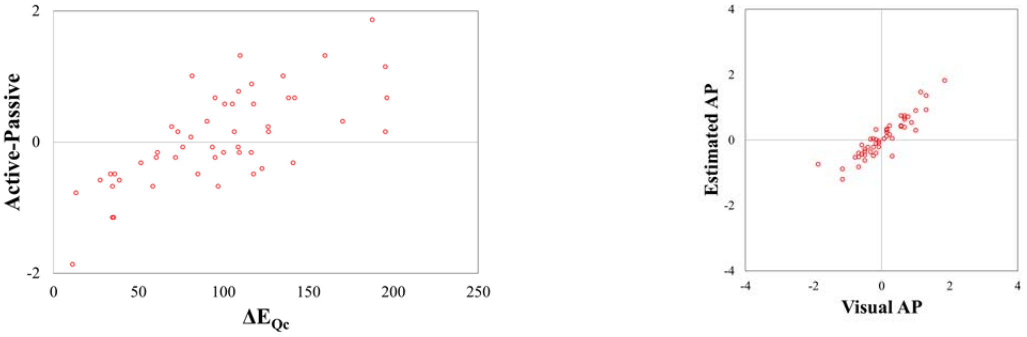
The coefficients (Q_0, a_0, b_0) are a coordinate of the most passive color stimulus in CAM97u and revised CIECAM02. Figure 46 (a) and (c) show linear relationship between “Active-Passive” and the color difference between the test color and most passive color stimulus. The color difference is called ΔE_{Qc} in the current research.

CAM97u



(a) (b)

reviesed CIECAM02



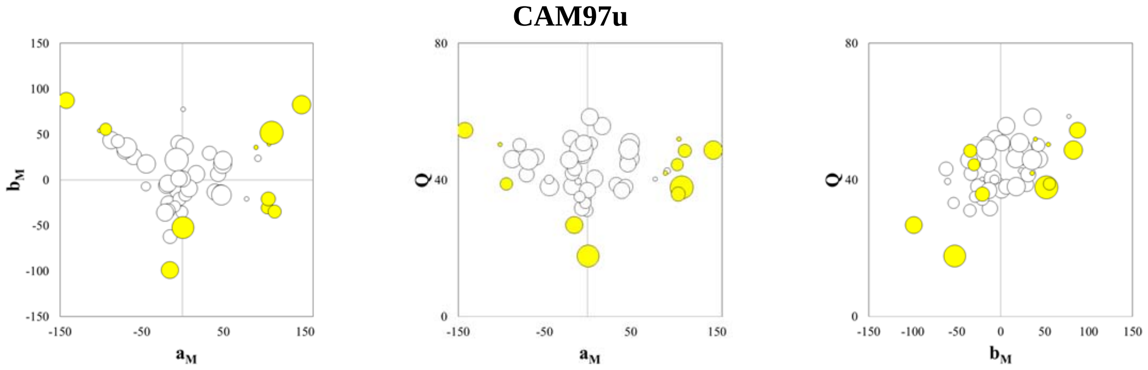
(c) (d)

Figure 46 Relations of “Active-Passive” (visual result) with (a), (c) color difference between the color stimuli and the medium bright neutral color and (b), (d) the final model

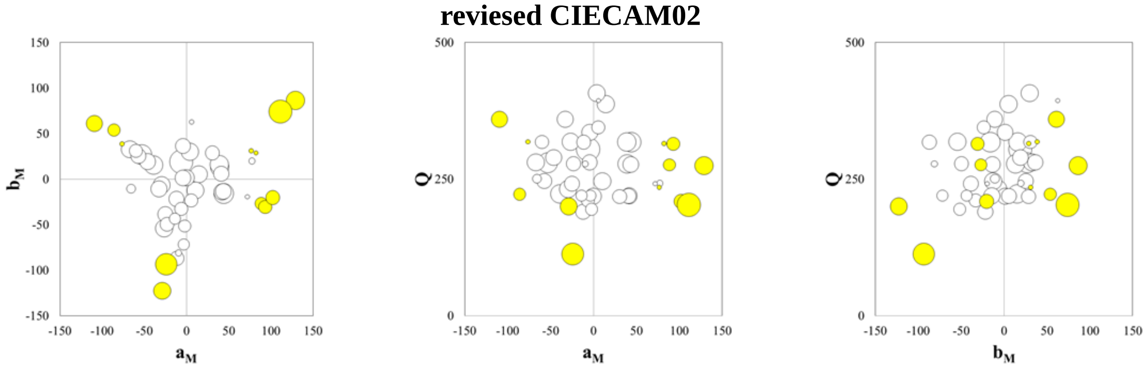
Table 22 Coefficients of “Active-Passive” color connotation equation

Models	Coefficients							
	k_0	k_D	k_Q	k_a	k_b	Q_0	a_0	b_0
CAM97u	-1.12	0.05	0.80	0.11	0.09	35	0	0
CIECAM02	-1.28	0.03	0.07	0.60	0.33	210	0	0

Hard-Soft


CAM97u

(a) a_M-b_M diagram (b) a_M-Q diagram (c) b_M-Q diagram


reviesed CIECAM02

(d) a_M-b_M diagram (e) a_M-Q diagram (f) b_M-Q diagram

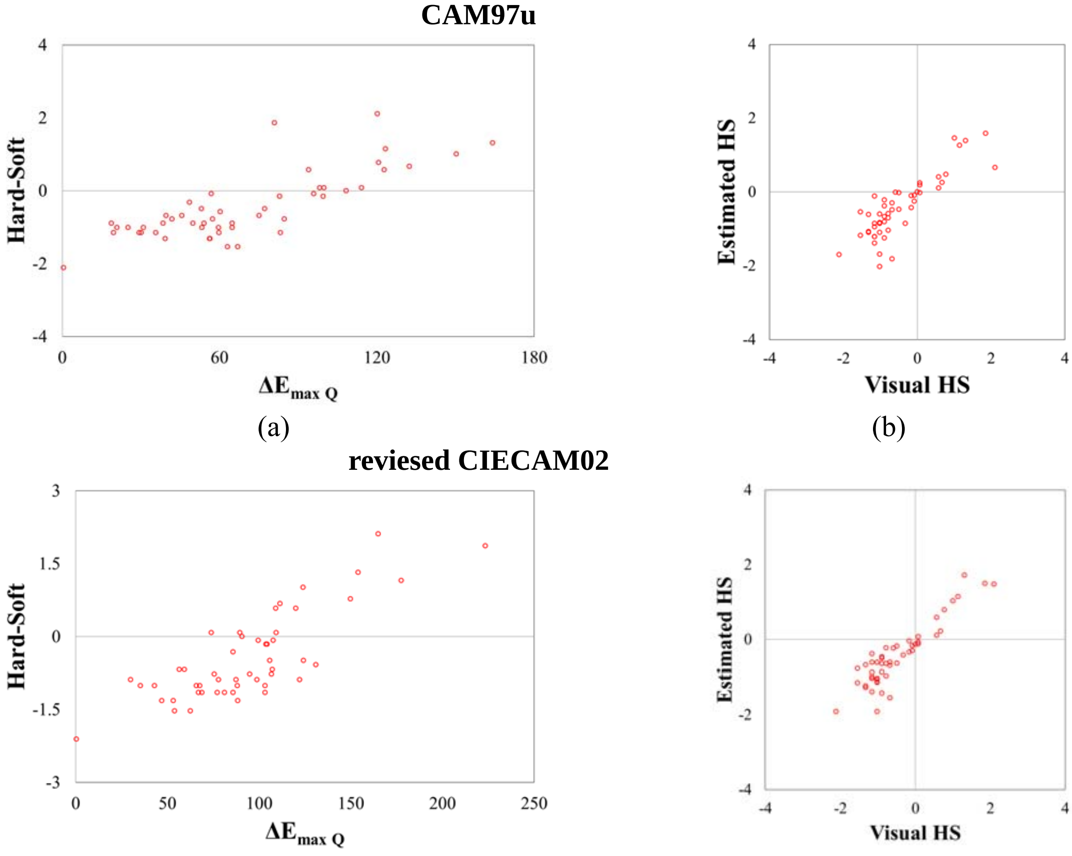
Figure 47 Bubble charts of "Hard-Soft" in CAM97u and revised CIECAM02

As shown in Figure 47 (a) to (f), yellow bubbles represent "hard" colors and white bubbles "soft" colors. The bubble charts show a similar geometric pattern between "Hard-Soft" and "Heavy-Light" - both scales had strong connection with color difference between the color stimuli and the brightest neutral color, as shown in Figure 48 (a) and (c). The colors in the outer part tend to be "harder" than those in the central area. These tendencies were reflected in the model, as shown in following equation.

$$HS = k_0 + k_D\left[k_Q(Q - Q_0)^2 + k_a(a_M - a_0)^2 + k_b(b_M - b_0)^2\right]^{\frac{1}{2}}$$

where Q is CAM97u brightness and a_M and b_M are related with hue and colorfulness in CAM97u. Above equation and variables can be also used in CIECAM02. Table 23 describes the coefficients of equation toward "Hard-Soft" color connotation scale. As shown in Figure 48 (b) and (d), this model was found to determine the experimental data of "Hard-Soft" to the likelihood of 72% (R^2 = 0.72, p-value = 0.00 at significance level 0.05) and 84% (R^2 = 0.84, p-value = 0.00 at significance level 0.05) in CAM97u and revised CIECAM02, respectively.

The coefficients (Q_0, a_0, b_0) are a coordinate of the softest color stimulus in CAM97u and revised CIECAM02. Figure 48 (a) and (c) shows linear relationship between “Hard-Soft” and the color difference between the color stimuli and bright neutral color at Q = 49 in CAM97u and 305 in revised CIECAM02. There was a little difference Q value of bright neutral color between “Hard-Soft” and “Heavy-Light.” This color difference value is called $\Delta E_{\max Q}$ in this section.



(a) (b)

(c) (d)

Figure 48 Relations of “Hard-Soft” (visual result) with (a), (c) color difference between the color stimuli and the medium bright neutral color and (b), (d) the final model

Table 23 Coefficients of “Hard-Soft” color connotation equation

Models	Coefficients							
	k_0	k_D	k_Q	k_a	k_b	Q_0	a_0	b_0
CAM97u	-2.25	0.12	0.93	0.03	0.04	49	0	0
CIECAM02	-2.42	0.04	0.16	0.46	0.38	305	0	0

IV.3.3. Modeling Color Connotation Components

The three color connotation components, “color solidity,” “color heat” and “color purity”, as have been identified in section IV.2.3, were modeled by analyzing the bubble chart. The models are given in as follows.

$$Color\ Solidity = k_0 + k_D\left[k_Q(Q - Q_0)^2 + k_a(a_M - a_0)^2 + k_b(b_M - b_0)^2\right]^{\frac{1}{2}}$$

$$Color\ Heat = k_0 + k_1(M)^n \cos(k_h h - k_2)$$

$$Color\ Purity = k_0 + k_D \times \left(\frac{Q_D - Q}{|Q_D - Q|}\right) \times \left[k_Q(Q - Q_0)^2 + k_a(a_M - a_0)^2 + k_b(b_M - b_0)^2\right]^{\frac{1}{2}}$$

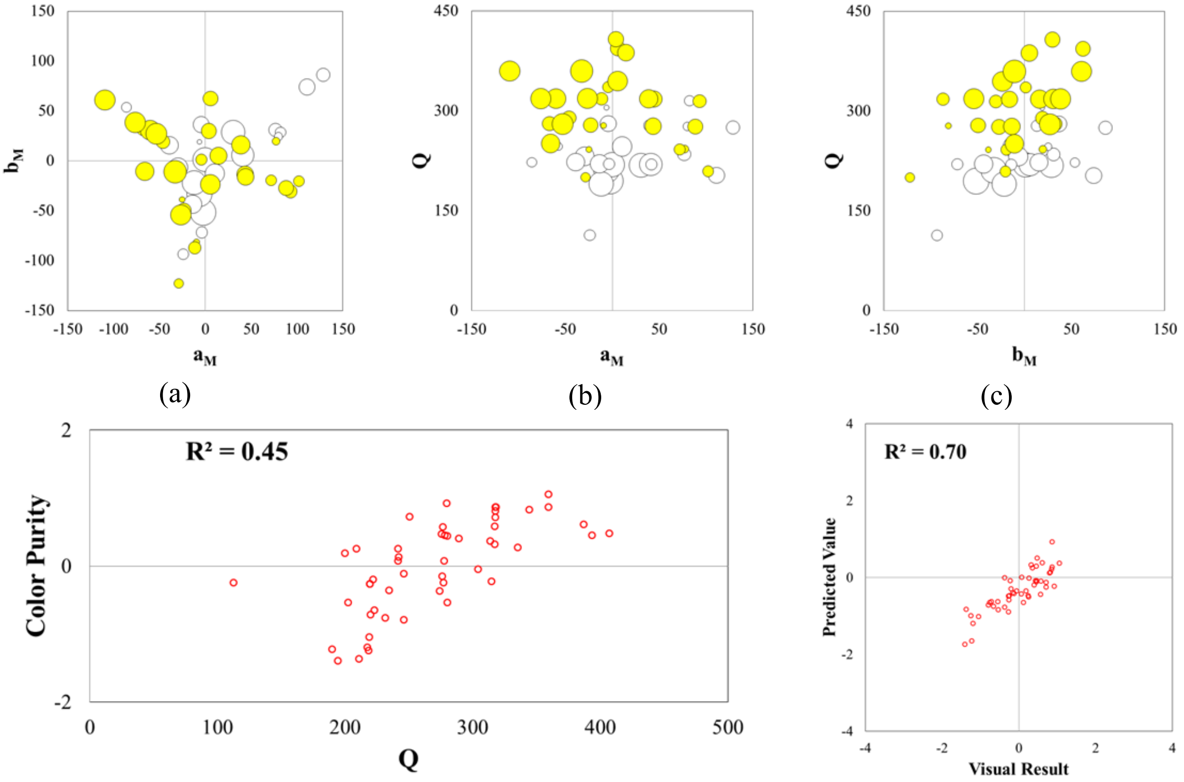
In this equation “Color Solidity” is determined by color difference between the color and a muddy yellow with (Q, a, b) = (313.16, 19.42, 19.62) and (Q, a, b) = (49.68, 21.12, 24.50) in revised CIECAM02 and CAM97u respectively, as shown in Table 24. This equation is similar to three models “Active-Passive,” “Heavy-Light” and “Hard-Soft”. “Color Solidity” and the three models appear to be related to colorfulness. The three models are determined by color difference from the color to a neutral color rather than to a muddy yellow. The difference between “Color Solidity” and the three models is simply due to the fact that “Color Solidity” includes all the features of “Active-Passive,” “Hard-Soft,” “Heavy-Light” and “Tense-Relaxed.” The model “Color Heat”, as shown in the equation, is similar to the model “Warm-Cool.” This is because “Color Heat” includes the features of “Warm-Cool” and “Feminine-Masculine”, especially “Color Heat” was closely connected with “Warm-Cool”, as shown in section IV.3.2. Table 25 summarizes coefficients of “Color Heat” model in CAM97u and revised CIECAM02. In Figure 49 (a), (b) and (c), the yellow bubbles represent “Clean” and “Fresh” colors, while the white bubbles represent “Dirty” and “Stale” colors. Brightness, as shown in Figure 49 (d), appears to be the most important factor of “color purity”—the lower the brightness, the more “Dirty” and “Stale”, because “Color Purity” includes the features of “Clean-Dirty” and “Fresh-Stale.”

Table 24 Coefficients of “Color Solidity” color connotation component

Models	Coefficients							
	k_0	k_D	k_Q	k_a	k_b	Q_0	a_0	b_0
CAM97u ($R^2 = 0.82$)	-3.06	0.17	0.90	0.03	0.07	49.68	21.12	24.50
CIECAM02 ($R^2 = 0.90$)	-3.15	0.06	0.09	0.40	0.51	313.16	19.42	19.62

Table 25 Coefficients of “Color Heat” color connotation component

Models	Coefficients				
	k$_0$	*k*$_1$	*k*$_2$	*k*$_h$	*n*
CAM97u ($R^2 = 0.83$)	-0.25	0.10	66.54	1.12	0.70
CIECAM02 ($R^2 = 0.81$)	-0.13	0.14	58.48	1.12	0.61



(a) (b) (c)

(d) (e)

Figure 49 Bubble charts of “Purity” in revised CIECAM02, the relations of “Color Purity” with (d) revised CIECAM02 brightness and (e) the final model

Table 26 Coefficients of “Color Purity” color connotation component

Models	Coefficients								
	k$_0$	*k*$_D$	*k*$_Q$	*k*$_a$	*k*$_b$	*Q*$_D$	*Q*$_0$	*a*$_0$	*b*$_0$
CAM97u ($R^2 = 0.65$)	-4.11	0.01	0.94	0.04	0.02	22.38	19.78	33.22	173.29
CIECAM02 ($R^2 = 0.70$)	-2.85	0.00014	0.12	0.49	0.11	192.61	81.33	20.86	147.63

IV.3.4. Summary

The aim of this part is to quantify relationships between color appearance attributes of unrelated colors and color connotation space deducted by this experiment 2, and to develop color connotation models for single colors. Brightness Q, colorfulness M and hue angle of CAM97u and revised CIECAM02 were used to quantify relationships.

Four color connotation scales, “Warm-Cool,” “Heavy-Light,” “Active-Passive” and “Hard-Soft”, were modeled in terms of color appearance attributes. The scale “Warm-Cool” was found in association with hue angle and colorfulness. The others were founded in connection with color difference between the color and neutral color of which brightness were different in the three color connotation scale. It indicated that “Heavy-Light,” “Active-Passive” and “Hard-Soft” were closely connected with colorfulness. Table 27 summarizes the performances (r^2) of color connotation models.

Table 27 Performances of color connotation models

Models	“Warm-Cool”	“Heavy-Light”	“Active-Passive”	“Hard-Soft”
CAM97u	0.89	0.74	0.78	0.72
Revised CIECAM02	0.91	0.81	0.83	0.84

Three axes of color connotation space developed in this research, “Color solidity,” “Color heat,” and “Color purity,” were also modeled in terms of color appearance attributes. The axis “Color solidity” was founded in closely connection with colorfulness rather than brightness and hue angle. The axis “Color heat” was found in relation with both hue angle and colorfulness, especially hue angle. “Color purity” was found in association with brightness rather than colorfulness and hue angle. Performances of the models were evaluated by coefficient of determination. Although performance of the “Color purity” models was relatively worse than other models, by and large, the models represented outstanding performance. R^2 of “Color solidity,” “Color heat” and “Color purity” were 0.90, 0.81 and 0.70 in revised CIECAM02 space, respectively.

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Conclusions

V. Conclusions

The aim of current research was to clarify the relation between color perception and connotation of unrelated colors, and to develop models for color connotation. To achieve these purposes, two psychophysical experiments were carried out.

Experiment 1 investigates color perception for unrelated color using 50 color stimuli beamed through square hole. Observers were asked to report magnitude of perceived color appearance attributes using magnitude estimation.

Experiment 2 studied color connotation for unrelated colors using 50 color stimuli. Observer were asked to answer their connotation to each color stimulus using 10 color connotation scales, including 9 nonaesthetic scale (i.e. "Warm – Cool," "Heavy – Light," "Modern – Classical," "Clean – Dirty," "Active – Passive," "Hard – Soft," Tense – Relaxed," "Fresh – Stale," and "Masculine – feminine") and an aesthetic scale (i.e. "like – Dislike").

The part "Modeling color connotation" quantified relationships between color appearance attributes of unrelated colors and color connotation space, and developed color connotation models for unrelated colors. Bubble charts were used to visualize patterns and to analyze relationships between color appearance attributes and color connotation scales. Brightness Q, colorfulness M and hue angle of CAM97u and revised CIECAM02 were used to quantify relationships as input variables. Major findings obtained from these experiments are summarized below.

V.1. Color Perception for Unrelated Colors

The perceptual data of unrelated colors was obtained from experiment 1, and it was used for quantifying color appearance attributes of unrelated colors. The results suggest the following claims.

The observer variation was compared between color attributes. The observer variation for hue was found smaller than those for the brightness and colorfulness. These results were similar to those found in earlier experiments for investigating related colors.

The three perceptual attributes of unrelated colors can be estimated by colorimetric properties of color stimuli. The three color attributes, brightness, colorfulness and hue, had firm linear relationships with estimation models derived by luminance, excitation purity and CIE 1976 hue-angle of color stimuli, as shown in the Table 28. The coefficient of determinations (r^2) for brightness, colorfulness and hue were 0.83, 0.74 and 0.99, respectively.

Table 28 Estimation models for color appearance attributes

Color appearance attributes	Models
Brightness	$\text{Brightness} = 8.25 \times \ln(luminance)$ $\text{Brightness} = 12.45 \times (luminance)^{0.26}$
Colorfulness	$\text{Colorfulness}_{CP} = 0.93 \times P_e$
Hue	$H_q = 1.14 \times (hue\ angle) + 14.44$

Revised CIECAM02 gave the best satisfactory estimations of brightness, colorfulness and hue under photopic vision. The coefficients of determination between the predictors of CAM97u and perceptual results were 0.71, 0.75 and 0.98 for brightness, colorfulness and hue, respectively. In the case of revised CIECAM02, the coefficients of determination were 0.83, 0.83 and 0.98 for brightness, colorfulness and hue, respectively. This indicated that the predictors of revised CIECAM02 show the best performance. R^2 values of revised CIECAM02 for color appearance attributes were greater than those of other models.

V.2. Color connotation for Unrelated Colors

Color connotation is defined as the relation between color stimuli and connotations evoked from these color stimuli. The results of experiment 2 suggest the following findings.

There is little gender effect on non-aesthetic color connotation. This is supported by the results in Experiment 2 in which the color connotation responses of male observers were found to agree well with those of female observers.

Color connotation of unrelated colors has a three-dimensional space, and the three axes are "Color solidity," "Color heat," and "Color purity." "Color solidity" is associated with "Hard-Soft," "Heavy-Light," "Tense-Relaxed," and "Active-Passive." "Color heat" is concerned with "Warm-Cool" and "Feminine-Masculine", and "Color purity" is related closely with "Clean-Dirty" and "Fresh-Stale."

V.3. Modeling Color Connotation

The relationships between color perception and connotation for unrelated color were determined by using the results of experiment 1 and 2. The results suggest the following claims.

Existing color emotion models for related color are barely suitable for estimating color connotation of unrelated color. The existing models are developed by using their own empirical visual data for unrelated color stimuli.

Color connotation of unrelated colors is a function of the three color appearance attributes which are brightness, colorfulness and hue. Table 29 summarizes color connotation models developed by this research, and Table 30 presents coefficients of the color connotation models. All the color connotation scales were found to correlate closely with these attributes. Four color connotation scales, “Warm-Cool,” “Heavy-Light,” “Active-Passive” and “Hard-Soft”, were modeled in terms of color appearance attributes. The scale “Warm-Cool” was found in association with hue angle and colorfulness, while “Warm-Cool” wasn’t related to brightness. The others were founded in connection with color difference between the color and neutral color of which brightness were different in the three color connotation scale. It indicated that “Heavy-Light,” “Active-Passive” and “Hard-Soft” were closely connected with colorfulness.

Table 29 Color connotation models developed by this research

Color connotation	Equation
“Warm - Cool”	$\mathrm{WC} = k_0 + k_1(M)^n \cos(k_h h - k_2)$
“Heavy - Light”	$HL = k_0 + k_D\left[k_Q(Q - Q_0)^2 + k_a(a_M - a_0)^2 + k_b(b_M - b_0)^2\right]^{\frac{1}{2}}$
“Active - Passive”	$AP = k_0 + k_D\left[k_Q(Q - Q_0)^2 + k_a(a_M - a_0)^2 + k_b(b_M - b_0)^2\right]^{\frac{1}{2}}$
“Hard - Soft”	$HS = k_0 + k_D\left[k_Q(Q - Q_0)^2 + k_a(a_M - a_0)^2 + k_b(b_M - b_0)^2\right]^{\frac{1}{2}}$

Table 30 Coefficients for color connotation models developed by this research

Color Connotation	Models	Coefficients							
		k_0 (k_0)	k_D (k_1)	k_Q (k_2)	k_a (k_n)	k_b (n)	Q_0	a_0	b_0
Warm Cool	CAM97u	0.29	0.39	60	1.04	0.34			
	CIECAM02	0.36	0.32	60	1.04	0.38			
Heavy Light	CAM97u	-2.50	0.08	0.87	0.05	0.08	60	0.00	0.00
	CIECAM02	-2.30	0.03	0.11	0.41	0.48	360	0.00	0.00
Active Passive	CAM97u	-1.12	0.05	0.80	0.11	0.09	35	0.00	0.00
	CIECAM02	-1.28	0.03	0.07	0.60	0.33	210	0.00	0.00
Hard Soft	CAM97u	-2.25	0.12	0.93	0.03	0.04	49	0.00	0.00
	CIECAM02	-2.42	0.04	0.16	0.46	0.38	305	0.00	0.00

The three-dimensional color connotation space for color connotation of unrelated colors is

concerned with color appearance attributes. Three axes of the space developed in this research, “Color solidity,” “Color heat,” and “Color purity,” were modeled in terms of color appearance attributes. The axis “Color solidity” was founded in closely connection with colorfulness rather than brightness and hue angle. The axis “Color heat” was found in relation with both hue angle and colorfulness, especially hue angle. “Color purity” was found in association with brightness rather than colorfulness and hue angle. The models of three color connotation components, “color solidity,” “color heat” and “color purity”, were also developed. Table 31 shows the models of the color connotation components, and Table 32 summarizes coefficients for the connotation components models. Performances of the models were evaluated by coefficient of determination. Although performance of the “Color purity” models was relatively worse than other models, by and large, the models represented outstanding performance. R^2 of “Color solidity,” “Color heat” and “Color purity” were 0.90, 0.81 and 0.70 in revised CIECAM02 space, respectively.

Table 31 Models of color connotation components developed by this research

Models

$$\boldsymbol{Color\ Solidity} = k_0 + k_D\left[k_Q(Q-Q_0)^2 + k_a(a_M-a_0)^2 + k_b(b_M-b_0)^2\right]^{\frac{1}{2}}$$

$$\boldsymbol{Color\ Heat} = k_0 + k_1(M)^n\cos(k_h h - k_2)$$

$$\boldsymbol{Color\ Purity} = k_0 + k_D \times \left(\frac{Q_D-Q}{|Q_D-Q|}\right) \times \left[k_Q(Q-Q_0)^2 + k_a(a_M-a_0)^2 + k_b(b_M-b_0)^2\right]^{\frac{1}{2}}$$

Table 32 Coefficients for color connotation components models developed by this research

Color Connotation Components	Coefficients									
	models	k_0 (k_0)	k_D (k_1)	k_Q (k_2)	k_a (k_n)	k_b (n)	Q_D	a_0	b_0	Q_0
Color Solidity	CAM97u	-3.06	0.17	0.9	0.03	0.07	49.68	21.12	24.5	
	CIECAM02	-3.15	0.06	0.09	0.4	0.51	313.16	19.42	19.62	
Color Heat	CAM97u	-0.25	0.1	66.54	1.12	0.7				
	CIECAM02	-0.13	0.14	58.48	1.12	0.61				
Color Purity	CAM97u	-4.11	0.01	0.94	0.04	0.02	22.38	33.22	173.3	19.78
	CIECAM02	-2.85	0.00	0.12	0.49	0.11	192.61	20.86	147.6	81.33

V.4. Future Work

Studies for unrelated colors are not yet enough to apply to various fields in comparison with related colors. A data set of color perception for unrelated colors was obtained by this research, and the performances of existing color appearance model were tested by using the data set of color perception. Furthermore, a data set of color connotation for unrelated colors was acquired, and color connotations were mathematically modeled by using the data set. This research is significant in the sense that it investigated unrelated colors from color perception to emotional reactions, simultaneously.

There is room for further improvement and development in this research. (1) The data sets obtained by this research need to examine repeatability, (2) relationships of color connotations between unrelated colors and related colors need to be analyzed, and (3) the results of this research should expend into applications in association with emotional lighting.

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Appendix

Appendix A – Instructions for Observers

A.1. Color Perception for unrelated colors

실험 개요

본 실험은 조명 색의 변화에 따라, 인간이 인지하는 조명에 대한 색상(Hue), 밝기(Brightness), 색조(colorfulness)를 정량화하는 실험이다.

※실험에 사용하는 조명은 LED(Light-Emitting Diode)로 구성된 조명으로 현재 국내 외에서 차세대 조명으로 각광받고 있는 조명으로 인체에 무해하니 안심하시기 바랍니다.

실험 방법

Session 1

1. 피실험자는 실험 전, color attributes에 대한 설명과 이를 구분하도록 훈련을 받는다.
2. 피실험자는 암실(Dark room)에서 15분간 암적응을 한다.
3. 실험에서 피실험자에게 주어지는 자극은 1m가량 떨어진 Light cabinet에서 3X3크기의 조명이다.
4. 15분간 암적응 후, 피실험자에게 색상 판단에 기준이 되는 anchor stimulus를 보여준다.
5. 피실험자는 실험 조명을 5초 정도 본 후, 실험자가 묻는 색상에 대해 anchor stimulus를 기준으로 대답한다.
6. 앞서 질문이 끝난 후, 10~20초 후 피실험자에게 다른 조명이 주어지며, 실험조명 5개마다 한 번씩 anchor stimulus를 반복하여 보여준다.

Session 2

Session1 종료 후, 5분 정도 휴식을 갖고 Session 1과 동일한 방법으로 진행하되 피실험자가 대답하기에 요구되는 color attributes는 밝기와 색조이다.

※실험에 사용하는 Color attributes는 총 3가지로 영어로 되어 있으며, 실험에서 주어지는 조명의 종류는 50개 이다.

실험시 주의사항

- 실험 전날 6시간 이상 수면이 요구되며, 실험 전날 음주는 피해주시기 바랍니다.
- 실험 당일 의상은 밝은 색 계열이나 형광색 계열의 옷보다는 무채색 계열의 옷을 입어주시기 바랍니다.
- 실험 도중, 실험에서 주어지는 조명 이외에 빛을 낼 수 있는 장비(휴대폰, 시계, MP3)를 사용할 수 없는 점 양해 부탁 드립니다.

A.2. Color connotation for unrelated colors

실험 개요

본 실험은 조명 색의 변화에 따라, 인간이 인지하는 조명에 대한 이미지를 정량화하는 실험이다.

※실험에 사용하는 조명은 LED(Light-Emitting Diode)로 구성된 조명으로 현재 국내 외에서 차세대 조명으로 각광받고 있는 조명으로 인체에 무해하니 안심하시기 바랍니다.

실험 방법

Session 1

1. 피실험자는 암실(Dark room)에서 15분간 암적응을 한다.
2. 15분간 암적응 후, 피실험자에게 1m가량 떨어진 Light cabinet에서 3X3크기의 조명이 주어진다.
3. 피실험자는 해당 조명을 5초 정도 본 후, 실험자가 묻는 감성 형용사 쌍 중에서, 반드시 하나를 선택하여 대답한다. 감성 형용사 쌍은 총 5쌍으로 구성되어 있다.
4. 앞서 질문이 끝난 후, 10~20초 후 피실험자에게 다른 조명이 주어지며 3번 과정을 반복한다.

Session 2

Session1 종료 후, 5분 정도 휴식을 갖고 Session 1의 실험을 반복한다.

※실험에 사용하는 감성 형용사 쌍은 총 10가지로 영어로 되어 있으며, 실험에서 주어지는 조명의 종류는 40~50개 이다.

실험시 주의사항

- 실험 전날 6시간 이상 수면이 요구되며, 실험 전날 음주는 피해주시기 바랍니다.
- 실험 당일 의상은 밝은 색 계열이나 형광색 계열의 옷보다는 무채색 계열의 옷을 입어주시기 바랍니다.
- 실험 도중, 실험에서 주어지는 조명 이외에 빛을 낼 수 있는 장비(휴대폰, 시계, MP3)를 사용할 수 없는 점 양해 부탁 드립니다.

A.3. Definition of the Word Pairs

(from Cambridge Advanced Learner’s Dictionary)

Warm – Cool

Warm: having or producing a comfortably high temperature, although not hot
Cool: Slightly cold; of a low temperature

Heavy – light

Heavy: weighing a lot; needing effort to move or lift
Light: weighing only a small amount; not heavy

Modern – Classical

Modern: (designed and made) using the most recent ideas and methods
Classical: traditional in style or form, or based on methods developed over a long period of time

Clean – Dirty

Dirty: covered with dirt
Clean: free from dirt; not dirty

Active – Passive

Active: busy in or ready to perform a particular activity
Passive: not acting to influence or change a situation; allowing other people to be in control

Hard – Soft

Hard: firm and solid; not easy to bend, cut, or break
Soft: not hard or firm; changing its shape when pressed

Tense – Relaxed

Tense: nervous, anxious and unable to relax
Relaxed: calm and less worried

Fresh – Stale

Fresh: new and therefore interesting or exciting
Stale: no longer new or fresh, usually as a result of being kept for too long

Feminine – Masculine

Feminine: having qualities that are traditionally considered to be suitable for women
Masculine: Having characteristics that are traditionally thought to be typical of or suitable for men

Like – Dislike

Like: to enjoy or approve of (something or someone)
Dislike: to not like; to find (someone or something) unpleasant, difficult, etc.

Appendix B – Color Perception Data

Color stimulus	Magnitude			Observer Variation		
	Brightness	Colorfulness	Hue Quadrature	Brightness	Colorfulness	Hue Quadrature
1	31	58	20	56%	27%	3%
2	49	79	100	35%	18%	6%
3	38	47	175	17%	39%	11%
4	34	44	280	37%	33%	6%
5	32	38	310	38%	43%	7%
6	28	50	58	36%	30%	23%
7	34	53	104	32%	33%	13%
8	24	37	257	60%	65%	16%
9	27	29	284	51%	36%	11%
10	47	37	60	20%	26%	67%
11	48	42	102	22%	18%	12%
12	47	39	205	23%	23%	22%
13	44	29	302	7%	23%	21%
14	40	41	103	28%	19%	22%
15	34	37	202	27%	51%	16%
16	32	30	439	36%	33%	13%
17	27	31	138	57%	33%	63%
18	47	29	111	30%	49%	56%
19	28	51	415	43%	18%	8%
20	35	60	414	49%	23%	4%
21	36	46	437	44%	21%	5%
22	34	62	416	74%	22%	4%
23	43	52	37	33%	18%	5%
24	43	63	18	40%	16%	4%
25	34	59	188	36%	26%	9%
26	33	46	184	31%	34%	19%
27	39	50	180	32%	30%	9%
28	37	53	177	27%	19%	10%
29	43	60	186	35%	19%	9%
30	47	59	179	21%	22%	13%
31	30	54	322	52%	24%	4%
32	31	39	287	37%	50%	6%
33	37	54	314	95%	24%	3%
34	41	44	284	20%	19%	7%
35	40	54	319	37%	26%	7%
36	40	44	287	43%	30%	7%
37	36	67	390	46%	26%	5%
38	31	47	392	47%	23%	6%
39	43	68	388	34%	20%	4%
40	38	51	392	24%	19%	5%
41	45	72	392	41%	23%	5%
42	46	51	398	21%	18%	7%
43	33	89	1	67%	21%	1%
44	33	92	3	71%	15%	1%
45	36	76	386	54%	21%	3%
46	36	58	216	39%	23%	12%
47	19	77	300	61%	27%	1%
48	37	80	308	57%	25%	12%
49	35	76	195	30%	21%	7%
50	50	80	187	41%	16%	9%

Appendix C – Color Connotation Scale Values

C.1. Female Data (z-scores)

Stimulus	Active Passive	Clean Dirty	Feminine Masculine	Fresh Stale	Hard Soft	Heavy Light	Like Dislike	Modern Classical	Tense Relaxed	Warm Cool
1	0.89	0.67	2.11	-0.16	0.16	-0.16	-0.32	0.16	0.67	2.11
2	0.67	2.11	2.11	0.67	-0.16	-0.89	0.49	-0.16	0.49	1.53
3	0.32	1.15	-0.16	0.49	-1.15	-1.53	0.16	-0.32	-0.67	0.32
4	-0.89	0.32	-0.16	0.16	-1.53	-1.53	0.67	-0.16	-1.15	-1.53
5	-0.89	0.00	-1.15	-0.89	-1.15	-0.32	-0.16	-0.16	-0.67	-0.89
6	-0.32	-0.16	1.53	-0.49	-0.89	-0.67	-0.16	0.00	0.00	2.11
7	0.49	0.49	2.11	0.00	-0.89	-1.15	0.49	-0.67	-0.49	1.15
8	-0.67	-0.16	-1.15	-0.16	-0.89	-0.89	0.16	0.00	-1.15	-0.32
9	-2.11	-0.49	-0.67	-0.67	-0.67	-0.67	-0.32	0.00	-0.67	-1.15
10	0.16	0.67	0.89	0.49	-1.15	-2.11	0.16	0.00	-0.49	1.15
11	0.32	0.89	2.11	0.49	-1.53	-1.53	0.67	0.00	-1.15	2.11
12	-0.67	1.15	-0.49	0.32	-1.15	-2.11	-0.32	0.16	-0.32	-0.89
13	-0.67	0.67	0.89	0.49	-0.67	-1.53	0.49	0.32	-0.16	-0.16
14	-0.89	0.67	1.15	0.00	-2.11	-2.11	0.16	-0.32	-1.15	0.89
15	-0.32	0.16	0.00	0.00	-2.11	-0.89	0.16	-0.16	-1.53	-0.16
16	-1.53	-0.32	1.53	-0.49	-1.53	-0.89	-0.16	0.00	-0.16	0.16
17	-1.15	-0.49	0.67	-0.32	-1.15	-0.89	-0.49	-0.67	-1.15	0.49
18	-0.89	0.49	0.49	0.32	-1.15	-1.53	0.00	0.32	-1.15	0.00
19	-0.16	-0.32	2.11	-0.67	-1.53	-1.15	-0.16	-0.16	-0.67	2.11
20	0.32	0.32	2.11	0.16	0.00	-0.32	0.16	0.67	1.15	2.11
21	-0.49	0.67	2.11	-0.49	-1.53	-1.15	0.49	-0.89	-0.49	2.11
22	1.15	0.16	1.53	0.16	0.00	0.00	0.00	0.49	1.53	2.11
23	-0.49	0.67	2.11	0.32	-2.11	-1.53	0.16	0.16	-0.32	1.53
24	0.49	0.49	2.11	0.00	0.16	0.49	-0.32	0.49	1.15	2.11
25	0.49	0.32	-0.49	0.89	-0.67	-1.15	0.32	0.00	-0.89	0.16
26	-0.32	-0.16	-0.32	-0.32	-1.53	-1.53	0.16	0.16	-0.89	0.49
27	0.16	0.67	-0.67	0.16	-1.15	-0.89	0.32	0.32	-0.32	-0.49
28	-0.16	1.53	0.00	0.67	-1.53	-1.15	0.49	0.16	-0.67	0.49
29	0.89	1.15	-0.16	0.49	0.67	-1.15	0.16	0.32	0.32	0.00
30	0.16	0.67	0.00	0.67	-0.67	-0.89	-0.16	0.67	0.00	0.16
31	-0.32	0.32	-0.89	-0.32	-0.32	-0.16	0.00	0.32	-0.16	-0.89
32	-0.89	-0.16	-0.89	-0.49	-0.67	-1.15	-0.49	0.49	-0.32	-1.53
33	0.00	0.49	-0.67	0.16	0.00	-0.32	0.16	0.89	-0.16	-2.11
34	-0.16	0.49	-0.67	0.49	-0.67	-1.53	0.89	0.49	-0.67	-1.53
35	-0.32	1.15	-1.15	0.32	-0.67	-0.32	0.32	1.15	-0.16	-1.53
36	-0.32	1.15	-0.49	0.16	-0.89	-1.15	0.32	1.15	-0.16	-1.15
37	1.53	0.89	1.53	0.00	-0.32	0.00	0.00	1.53	1.15	1.15
38	-0.16	0.49	1.53	-0.49	-1.15	-1.53	0.32	0.32	-0.89	0.89
39	0.67	1.15	1.53	0.67	0.67	0.16	0.00	1.15	1.15	0.89
40	-0.32	1.53	2.11	0.49	-0.89	-1.53	0.32	0.32	-0.49	2.11
41	0.67	0.89	1.53	0.16	1.53	0.16	-0.67	1.15	1.53	1.15
42	0.00	0.67	2.11	0.16	-1.15	-1.53	0.89	0.49	0.00	1.53
43	1.53	0.67	0.32	0.32	2.11	1.15	-0.89	0.16	1.53	2.11
44	2.11	0.32	0.32	0.16	1.53	1.53	-1.15	0.16	2.11	1.53
45	1.53	1.15	2.11	0.16	0.89	0.89	-0.16	0.89	1.53	0.89
46	0.49	1.53	-0.16	0.89	-0.16	-0.49	0.16	0.32	0.67	-1.53
47	0.32	0.16	-0.89	0.16	1.53	0.67	-0.67	0.49	1.15	-2.11
48	1.15	0.32	-2.11	0.49	1.53	1.53	-0.89	0.49	1.15	-2.11
49	0.67	1.15	-1.15	0.67	0.49	0.49	-0.67	0.00	1.15	-0.16
50	1.53	1.15	-0.67	0.67	1.15	-0.49	-0.67	0.32	0.49	0.00

C.2. Male Data (z-scores)

Stimulus	Active Passive	Clean Dirty	Feminine Masculine	Fresh Stale	Hard Soft	Heavy Light	Like Dislike	Modern Classical	Tense Relaxed	Warm Cool
1	0.32	-0.16	1.15	-0.16	0.00	0.00	-0.16	0.16	0.32	1.15
2	0.67	0.49	0.32	0.16	0.00	-0.16	1.15	-0.32	0.89	1.53
3	-0.49	0.49	-0.16	0.67	-0.89	-0.67	0.89	0.89	-1.15	0.32
4	-0.32	0.67	-0.89	0.16	-0.49	-0.49	-0.16	0.49	-0.32	-0.67
5	-0.16	-0.49	-0.67	-0.89	-0.16	-0.32	-0.49	-0.32	-0.67	0.00
6	-0.16	-0.49	0.67	-0.89	-0.67	-0.16	0.16	-0.16	-0.67	1.53
7	0.16	-0.16	0.67	-0.32	-0.89	-0.32	0.67	-0.32	-0.16	1.15
8	-0.67	-0.89	-1.15	-0.67	-0.89	-0.16	-0.67	-0.16	-0.32	0.16
9	-1.53	-0.49	-0.89	-0.67	-0.67	0.16	-0.49	0.16	-0.89	-0.32
10	0.49	0.89	1.53	0.00	-1.15	-1.15	0.67	0.49	-0.32	0.89
11	0.00	0.89	1.15	0.49	-0.89	-1.15	0.89	-0.49	-0.67	0.89
12	0.00	0.89	-0.32	0.49	-0.89	-2.11	0.32	0.32	-0.67	-0.49
13	-0.16	0.89	0.32	0.67	-0.67	-1.15	0.67	0.32	-0.32	-0.16
14	-0.49	0.16	0.49	0.00	-2.11	-1.15	0.67	-0.32	-0.89	0.49
15	-0.67	0.00	-0.49	-0.49	-0.67	-0.49	0.32	0.00	-1.15	-0.32
16	-0.89	0.00	0.32	-0.49	-0.89	-0.32	0.49	-0.16	-0.67	0.16
17	-1.15	0.00	0.00	-0.67	-0.89	-0.49	-0.16	-0.67	-1.53	-0.16
18	-0.16	0.49	0.16	0.49	-0.89	-1.15	0.89	-0.16	-0.67	0.32
19	-0.16	0.16	0.89	-0.67	-0.49	-0.16	0.49	-0.16	-0.67	1.53
20	0.89	0.67	0.89	-0.16	-0.32	0.00	1.15	0.67	0.49	0.89
21	-0.49	0.67	1.15	0.16	-1.15	-0.67	0.67	0.00	-1.15	1.53
22	0.67	0.67	0.89	-0.32	0.00	-0.16	0.32	0.32	0.32	1.53
23	0.16	1.15	0.89	0.32	-0.89	-2.11	1.15	-0.49	-0.49	1.53
24	0.89	0.49	1.53	-0.16	0.00	0.00	0.67	0.32	0.00	1.53
25	-0.32	0.16	-0.49	0.00	-1.15	-0.67	0.49	-0.16	-0.49	-0.16
26	-1.15	0.00	-0.32	0.00	-1.15	-0.49	0.32	0.16	-1.15	0.32
27	0.16	1.15	-0.67	0.89	-1.15	-0.89	0.67	-0.16	-0.49	0.32
28	-0.32	0.67	-0.16	0.67	-1.53	-2.11	0.16	0.67	-0.49	0.49
29	0.49	0.89	-0.32	0.67	-0.49	-1.15	0.89	0.16	0.16	0.32
30	0.16	1.53	-0.16	0.89	-0.67	-0.89	0.49	0.16	-0.67	0.16
31	-0.89	0.67	-0.16	0.00	-0.67	-0.16	0.67	0.16	0.00	-0.49
32	-0.67	-0.16	-0.32	-0.67	-0.32	-0.32	0.00	0.16	-0.49	-0.89
33	0.32	0.49	-0.49	0.00	-0.32	0.00	0.32	0.89	0.00	-0.67
34	-0.32	0.89	-1.15	0.16	-0.89	-0.67	1.15	0.89	-0.32	-0.49
35	0.00	0.67	-0.32	-0.16	-0.89	-0.16	0.67	0.67	-0.32	-0.89
36	0.00	0.89	-0.67	0.00	-1.53	-1.53	0.32	0.89	-0.32	-0.89
37	0.67	0.16	1.53	0.32	0.16	-0.32	0.16	0.16	0.49	1.15
38	-0.49	0.16	1.53	-0.16	-0.89	-1.15	0.00	-0.32	-1.15	1.53
39	0.89	0.67	1.15	-0.16	0.49	0.49	0.49	0.89	0.89	1.53
40	0.16	0.49	1.15	0.00	-1.15	-1.53	1.53	-0.32	-0.49	1.15
41	1.53	0.32	1.53	0.16	0.16	0.00	0.00	0.49	1.15	1.15
42	-0.16	0.67	1.15	0.49	-2.11	-1.15	0.89	0.49	-1.15	0.89
43	1.15	0.00	0.00	0.32	2.11	1.53	-0.49	0.32	1.53	1.53
44	1.53	0.67	0.49	0.00	1.15	1.15	-0.49	0.49	1.53	1.15
45	1.15	0.32	0.89	0.00	0.67	0.67	-0.67	0.89	2.11	1.15
46	0.00	0.67	-1.53	0.32	-0.49	-0.16	-0.16	0.49	0.32	-0.67
47	0.16	0.67	-1.15	0.00	2.11	2.11	-0.49	0.89	1.15	-2.11
48	0.32	0.67	-0.89	0.89	0.89	0.67	0.32	0.67	1.53	-2.11
49	0.49	0.00	-0.49	0.00	0.67	0.67	-0.16	-0.16	1.15	0.00
50	0.89	1.15	-0.67	1.53	0.89	0.67	0.32	0.67	1.53	0.32

C.3. Combined Data (z-scores)

Stimulus	Active Passive	Clean Dirty	Feminine Masculine	Fresh Stale	Hard Soft	Heavy Light	Like Dislike	Modern Classical	Tense Relaxed	Warm Cool
1	0.58	0.24	1.53	-0.16	0.08	-0.08	-0.24	0.16	0.49	1.53
2	0.67	1.01	0.89	0.40	-0.08	-0.49	0.78	-0.24	0.67	1.53
3	-0.08	0.78	-0.16	0.58	-1.01	-1.01	0.49	0.24	-0.89	0.32
4	-0.58	0.49	-0.49	0.16	-0.89	-0.89	0.24	0.16	-0.67	-1.01
5	-0.49	-0.24	-0.89	-0.89	-0.58	-0.32	-0.32	-0.24	-0.67	-0.40
6	-0.24	-0.32	1.01	-0.67	-0.78	-0.40	0.00	-0.08	-0.32	1.86
7	0.32	0.16	1.15	-0.16	-0.89	-0.67	0.58	-0.49	-0.32	1.15
8	-0.67	-0.49	-1.15	-0.40	-0.89	-0.49	-0.24	-0.08	-0.67	-0.08
9	-1.86	-0.49	-0.78	-0.67	-0.67	-0.24	-0.40	0.08	-0.78	-0.67
10	0.32	0.78	1.15	0.24	-1.15	-1.53	0.40	0.24	-0.40	1.01
11	0.16	0.89	1.53	0.49	-1.15	-1.32	0.78	-0.24	-0.89	1.32
12	-0.32	1.01	-0.40	0.40	-1.01	-2.11	0.00	0.24	-0.49	-0.67
13	-0.40	0.78	0.58	0.58	-0.67	-1.32	0.58	0.32	-0.24	-0.16
14	-0.67	0.40	0.78	0.00	-2.11	-1.53	0.40	-0.32	-1.01	0.67
15	-0.49	0.08	-0.24	-0.24	-1.15	-0.67	0.24	-0.08	-1.32	-0.24
16	-1.15	-0.16	0.78	-0.49	-1.15	-0.58	0.16	-0.08	-0.40	0.16
17	-1.15	-0.24	0.32	-0.49	-1.01	-0.67	-0.32	-0.67	-1.32	0.16
18	-0.49	0.49	0.32	0.40	-1.01	-1.32	0.40	0.08	-0.89	0.16
19	-0.16	-0.08	1.32	-0.67	-0.89	-0.58	0.16	-0.16	-0.67	1.86
20	0.58	0.49	1.32	0.00	-0.16	-0.16	0.58	0.67	0.78	1.32
21	-0.49	0.67	1.53	-0.16	-1.32	-0.89	0.58	-0.40	-0.78	1.86
22	0.89	0.40	1.15	-0.08	0.00	-0.08	0.16	0.40	0.78	1.86
23	-0.16	0.89	1.32	0.32	-1.32	-1.86	0.58	-0.16	-0.40	1.53
24	0.67	0.49	1.86	-0.08	0.08	0.24	0.16	0.40	0.49	1.86
25	0.08	0.24	-0.49	0.40	-0.89	-0.89	0.40	-0.08	-0.67	0.00
26	-0.67	-0.08	-0.32	-0.16	-1.32	-0.89	0.24	0.16	-1.01	0.40
27	0.16	0.89	-0.67	0.49	-1.15	-0.89	0.49	0.08	-0.40	-0.08
28	-0.24	1.01	-0.08	0.67	-1.53	-1.53	0.32	0.40	-0.58	0.49
29	0.67	1.01	-0.24	0.58	0.08	-1.15	0.49	0.24	0.24	0.16
30	0.16	1.01	-0.08	0.78	-0.67	-0.89	0.16	0.40	-0.32	0.16
31	-0.58	0.49	-0.49	-0.16	-0.49	-0.16	0.32	0.24	-0.08	-0.67
32	-0.78	-0.16	-0.58	-0.58	-0.49	-0.67	-0.24	0.32	-0.40	-1.15
33	0.16	0.49	-0.58	0.08	-0.16	-0.16	0.24	0.89	-0.08	-1.15
34	-0.24	0.67	-0.89	0.32	-0.78	-1.01	1.01	0.67	-0.49	-0.89
35	-0.16	0.89	-0.67	0.08	-0.78	-0.24	0.49	0.89	-0.24	-1.15
36	-0.16	1.01	-0.58	0.08	-1.15	-1.32	0.32	1.01	-0.24	-1.01
37	1.01	0.49	1.53	0.16	-0.08	-0.16	0.08	0.67	0.78	1.15
38	-0.32	0.32	1.53	-0.32	-1.01	-1.32	0.16	0.00	-1.01	1.15
39	0.78	0.89	1.32	0.24	0.58	0.32	0.24	1.01	1.01	1.15
40	-0.08	0.89	1.53	0.24	-1.01	-1.53	0.78	0.00	-0.49	1.53
41	1.01	0.58	1.53	0.16	0.67	0.08	-0.32	0.78	1.32	1.15
42	-0.08	0.67	1.53	0.32	-1.53	-1.32	0.89	0.49	-0.49	1.15
43	1.32	0.32	0.16	0.32	2.11	1.32	-0.67	0.24	1.53	1.86
44	1.86	0.49	0.40	0.08	1.32	1.32	-0.78	0.32	1.86	1.32
45	1.32	0.67	1.32	0.08	0.78	0.78	-0.40	0.89	1.86	1.01
46	0.24	1.01	-0.67	0.58	-0.32	-0.32	0.00	0.40	0.49	-1.01
47	0.24	0.40	-1.01	0.08	1.86	1.15	-0.58	0.67	1.15	-2.11
48	0.67	0.49	-1.32	0.67	1.15	1.01	-0.24	0.58	1.32	-2.11
49	0.58	0.49	-0.78	0.32	0.58	0.58	-0.40	-0.08	1.15	-0.08
50	1.15	1.15	-0.67	1.01	1.01	0.08	-0.16	0.49	0.89	0.16