CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Theoretical Consideration

2.1.1 The Sensation of Color

Color sensation involves three basic factors the source of light, objects under illumination, and the eyes and neural responses of observers. The visual process begins when radiant energy from the source strikes the object and some of this energy is reflected and passes through the lens to strike the retina in the eye. The retina is made up of a complex network of cells and neurons. The retina consists of a large number of cells which are sensitive to light, these receptors cells are of two kinds, rods and cones. Rods are sensitive to brightness of light only at low illuminate. Cones are cells of three different types which respond to red, blue and green regions of light, respectively, and it is through these that all colors are seen. When the three types of cones are all stimulated equally, the eye and the brain see achromatic, but if one type of cone is stimulated more than the other two, the image appears to be tinted with the corresponding primary hue.

The most central part of the retina is called the fovea and it has the largest concentration of cells. The fovea vision is used for distinguishing very fine detail, such as reading and seeing objects at distance. Outside the fovea, the number of cones is greatly reduced and they are situated quite apart from one another. The rods are completely absent from the fovea and fall out to the extreme periphery. The signals leave the retina via the optic nerve and eventually arrive at the back of the brain. The brain signals are interpreted through mental impressions that result in sensation (*6,7*).

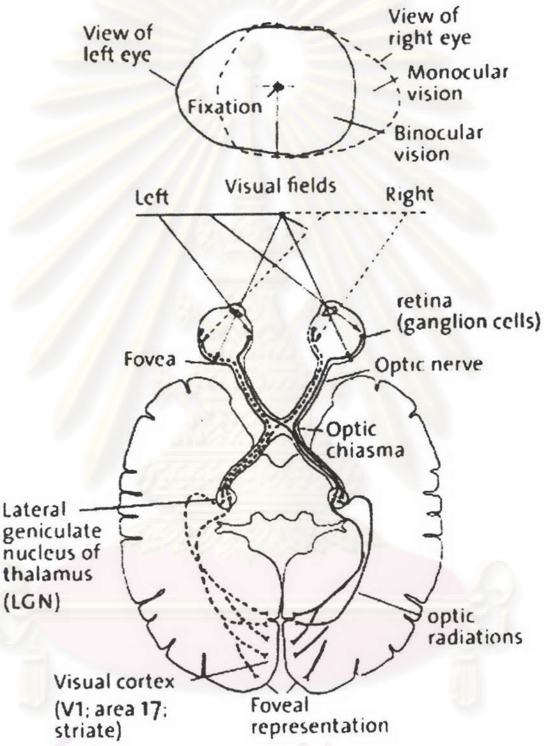

Figure 2-1 Diagrammatic process of the human color sensation.

2.1.2 PCCS (Practical Color Co-ordinate System) color system

PCCS is a color system made in 1964 by Japan Color Research Institute. It is developed primarily to provide a systematic method for resolving color harmony problems (*8*). PCCS is constructed using the three attributes of attributes of color as hue, lightness and saturation. PCCS is characterized by its capacity to be used as a hue/tone.

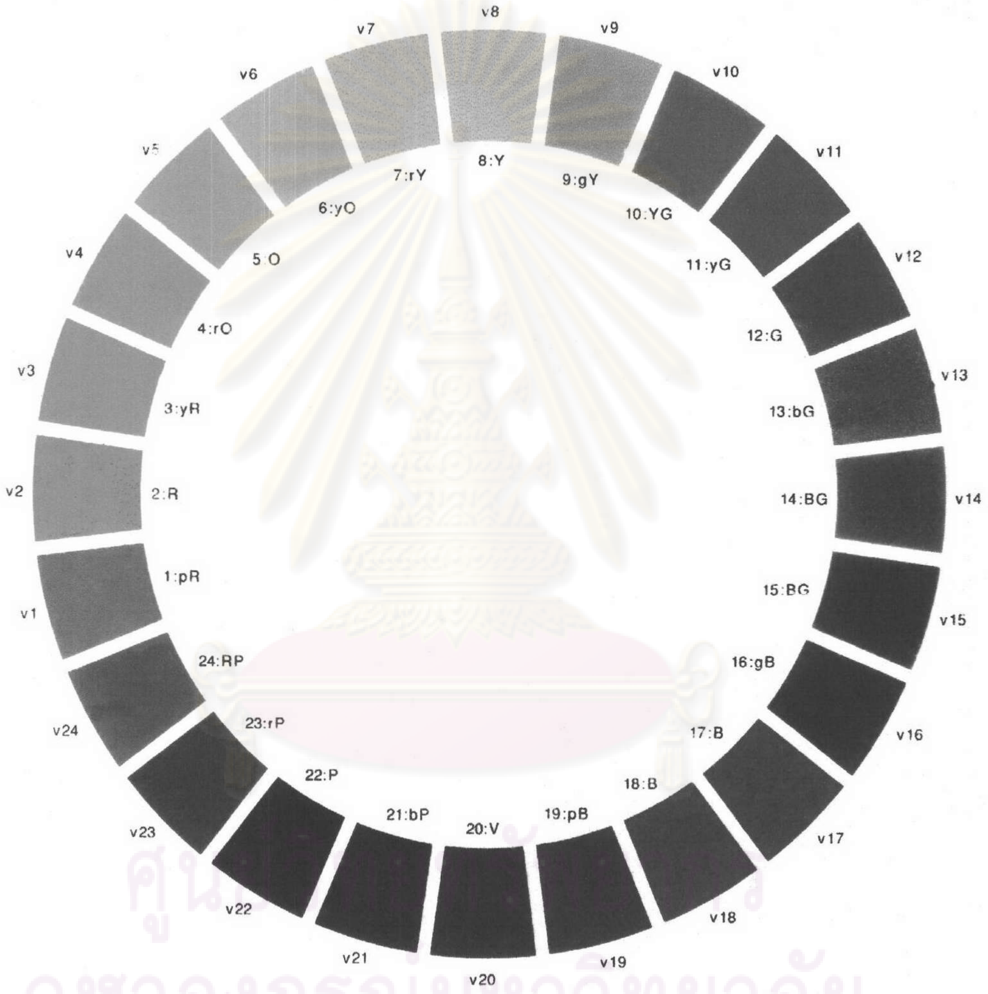

Figure 2-2 24 color circle of PCCS color system.

Table2-1 PCCS indices relevant to 24 color hue circle

PCCS indices	**Munsell** hue	**Color**	**PCCS** indices	**Munsell** hue	**Color**
v1	10RP	Purplish red(pR)	v13	9G	Bluish green(bG)
v2	4R	Red(R)	v14	5BG	Blue green(BG)
v3	7R	Yellowish red(yR)	v15	10BG	Blue green(BG)
v4	10R	Reddish orange(rO)	v16	5B	Greenish Blue(gB)
v5	4YR	Orange(O)	v17	10B	Blue(B)
v6	8YR	Yellowish orange(yO)	v18	3PB	Blue(B)
V7	2Y	Reddish yellow(rY)	v19	6PB	Purplish blue(pB)
V8	5Y	Yellow(Y)	v20	9PB	Violet(V)
V9	8Y	Greenish yellow(gY)	v21	3P	Bluish purple(bP)
V10	3GY	Yellow green(YG)	v22	7P	Purple(P)
V11	8GY	Yellowish green(yG)	v23	1RP	Reddish purple(rP)
V12	3G	Green(G)	v24	6RP	Red purple(RP)

PCCS tone are the concept of lightness and saturation, and are classified using adjectives ordinarily used describe colors such as pale/deep, bright/dark, and vivid/grayish. Tone classification is as indicated in Figure2-3.

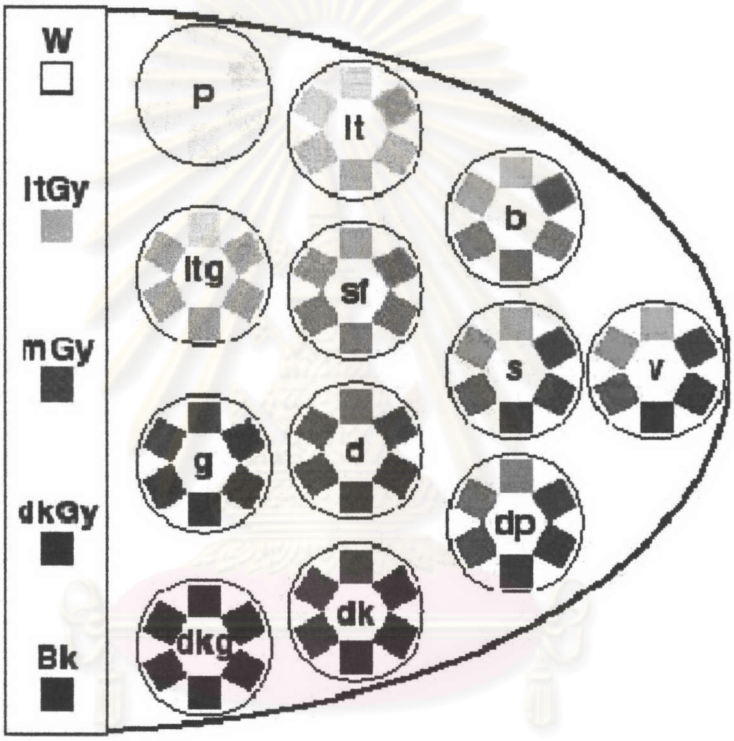

Figure 2-3 12 tone of PCCS color system.

Table2-2 PCCS symbols relevant to 12 tone of PCCS

Symbol	Tone	Symbol	Tone
v	vivid	sf	soft
dp	deep	d	dull
dk	dark	ltg	light grayish
p	pale	g	grayish
lt	light	dkg	dark grayish
b	bright	s	strong

The indication of colors can be carried out with hue and tone, these are indicated as symbol v2 (vivid red), d8(dull yellow), dp12(deep green), lt18(light blue), etc., combining the hue number from 1 to 24 with the tone symbol.

2.1.3 The CIE Color System

In 1931, the CIE (Commission International de l'Eclairage or International Commission on Illumination) developed the standards for description aspects of color specification called colorimetric. The standards of colorimetric to be concerned with the relative spectral distribution of radiant flux emitted by the source and incident on the object, the spectral reflectance factors of the object and the color matching function of the observer viewing the object (*9*). The CIE color system is a system to specify a color appearance quantitatively. It is not directly based on psychological scaling of colors like the Munsell color system.

2.1.3.1CIE Illuminants

The CIE has established a number of spectral power distributions as CIE illuminants for colorimetric. These distributions based on physical standards, such as blackbody radiators or Planckian radiator, or are based on statistical representations of measured light. Followings are the standard light sources:

- CIE illuminant A represents a Planckian radiator with a color temperature of 2856 K, as shown in Figure 2-4 (*10*). It is used for colorimetric calculations when incandescent illumination is of interest.

- CIE illuminant C is the spectral power distribution of illuminant A as modified by particular liquid filters defined by the CIE. It represents a daylight simulator with a correlated color temperature of 6774 K, as shown in Figure 2-5 (*11*).

- CIE illuminants D65 and D50 are part of the CIE D series illuminants that have been statistically defined based upon a large number of measurements of natural daylight. Illuminant D65 represents an average daylight with a correlated color temperature of 6500 K, and D50 represents an average daylight with a correlated color temperature of 5003 K, as shown in Figure 2-5. D65 is commonly used in colorimetric applications, such as paints, plastics, and textiles. D50 is often used in graphic arts and computer industries. CIE D illuminants with other correlated color temperatures can be easily obtained.

- CIE F series illuminants represent typical spectral power distributions for various types of fluorescent sources including standard cool white, warm white, "full spectrum," and tri-band, 12 in all. CIE illuminant F2 represents cool white fluorescent with a correlated color temperature of 4230 K. Illuminant F8 represents a fluorescent D50 simulator with a correlated color temperature of 5000 K, and illuminant F11 represents a tri-band fluorescent sources with a correlated color temperature of 4000 K, as shown in Figure 2-6 and in Figure 2-7 (*12*). Tri-band fluorescent sources are popular because of their efficiency, efficacy, and pleasing color-rendering properties.

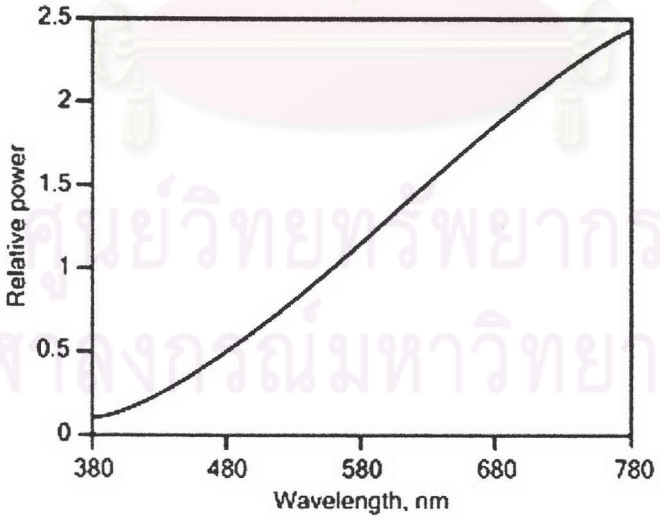

Figure 2-4 Spectral power distribution of CIE illuminant A.

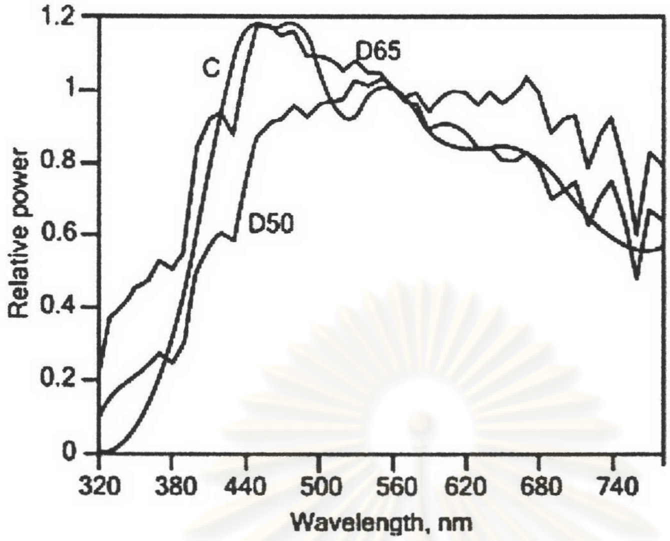

Figure 2-5 Spectral power distribution of CIE illuminants D50, D65 and C.

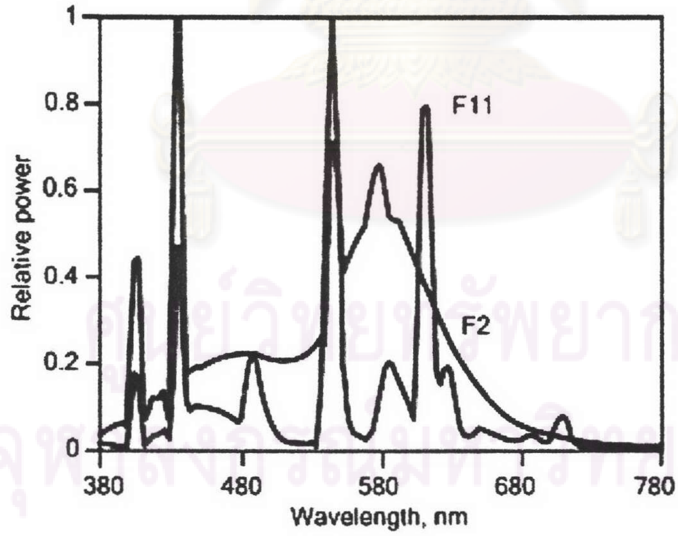

Figure 2-6 Spectral power distribution of CIE illuminant F2 and F11.

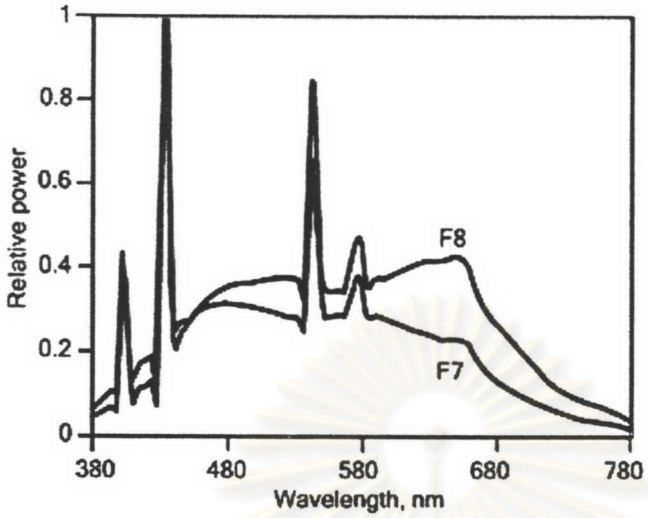

Figure 2-7 Spectral power distribution of CIE illuminants F7 and F8.

2.1.3.2 Standard of Reflectance Factor

The CIE recommends that reflectance measurement should be made relative to the perfect reflecting diffuser. There is no object surface that has the properties of the perfect reflecting diffuser, but working standards of known spectral reflectance factors is normally used. The working standards for reflectance factor measurement are also called white standard. The effect of an object on light can be described by its spectral transmittance or reflectance curve. The spectral reflectance curve describes the object just as the spectral power distribution curve describes a source, as shown in Figure 2-8 (*13*).

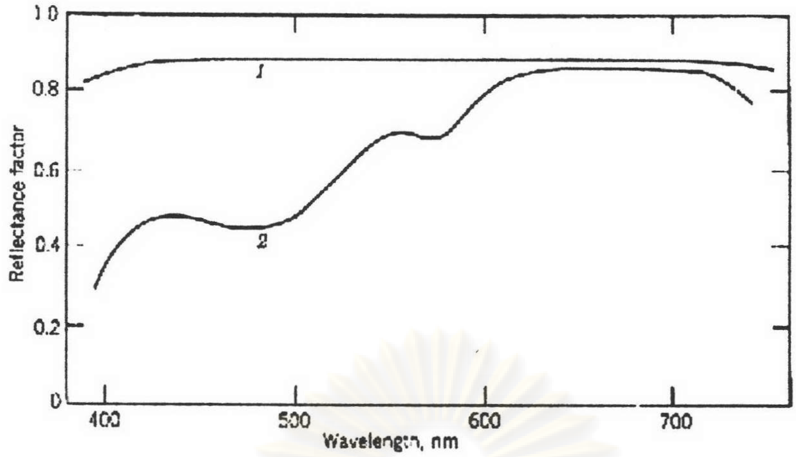

Figure 2-8 Spectral reflectance factor of hypothetical white standard (1), compared with that of a specimen (2)

2.1.3.3 CIE Standard Observers

The colorimetric specifications of color based on the spectral tristimulus values of $\bar{x}_{\lambda}$, $\bar{y}_{\lambda}$ *and* $\bar{z}_{\lambda}$ which are also called the color matching functions. There are two sets of color-matching functions established by the CIE. The CIE 1931 standard colorimetric observer was determined from experiments by Guild and Wright, using a visual field that subtended 2 degrees that the matching stimuli were imaged onto the retina completely within the fovea. In 1964, the CIE recommended a set of color-matching functions are notated as $\bar{x}_{10\lambda}$, $\bar{y}_{10\lambda}$ and $\bar{z}_{10\lambda}$ for the experiments using a 10° visual field that excluded the central fovea. The results for large fields were deemed significantly different from the 2° standard, enough to warrant the establishment of the CIE 1964 supplementary standard colorimetric observer, sometimes called the 10° observer, as shown in Figure 2-9 (*14*). Nowadays standards exist for two field sizes, 2° and 10°.

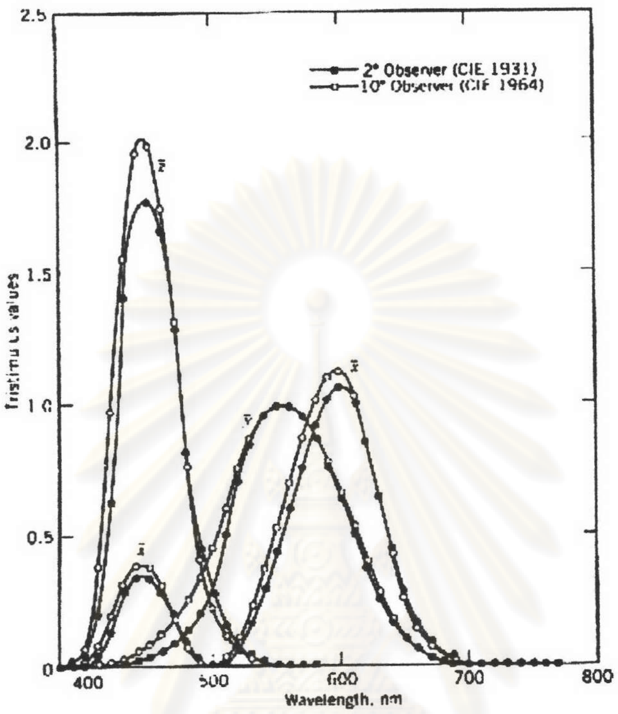

Figure 2-9 Comparison of color matching functions of the 1931 CIE standard observers and the 1964 CIE supplementary observers

2.1.3.4 CIE XYZ Tristimulus Values

The CIE tristimulus values X, Y, and Z of color are obtained by multiplying together the relative power of a CIE standard illuminant, the reflectance factor or the transmittance of the object and the standard observer function, as shown in Figure 2-10 (*15*), by the equations as below:

$$X = k\sum S_{\lambda} R_{\lambda} \bar{x}_{\lambda} \Delta\lambda$$

$$Y = k\sum S_\lambda R_\lambda y_\lambda \Delta\lambda$$

$$Z = k\sum S_\lambda R_\lambda z_\lambda \Delta\lambda$$

$$k = 100 / \sum S_\lambda y_\lambda \Delta\lambda \qquad (2.1)$$

Where, S_λ is the spectral power distribution of light illuminant or source

R_λ is the spectral reflectance factor of object

$\bar{x}_\lambda$, $\bar{y}_\lambda$ and $\bar{z}_\lambda$ are the color matching functions

k is a normalizing constant

$\Delta\lambda$ is the measurement wavelength interval

$\sum_\lambda$ is summation across wavelength

By convention, the value Y = 100, assigned to perfect white object reflecting 100% at all wavelengths, or to the perfect colorless sample transmitting 100% at all wavelengths, is the maximum value that Y can have for non fluorescent sample.

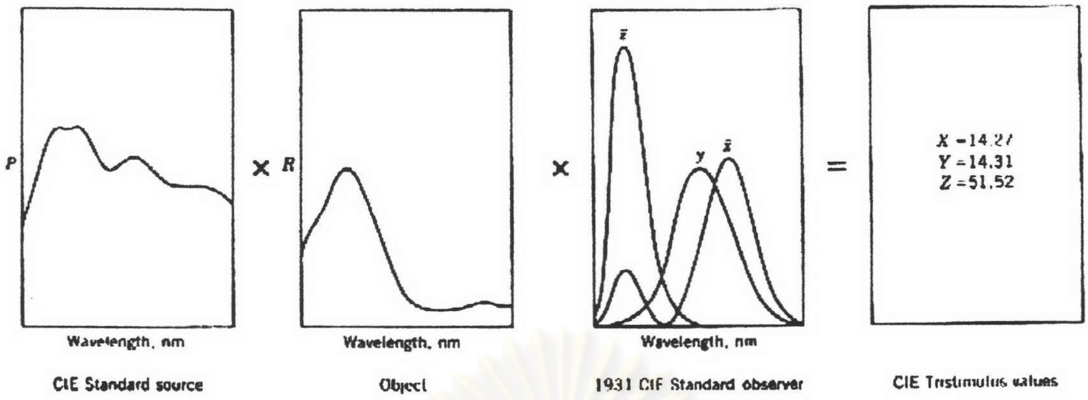

Figure 2-10 CIE tristimulus values X, Y and Z of color

2.1.4 The CIE L* a* b* Color Space, The CIE L* C* h Color Space

The limitation of the x, y, Y CIE system is its non-uniformity. Many attempts were to find out a more uniform system. The CIE L* a* b* 1976 color space, thus is established. This space extends tristimulus colorimetry to three-dimensional space with dimensions that approximately correlate with the perceived lightness, chroma and hue of a stimulus.

The variables used in the CIE L* a* b* system are L* as the correlate of lightness, a* as the correlate of redness or greenness, and b* as the correlate of yellowness or blueness, as shown in Figure 2-10 (*16*), are defined as follow.

$$L^* = 116(Y/Y_n)^{1/3} - 16$$

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

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

$$C^* = (a^{*2} + b^{*2})^{1/2}$$

$$h = \tan^{-1}(b^*/a^*) \qquad (2.2)$$

where, X/X_n, Y/Y_n, Z/Z_n, > 0.008856

X, Y and Z	are	the tristimulus values of the stimulus
X_n, Y_n and Z_0	are	the tristimulus values of the reference white
C*	is	chroma
h	is	hue angle

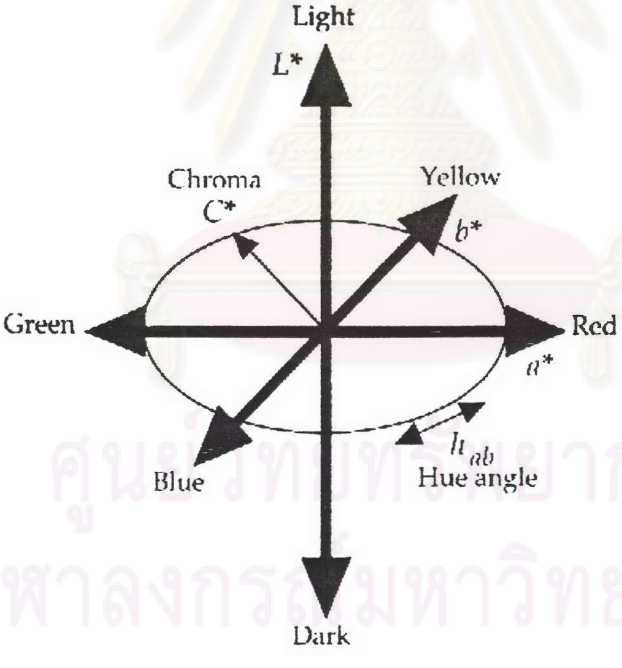

Figure 2-11 The cylindrical representation of the CIE L* a* b*(CIE L* C* h)

2.1.5 Color-Difference on CIE L* a* b* , CIE L* C* h Color Space

The differences in color between a standard and batch are defined by their difference in lightness (ΔL^*), redness or greenness (Δa^*) and yellowness or blueness (Δb^*) (*17*).

$$\begin{aligned} \Delta L^* &= L^*_{batch} - L^*_{standard} \\ \Delta a^* &= a^*_{batch} - a^*_{standard} \\ \Delta b^* &= b^*_{batch} - b^*_{standard} \end{aligned} \qquad (2.3)$$

The total color difference between the two samples is the slant (Euclidean) distance in CIELAB

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\,]^{1/2} \qquad (2.4)$$

The differences in color are also defined by differences in lightness (ΔL^*), chroma (ΔC^*_{ab}), and hue (ΔH^*_{ab})

$$\begin{aligned} \Delta L^* &= L^*_{batch} - L^*_{standard} \\ \Delta C^*_{ab} &= C^*_{ab,batch} - C^*_{ab,standard} \\ &= (a^{*2}_{batch} + b^{*2}_{batch})^{1/2} - (a^{*2}_{standard} - b^{*2}_{standard})^{1/2} \\ \Delta H^*_{ab} &= [(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2]^{1/2} \end{aligned} \qquad (2.5)$$

Note that hue difference is calculated as what is "left over" once the lightness and chroma differences are subtracted from the total color difference. ΔH^*_{ab} is assigned a positive value when Δh_{ab} is positive and assigned a negative value when Δh_{ab} is negative.It is also possible to calculate ΔH^*_{ab} directly(Stokes 1992, Seve 1996).

$$\Delta H^*_{ab} = \frac{a^*_{batch} b^*_{std} - a^*_{std} b^*_{batch}}{[0.5(C^*_{ab,batch} C^*_{ab,std} + a^*_{batch} a^*_{std} + b^*_{batch} b^*_{std})]^{1/2}} \qquad (2.6)$$

The total color difference is also calculated in terms of lightness, chroma, and hue differences.

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta C^*_{ab})^2 + (\Delta H^*_{ab})^2]^{1/2} \qquad (2.7)$$

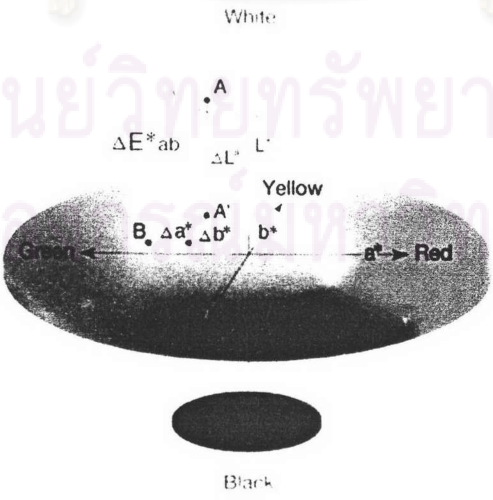

Figure 2-12 Color differences on CIEL*a*b* color space.

2.1.6 Regression analysis

2.1.6.1 Simple Linear Regression

Regression analysis (*18*) is a statistical method that uses a relationship between two or more variables so that one variable can be predicted or explained by using information on the others. The relation between the variables using a mathematical formula is called the regression model. The simple linear regression model is the relationship is specified to have only one factor variable and the relationship is decried by a straight line, is of the from;

$$Y = \beta_0 + \beta_1 X + \varepsilon \tag{2.8}$$

where, Y is the dependent variable

X is the independent variable

β_0 is the constant

β_1 is the regression coefficient

ε is The error or residual

2.1.6.2 Multiple Linear Regression

The multiple linear regression (*19*) is a statistical technique that can be used to analyze the relationship between a single dependent variable and several independent variables. The objective of multiple linear regression is to use the independent variables predict the single dependent value. Each predicted variable is weighted, the weights denoting their relative contribution to the overall prediction. In calculating the weights, the regression analysis procedure ensures maximal prediction from the set of independent variables in the variate. These weights also facilitate interpretation as to the influence of each variable in making the prediction, although correlation among the independent variables complicates the interpretative process.The multi linear regression equation as follow;

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p + \varepsilon \tag{2.9}$$

where, p is the number of independent variable

Y is the dependent variable

X is the independent variable

β_0 is the constant

β_i is the regression coefficient

ε is the error or residual

2.1.6.3 Polynomial Regression

Polynomail regression *(20)* is power transformations of an independent variable that add a nonlinear component for each additional power of the independent variable. The power of $1(X^1)$ represents the linear component and the power of 2, the variable squared (X^2), represents the quadratic component. In graphical terms, X^2 represents the first inflection point. A cubic component, represented by the variable cubed (X^3), adds a second infection point. With these variables, and even higher powers, more complex relationships can be accommodated than are possible with only transformations. The polynomail regression equation as follow;

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \ldots . + \beta_p X^p + \varepsilon \qquad (2.10)$$

where, p is the number of independent variable
Y is the dependent variable
X is the independent variable
β_i is the constant
ε is the error or residual

2.1.6.4 Correlation Coefficient

The correlation coefficient, r *(21)*, is a measure of the strength of the linear relationship between two variables x and y, which just as does the slope β_1. However, unlike the slope, the correlation coefficient is scaleless. It is computed as follow:

$$r = \frac{\sum_{i=1}^{n} y_i (x_i - \bar{x})}{\left[\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2 \right]^{1/2}} \qquad (2.11)$$

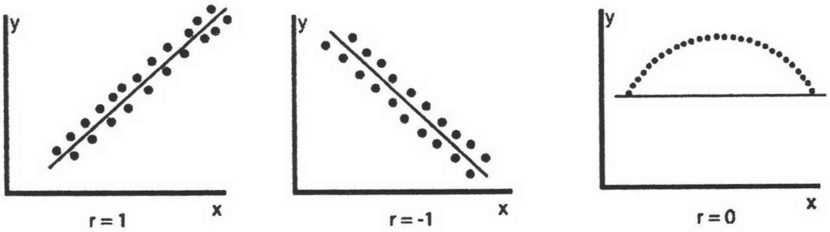

Figure 2-13 Diagram of the Pearson Correlation Coefficient.

The correlation coefficient has the following properties:

- Its value is between +1 and –1
- Value of +1 and –1 signify an exact positive and negative relationship, respectively, between the variables. That is the values of x and y exactly describes a straight line with a positive or negative slope depending on the sign of r.
- A correlation of zero indicates no linear relationship exist between the two variables. This condition does not, however, imply that there is no relationship since correlation does not measure the strength of curvilinear relationship.
- The correlation coefficient is symmetric with respect to x and y. It is thus a measure of the strength of a linear relationship regardless of whether x or y is the independent variable.

2.1.7 Factor Analysis

Factor analysis (*22*) includes variations such as component analysis and common factor analysis. It is a statistical approach that can be used to analyze interrelationships among a large number of variables and to explain these variables in terms of their common underlying dimensions (factors). The objective is to find a way of condensing the information contained in a number of original variables into a smaller set of variates (factors) with a minimum loss of information.

2.2 Literature Reviews

Sato, T et al. (*23*) performed a visual experiment to analyze quantitatively the feeling of color in terms of colorimetric values. The visual experiment confirmed that the feeling were mainly affected by Munsell chroma and Munsell value. Finally, the empirical formulae were established to represent the feeling as follow.

$$CI = [\{k_v(V - V_0)\}^2 + \{k_c(C - C_0)\}^2]^{1/2} \tag{2.12}$$

Where,	CI	is color image value
	V	is Munsell value
	C	is Munsell chroma
	V_0	is Munsell value when the color image percent is minimum
	C_0	is Munsell chroma when the color image percent is minimum
	kv	is the contribution of Munsell value for the color image

kc	is the contribution of Munsell chroma for the color image
ks	is the scaling of the color image

Ngampatipatpong, D.(*24*) attempts to link the gap between physical and perceptual colors parameter by deriving the quantitative visual scale of the word which express human color sensation which using the twelve opponent word pair and relevant to colorimetric values. The derivation of the visual assessment and colorimetric values establishes the color sensation equation. It can analyze the colorimetric characteristric of the visual scale in CIE L*,C*,h color space and then obtain the color sensation map. This diagram determines the relationship between the twelve opponent word pairs into three groups, which are dominated by chroma, lightness and hue, respectively.

Xin, J.H. et al. (*25*) investigated the twelve color emotion pairs and quantifying them with standard color specifications. The mathematical models were derived using the obtained visual assessment result from Hong kong Chinese. Chroma of a color was found to be the dominant parameter affecting the 'Warm-Cool', 'Vivid-Sombre', 'Gaudy-Plain', 'Striking-Subdued' and 'Dynamic-Passive' color emotion. Lightness of color was found to be the dominant parameter affecting the 'Deep-Pale', 'Heavy-Light', 'Transparent-Turbid', 'Soft-Hard' and 'Strong-Weak' color emotion. For the 'Light-Dark' and 'Distinct-Vague' color emotions were influenced by both the chroma and lightness of colors. The obtained visual assessment results from the Japanese, Thai and Hong Kong Chinese people were compared and very good correlation in the 'Transparent-Turbid' was found among these countries.

Bangchokdee, Y et al.(*26*) studied the numerical expression of the color sensation corresponding to twelve opponent word pairs through two-point and seven-point assessments carried out by Thai observers. The twelve color sensation equations were derived from the relationship between the colorimetric values and visual assessments. The obtained visual results between methods and countries (Thailand-Japan) were compared by determining correlation coefficients and paired t-test in terms of hue and tone. They found that the relationships of twelve word pairs between methods were high, while hue difference had influence on "Warm-Cool" and "Gaudy-Plain" of achromatic color and tone comparisons were different at all twelve tones. There was a significant relationship between countries, with the exception of the "Deep-Pale". Hue differences were found in "Warm-Cool", "Deep-Pale" and "Striking-Subdued". Tone differences tended to occur in all twelve tones.

Ou, L.C. et al.(*27*) studied the influence of a holistic color interval on color harmony. They found that the relationship between holistic color interval and degree of color harmony were cubic relationship. The graph obtained was devided into 4 harmonious/disharmonious regions, that corresponds to the first ambiguity, similarity, second ambiguity and contrast color interval in Moon and Spencer's model of color harmony. The result of this studied supports the general assumption of the influence of "contrast" color combinations and "equal-hue" color combination on sensation of color harmony. Further more, he made assumption that influence of preferred colors significantly affects on the sensation of harmony.

Burchett, K.E.(*28*) studied the attributes of color harmony. He categorized into 8 attribute, including area, association, attitude, configuration, interaction, order, similarity, tone. Followings are the meanings of each attribute:

area : angular size, proportion and scale.

association : color retention, local color and taste.

attitude : climate, mood and temperature.

configuration : background, form and space.

interaction : adaptation dynamics, illusion and simultaneous contrast.

order : color space, interval and schemes.

similarity : analogous, attraction and color connection.

tone : hue, saturation and value.

Luo, M.R. et al.(*29*) studied the color emotion of two color combination. The results indicate that the color emotion “feminine-masculine” has significant difference between genders, while “hard-soft”, “cool-warm”, “modern-classical” and “tense-relaxed have slight difference between two races. Based on the eleven scales, a three-dimensional color emotion space was developed with three orthogonal dimension “color activity”, “color weight” and “color heat”. An additivity relationship between single colors and combination generated by them was found, indicating that the average of emotional effect for two colors can be predicted for their combination.

Kobayashi, S.(*30*) investigated color harmony in the field of color psychology. He created three dimensional color emotion space, called “color image scale”. The color emotion space represents, 3 dimension scales as followings: “Warm-Cool”, “Soft-Hard” and “Clear-Grayish”. These scales are mapped with the position of color emotion word to describe the characteristic of each color combination pairs.