Influence of a Holistic Color Interval on Color Harmony

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Abstract: This study investigates how a holistic color interval, i.e., the nondirectional color difference between a pair of colors in a CIELAB uniform color space, influences perceived color harmony. A set of 1035 test color pairs displayed on a CRT was evaluated for the degree of harmony. These test color pairs consist of pairs combined from among the selected 46 test colors evenly distributed in color space. The subjects were asked to select their three preferred colors from these 46 test colors and then to evaluate the degree of harmony of the test color combinations. The color intervals (ΔE^*_{ab}) of each test color combination were calculated and treated as values of an independent variable. In addition, the evaluated degrees of color harmony were considered as values of a dependent variable, in which statistical analysis confirmed the relationship: the degree of harmony is a cubic function of the color interval. Moreover, the plot of this relationship allowed us to identify four color intervals: roughly corresponding to the regions of first ambiguity, similarity, second ambiguity, *and* contrast *in Moon and Spencer's model. However, our results indicated that Moon and Spencer's principles for classifying harmonious/disharmonious regions in terms of the color interval for three color attributes—lightness, chroma and hue—may be inappropriate in predicting perceived color harmony. As for the color intervals between a pair of colors considered as a function of the three attributes, the interval for lightness may have a predominant effect on color harmony, expressed in terms of a cubic relationship. Results of the study further demonstrated that the subject's choice of colors significantly influences perceived color harmony.* © 2001 John Wiley & Sons, Inc. Col Res Appl, 26, 29–39, 2001

Key words: color harmony; holistic color interval; uniform color space; preferable colors; color combination

INTRODUCTION

Artists may intuitively select harmonic color combinations for their works. In the field of design, however, designers must objectively decide the most pleasing color combinations for the product's users. Therefore, colorists have always searched for the so-called "laws of color harmony," which describe the invariant relations between the psychological experience of color harmony and the physical attributes of color stimuli.[1] For example, Munsell[2] (1905) and Ostward[3] (1931) claimed that the geometric order of color space in a given combination would lead to color harmony.

An even more recent and fascinating idea of color harmony was the ability to express the relationship between the degree of color harmony and the attributes of color stimuli in a neat mathematical formula with as few variables as possible.[1] In 1944, Moon and Spencer proposed a mathematical model to define the relation between harmonious color combinations with color intervals and area factors.[4-6] Although this model has attracted considerable attention, it has been criticized as having a weak theoretical basis and poor predictive value.[7,8]

In fact, color harmony is a very complex phenomenon. It may be influenced by many factors. For instance, based on the content analysis found in several color-related text books, Burchett categorized factors influencing color harmony as follows: association, order (including system and interval), configuration, area, interaction, and similarity.[9] Thus, some researchers doubt the existence of a simple law of color harmony with limited variation in conditioning factors.

Moreover, Burchett has concluded that the association factor is most important in influencing color harmony.[9] Many researchers have agreed not only that color is a personal experience, but also that selecting harmonious color combinations is a creative process in which subjective judgment must be considered.[10,11] Therefore, the existence of the so called "objective laws of color harmony" has been denied. Sivik quotes Pope[1,7]: "In the discussion of color

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harmony. . .. . . There are no rules; there are only possibilities."

In spite of the dispute concerning the laws of color harmony discussed above, designers do urgently need some guidelines with regard to the creation of pleasing color combinations for their clients. There does seem to be some general agreement on the most pleasing color combinations,[12] though there are as yet no established theories. It is, therefore, necessary to try to determine statistically the predominant trend or tendency in viewers' perception of color harmony.

Although Moon and Spencer's model of color harmony has been seriously criticized and shown to be impracticable, as mentioned above, its concept of pleasing/displeasing (ambiguous) color intervals between a pair of colors in a color scale is interesting, and may be related to a common, residual evolutionary trait of people. In ancient times, people needed to receive clear and certain messages to survive. Uncertainty and ambiguity of received messages might lead to the feeling of instability and discomfort. Likewise, a color combination with an ambiguous interval (distinction) may lead to an unpleasant feeling. Here, assuming such an effect of color ambiguity as our hypothesis, we further investigate the possibility of finding some general trends in the perception of color harmony.

However, we doubt the definition of the color interval in Moon and Spencer's model of color harmony. In their model, three color intervals must be determined, allowing for the color attributes of hue, value, and chroma, where color interval is defined as the difference between each pair of colors. In practice, individuals do not judge color combinations by combining the variations in hue, value, and chroma between a pair of colors. In other words, the judgment that "this color combination is harmonious" probably does not owe to the fact that we have perceived the variations in hue, value, and chroma of the component colors in that combination first, then summed up the three corresponded degrees of harmony accordingly, as shown in Fig. 1(a). More likely, we have sensed that the holistic difference between the component colors in that combination is a direct function of the degree of harmony, as depicted in Fig. 1(b).

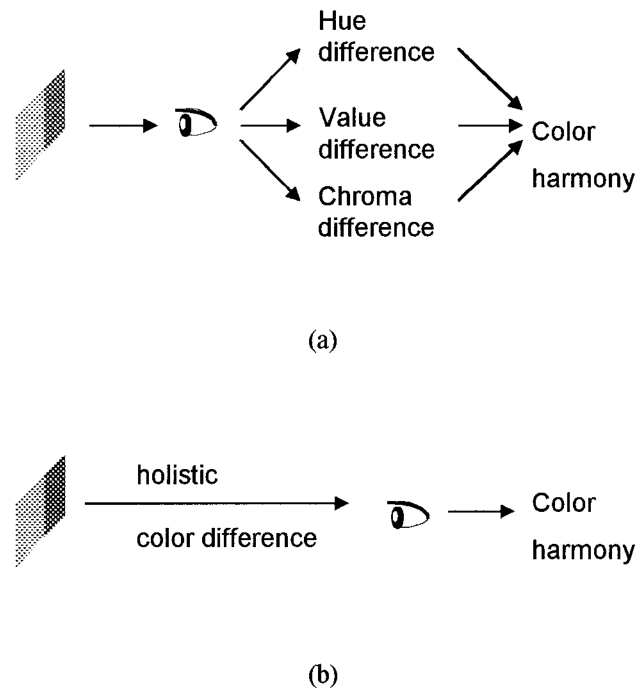

FIG. 1. The proposed models of color harmony perception.

In light of the above discussion, the following questions arise: What is the *holistic difference* between colors in relation to color harmony? How does variation in this holistic difference influence perception of color harmony? Can the holistic difference be classified into different pleasing/displeasing color intervals according to its value, as proposed by Moon and Spencer? To answer these questions, this study evaluates the perceived harmony of color combinations with various color intervals.

The *holistic difference* (interval) of a pair of colors in this study is defined as the Euclidean distance between these two colors in the CIELAB color space, i.e., ΔE^*_{ab}. CIELAB color space is a recent conceptual model intended to approximate perceptually uniform color space,[13] although it is derived from physical measurements. In a perceptually uniform 3-dimensional color scale, the distance between a pair of colors is proportional to the degree of perceived difference between the two colors. This space aids the selection of harmonious color combinations.[14] The CIELAB 1976 color space was recommended by the CIE Colorimetry Committee,[14] and adopted by many organizations for extensive use.[13] It has also been widely adopted in the study of color. For example, Chen has designated the interval between a pair of colors in the CIELAB 1976 color space as the perceived color contrast, in order to investigate its relation to legibility.[15]

Another difficulty in studying color harmony comes from the ambiguous concept of "harmony" *per se*.[1] "Pleasing" is perhaps less ambiguous term than "harmonious," as the question is always one of the viewer's own perception, sense, or feeling. Thus, in this study, we define *harmonious* as "that which pleases the viewer" or "that which is perceived as harmonious."

METHODS

Subjects in this study were asked to evaluate the degrees of harmony in a series of color combinations displayed on a CRT. The relationships among degrees of harmony and color intervals in a range of color combinations was then deduced from the data collected.

Test Colors and Color Combinations

A ViewSonic 15GA monitor was used to display various test color combinations with a specific pattern. Each color combination was consecutively presented screen by screen.

Test Pattern. The test pattern of a pair of colors, as shown in Fig. 2(a), was designed to cover, to the maximum degree,

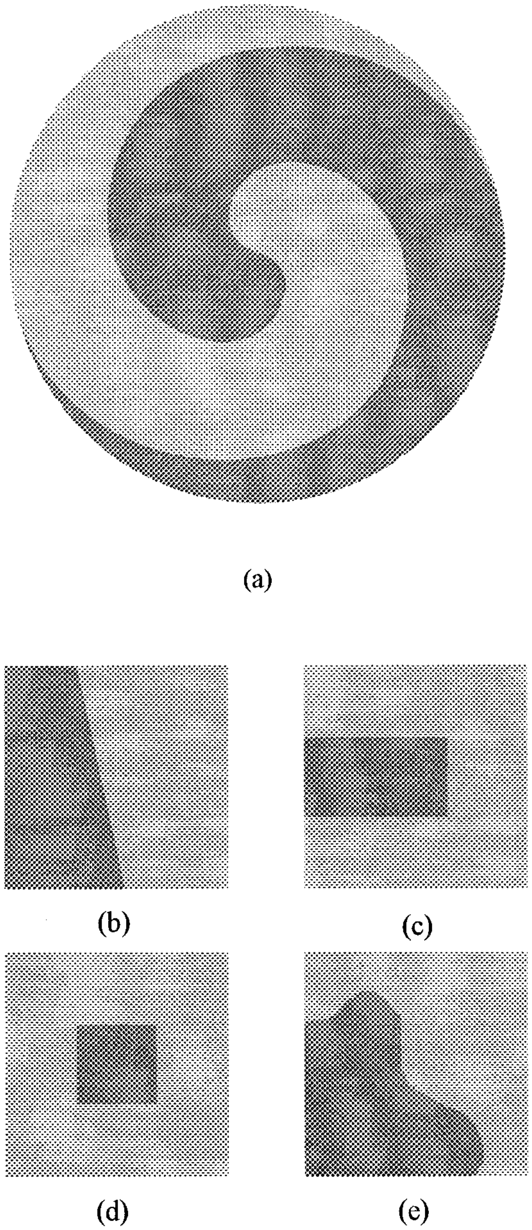

FIG. 2. The test pattern and four main formal relationships in contiguous space.

various kinds of formal relationships in spatial contiguity between two component colors. These experimental results could be extensively applied to new situations. There are four main formal relationships in contiguous space: juxtaposed, penetrated, surrounded, and irregularly bordered, as shown in Fig. 2(b)–(e). Such relationships can be covered with this test pattern. Besides, this pattern could be easily drawn on a computer and adjusted to the relative proportion between the areas of two component colors, without affecting their spatially contiguous relationship. The adjusted patterns were used to investigate how area affects color harmony in a follow-up study. The actual radius of the test pattern displayed on the screen was 6 cm.

*Test Color Samples.*To thoroughly distribute the test color samples throughout the entire color space, eight tones

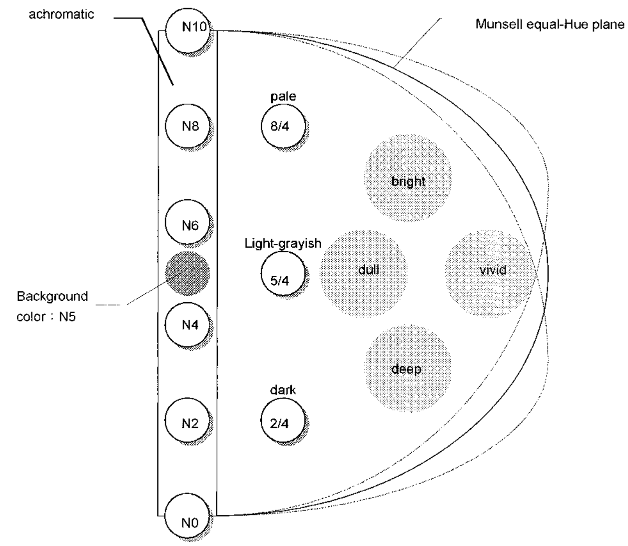

FIG. 3. The color tones for recruiting test colors.

in the PCCS (Practical Color Coordinate System, developed by the Color Research Institute of Japan)—vivid, bright, deep, dull, pale, light grayish, dark, and achromatic, as shown in Fig. 3—were first selected as pools to recruit test colors. Based on these tones, 46 color samples from the Munsell Color System were then selected. For a vivid tone, the ten Munsell Hues (pure colors) were selected. The achromatic colors adopted were Munsell N10, N8, N6, N4, N2, and N0. For pale and dark tones, the test colors were selected from each of the five principal Munsell Hues with value/chroma values of 8/4 and 2/4, respectively. The test colors for light grayish tone were selected from each of the five intermediate Munsell Hues with value/chroma values of 5/4. The test colors for dull tone were selected from each of the five principal Munsell Hues as well. However, the value/chroma values of test colors in different hues are not fixed for these tones, but vary somewhat with the different shapes of equal-hue planes for different hues. For bright and deep tones, the test colors were selected from each of the five intermediate Munsell hues with value/chroma values varying in accordance with the different shapes of equal-hue planes. Table I summarizes the 46 test colors. These colors were evaluated for preference by subjects and were then combined with each other so that the resulting color harmony could be evaluated.

TABLE I. The 46 test colors.

Tone	Munsell color notation
Vivid	5R 4/14, 5YR 7/14, 5Y 8/14, 5GY 7/12, 5G 5/10 5BG 5/10, 5B 5/10, 5PB 4/12, 5P 4/12, 5RP 5/12
Bright	5YR 8/8, 5GY 8/8, 5BG 6/8, 5PB 6/8, 5RP 7/8
Deep	5YR 4/8, 5GY 4/8, 5BG 4/8, 5PB 3/8, 5RP 3/8
Dull	5R 5/8, 5Y6/8, 5G5/6, 5B 5/6, 5P 4/6
Pale	5R 8/4, 5Y 8/4, 5G 8/4, 5B 8/4, 5P 8/4
Dark	5R 2/4, 5Y 2/4, 5G 2/4, 5B 2/4, 5P 2/4
Light-grayish	5YR 5/4, 5GY 5/4, 5BG 5/4, 5PB 5/4, 5RP 5/4
Achromatic	N0, N2, N4, N6, N8, N10

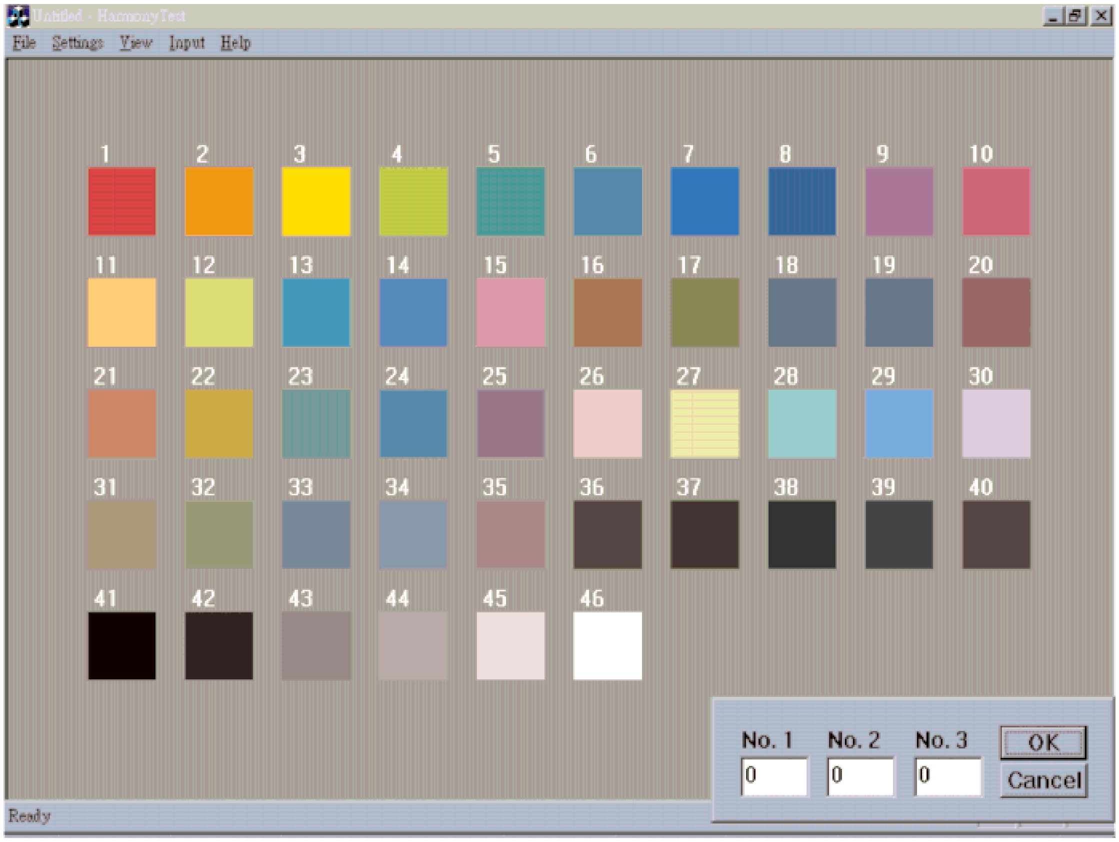

FIG. 4. The 46 test colors displayed on the monitor for subjects to select 3 most preferable colors.

Test Color Combinations. All mutual combinations of these forty-six color samples with the above-described test pattern were used as test pairs. Therefore, $C_2^{46} = 1035$ pairs of color combinations were evaluated in this experiment. In addition to these test pairs, 15 repeated test pairs, randomly selected from the 1035 pairs were included in the experiment for a reliability test. Thus, the total number of color pairs to be evaluated by each subject was 1050.

Color Rendering and Calibration

A PR-650 SpectraColorimeter was used to measure the tristimulus values of the full R, G, B of the monitor in the experiment. Next, a transfer matrix was derived by inverting the matrix of these three sets of tristimulus values. By using this transfer matrix, the *X*, *Y*, *Z* values of the selected Munsell colors obtained from the reference table[16] were converted to the corresponding R, G, B values and, correspondingly, the colors were displayed on the monitor. The tristimulus values of these colors were measured and then compared to the corresponding target tristimulus values in order to deduce the necessary correcting functions and coefficients through regression analysis. After correction, the average deviation between the measured tristimulus values of the 46 test colors and their corresponding target tristimulus values was about 1.04%.

Subjects

Thirty Taiwanese college students, 20 males and 10 females, were recruited as subjects in this experiment. All the subjects had normal color vision. They ranged in age from 20–31, with an average age of 25.33 years.

Experimental Setting

To minimize the effects of reflection, the entire experiment was conducted in a dark room with walls, ceiling, and floor covered with black materials. The only light source was the computer monitor. To maintain the stability of color definition, turning on the monitor for the experiment involved a calibration after warming up for more than 30 min. Each subject sat in front of the monitor at a visual distance of about 30–40 cm from the monitor. The subject was then asked to evaluate, clicking a mouse, the color patches appearing on the display against a neutral gray (Munsell N5) background.

Experimental Procedure

In the beginning, each subject was requested to select three favorite colors from the 46 color samples displayed on a screen, as shown in Fig. 4. Instead of attempting to survey the currently fashionable colors, this step focused on investigating how the subjects' favorite colors affect color har-

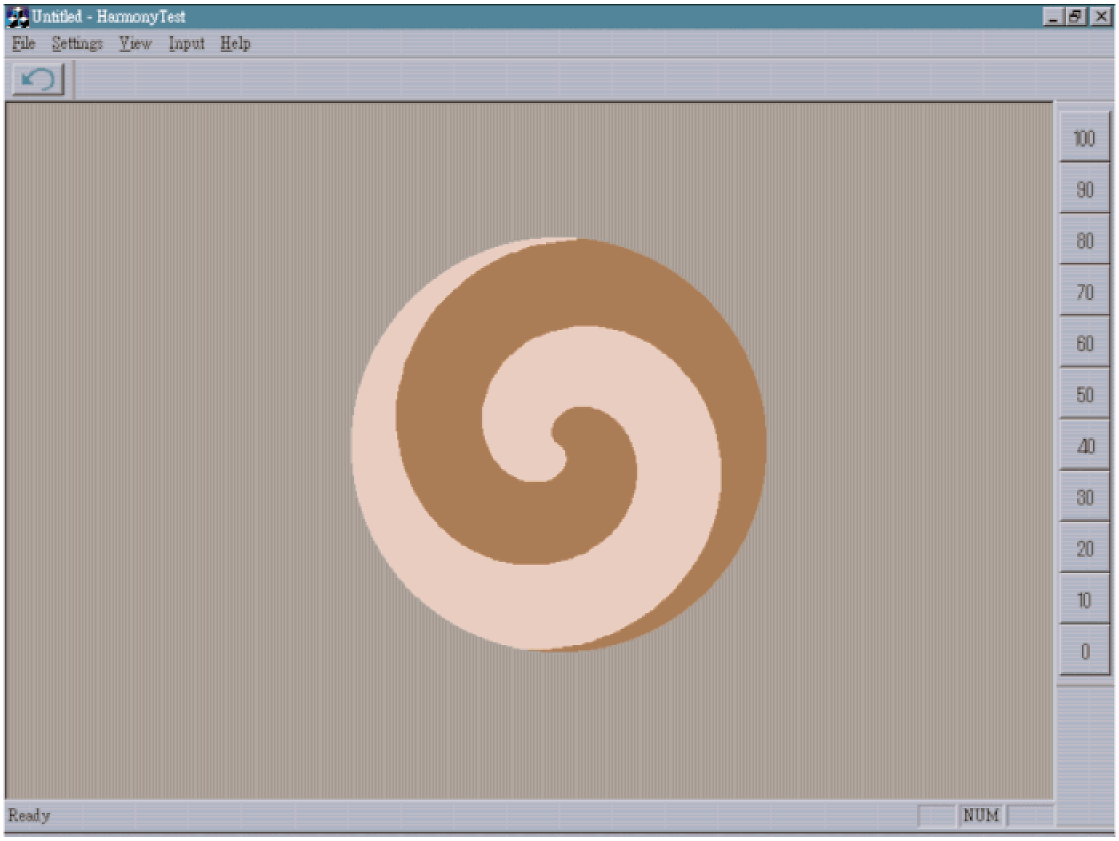

FIG. 5. A test color combination displayed on the monitor for subjects to evaluate its degree of harmony.

mony. Next, the 1050 test color combinations were presented sequentially on the screen, as shown in Fig. 5, in a random order. After receiving a brief explanation about the definition of color harmony, subjects were asked to rate the degree of their sense of harmony with each test color combination, by using a scale ranging from 0–100 in intervals of 10. To prevent subjects from becoming tired or bored, each experimental session contained three rest periods. Approximately 1 h was required for each subject to complete the experimental session.

RESULTS AND DISCUSSION

Because 15 repeated color combinations were arranged for testing each subject's reliability in this experiment, the test-retest reliability (Pearson correlation coefficient) of each subject was calculated first. The results indicated that, among 30 subjects, only 15 had correlation coefficients higher than 0.50, implying that color harmony is not an unequivocal and stable feeling for some people. Such a low reliability may also be attributed to the fact that the 1050 judgments to be made in this experiment are too many for subjects to focus their attention throughout the complete experimental session. However, verifying the above assumptions would require further study. Consequently, the 15 most reliable subjects were adopted for further statistical analyses.

Relationship between Holistic Color Interval and Color Harmony

During the first step of data analysis, the degrees of color harmony for each of the 1035 test color combinations were averaged over the 15 subjects and scaled in a range from 0–1. The averaged degrees of harmony were then treated as values of the dependent variable. On the other hand, the color interval (distance) between the two component colors in each test color combination in a UCS color space, the CIELAB color space, was computed and treated as a value of the independent variable. This holistic color interval (ΔE^*_{ab}) can be expressed as follows:

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

where ΔL^*, Δa^*, and Δb^* denote the differences in L^*, a^*, and b^* values, respectively, between the two component colors.[12]

The scatter plot of these 1035 data points, as depicted in Fig. 6(a), was then generated. These averaged data initially appeared to be spread too widely to reveal any distinguishing tendency. However, close examination of this plot revealed a fuzzy pattern embedded in the spread points. To allow this pattern to clearly emerge, we lowered the resolution of the color interval and set ten units of ΔE^*_{ab} as the class width. The degrees of color harmony for color combinations in the same class of color intervals were averaged. Based on these data, the mean and 95% confidence intervals

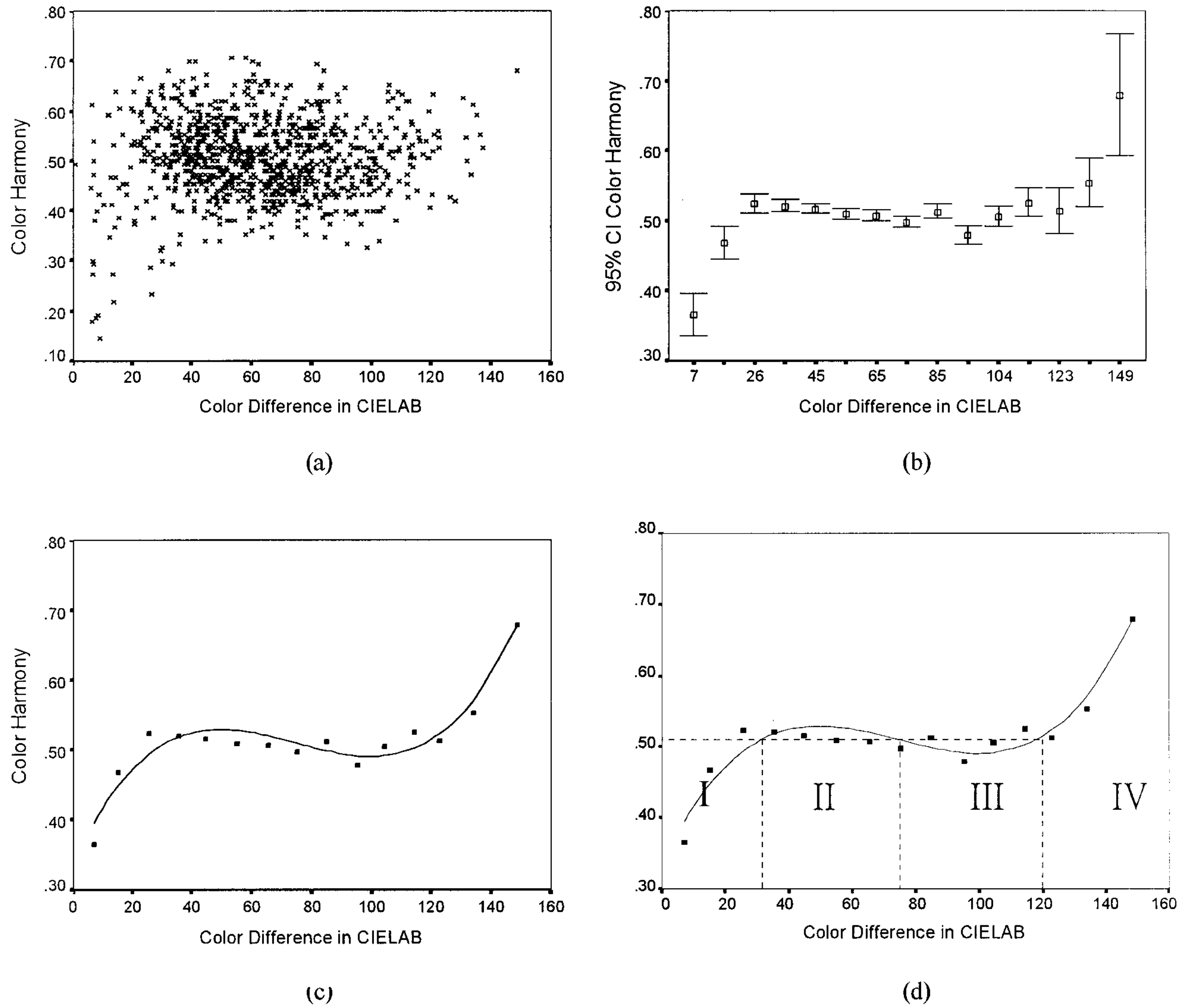

FIG. 6. (a) The scattering of color harmony against the corresponding CIELAB color difference. (b) The mean and 95% confidence intervals of color harmony against the corresponding group means of CIELAB color difference. (c) The least squares cubic fitting curve. (d) The four harmonious/disharmonious intervals identified.

of color harmony were calculated against the corresponding class midpoint of the CIELAB color interval, and presented in Fig. 6(b). This plot clearly indicates that increasing the color interval from a value of 0 causes the degree of color harmony to increase rapidly and reach a certain peak; it then descends slowly to a valley and rises rapidly again. Regression analysis of the mean values and their corresponding color intervals generated a least squares cubic fitting curve, with $R^2 = 0.92$, as shown in Fig. 6(c). The above-mentioned trend is clearly depicted by this curve. The equation for this cubic curve can be expressed as follows:

$$\text{Color harmony} = 0.3359 + 9.3 \times 10^{-3}(\Delta E^*_{ab}) - 1.4 \times 10^{-4}(\Delta E^*_{ab})^2 + 6.2 \times 10^{-7}(\Delta E^*_{ab})^3. \quad (2)$$

Setting the second derivative of this equation at zero and solving the derived equation allowed us to identify the inflection point of this curve at a color interval of 75.3, with a corresponding degree of color harmony of 0.51. A horizontal line extending from this point crosses the curve at three points (including the inflection point itself): they are at color intervals of 30.2, 75.3, and 120.4, respectively. The three points divide the curve into four regions, as shown in Fig. 6(d). The curve in the first (with a color interval under 30.2) and third region (color interval from 75.3–120.4) is under the horizontal line. Meanwhile, the curve in the second (color interval from 30.2–75.3) and fourth region (color interval beyond 120.4) is above the horizontal line. It is clear that the degrees of color harmony in the second and fourth regions are comparatively higher than those in the first and third regions. Thus, the second and fourth regions can be defined as "harmony" regions and the first and third as "disharmony" regions. This alternating harmonious/disharmonious pattern of color harmony generated by an increase in color interval roughly corresponds to Moon and Spencer's model of color harmony.

In the first and fourth regions, the degree of color har-

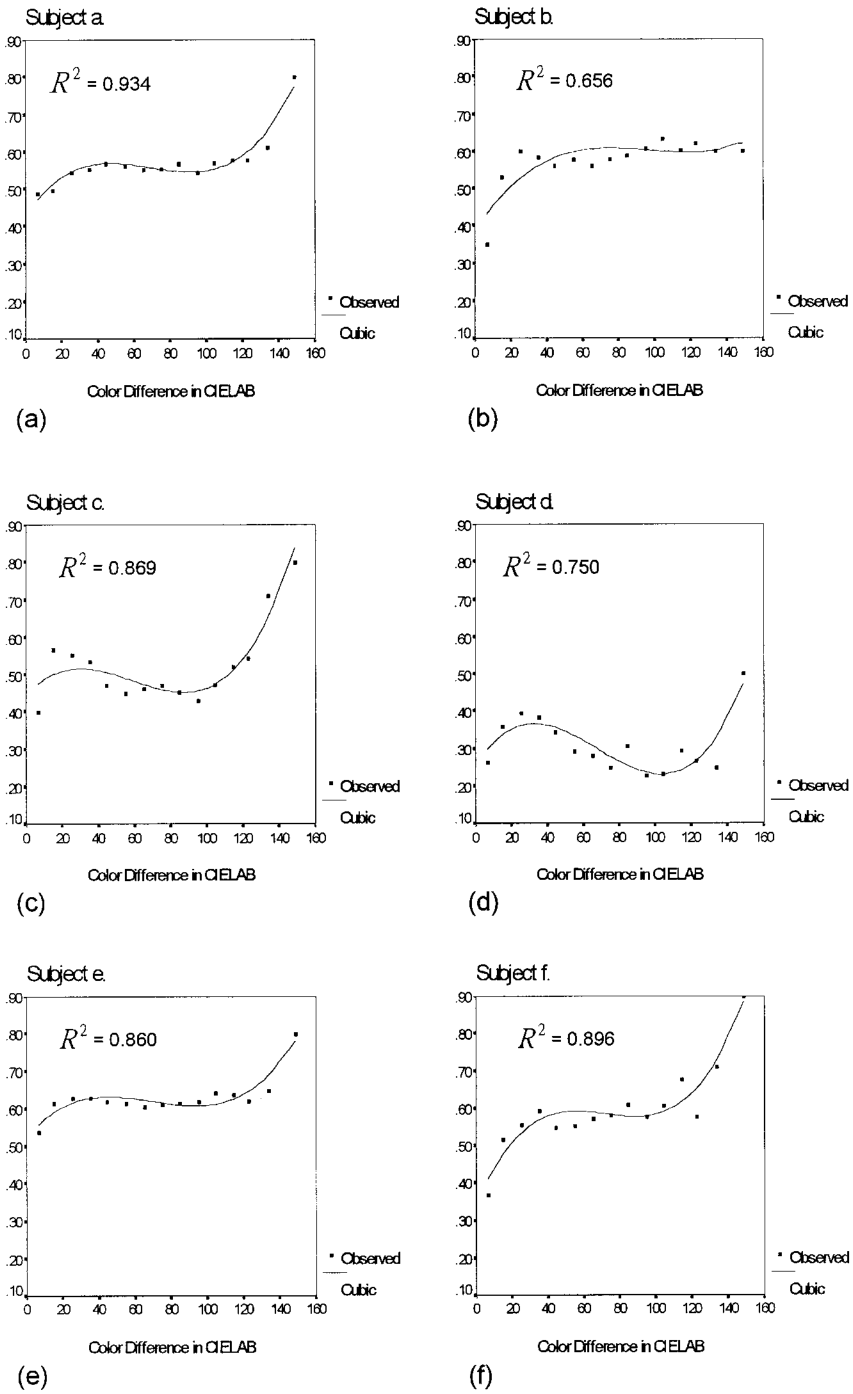

FIG. 7. The judged degree of color harmony as a function of color interval for each subject. (*Figure continued on next two pages.*)

mony dramatically increases with an increase in color interval; meanwhile, the fourth region has a substantially higher average degree of harmony than the first region. In the second region, the degree of color harmony increases gradually to a peak and then decreases gradually before reaching the inflection point in the curve. The third region reverses the order of the second region, but with a lower average degree of color harmony.

The cubic curve and four-regions pattern were obtained through the data averaged over all 15 subjects. To investigate whether this trend in color harmony discrimination is still preserved in each individual subject, we analyzed the individual data for each of the 15 subjects in the same manner as above. The results of regression analysis plotted in Fig. 7(a)–(o) reflected the judged degree of color harmony as a function of color interval for each subject. In most of these plots, the cubic curve as well as the four regions can be identified as before, though in some curves the peaks and valleys for regions II and III are either not obvious or nonexistent, as in Fig. 7(h), (k), and (l).

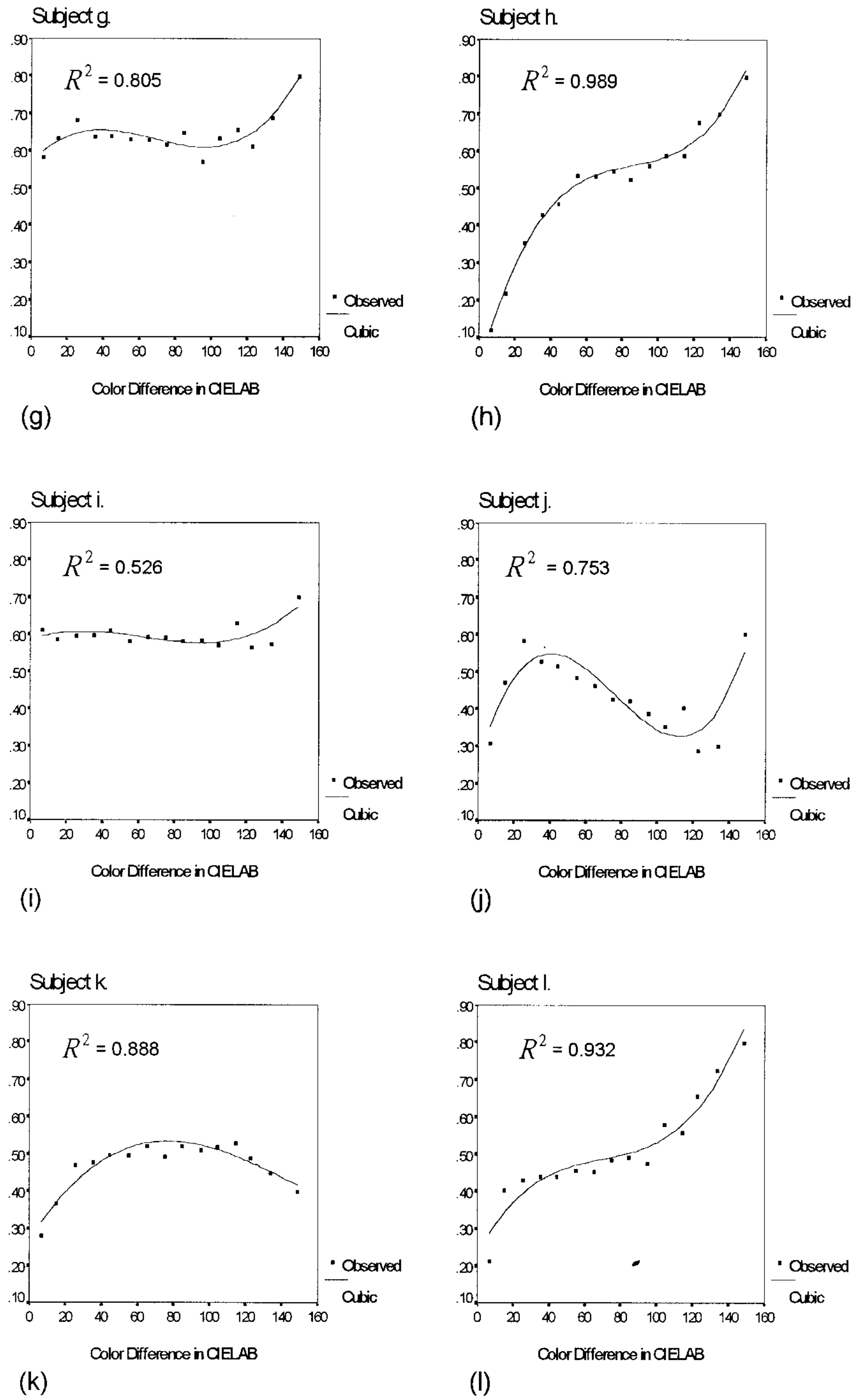

FIG. 7. (*Continued*)

In each of the 15 cubic curves for individual subjects, the inflection point was derived as before. Except for the curve of subject K, these inflection points are concentrically distributed around a certain area with an average value of color interval ΔE^*_{ab} of 74.5, which is close to the location of the inflection point derived from all subjects at $\Delta E^*_{ab} = 75.27$, as mentioned above.

In a further study of color harmony by the authors, in which other experimental conditions and procedures were kept the same except that object colors (painted color chips) were used as testing samples, a similar cubic curve was derived.[17] Again, alternating regions of harmony/disharmony can be identified from this curve.

Relationship between Color Harmony and Color Interval for Lightness, Chroma, and Hue

As mentioned earlier, Moon and Spencer's model of harmony considers how the color interval of each attribute affects color harmony independently. Therefore, in the following analyses, we investigated the relationship between

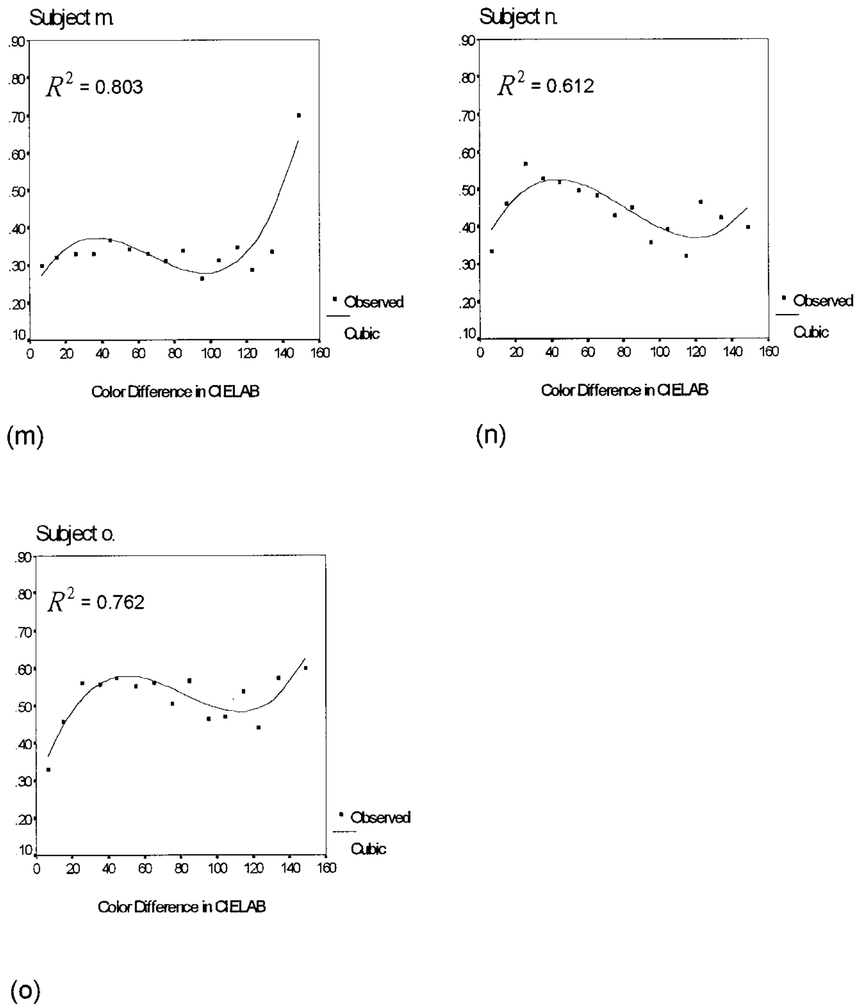

FIG. 7. (*Continued*)

color harmony and the color interval of a color pair for the three attributes of lightness, chroma, and hue.

Color Harmony and Color Interval of Lightness. In this study, the luminance difference between two component colors in a color combination (ΔL^*) is defined as the difference between the two L^* values. This was treated as an independent variable, and the degree of color harmony was treated as a dependent one. Treating independent variable classification as before, Fig. 8(a) plots the values of the mean and 95% confidential interval of the data. This plot closely resembles that of Fig. 6(b) in form. Thus, a cubic curve and four color interval regions corresponding to the color interval of Moon and Spencer's first ambiguity, similarity, second ambiguity, and contrast can be inferred as in the previous analysis of holistic color intervals. As will be demonstrated, this pattern does not appear in the plots of color interval for chroma and hue. Therefore, the color interval of lightness is probably the dominating factor, when we consider the influence of color difference on color harmony.

Color Harmony and the Color Interval of Chroma. The chroma difference between two component colors in a color combination (ΔC^*) was now treated as an independent variable, whereas the degree of color harmony was treated as a dependent one. ΔC^* denotes the difference between two C^* values for component colors. C^* is defined as follows:

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2}. \tag{3}$$

After similar treatment of independent variable classification, Fig. 8(b) plots the values of the mean and 95% confidence interval for the data. This plot contains no distinct pattern, except that colors contrasting in chroma are more harmonious.

Color Harmony and the Color Interval of Hue. Finally, the hue difference between two component colors in a color combination was treated as an independent variable. In addition, the degree of color harmony was treated as a dependent variable, as previously. The hue difference (DH^*) is defined by Sève's formula[18]:

$$\Delta H^* = \frac{a_1^* b_2^* - a_2^* b_1^*}{[0.5(C_1^* C_2^* + a_1^* a_2^* + b_1^* b_2^*)]^{1/2}}. \tag{4}$$

After similar treatment independent variable classification, Fig. 8(c) plots the values of the mean and 95% confidence intervals of the data. Again, this plot contains no distinct

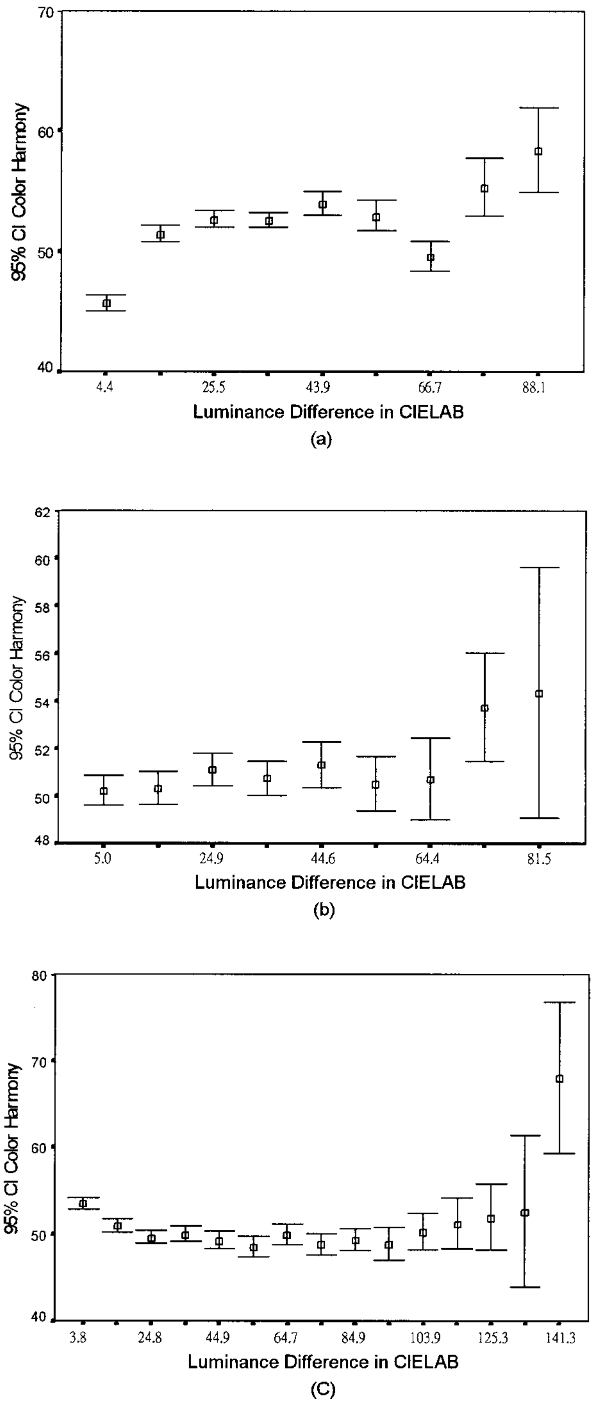

FIG. 8. (a) The mean and 95% confidence intervals of color harmony against the corresponding CIELAB luminance difference. (b) The mean and 95% confidence intervals of harmony against the corresponding CIELAB chroma difference. (c) The mean and 95% confidence intervals of color harmony against the corresponding CIELAB hue difference.

pattern, except that colors contrasting in hue are more harmonious.

Review of Some Color Harmony Theories

Most color harmony theories, according to Heddell,[19] can be grouped into two categories: those based on complementary color relationships and those based on a common color denominator. On the other hand, Sivik[1] has criticized the color theories based on complementary color relationships for their failure to clarify the concept of complementary color, given several possible definitions. However, if we are not so strict in the definition of complementary color and color harmony theory, the complementary color harmony theory may be restated as: "color pairs with high contrast tend to be harmonious." Our results then support this statement of the general tendency of color harmony perception, especially the tendency for perceived harmony to be based on lightness contrast.

To verify color harmony theories based on a common color denominator, we have analyzed our data according to the theory of "equal-luminance," the theory of "equal-chroma," the theory of "equal-hue," and the theory of "equal-value" (i.e., the same luminance and chroma on the Munsell scale), respectively. In each case, all test color combinations were dichotomized into two classes: color combinations with a common color denominator or color combinations without a common color denominator. For instance, in attempting to verify the theory of equal-luminance, test color combinations were classified into combinations with equal-luminance or combinations with unequal-luminance. Next, the *t*-tests were performed to judge whether the mean degree of color harmony for color combinations with an equal denominator is significantly greater than that for color combinations without an equal denominator. Our results demonstrate that, assuming a significance level of 0.05, only the color combinations with equal-hue display a significantly higher degree of color harmony than combinations with unequal-hue (with a mean difference here of 5.32).

Influence of Preferred Colors on Color Harmony

Each subject was asked to select three favorite colors from 46 test colors before the test to evaluate color harmony. This allowed us to verify the influence of preferred colors on perceived color harmony. Depending on whether or not a color combination includes a favorite color, the 1035 test color combinations can be categorized as follows: (1) both component colors are favorite colors; (2) one of the component colors is a favorite color; and (3) neither component color is a favorite color. The mean degrees of color harmony of these three groups of color combinations were then compared. Three observations are worth mentioning. First, ANOVA results indicate a significant difference among them. The subsequent multiple range *t*-test reveals that the mean degree of color harmony for color combinations with two favorite colors is very significantly higher than that for combinations with one favorite color. Moreover, the degree of color harmony of color combinations with one favorite color is also very significantly higher than that for those containing no favorite color. Therefore, the above results verify the influence of the presence of preferred colors on perceived color harmony.

CONCLUSIONS

Although this study has demonstrated that the awareness or sense of color harmony may not be very concrete and stable, our somewhat fuzzy data allow us to infer a cubic function of holistic color interval between a color combination and its perceived degree of color harmony. From this cubic relationship, four harmonious/ disharmonious regions have been identified, roughly corresponding to the first ambiguity, similarity, second ambiguity, and contrast color intervals in Moon and Spencer's model of color harmony. Furthermore, it seems that when we consider the color intervals of the three color attributes—lightness, chroma, and hue—the color interval of lightness may be the dominating factor with respect to the influence of (perceived) color difference on (perceived) color harmony.

The results of this study support the general assumption of the influence of "contrast" color combinations and "equal-hue" color combinations on perception of color harmony. Moreover, our results clearly verify the significant influence of preferred colors on perception of harmony.

Although the colors investigated in this study are colored lights emitted from a CRT, most colors surrounding us in our daily life are object colors. Thus, we have conducted a corresponding study based on using object colors as testing samples. Results similar to those above were also obtained from this study.

Obviously, the factors influencing perception of color harmony are sophisticated and complex; they cannot be isolated in a single investigation. Further elucidation of the problem of color harmony perception will require the continuing effort to explore this from different perspectives, especially psychological and cultural ones. For example, the authors are now conducting a study of color harmony perception in a more or less psychologically derived color space, one generated from semantic differential surveys. The use of the NCS-system of color description for studying the harmony of color combinations, as suggested by Sivik,[1] might also benefit future studies.

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