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RESEARCH ARTICLE

Research on Attribute Analysis and Modeling of Color Harmony Based on Objective and Subjective Factors

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ABSTRACT Color harmony is the hotspot of many researchers in the fields of art and design which is widely used in various artworks and design activities. As for psychology, color harmony is closely related to human's perception and cognition, although, the research of its generation process has not been fully focused on. With experimental psychology with artificial intelligence technology combined together, our aim is to investigate the factors affecting color harmony on the basis of the generation process from perception to cognition, and construct a mathematical model to predict its degree, so as to realize the quantitatively analysis and measurement of color harmony. We classify the factors affecting color harmony into objective and subjective ones. Among them, the objective factors are constructed based on the three principle elements of color with a total of 21-dimensional color-pair objective physical features extracted. And the subjective factors are divided into direct psychological effects and indirect psychological effects. 180 two-color combinations were evaluated by 30 subjects based on color harmony and its subjective factors on discrete scales ranging from −2 to 2. Correlation analysis reveals that color harmony is not only affected by objective factors, but also by subjective factors which has a stronger correlation than that of the objective ones. Finally, machine learning algorithms were adopted to construct a mathematical model, which has been proved that the linear relationship can well explain the generation mechanism of color harmony.

INDEX TERMS Color harmony, objective factor, subjective factor, hierarchy model of color harmony generation, color emotion, experimental psychology, machine learning.

I. INTRODUCTION

Color harmony refers to the overall effect of two or more colors juxtaposed in the same time and space [1]. Since ancient times, the theory of color harmony has been the focus of many researchers in the field of art and design, and its research results have been widely used in various artworks and design activities. With the development of signal processing and artificial intelligence technologies, more and more researchers try to predict the degree of color harmony in a data-driven way, and intelligently generate color combination schemes. In addition, in the fields of psychology and neurobiology, researchers have also conducted some exploratory studies on the relationship among color harmony, perception, and cognition.

Specifically, the theory of color harmony came about after the art of painting had been developed for hundreds of years. During the Renaissance, Leonardo da Vinci [2] had a theoretical method of color harmony, and the German poet Goethe [3], [4] also wrote a theory of color harmony. The classical

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theory of color harmony started from the descriptions of color harmony summarized by Cheruer. He gave a qualitative description of color harmony and summarized his harmony theory into 10 qualitative rule [5]. Since Cheruer's theory of color harmony was established, the research on color harmony has been deepening continuously. So far, there is no color harmony theory that can cover all aspects of color harmony and solve all the problems in color harmony design. In the 20th century, color science has established a quantitative and rational color representation system, and established a strict relationship and systematic order between colors, thus creating good conditions for the establishment of modern color harmony theory. The representative ones are Munsell's theory of color harmony [6], Ostwald's theory of color harmony [7], and Moon-Spencer's theory of color harmony [8], [9]. The establishment of the color harmony theories makes color design to get rid of the painter's feeling, so that the color design is included in the scope of engineering to a certain extent. However, due to the unique comprehensiveness and complexity of color harmony, using mathematical methods to create convincing color harmony rules that meet aesthetic requirements is a difficult point in color harmony research and has not yet reached a comprehensive and practical stage.

At present, the theory of color harmony keeps developing, and every aspect of social life cannot be separated from color design. Therefore, more practical color harmony theory is constantly called for. Researchers have applied more quantitative analysis methods, and the color system is constantly improved and perfected. Szabó F. *et al.* developed several color harmony formulae to describe observers' impressions of color harmony for two-and three-color combinations, and defined a new light source color quality metric named ''color harmony rendering index'' [10]. Hsiao *et al.* constructed a color design/selection system for predicting the color trend based on aesthetic measures. The analytic hierarchy process theory was used to evaluate the weights for four major consumption style factors in human environment, including Economy, Education, Culture, and Technology [11]. Kim *et al.* proposed a method to achieve a harmonious combination of an image and a color element by increasing the hue similarity between them based on the insights from designers [12]. Ou *et al.* developed a new set of quantitative models of color emotion and color harmony using psychophysical data collected from 12 regions in the world. For color harmony, a new color harmony model was constructed based on the physical parameters quantified from CIELAB color space, which had a satisfactory predictive performance. In addition, Ou *et al.* also found that the common color harmony principles, including hue similarity, chroma similarity, lightness difference and high lightness principles, were partly agreed by observers of the same region [13].

With the help of signal processing and artificial intelligence technology, color harmony theory have developed rapidly in the field of computer-aided design. Hu *et al.* abstracted the color combination features into a six-dimensional color relationship model, namely hue, chroma, brightness, span of hue, span of chroma, and span of brightness, and characterized individual preference as a specific parameter, so as to refactor the preferred color scheme to meet individual needs [14]. Aiming at the problem that the existing color harmony model overly relies on classical rules and ignores image semantic information, Lu *et al.* introduced image semantic features (multi-color perceptual features and emotional features) to represent the image contents, so as to construct a color harmony prediction model which is more consistent with human's visual perception than the traditional ones [15]. Wu *et al.* took color preference as prior knowledge, and used a multi-objective interactive genetic algorithm to automatically generate color combination schemes that conform to individual preferences. The result shows that the algorithm can reduce designers' work barriers and speed up design [16]. Yang *et al.* took color pairs as the research object, and based on the positive effect of color harmony on emotion, an initial prediction of color harmony was given, and then the initial score was corrected by Back Propagation Neural Network, so as to construct a more flexible color harmony model [17]. The above researches are carried out independently for a specific application, and have achieved good results in related fields, but the model has poor interpretability.

In terms of the relationship between color combination and cognition, the research results from Nippon Color & Design Research Institute (NCD) are the most significant. Based on the color image scale [18] constructed by themselves, NCD picked the color combinations of 12 representative colors (nine chromatic colors and three achromatic colors) popular in Japanese society to conduct subjective evaluation on 180 color image descriptors (including color harmony) [19]. Then, NCD mapped the color combinations to the two-dimensional scale of ''cool/warm'' and ''soft/hard'', so as to summarize the color image rules and spatial characteristics among different color combinations. However, their research is limited to the qualitative analysis of color combinations without the quantitative relationship with image descriptors (including color harmony), which results in the unpredictability of the degree of color harmony. In addition, color preference from different regions was not taken into account, so the generalization needs to be further verified.

Color emotion is one of the most popular researches in the field of color cognition, which are often carried out in specific scenes and groups due to individual differences in emotion. Valdez *et al.* explored the relationship between different color attributes and emotions, which proved that the color with high saturation could make people feel happy with arousal enhancing [20]. Solli *et al.* used the categorical scale and the interval scale respectively to evaluate the three emotional factors, namely activity, weight and heat, and extended the evaluation object from single color to paired colors [21]. Hanada firstly tried to study the generation mechanism of color emotion through consistency analysis (CA) and revealed the correlation between color temperature perception and emotion [22]. Wang *et al.* used the SD method to characterize the color emotion by three mutually orthogonal factors, and constructed the features related to each factor through factor interpretation. Then, the support vector regression (SVR) algorithm was used to accurately model the perception factors, so as to realize the retrieval of image emotion [23]. Then, Ou *et al.* found that the universal model of color emotion is relatively more culture-independent than that of color harmony, which is the first study on the relationship between color emotion and color harmony through modeling [13].

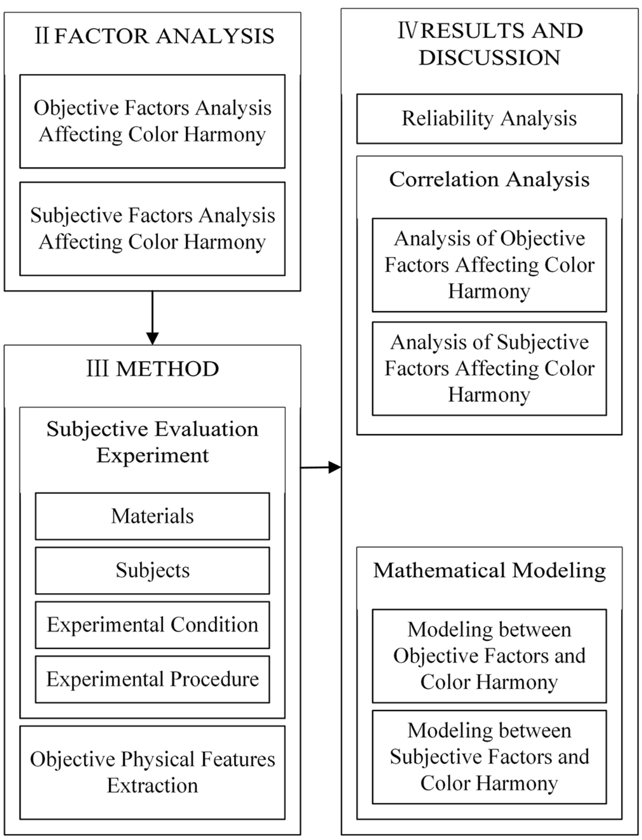


FIGURE 1. The section arrangement.

To sum up, the current research on color harmony mainly includes two aspects: one is the study of color harmony theory and its mathematical methods, and the other is the construction of color harmony prediction model. Aiming at the common problems in color harmony research, we take two-color combinations (abbreviated as color pair below) as the research object, based on the generation mechanism of color harmony, comprehensively analyze the factors affecting color harmony, and construct a color harmony prediction model. On this basis, we further studied the relationship between color harmony and emotion, tried to construct a complete research paradigm of color harmony, and verify the traditional color harmony theory based on the research results. The specific sections are arranged as shown in Figure 1.

TABLE 1. The objective and subjective factors that affect the color harmony perception.

The objective factor	The subjective factor	
Hue	Cool/warm	Pleasure
Chroma	Soft/hard	Arousal
Lightness	Transparent/turbid	Dominance

II. FACTOR ANALYSIS AFFECTING COLOR HARMONY

Human's judgment on the degree of color harmony is affected by many factors. We divide the factors into objective factors and subjective factors. The objective factors refer to the inherent physical attributes of the generator of color harmony, so they can be accurately quantified by objective features, such as hue, chroma, lightness, etc., with certainty and universality. The subjective factors refer to the additional attributes possessed by the receiver of color harmony, which are based on human's subjective feeling as the basic premise, and works synergistically with color harmony, such as emotion, with ambiguity and specificity. The objective and subjective factors that affect the perception of color harmony are as shown in Table 1.

A. OBJECTIVE FACTORS

Hue, chroma, and lightness are the basic attributes of color proposed based on the principle of color perception [24], which are in line with human's logical psychology and color vision characteristics, and are the most important and stable three elements in color [25]. According to CIE Publication No. 17.4, 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. Chroma is the colorfulness of an area judged in proportion to the brightness of a reference white. Lightness is the brightness of an area judged relative to the brightness of a reference white. Both colorfulness and lightness are determined by the amplitude of the light. At present, color harmony theory takes these three color attributes as the constraint objects. Therefore, hue, chroma, lightness, and their statistical characteristics were analyzed systematically as the objective factors affecting color harmony.

First of all, it is necessary to quantify the three attributes of color, that is, to select a color system that can accurately represent hue, chroma, and lightness. The CIELAB color space (L^* represents lightness, a^* represents red/green, and b^* represents yellow/blue) was proposed by the International Commission on Illumination (CIE) in 1976 [26], which is a perceptually uniform color space to linearly represent the perceptual difference between colors. Therefore, the CIELAB color space was adopted to extract the objective physical features. Among them, we selected the L^* dimension to represent lightness, and the h dimension and C^* dimension which calculated by the a^* and b^* dimension to represent hue angle and chroma.

B. SUBJECTIVE FACTORS

Color can affect human's psychological activities in many ways, from direct visual stimulation to indirect association, subtly influence human's emotions, thoughts and behaviors, and interact with human's perception of color harmony. As shown in Figure 2, the psychological effects stimulated by color are divided into direct psychological effects and indirect psychological effects according to the psychological change law from simple to complex when triggering psychological reflex [1], [27]. The former is the direct influence of the physical light stimulus of color on human's physiology, which is also called the physical psychological illusion of color, e.g., red with longer wavelength makes people feel warm; blue with shorter wavelength makes people feel cold [28]. The latter refers to a more complex psychological feeling generated by combining associations, thinking, and memories on the basis of physical stimulus, e.g., red is related to concepts such as fire and blood, which makes people feel sad by conjuring up images of war [29]. Narrowly speaking, the direct psychological effect of color refers to color perception with objectivity and consistency [30], e.g., temperature sense (''cool/warm'') [31], [32]. And the indirect psychological effect of color refers to color emotion with subjectivity and specificity, which evokes more intense and complex feelings instead of staying in the shallow level of psychological stage [33].

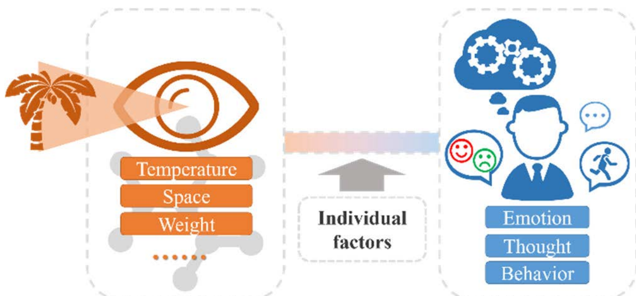


FIGURE 2. The visual cognitive process from direct psychological effects to indirect psychological effects.

On the basis of the Hue and Tone System, NCD constructed a color image space formed by the three psychological axes, namely ''cool/warm'', ''soft/hard'', and ''transparent/turbid''. Taking the different preferences of colors and words in different cases into consideration, various color-image research and analysis was conducted by NCD. The check points were the differences among subjects of research (individual and groups of people), the difference between single colors and color combinations, the differences in research methods, the color differences in various design fields, and the differences of image caused by the spatial effects of colors. In each case, the axes for the measurement of colors (''cool/warm'', ''soft/hard'', and ''transparent/turbid'') were extracted as a result of factors analysis [18]. Therefore, these axes are statistically primary, basic, and definite in spite of the differences mentioned above.

Personal differences in taste from different regions are supposed to be focused on. Jonauskaite *et al.* [34] tested color-emotion associations in 4,598 participants from 30 nations and the pattern-similarity analysis revealed universal color-emotion associations (average similarity coefficient: $r = 0.88$). In addition, Wang *et al.* [35] analyzed the effectiveness of color basic attributes for the multi-color perceptual features. For ''cool/warm'', *color moment* (the third-order moment hue), which is a mathematical method in which the original value is the mathematical expectation, and the third-order moment hue represents the average value of hue cubed, has the highest effectiveness (Pearson's correlation coefficient: $r = 0.55$). For ''soft/hard'', *brightness* has the highest effectiveness (Pearson's correlation coefficient: $r = 0.41$). For ''transparent/turbid'', *chroma* is the most relevant to it (Pearson's correlation coefficient: $r = 0.26$). Therefore, ''cool/warm'', ''soft/hard'', and ''transparent/turbid'' can construct a good mapping relationship with corresponding dimension of HSV color space.

Since the color image space can be used as the benchmark for color image judgment, that is, any single color, psychological effect descriptor and color combination can be placed on it, ''cool/warm'', ''soft/hard'', and ''transparent/turbid'' were adopted as direct psychological effect descriptive words on the basis of the research from NCD. Further, in terms of indirect psychological effects, due to the general connection between color and emotion, we selected emotion as the evaluation object, and the PAD emotional model was adopted to represent emotions (P represents pleasure, A represents arousal, and D represents dominance) [36], as shown in Table 2.

III. METHOD

In this section, we firstly introduced the process of evaluation subjective experiment to quantify the subjective factors. On this basis, we introduced the method of objective physical features to quantify the objective factors.

A. SUBJECTIVE EVALUATION EXPERIMENT OF COLOR HARMONY

1) MATERIALS

We adopted the ''main color + assistant color'' mode to design and process two-color materials. It is noting that the ''main color + assistant color'' mode is only for the convenience of making materials, and there is actually no main or assistant color in the color pair. The main color were from the research results of NCD, based on the Munsell color system, which composed of nine kinds of chromatic colors and three kinds of achromatic colors, as shown in Table 3. On this basis, the assistant color design was carried out on the basis of color image [37]. (The CIELAB L^*, a^*, and b^* values of all the ''main color'' and ''assistant color'' are shown in Appendix, Table 8 and Table 9.)

The materials contain a total of 180 pictures, and each main color contains 12 color pairs. The original size is

TABLE 2. The statistics of descriptive words of psychological effect affecting color harmony [35].

The Chinese descriptive words	English name, abbreviation	Description
冷/暖	Cool/warm, CW	• Cool: (feel) lower temperature; • Warm: (feel) higher temperature.
软/硬	Soft/hard, SH	• Soft: loose internal structure, easy to deform; • Hard: tight internal structure, difficult to deform.
透明/浑浊	Transparent/turbid, TT	• Transparent: (an object) can penetrate light; • Turbid: contain impurities.
愉悦度	Pleasure, P	The positive and negative characteristics of an individual's emotional state, including the two opposing states of positive or negative emotion.
激活度	Arousal, A	The individual's neurophysiological activation level, which is related to the activation degree of the body's energy associated with emotional states, including two states of low arousal (such as quiet) and high arousal (such as excited).
优势度	Dominance, D	The individual's state of control over the situation and others, and is used to distinguish whether the emotional state is subjectively issued by the individual or the influence of the objective environment, including active and passive states.

Note: "cool/warm", "soft/hard", and "transparent/turbid" belong to the category of direct psychological effects, and pleasure, arousal, and dominance belong to the category of indirect psychological effects.

TABLE 3. The $L^*/a^*/b^*$ value of the main colors.

The color name	L^*	a^*	b^*
R/V	49	75	61
YR/Dp	38	38	48
YR/V	68	46	75
Y/V	94	-10	91
G/V	54	-45	25
PB/V	30	13	-53
PB/Dk	10	17	-39
P/V	28	42	-48
RP/P	79	31	2
N1.5	0	0	0
N5	66	0	0
N9.5	100	0	0

Note: According to "Color Image Scale", the main colors naming adopted the naming paradigm of "hue/color tone". Among them, R represents red, YR represents orange, Y represents yellow, G represents green, PB represents blue-purple, P represents purple, RP represents purple-red, N represents achromatic color; V represents vivid tone, P represents pale tone, Dp represents deep tone, Dk represents dark tone.

813 pt × 813 pt, and the horizontal and vertical resolution is both 300 ppi. In order to avoid the influence of areas and adjacent relationships in color pair on subjective evaluation, the presentation method is shown in Figure 3. In addition, the spatial distributions of the objective physical features of the materials are shown in Figures 4(a) and 4(b). It can be seen from the figures that the distributions of the features are uniform and complete, which can support the research of the later experiments.

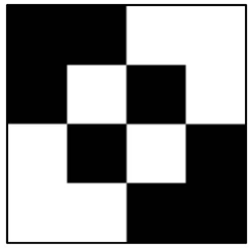


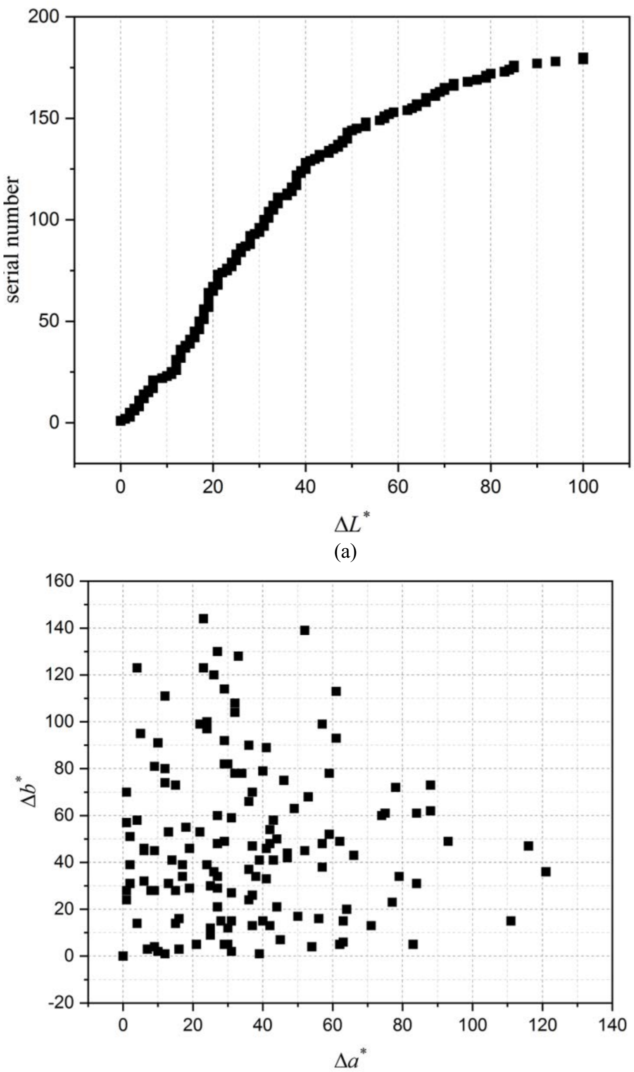
FIGURE 3. **The "main color + assistant color" presentation form. This presentation method can ensure the consistency of the area and adjacent relationship. In addition, the coloring areas of the main color and the assistant color are randomly selected, not limited to a certain fixed position.**

2) SUBJECTS

A total of 30 subjects participated in this experiment. The subjects were university students, Chinese nationality, aged between 18 and 25 years old (Mean: 20.3, SD: 1.16), and the sex ratio was 7 (male): 11 (female). No subjects were major in color-related professional courses and reserved color-related professional knowledge. All subjects had passed the Ishihara Color Blindness Test [38]. In addition, subjects signed an informed-consent form and were compensated for their participation.

3) EXPERIMENTAL CONDITION

Figure 5 shows the experiment settings. To avoid the interference of noise on the perceptual evaluation, the subjective evaluation experiment was carried out in a 5.37 m × 6 m standard listening room, where the background noise was kept below 30 dB(A). A 75-inch Sony KD-75X9400D HD monitor was adopted with a resolution of 4K (3840 × 2160), and the actual size presented on the monitor is 15 inch × 15 inch. According to the Methodology for the Subjective Assessment of the Quality of Television Pictures (ITU-R BT.500-14), the ambient illumination of the monitor (i.e., the incident light by the surrounding environment on the monitor, measured in the vertical direction of the monitor) was set to 200 lx (an illumination unit, representing the luminous flux received on the monitor per unit area). Then, the luminance is 596.5 cd/m^2, and the luminance uniformity is 0.03 cd/m^2 (Input signal: black level; Value: SD; Method: Nine-point Test) and 10.69 cd/m^2 (Input signal: white level; Value: SD; Method: Nine-point Test). A "slideshow" function in the ACDSee software (official free version; ACD Systems International Inc., Shanghai) was used to randomly present the stimuli. The seats were arranged in an arc with the monitor as the center, so as to make the distance between the subjects and the monitor fixed at 2 m. The horizontal viewing angle of the display is 178°, and the actual viewing angle from the subjects sitting on either of two



(a)

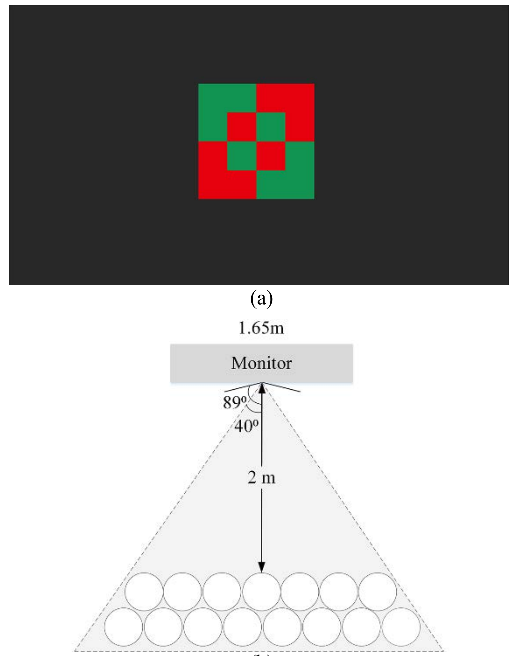
(b)

FIGURE 4. **The spatial distributions of the objective physical features. Among them, Figure 4(a) shows the distribution of ΔL^* value between the main color and the assistant color with Y-axis representing the serial number of ΔL^* value ranging from smallest to largest, and Figure 4(b) shows the plane distribution of a^* difference and b^* difference between the main color and the assistant color.**

sides is 80°, so as to ensure the consistency of color displaying.

4) EXPERIMENTAL PROCEDURE

The experiment was conducted in four groups with 13 or 14 subjects in each group. Each subject was asked to score a total of 200 two-color pictures (including 20 repeated ones) based on color harmony and subjective factors. During the experiment, the subjects were prohibited to talk or signal to each other. The presentation time of each picture was 30 seconds, and a 10-minute break was provided for each 100 pictures completed in the evaluation. It took a total of two hours for each subject to complete the experiment.



(a)

(b)

FIGURE 5. **The experimental environment and the presentation method of each picture. Among them, Figure 5(a) shows the presentation form of each picture on the 75-inch monitor, the size of the monitor is 16:9, the actual size is 15 inch × 15 inch, and the stimulus is centered with a grey background (Munsell: N2); Figure 5(b) shows the seat arrangement, and the main decorative materials such as walls and floors are all grey (Munsell: N4).**

The experiment was divided into two steps. *The first step is to evaluate color harmony*. In our experiment, the Series Category (SC) method was adopted to establish the psychological evaluation scale of color harmony, so as to realize the quantitative analysis. As shown in Table 4 (a), subjects were asked to score the degree of color harmony on a 5-level scale. *The second step is to evaluate the subjective factors affecting color harmony*. The SC method was also adopted to clarify the psychological evaluation scale. As shown in Table 4 (b), the subjects were asked to score all the pictures on a 5-level scale of six subjective descriptive words.

B. OBJECTIVE PHYSICAL FEATURES EXTRACTION

Based on the analysis results of objective factors in Section II, the Image Processing Toolbox and Statistics Toolbox of MATLAB software (R2014a; The MathWorks, Inc., Natick, MA) was adopted to extract a total of 21-dimensional color-pair objective physical features, as shown in Table 5. According to the representation method of the CIELAB color space, it is divided into six categories of eigenvectors, which are lightness eigenvector, red/green eigenvector, yellow/blue eigenvector, hue eigenvector, chroma eigenvector, and distance eigenvector. Firstly, the quantifying methods of the basic parameters of hue, chroma, and distance eigenvectors are as follows.

$$h = tan^{-1}(\frac{b^*}{a^*}) \quad (1)$$

TABLE 4. The subjective evaluation scale.

(a)				
-2	-1	0	1	2
disharmonious		→		harmonious
(b)				
-2	-1	0	1	2
cool		→		warm
-2	-1	0	1	2
soft		→		hard
-2	-1	0	1	2
transparent		→		turbid
-2	-1	0	1	2
unpleasant		→		pleasant
-2	-1	0	1	2
unarousable		→		arousable
-2	-1	0	1	2
submissive		→		dominant

Note: A 5-level scale was adopted to score, and the psychological evaluation scale range is {-2, -1, 0, 1, 2}. E.g., using the SC method to evaluate color harmony, -2 represents disharmonious, -1 represents a little disharmonious, 0 represents none, 1 means a little harmonious, and 2 represents harmonious.

TABLE 5. The statistics of color-pair objective physical features.

Category	The objective physical features	Dimensions
Lightness	L_1^*, L_2^*, $mean\_L*$, ΔL^*	4
Red/green	a_1^*, a_2^*, $mean\_a*$, Δa^*	4
Yellow/blue	b_1^*, b_2^*, $mean\_b*$, Δb^{**}	4
Hue	$h1$, $h2$, $mean\_h$, Δh	4
Chroma	C_1^*, C_2^*, $mean\_C*$	3
Distance	ΔE, ΔC^*	2

Note: 1 represents the eigenvalues of the main color, and 2 represents the eigenvalues of the assistant color.

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{2}$$

$$\Delta E = \sqrt{\left(L_1^* - L_2^*\right)^2 + \left(a_1^* - a_2^*\right)^2 + \left(b_1^* - b_2^*\right)^2} \tag{3}$$

$$\Delta C^* = \sqrt{\left(a_1^* - a_2^*\right)^2 + \left(b_1^* - b_2^*\right)^2} \tag{4}$$

where h represents the hue angle value in the CIELAB color space; C^* represents the chroma attribute in the CIELAB color space; ΔE represents the total difference between two colors, which quantified by the Euclidean distance between two points in the CIELAB three-dimensional color space. ΔC^* represents the chroma difference between two colors, which quantified by the Euclidean distance between points on the $a^* \circ b^*$ plane.

Except for distance eigenvector, each eigenvector has four dimensions, including the eigenvalues of the main and assistant colors, the average eigenvalue of the main and assistant colors, and the difference eigenvalue between the main and assistant colors. Taking the red/green eigenvectors as an example, a_1^* represents a^* of the main color, a_2^* represents a^* of the assistant color, $mean\_a^*$ represents the average value of a^* of the main and assistant colors, and Δa^* represents the difference value of a^* between the main and assistant colors.

IV. RESULTS AND DISCUSSION

Firstly, after all the experimental steps were completed and the experimental results were summarized and sorted, test-retest [39] and Cronbach's alpha [40] were adopted to check the consistency of the data. On this basis, correlation analysis was carried out to analyze valid data qualitatively and a hierarchy model was constructed to visualize the correlation relationships. Finally, based on the analysis results of objective factors, the machine learning algorithms were adopted to construct the mathematical model of color harmony on the basic of the objective factors and subjective factors quantified in Section III, so as to further explore the generation mechanism of color harmony accurately.

A. RELIABILITY ANALYSIS

Test-retest and Cronbach's alpha were adopted to evaluate the reliability of the experimental data. Test-retest is used to measure the reliability of the single picture. If the same picture has a consistent distribution in two repeated measurements, the results are reliable. Test-retest is calculated by calculating the Pearson's correlation coefficient for the results of two repeated measures. Table 6 shows the test-retest results after removing the experimental data whose Pearson's correlation coefficient is lower than 0.5 for each scale, and the Pearson's correlation coefficients are: $r = 0.82, p < 0.001$ ("cool/warm"), $r = 0.72, p < 0.001$ ("soft/hard"), $r = 0.64, p < 0.001$ ("transparent/turbid"), $r = 0.75, p < 0.001$ (pleasure), $r = 0.72, p < 0.001$ (arousal), $r = 0.71, p < 0.001$ (dominance). Among them, the Pearson's correlation coefficient of "cool/warm" is the highest, and the "transparent/turbid" is the lowest (Mean: 0.72, SD: 0.05). In addition, as shown in Equation (1), the effective rates of "cool/warm", pleasure, and arousal are 88%, 82%, and 82%, all above 80%, indicating that the above-mentioned factors of the pictures are complete, and the descriptive words are accurate and easy for the subjects to understand. The effective rates of "soft/hard" and dominance are the second, both are 78%, close to 80%. The lowest effective rate of "transparent/turbid" is 74%. The possible reasons are: (1) The factor completeness of the pictures was poor. (2) This factor was not suitable for describing color pairs. (3) The subjects did not accurately understand the meaning of the descriptive words.

$$effective\ rate = \frac{M}{N} \tag{5}$$

where M represents the number of subjects whose Pearson's correlation coefficient is greater than 0.5; N represents the total number of subjects, which is equal to 30.

Then, the Cronbach's alpha is used to measure the internal consistency of the evaluation results, usually above 0.7 is considered to be more reliable:

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_i^2}{\sigma_x^2}\right) \tag{6}$$

where K represents the number of subjects, σ_i^2 represents the score variance of all the subjects on the i^{th} measurement

TABLE 6. The result of the reliability analysis.

(a)		
Descriptive words	**Test-retest**	**Cronbach's Alpha**
harmony	0.73	0.86
(b)		
Descriptive words	**Test-retest**	**Cronbach's Alpha**
cool/warm	**0.82**	**0.94**
soft/hard	0.72	0.88
transparent/turbid	*0.64*	*0.81*
pleasure	0.75	0.87
arousal	0.72	0.9
dominance	0.71	0.81

Note: Table VI(a) shows the test-retest coefficient and Cronbach's Alpha of color harmony, and Table VI(b) shows the test-retest coefficient and Cronbach's Alpha of the subjective factors affecting color harmony. The maximum values are bolded, and the minimum values are italics.

item, and σ_x^2 represents the total variance of the total scores obtained by all the subjects. As shown in Table 6, all the scales have very good internal consistency among the 30 subjects, and the Cronbach's alpha are: 0.94 (''cool/warm''), 0.88 (''soft/hard''), 0.81 (''transparent/turbid''), 0.87 (pleasure), 0.9 (arousal), and 0.81 (dominance). Among them, the Cronbach's alpha of ''cold/warm'' is the highest, and the ''transparent/turbid'' is the lowest (Mean: 0.87, SD: 0.05).

B. ANALYSIS OF OBJECTIVE FACTORS AFFECTING COLOR HARMONY

In this section, the correlation analysis was evaluated by the Pearson's correlation coefficient, which mainly including three parts: (1) correlation analysis between objective factors (including color basic attributes and 21-dimensional objective physical features) and color harmony; (2) correlation analysis between subjective factors (including direct psychological effects and indirect psychological effects) and color harmony. In addition, some comparative studies were carried out with the classical color harmony theory.

1) ANALYSIS OF COLOR BASIC ATTRIBUTES AFFECTING COLOR HARMONY

Firstly, we applied scatter plots into intuitively showing the mapping relationship between color basic attributes (including hue, chroma, and lightness) and color harmony. For hue attribute, the materials were classified into 12 categories according to the main colors, namely R/V, YR/Dp, YR/V, Y/V, G/V, PB/V, PB/Dk, P/V, RP/P, N1.5, N5, and N9.5. For chroma attribute, according to the average value of chroma with main and assistant colors, 180 two-color combinations were divided into three categories: when $0 \leq C^* < 40$, it belongs to low category; when $40 \leq C^* \leq 60$, it belongs to medium category; when $60 < C^* \leq 100$, it belongs to high category. For lightness attribute, according to the average value of lightness with main and assistant colors, 180 two-color combinations were divided into three categories: when $0 \leq L^* < 40$, it belongs to low category; when $40 \leq L^* \leq 60$, it belongs to medium category; when $60 < L^* \leq 100$, it belongs to high category.

As shown in Figure 6(a), the materials with R/V, YR/Dp, G/V, and P/V as the main colors have uniform distributions. The materials with YR/V, Y/V, RP/P, N1.5, and N9.5 as the main colors have centralized distributions. Among them, the two-color combinations with RP/P and N9.5 as the main colors tend to be more harmonious. The two-color combinations with N1.5 as the main colors tend to be more disharmonious. In addition, a two-color combination with G/V as the main color obtained the highest degree of color harmony, and a two-color combination with N1.5 as the main color obtained the lowest degree of color harmony. As shown in Figure 6(b), the clear and definite relationship between chroma and color harmony cannot be found from the scatter plot, which may result from the weak correlation between chroma and color harmony. And a correlation analysis between objective physical features and color harmony will be carried out to further verify this result in the next. As shown in Figure 6(c), there is a centralized distribution of the materials with low lightness, which tend to be more disharmonious. On the other hand, the average value of color harmony degree with high lightness is greater than 0, the avearge value of color harmony degree with medium lightness is close to 0, and the average value of color harmony degree with low lightness is less than 0, indicating that there maybe a linear relationship between lightness and color harmony.

2) ANALYSIS OF OBJECTIVE PHYSICAL FEATURES AFFECTING COLOR HARMONY

According to the subjective evaluation experiment in Section III (A) and the feature extraction in Section III (B), the scatter plot and the Pearson's correlation coefficient (r) were adopted to measure the correlation between objective physical features and color harmony. Basically speaking, the r value exceeding 0.8 is interpreted as a strong correlation, and below 0.5 a poor correlation. Therefore, this article drew the scatter plots to examine the correlation, and calculated the r values after removing the abnormal distribution on the plots. The scatter plots with correlation are shown in Figure 7. There is a significant correlation between objective physical features, namely lightness category and distance category, and color harmony. Specifically, L_1^*, L_2^*, and $mean\_L^*$ are positively correlated with color harmony, and ΔE and ΔC^* are negatively correlated with color harmony. (The total correlation coefficient matrix is shown in Appendix, Figure 15.)

For the lightness categories, specifically, the Pearson's correlation coefficient between L_1^* and color harmony is: $r = 0.531, p < 0.001$, the Pearson's correlation coefficient between L_2^* and color harmony is: $r = 0.577, p < 0.001$, and the Pearson's correlation coefficient between $mean\_L^*$ and color harmony is: $r = 0.738, p < 0.001$, that is, *there is a correlation between lightness and color harmony. The data show that in the* same *color pair, the greater the lightness of the main and assistant colors is, the more harmonious the color pair is*.

For the distance category, specially, the Pearson's correlation coefficient between ΔE and color harmony is:

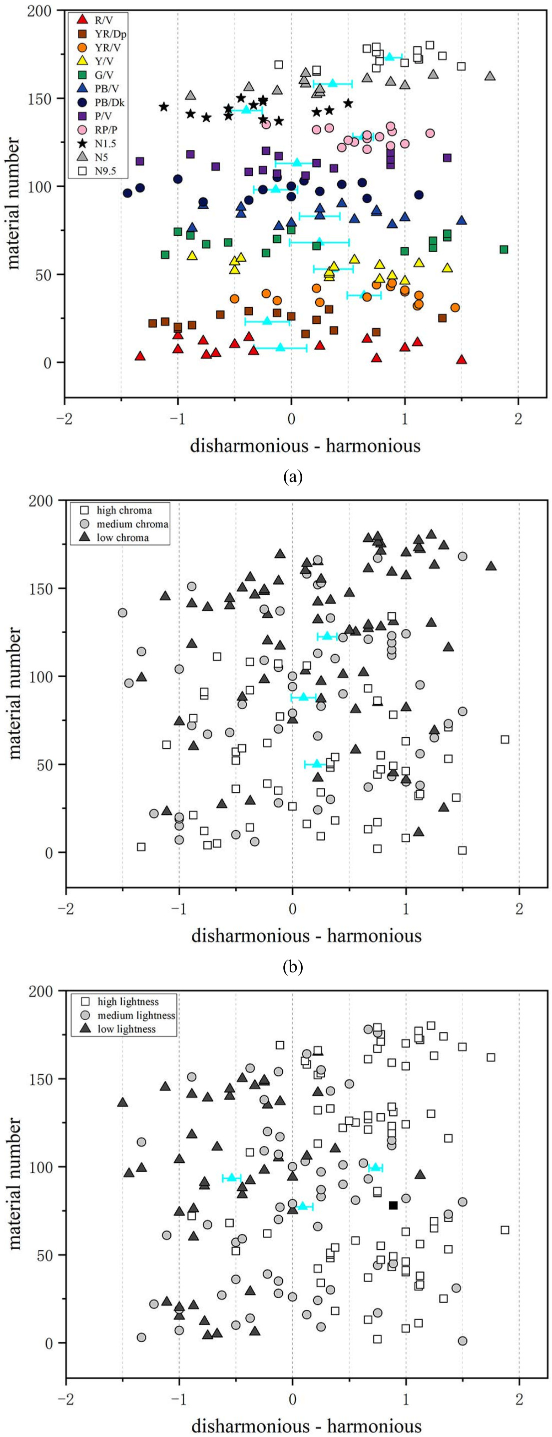


FIGURE 6. The scatter plots between color basic attributes and color harmony. Among the m, Figure 6(a) shows the correlation between hue and color harmony, Figure 6(b) shows the correlation between chroma and color harmony, and Figure 6(c) shows the correlation between lightness and color harmony. As shown in Figure 6(a), the materials with R/V, YR/Dp, G/V, and P/V as the main colors have uniform distributions. The cyan triangles show the average of color harmony degree from each hue category, and the error bars show the standard deviation of color harmony degree from each hue category. (The scatter plots between color basic attributes and subjective factors are shown in Appendix, Figure 14.)

$r = -0.5, p < 0.001$, and the Pearson's correlation coefficient between ΔC^* and color harmony is: $r = -0.509, p < 0.001$, that is, *there is a correlation between distance attribute and color harmony. The data show that in the same color pair, the smaller the color difference between the main and* assistant *colors is, the more harmonious the color pair is*. Compare to Δa^* and Δb^*, the distance attribute is more correlated with color harmony, indicating that the Euclidean distance can better represent the difference between two colors.

Further, we made a comparison with the Moon-Spencer color harmony model. The lightness difference of color pairs was divided into three categories on the basis of the Moon-Spencer color harmony model, namely identity ($\Delta V = 0$), similarity ($\Delta V \in [0.5, 1.5]$), contrast ($\Delta V \in [2.5, 3]$), glare ($\Delta V \in (3, 10]$) and the reset are ambiguous areas, where V represents the value dimension in the Munsell color system. On this basis, the changing law of the color harmony perception can be studied under the different lightness relationship. Firstly, we need to transform L^* in the CIELAB color space to V in the Munsell color system. As shown in Figure 8(a), the degree of color harmony in different lightness harmony modes shows the consistent changing trend with Moon-Spencer color harmony model, that is, the degree of color harmony increases synchronously with the lightness difference, and decreases rapidly when the lightness difference reaches a certain limit. Specifically, the average value of identity harmony is 0.27, the average value in the 1st ambiguous area is 0.261, the average value of similar harmony is 0.228, the average value in the 2nd ambiguous area is 0.132, the average value of contrastive harmony is 0.349, which is the highest, and the average value of glare harmony is 0.204. It is worth noting that, although the changing trend is similar, there are differences between our analysis results and the Moon-Spencer color harmony model in the classification of lightness difference.

Then, the hue difference of color pairs was divided into three categories on the basis of the Moon-Spencer color harmony model, namely identity ($\Delta H = 0°$), similarity ($\Delta H \in [25°, 43°]$), and contrast ($\Delta H \in [100°, 180°]$), and the reset are ambiguous areas, where H represents the hue dimension in the Munsell color system. On this basis, the changing rule of color harmony can be studied under the different hue differences. Similarly, because h represents the radian in each quadrant, we need to transform h in the CIELAB color space to H in the Munsell color system [41].

$$h' = \begin{cases} h, & \textit{in the 1st quadrant} \\ 180° + h, & \textit{in the 2nd quadrant} \\ 180° + h, & \textit{in the 3rd quadrant} \\ 360° + h, & \textit{in the 4th quadrant} \end{cases} \tag{7}$$

Then, since the Moon-Spencer color harmony model quantifies the H interval with the angle between hues on the ring, it cannot linearly represent the perceptual

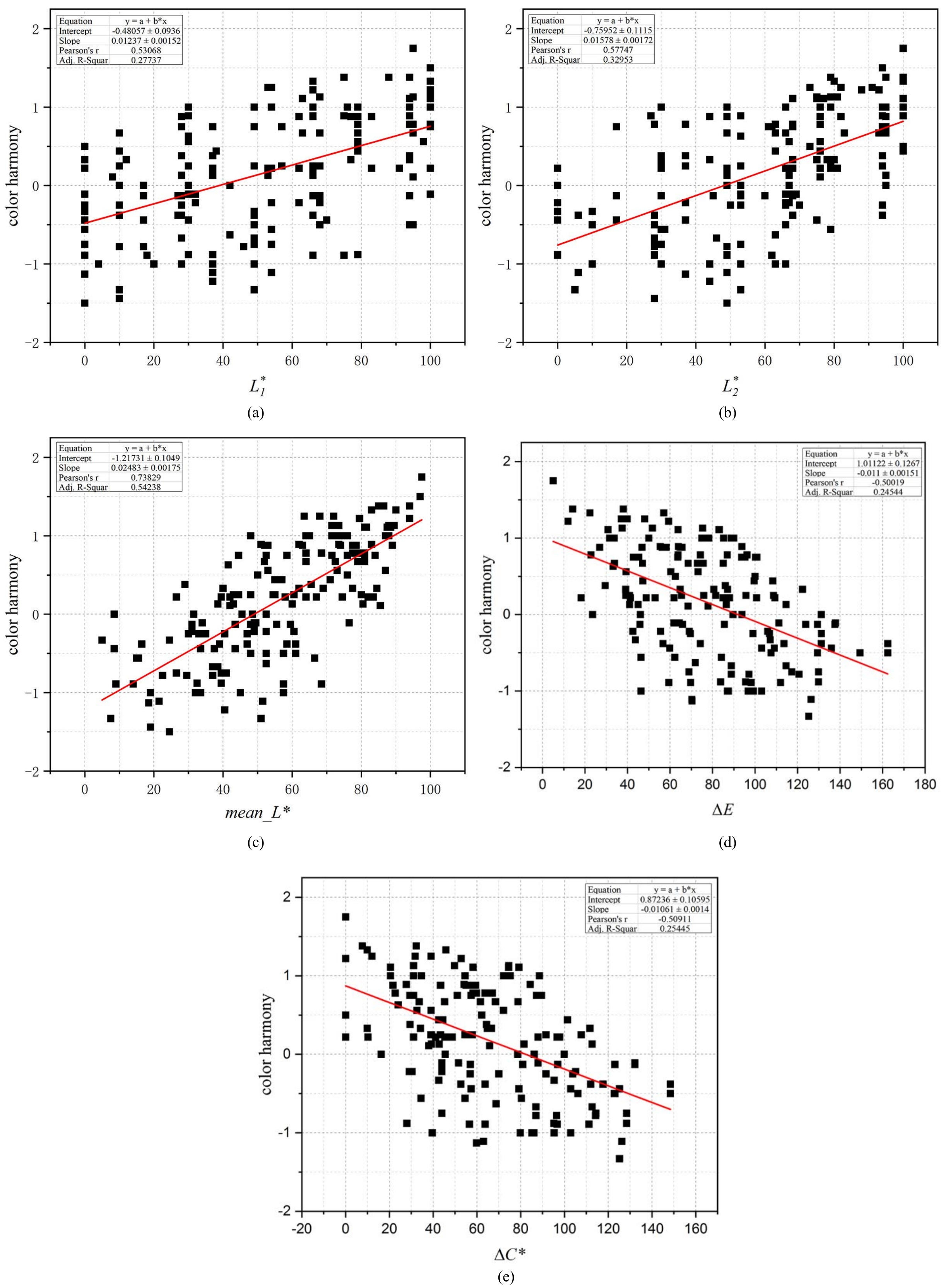


FIGURE 7. The scatter plots between objective physical features and color harmony. The X-axis represents the corresponding objective physical feature, and the Y-axis represents the degree of color harmony.

difference. We put forward the following method to calculate the H interval:

$$\Delta H = \begin{cases} h'_2 - h'_1, & if\ h'_2 - h'_1 \leq 180^\circ \\ 360^\circ - h'_2 + h'_1, & if\ h'_2 - h'_1 > 180^\circ \end{cases} \quad (8)$$

where h'_1 and h'_2 respectively represent the hue angle values of the main color and the assistant color in the CIELAB color space, and $h'_2 > h'_1$.

As shown in Figure 8(b), the degree of color harmony in different hue harmony modes shows a trend of "monotonically decreasing overall and slightly fluctuating locally except identity harmony" with the increase of hue difference, which is consistent with the above rules. Specifically, according to the hue interval from small to large, the average value of identical harmony is 0.69, the average value in the 1st ambiguous area is 0.595, the average value of similar harmony is 0.928, the average value in the 2nd ambiguous area is 0.352, and the average value of contrastive harmony is -0.261. Among them, the average value of similarity is highest, the average values from similarity to contrast decrease in turn, the average values of identity and similarity are higher than that in the 1st and 2nd ambiguous areas. The above data analysis results are in line with the basic rule of the Moon-Spencer color harmony model. However, and the average value of contrast is negative and lower than that of the 1st and 2nd ambiguous areas, which is inconsistent with the Moon-Spencer color harmony model.

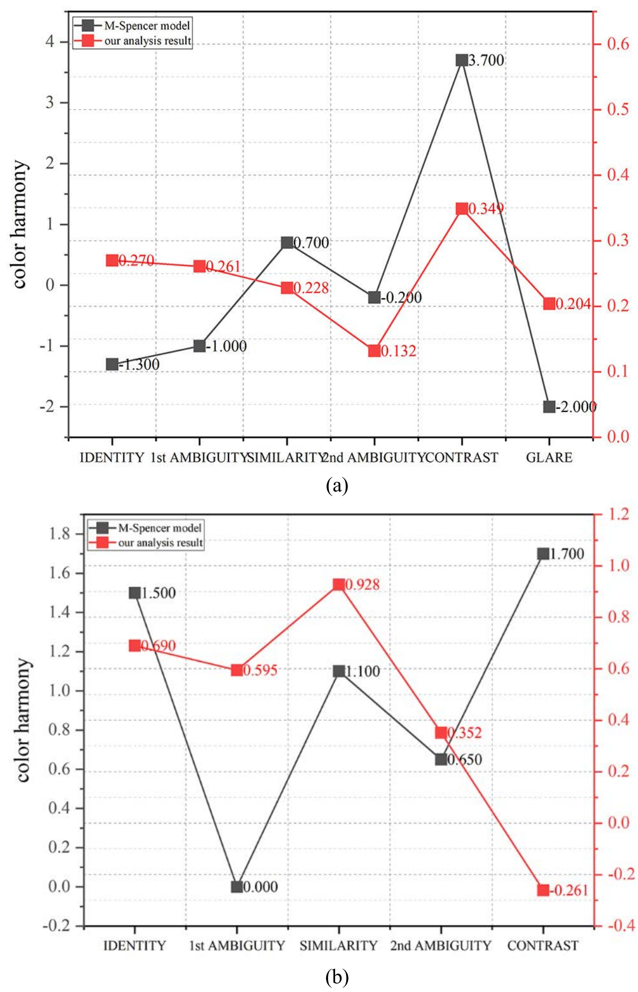


FIGURE 8. The comparison between our analysis results and the Moon-Spencer color harmony model. Among them, Figure 8(a) shows the comparison to the lightness category, and Figure 8(b) shows the comparison to the red/green and yellow/blue categories.

3) ANALYSIS OF DIRECT PSYCHOLOGICAL EFFECTS AFFECTING COLOR HARMONY AFFECTING COLOR HARMONY

First, the Pearson's correlation coefficient was adopted to measure the degree of correlation between direct psychological effects and color harmony. There is a correlation between direct psychological effects (including "cool/warm", "soft/hard", and "transparent/turbid") and color harmony. Specifically, the Pearson's correlation coefficient between SH and color harmony is: $r = -0.59, p < 0.001$, that is, *there is a strong correlation between the "soft/hard" sense and color harmony*. The data show that the color pair with a softer color combination tends to be more harmonious. The Pearson's correlation coefficient between TT and color harmony is: $r = -0.717, p < 0.001$, that is, *there is a very strong correlation between the "transparent/turbid" sense and color harmony*. The data show that the color pair with a more transparent color combination tends to be more harmonious.

Similar to the generation process of color harmony, the direct psychological effects of subjective factors are influenced by the objective physical features. Therefore, we further analyzed the degree of correlation between objective factors and direct psychological effects. As shown in Figure 9, *there is a correlation between the "cool/warm" sense and the red/green, yellow/blue, and chroma categories in objective factors*. Specifically, CW has the highest correlation with *mean_a**, *mean_b**, and *mean_C**, respectively, and the Pearson's correlation coefficients are: $r = 0.518, p < 0.001$, $r = 0.648, p < 0.001$, and $r = 0.559, p < 0.001$. *There is a correlation between "soft/hard" sense and the lightness category in objective factors*. Specifically, SH has the highest correlation with L_2^* and *mean_L**, respectively, and the Pearson's correlation coefficients are:$r = -0.563$, $p < 0.001$, and $r = 0.685, p < 0.001$. *There is a correlation between "transparent/turbid" and the lightness categories*. Specifically, TT has the highest correlation with L_1^* and *mean_L**, respectively, and the Pearson's correlation coefficients are: $r = 0. - 0.532, p < 0.001$ and $r = 0.669, p < 0.001$. *Of all the objective factors, lightness categories has the strongest correlation with direct psychological effects, which is as the same to color harmony.*

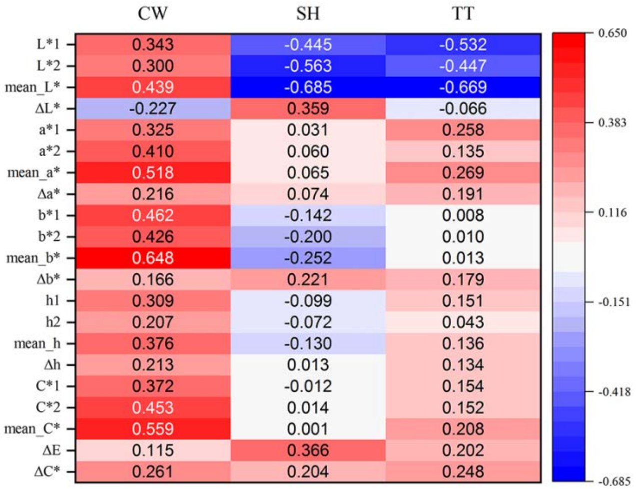


FIGURE 9. The heat map of the Pearson's correlation coefficient between 21-dimensional objective physical features and the direct psychological effects.

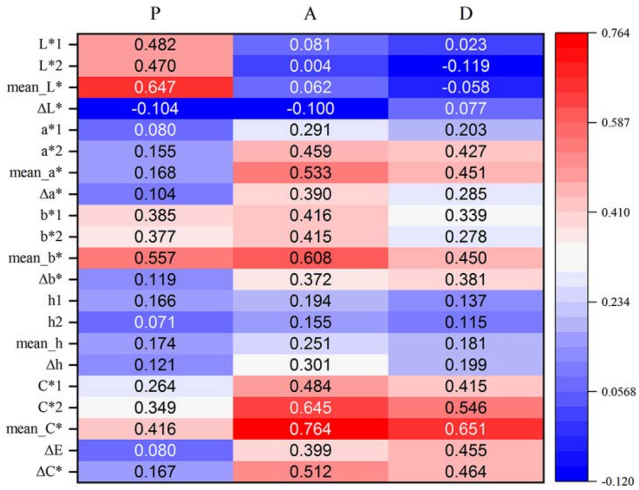


FIGURE 10. The heat map of the Pearson's correlation coefficient between 21-dimensional objective physical features and the indirect psychological effects.

4) ANALYSIS OF INDIRECT PSYCHOLOGICAL EFFECTS AFFECTING COLOR HARMONY AFFECTING COLOR HARMONY

Then, the Pearson's correlation coefficient was adopted to measure the degree of correlation between indirect psychological effects and color harmony. There is a correlation between indirect psychological effects (including pleasure, arousal, and dominance) and color harmony. Specifically, the Pearson's correlation coefficient between pleasure and color harmony is: $r = 0.545, p < 0.001$, that is, *there is a strong positive correlation between pleasure and color harmony*. However, the Pearson's correlation coefficients of A and D are low, that is, *the sense of arousal and dominance produced by color pairs has no clear relationship with color harmony*.

Further, in order to compare with indirect psychological effects, we analyzed the degree of correlation between objective factors and indirect psychological effects. As shown in Figure 10, *there is a correlation between pleasure and the lightness and yellow/blue categories in objective factors*. Specifically, pleasure has the highest correlation with *mean_L** and *mean_b**, respectively, and the Pearson's correlation coefficients are: $r = 0.647, p < 0.001$ and $r = 0.557, p < 0.001$. *There is a correlation between arousal and almost all the objective factors, namely red/green, yellow/blue, chroma, and distance categories*. Specifically, arousal has the highest correlation with *mean_a**, *mean_b**, C_2^*, *mean_C**, and ΔC^*, respectively, and the Pearson's correlation coefficients are: $r = 0.533, p < 0.001$, $r = 0.608, p < 0.001$, $r = 0.645, p < 0.001$, $r = 0.764, p < 0.001$ and $r = 0.512, p < 0.001$. *There is a correlation between dominance and the chroma category*. Specifically, dominance has the highest correlation with C_2^* and *mean_C**, respectively, and the Pearson's correlation coefficients are: $r = 0.546, p < 0.001$ and $r = 0.651, p < 0.001$. *Of all the objective factors, chroma categories has the strongest correlation with indirect psychological effects*.

TABLE 7. The Pearson's correlation coefficients between direct psychological effects and indirect psychological effects, complement with color harmony.

	Pearson's correlation coefficient		
	CW	SH	TT
pleasure	**0.777**	**-0.611**	-0.338
arousal	**0.767**	0.005	0.283
dominance	**0.523**	0.185	0.199
color harmony	0.207	**-0.59**	**-0.717**

Note: Bold indicates that there is a correlation.

Finally, the degree of correlation between direct psychological effects and indirect psychological effects is as shown in Table 7. *There is a correlation between pleasure and direct psychological effects, namely "cool/warm", and "soft/hard"*. Specifically, the Pearson's coefficients between them are: $r = 0.777, p < 0.001$ ("cool/warm") and $r = -0.611, p < 0.001$ ("soft/hard"). The data show that warmer, softer color combinations are more likely to generate pleasant emotions. In addition, arousal and dominance also have the correlation with CW, and the Pearson's correlation coefficients are: $r = 0.767, p < 0.001$ (arousal) and $r = 0.523, p < 0.001$ (dominance). *In other words, emotion has the strongest correlation with the "cool/warm" sense of color, whereas color harmony has the strongest correlation with the "transparent/turbid" sense.*

C. MATHEMATICAL MODELING OF COLOR HARMONY

According to the CHG hierarchy model, machine learning was adopted to construct the hierarchical mathematical model between associated layers, which mainly including three parts: (1) model construction between objective factors and color harmony; (2) model construction between subjective factors (including direct psychological effects and indirect psychological effects) and color harmony; and (3) model construction from objective physical features to color harmony with the subjective factors as the connecting bridge. In addition, some comparative studies were carried out among (1), (2), and (3).

1) MODELING BETWEEN OBJECTIVE PHYSICAL FEATURES AND COLOR HARMONY

In order to further study the important relationship between objective factors and color harmony and the influence strength of multiple objective factors on color harmony, machine learning algorithms were adopted to construct the mathematical model. From the correlation analysis results, it is possible that there is a linear correlation between the objective physical features and color harmony, and they are independent of each other. Therefore, in the first, the Multivariable Linear Regression (MLR) algorithm [42] was adopted to mathematically model color harmony. Let $D = \{(\boldsymbol{X}, y_1), (\boldsymbol{X}, y_2), \cdots, (\boldsymbol{X}, y_m)\}$ be the training set, where, for 180 pictures, $\boldsymbol{X}$ is the color objective physical feature vector containing 21 dimensions (see Table 5), and y_i is the average score of the effective data from 30 subjects on color harmony. The steps are as follows.

Step 1: To eliminate the influence of the difference in dimensions among different data, normalization to [0, 1] was implemented:

$$x_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{9}$$

$$y_i = \frac{y_i - y_{min}}{y_{max} - y_{min}} \tag{10}$$

Step 2: Construct linear regression function $f(\boldsymbol{X})$ to make $|f(\boldsymbol{X}) - y_i|$ as close as possible to ε. Among them, $f(\boldsymbol{X})$ represents the degree of color harmony, and ε is usually equal to 0. For MLR:

$$f(\boldsymbol{X}) = \boldsymbol{\omega}^T \Theta(\boldsymbol{X}) + b \tag{11}$$

where $\boldsymbol{\omega}$ and b are the regression coefficients; Θ is the linear mapping of $\boldsymbol{X}$.

Step 3: When $|f(\boldsymbol{X}) - y_i| \leq \varepsilon$, the loss is zero. Therefore, the Mean Squared Error (MSE) to construct the loss function $J(\omega, b)$:

$$J(\boldsymbol{\omega}, b) = \sum (f(\boldsymbol{X}) - y_i)^2 \tag{12}$$

Step 4: Minimize the loss function $J(\boldsymbol{\omega}, b)$, and solve for the regression coefficients $\boldsymbol{\omega}$ and b.

The weka software (3.8.3; The University of Waikato, Hamilton, New Zealand) with functions of machine learning and data mining was adopted to construct the MLR model. Finally, the following is the MLR equation.

$$\begin{aligned} color\ harmony = {} & 0.404L_1^* + 0.354L_2^* + 0.261\Delta L^* \\ & - 0.438a_1^* - 0.331a_2^* + 0.467mean_{a^*} \\ & - 0.22\Delta a^* + 0.212b_2^* - 0.468mean_{b^*} \\ & - 0.28\Delta E - 0.222\Delta C^* + 0.298h_1 \\ & + 0.174h_2 - 0.279mean_h + 0.133C_1^* \\ & + 0.333mean_C + 0.228 \end{aligned} \tag{13}$$

From the Equation (13), it can be seen that the degree of color harmony is affected by a variety of objective factors, namely lightness, red/green, yellow/blue, hue, chroma, and distance categories. Specifically, it includes the following rules: (1) The degree of color harmony is most sensitive to *mean_a** and *mean_b** between color pairs. Among them, the average value of red/green increases by 1, the color harmony degree increases by 0.467, and the average value of yellow/blue increases by 1, the color harmony degree decreases by 0.468. (2) The degree of color harmony is more sensitive to the lightness category between color pairs. The higher the overall lightness is, the more harmonious the color is. Among them, the value of L_1^*, L_2^*, and ΔL^* increases by 1, and the color harmony degree increases by 0.404, 0.354, and 0.261 respectively. (3) The degree of color harmony is less sensitive to the hue and chroma categories.

Then, three other nonlinear machine learning algorithms were adopted to construct the mathematical model, namely, the SVR algorithm [43], the random forest (RF) algorithm [44], and the back propagation neural network (BP) algorithm [45]. In this article, we selected 10-fold cross validation to evaluate the accuracy of the model, that is, the dataset is divided into 10 subsets, and nine of them are taken as training sets without repetition, and the prediction errors of the remaining subsets are evaluated, and the evaluation indexes are Pearson's correlation coefficient (r), r square, and mean absolute error (MAE). It can be seen from Figure 11 that the MLR algorithm has the best prediction performance. Therefore, *the linear mathematical model can well explain the generation process from objective factors to color harmony*.

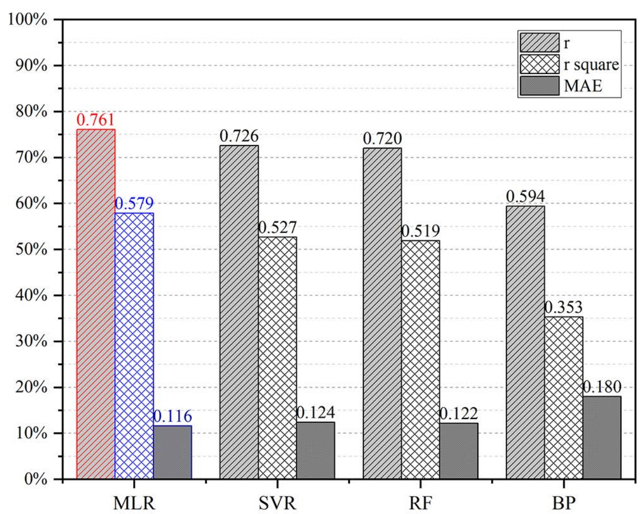


FIGURE 11. The 10-fold cross validation results of the model between objective factors and color harmony.

Although, for machine learning, the more parameters the better; but, for discussing the phenomenon of color harmony, the model for color harmony better involves significant parameters only. Therefore, according to Section IV (B) (2), the objective physical features of lightness category and distance category which significantly correlated with color harmony were selected to construct the MLR model:

$$color\ harmoy = 0.326L_1^* + 0.372L_2^* - 0.275\Delta L^* - 0.435\Delta E \quad (14)$$

The evaluation indexes are: 0.754 (r), 0.568 (r square), and 0.116 (MAE).

2) MODELING BETWEEN DIRECT PSYCHOLOGICAL EFFECTS AND COLOR HARMONY

Similarly, the weka software was adopted to construct the multivariable linear regression equation between the direct psychological effects and color harmony. Finally, the following is the multivariable linear regression equation.

$$color\ harmony = -0.315SH - 0.517TT + 0.946 \quad (15)$$

From the Equation (15), it can be seen that the degree of color harmony is mainly affected by ''soft/hard'' sense and ''transparent/turbid'' sense. Specifically, it includes the following rules: (1) The degree of color harmony is sensitive to ''soft/hard'' sense, and the softer the feeling is, the more harmonious the color pair is. Among them, the SH increases by 1, and the color harmony degree decreases by 0.315. (2) The degree of color harmony is most sensitive to the ''transparent/turbid'' sense, and the more transparent the color pair is, the more harmonious it is. Among them, the TT increases by 1, and the color harmony degree decreases by 0.517.

Then, SVR algorithm, RF algorithm, and BP algorithm were also adopted to construct the mathematical model. The evaluation results of 10-fold cross validation are as shown in Figure 12. It can be seen that the MLR algorithm also has the best prediction performance. Therefore, *the linear mathematical model can well explain the generation process from direct psychological effects to color harmony*.

3) MODELING BETWEEN INDIRECT PS YCHOLOGICAL EFFECTS AND COLOR HARMONY

The following is the multivariable linear regression equation between indirect psychological effects and color harmony.

$$color\ harmony = 0.813P - 0.616A + 0.374 \quad (16)$$

From the Equation (16), it can be seen that the degree of color harmony is mainly affected by pleasure and arousal. Specifically, it includes the following rules: (1) The degree of color harmony is very sensitive to pleasure, and the more pleasant the emotion is, the more harmonious the color pair is. Among them, the P increases by 1, and the color harmony degree decreases by 0.813. (2) The degree of color harmony is sensitive to the arousal, and the less arousable the color pair is, the more harmonious it is. Among them, the A increases by 1, and the color harmony degree decreases by 0.616.

Then, SVR algorithm, RF algorithm, and BP algorithm were also adopted to construct the mathematical model.

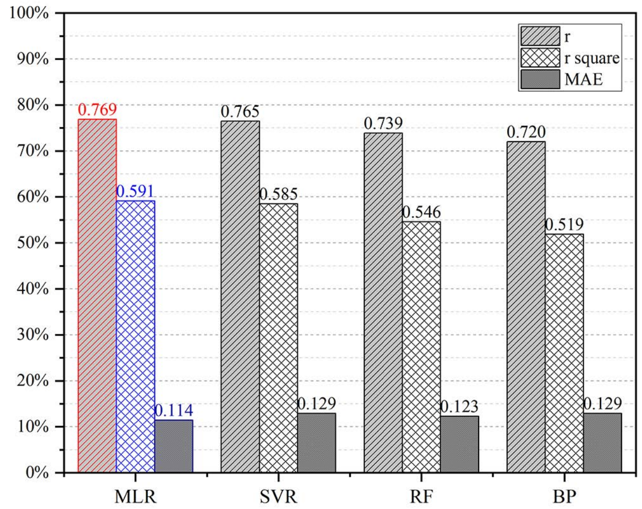


FIGURE 12. The 10-fold cross validation results of the model between direct psychological effects and color harmony.

The evaluation results of 10-fold cross validation are as shown in Figure 13. It can be seen that the BP algorithm has the best prediction performance, indicating that *the relationship between emotion and color harmony can be explained as a more complex nonlinear model*.

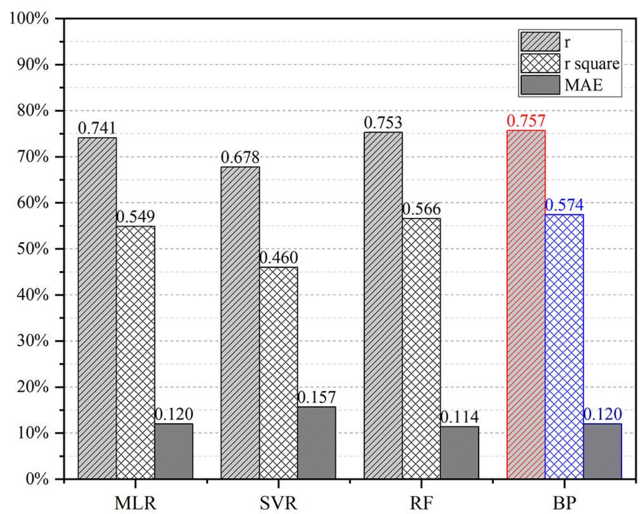


FIGURE 13. The 10-fold cross validation results of the model between indirect psychological effects and color harmony.

It is worth noting that, compared with the model constructed by objective factors, the model constructed by subjective factors has higher prediction accuracy. The possible reasons are: (1) Color harmony is not only affected by objective factors, but also by subjective factors, and the correlation between subjective factors is stronger than by objective factors. (2) Although color harmony is produced by the physical stimulation of color, there is a ''semantic gap'' between objective physical features and indirect psychological effects at the signal processing level. Therefore, the subjective

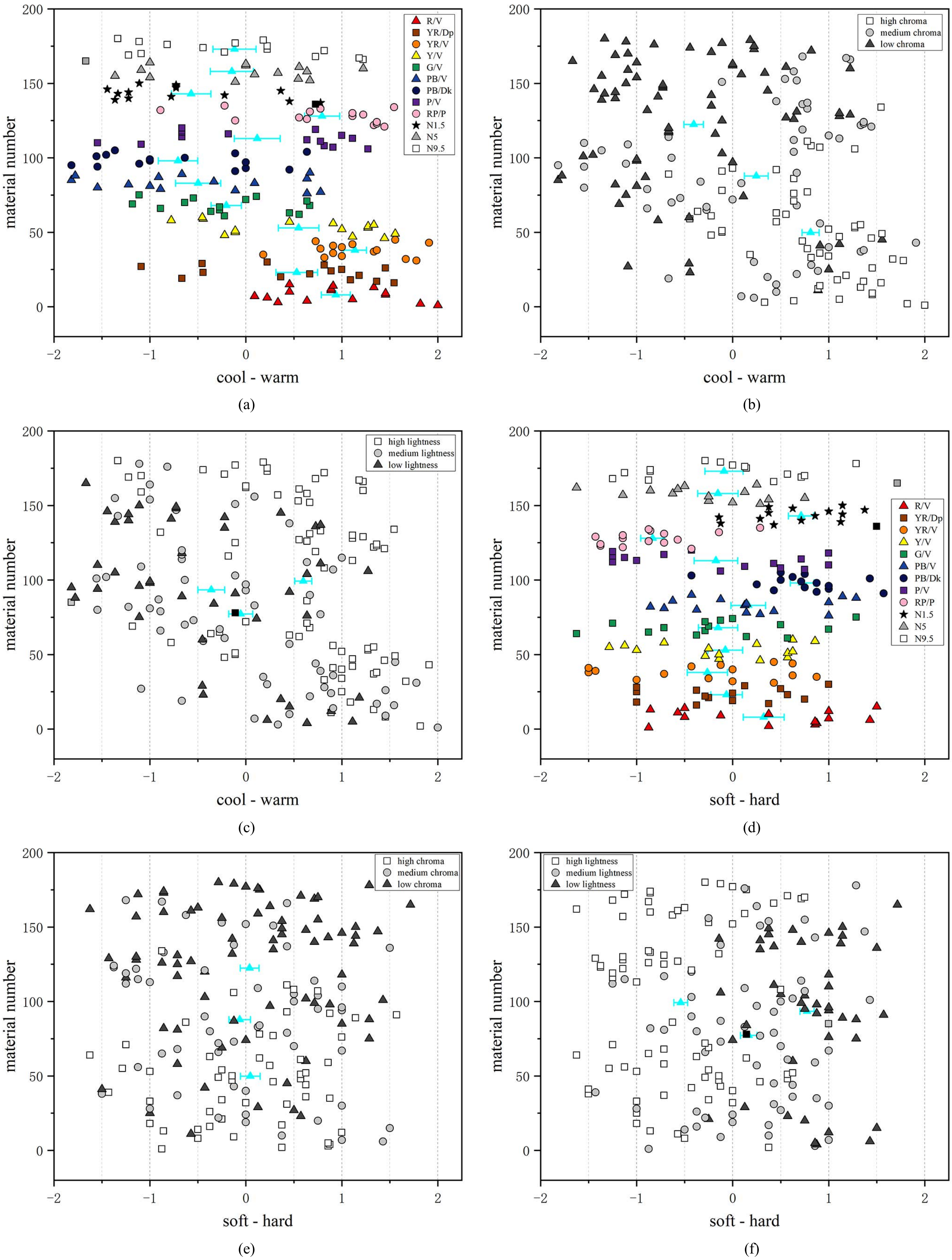


FIGURE 14. **The value distributions of subjective factors of different color basic attribute categories. Among them, X-axis shows the value of each subjective factor, namely "cool/warm", "soft/hard", "transparent/turbid", pleasure, arousal, and dominance; Y-axis shows the corresponding material number.**

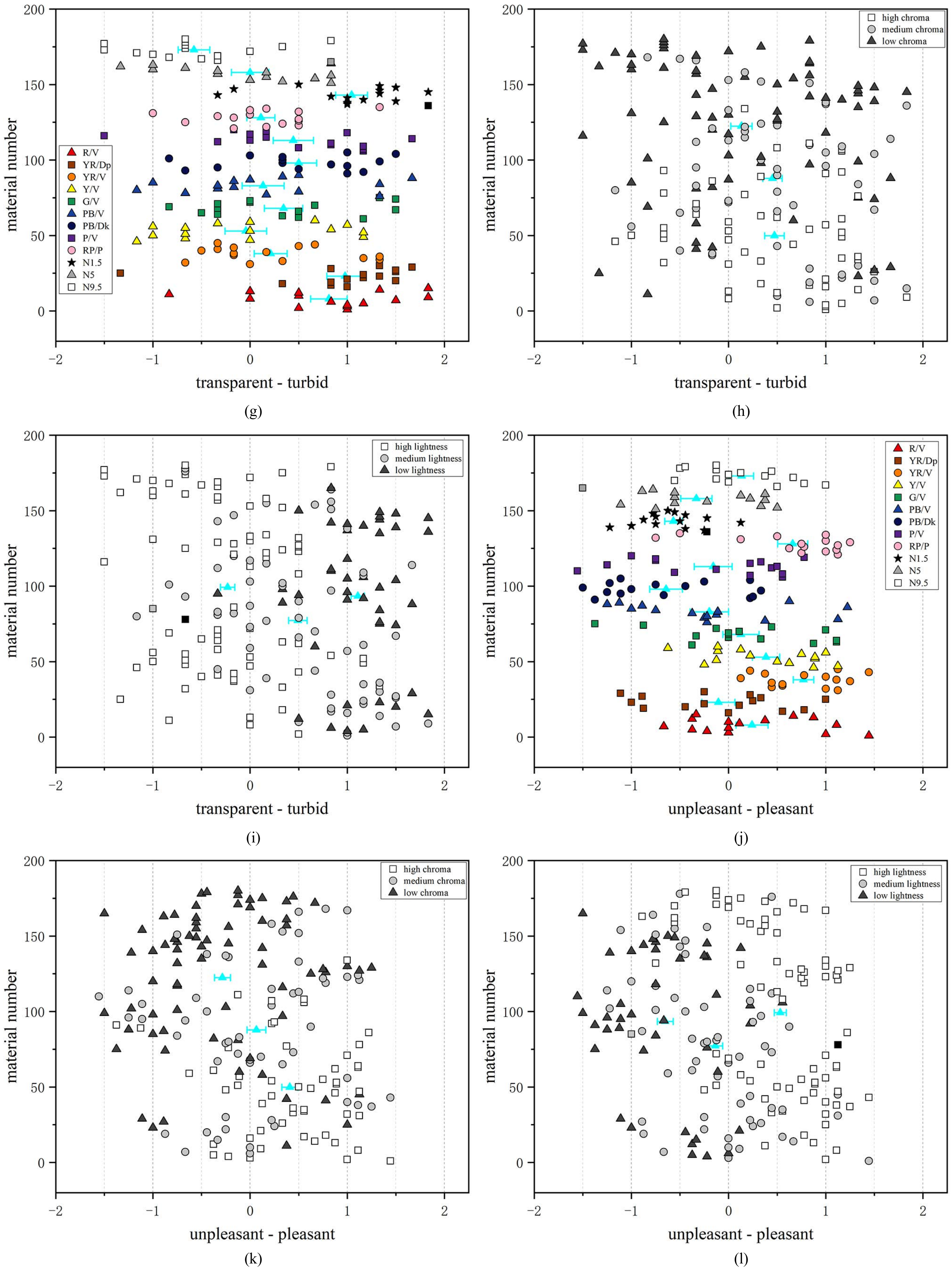


FIGURE 14. ***(Continued.)*** **The value distributions of subjective factors of different color basic attribute categories. Among them, X-axis shows the value of each subjective factor, namely "cool/warm", "soft/hard", "transparent/turbid", pleasure, arousal, and dominance; Y-axis shows the corresponding material number.**

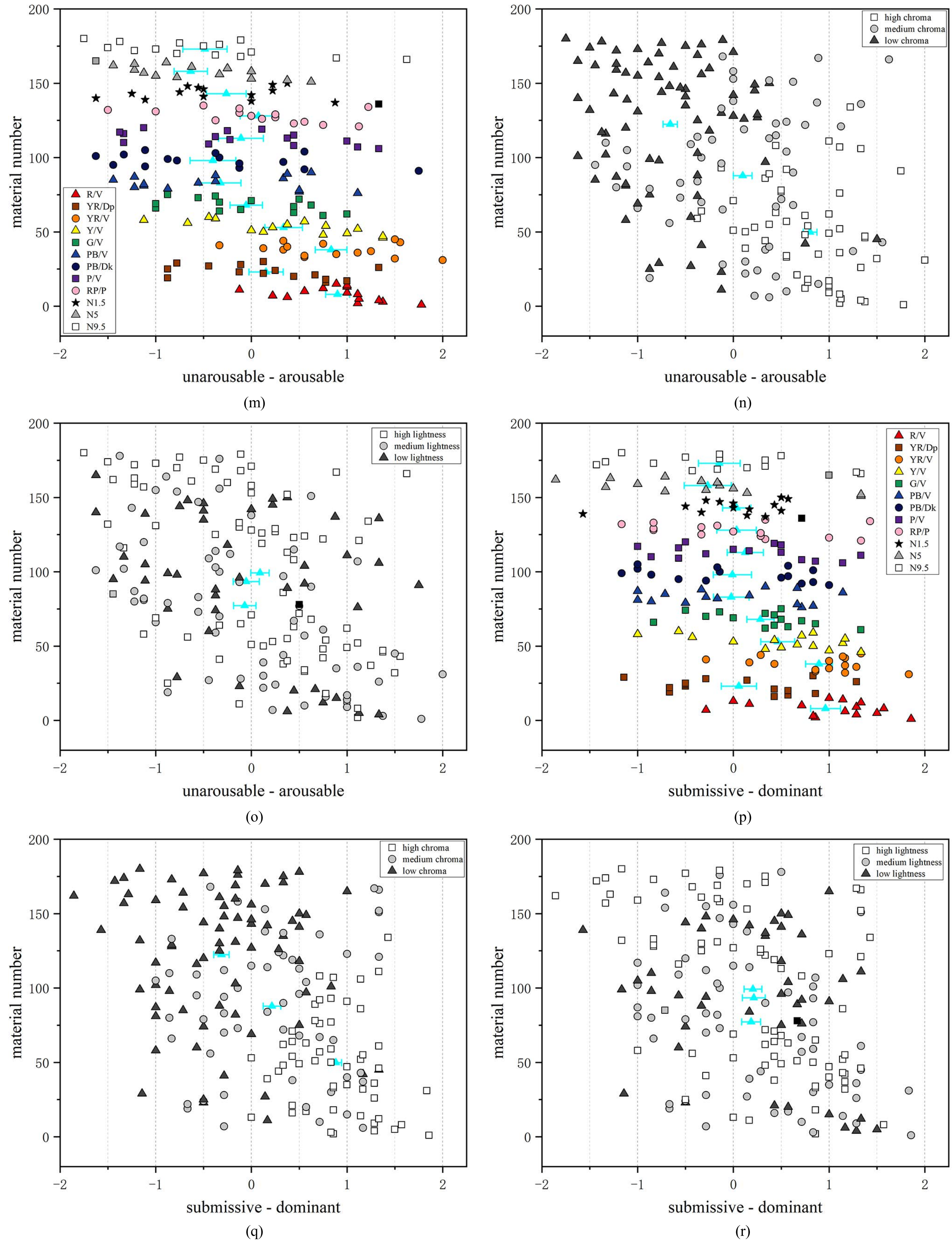


FIGURE 14. ***(Continued.)*** **The value distributions of subjective factors of different color basic attribute categories. Among them, X-axis shows the value of each subjective factor, namely "cool/warm", "soft/hard", "transparent/turbid", pleasure, arousal, and dominance; Y-axis shows the corresponding material number.**

	objective factors																						subjective factors						color harmony
																							indirect psychological effects			direct psychological effects			
	L^*_1	L^*_2	$mean\_L^*$	ΔL^*	a^*_1	a^*_2	$mean\_a^*$	Δa^*	b^*_1	b^*_2	$mean\_b^*$	Δb^*	ΔE	ΔC^*	$h1$	$h2$	$mean\_h$	Δh	C^*1	C^*2	$mean\_C^*$	ΔC^*	CW	SH	TT	P	A	D	
L^*_1	1	0.080	**0.780**	-0.198	-0.161	0.004	-0.102	0.058	0.454	-0.045	0.290	-0.084	-0.121	-0.035	0.077	-0.016	0.044	-0.033	0.030	-0.003	0.018	0.012	0.343	-0.455	**-0.532**	0.482	0.081	0.023	**0.531**
L^*_2		1	**0.687**	-0.047	-0.021	-0.232	-0.187	-0.027	-0.078	0.462	0.291	-0.085	-0.100	-0.072	0.019	0.005	0.022	-0.024	-0.078	0.070	-0.007	0.035	0.300	**-0.563**	-0.447	0.470	0.004	-0.119	**0.577**
$mean\_L^*$			1	-0.174	-0.131	-0.142	-0.191	0.025	0.282	0.258	0.394	-0.115	-0.151	-0.071	0.068	-0.009	0.046	-0.039	-0.027	0.042	0.009	0.031	0.439	**-0.685**	**-0.669**	**0.647**	0.062	-0.058	**0.738**
ΔL^*				1	-0.171	-0.021	-0.128	-0.192	-0.128	-0.003	-0.093	0.205	0.475	0.070	-0.245	-0.146	-0.284	-0.101	-0.181	-0.005	-0.129	0.130	-0.227	0.359	-0.066	-0.104	-0.100	0.077	-0.025
a^*_1					1	0.016	**0.666**	0.145	0.063	-0.019	0.030	0.057	0.050	0.131	0.446	0.073	0.367	0.104	0.425	-0.035	0.271	-0.002	0.325	0.031	0.258	0.080	0.291	0.203	-0.144
a^*_2						1	**0.757**	0.007	-0.001	0.069	0.051	0.176	0.101	0.134	-0.044	0.424	0.288	0.080	0.044	0.420	0.310	0.124	0.410	0.060	0.135	0.155	0.459	0.427	-0.123
$mean\_a^*$							1	0.100	0.040	0.039	0.058	0.169	0.108	0.185	0.258	0.364	0.455	0.128	0.311	0.290	0.408	0.091	**0.518**	0.065	0.269	0.168	**0.533**	0.451	-0.186
dif_a^*								1	0.220	0.154	0.273	0.023	0.354	0.493	0.099	0.081	0.127	0.120	0.328	0.266	0.404	0.146	0.216	0.074	0.191	0.104	0.390	0.285	-0.306
b^*_1									1	-0.066	**0.663**	-0.007	0.055	0.122	0.372	-0.073	0.206	0.060	**0.505**	0.074	0.398	-0.003	0.462	-0.142	0.008	0.385	0.416	0.339	0.088
b^*_2										1	**0.704**	0.074	0.115	0.155	0.004	0.206	0.155	0.167	-0.028	**0.591**	0.374	0.221	0.426	-0.200	0.010	0.377	0.415	0.278	0.172
$mean\_b^*$											1	0.051	0.126	0.203	0.268	0.103	0.263	0.168	0.339	0.496	**0.564**	0.164	**0.648**	-0.252	0.013	**0.557**	**0.608**	0.450	0.192
Δb^*												1	**0.819**	**0.864**	-0.241	-0.216	-0.336	0.351	0.294	0.426	0.487	0.327	0.166	0.221	0.179	0.119	0.372	0.381	-0.278
ΔE													1	**0.889**	-0.202	-0.200	-0.298	0.285	0.287	0.405	0.468	0.284	0.115	0.366	0.202	0.080	0.399	0.455	**-0.509**
ΔC^*														1	-0.150	-0.170	-0.238	0.380	0.430	**0.510**	**0.637**	0.313	0.261	0.204	0.248	0.167	**0.512**	0.464	**-0.509**
$h1$															1	-0.057	**0.662**	-0.109	-0.053	-0.005	-0.039	0.138	0.309	-0.099	0.151	0.166	0.194	0.137	0.015
$h2$																1	**0.709**	0.042	0.033	-0.058	-0.016	0.010	0.207	-0.072	0.043	0.071	0.155	0.115	0.003
$mean\_h$																	1	-0.046	-0.017	-0.051	-0.045	0.102	0.376	-0.130	0.136	0.174	0.251	0.181	0.017
Δh																		1	0.266	0.272	0.365	0.011	0.213	0.013	0.134	0.121	0.301	0.199	-0.152
C^*1																			1	0.085	**0.748**	-0.210	0.372	-0.012	0.154	0.264	0.484	0.415	-0.078
C^*2																				1	**0.725**	0.223	0.453	0.014	0.152	0.349	**0.645**	**0.546**	-0.053
$mean\_C^*$																					1	0.003	**0.559**	0.001	0.208	0.416	**0.764**	**0.651**	-0.089
ΔC^*																						1	0.111	0.049	0.037	0.040	0.171	0.176	-0.111
CW																							1	-0.471	-0.016	**0.777**	**0.767**	**0.523**	0.207
SH																								1	0.455	**-0.611**	0.005	0.185	**-0.590**
TT																									1	-0.338	0.283	0.199	**-0.717**
P																										1	**0.542**	0.398	**0.545**
A																											1	**0.796**	-0.150
D																												1	-0.116
color harmony																													1

FIGURE 15. The total correlation coefficient matrix.

factors can improve the problem of accuracy decreasing resulted from this gap, so as to increase the interpretability of the model.

V. CONCLUSION

This article tacked color pair as the research object, divided the factors affecting color harmony into objective factors and subjective factors, studied the relationship among three of them, and constructed the mathematical model to predict color harmony. Among them, the objective factors were constructed based on the three elements of color (hue, chroma, and lightness), including a total of 21-dimensional color objective physical features. Subjective factors are divided into direct psychological effects and indirect psychological effects according to the process of color stimulating human's psychological perception and cognition. Direct psychological effects are based on ''Hue and Tone System'' theory from NCD, including ''cool/warm'', ''soft/hard'', and ''transparent/turbid''; indirect psychological effects are represented by emotion, which is represented by the PAD emotional model, including pleasure, arousal, and dominance. On this basis, this article abstracted the generation process of color harmony from objective factors to subjective factors, and tried to construct a research paradigm of color harmony. The main contributions are as follows:

(1) In terms of objective factors, for the lightness category, research shows that there is a correlation between L_1^*, L_2^*, $mean\_L^*$, and color harmony. The data show that in the same color pair, the greater the lightness of the main and assistant colors is, the more harmonious the color pair is. For the distance category, research shows that there is a correlation between ΔE, ΔC^*, and color harmony. The data show that in the same color pair, the smaller the color difference between the main and assistant colors is, the more harmonious the color pair is.

(2) In terms of subjective factors, for the direct psychological effect, research shows that there is a correlation between the ''soft/hard'' sense and color harmony. The data show that the color pair with a softer color combination tends to be more harmonious. There is a correlation between the ''transparent/turbid'' sense and color harmony. The data show that the color pair with a more transparent color combination tends to be more harmonious. *For the indirect psychological effect*, there is a positive correlation between pleasure and color harmony, but the sense of arousal and dominance produced by color pair has no clear relationship with color harmony.

(3) Construct the objective factor-color harmony mathematical model and the subjective factor-color harmony mathematical model respectively. Through the 10-fold cross validation, the MLR algorithm also has the best prediction performance, indicating that the linear mathematical model can well explain the generation process of color harmony.

The future works will focus on the following aspects. Firstly, in order to study the influence of other external factors on color harmony in addition to the basic attributes of color, a richer dataset containing more situations will be constructed. Secondly, the research object will be expanded from color pair to multiple color combinations, and the objective physical features are also supposed to be designed and quantified according to the attributes of color combinations, so as to expand the application scope. Thirdly, in addition to the general rules of color harmony, the influence of color preference on color harmony will be studied, and the personalized parameters are supposed to be introduced into the color harmony model by increasing the number of differentiated subjects. Finally, the accuracy of the mathematical model is planned to be improved by the technologies of small sample learning and automatic labeling.

APPENDIX

All the materials of two-color combination are shown in Table 8.

The values of L^*, a^*, and b^* in the CIELAB color space of main and assistant colors are shown in TABLE 9.

The value distributions of subjective factors of different color basic attribute categories are shown in Figure 14(a)-(r).

TABLE 8. All the materials of two-color combination.

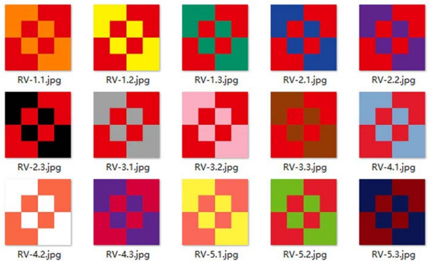
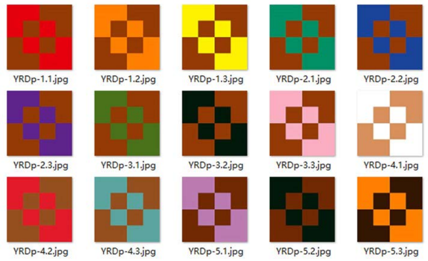
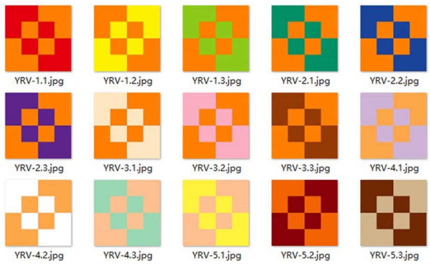
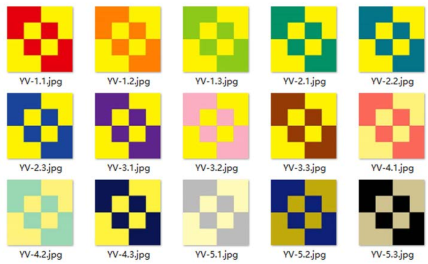
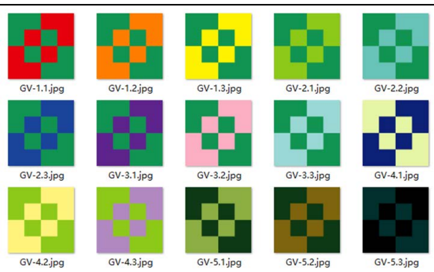
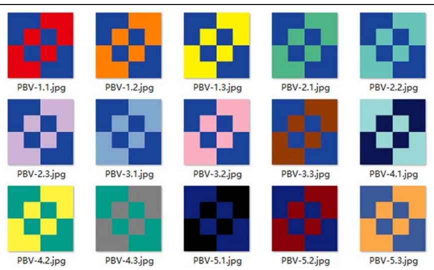
Category	Materials
R/V	 RV-1.1.jpg RV-1.2.jpg RV-1.3.jpg RV-2.1.jpg RV-2.2.jpg RV-2.3.jpg RV-3.1.jpg RV-3.2.jpg RV-3.3.jpg RV-4.1.jpg RV-4.2.jpg RV-4.3.jpg RV-5.1.jpg RV-5.2.jpg RV-5.3.jpg
YR/Dp	 YRDp-1.1.jpg YRDp-1.2.jpg YRDp-1.3.jpg YRDp-2.1.jpg YRDp-2.2.jpg YRDp-2.3.jpg YRDp-3.1.jpg YRDp-3.2.jpg YRDp-3.3.jpg YRDp-4.1.jpg YRDp-4.2.jpg YRDp-4.3.jpg YRDp-5.1.jpg YRDp-5.2.jpg YRDp-5.3.jpg
YR/V	 YRV-1.1.jpg YRV-1.2.jpg YRV-1.3.jpg YRV-2.1.jpg YRV-2.2.jpg YRV-2.3.jpg YRV-3.1.jpg YRV-3.2.jpg YRV-3.3.jpg YRV-4.1.jpg YRV-4.2.jpg YRV-4.3.jpg YRV-5.1.jpg YRV-5.2.jpg YRV-5.3.jpg
Y/V	 YV-1.1.jpg YV-1.2.jpg YV-1.3.jpg YV-2.1.jpg YV-2.2.jpg YV-2.3.jpg YV-3.1.jpg YV-3.2.jpg YV-3.3.jpg YV-4.1.jpg YV-4.2.jpg YV-4.3.jpg YV-5.1.jpg YV-5.2.jpg YV-5.3.jpg
G/V	 GV-1.1.jpg GV-1.2.jpg GV-1.3.jpg GV-2.1.jpg GV-2.2.jpg GV-2.3.jpg GV-3.1.jpg GV-3.2.jpg GV-3.3.jpg GV-4.1.jpg GV-4.2.jpg GV-4.3.jpg GV-5.1.jpg GV-5.2.jpg GV-5.3.jpg
PB/V	 PBV-1.1.jpg PBV-1.2.jpg PBV-1.3.jpg PBV-2.1.jpg PBV-2.2.jpg PBV-2.3.jpg PBV-3.1.jpg PBV-3.2.jpg PBV-3.3.jpg PBV-4.1.jpg PBV-4.2.jpg PBV-4.3.jpg PBV-5.1.jpg PBV-5.2.jpg PBV-5.3.jpg

TABLE 8. *(Continued.)* All the materials of two-color combination.

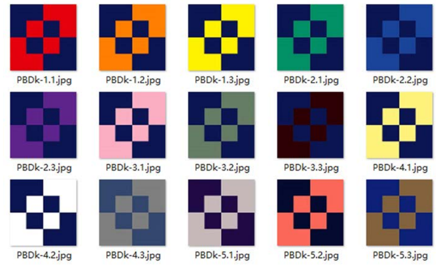
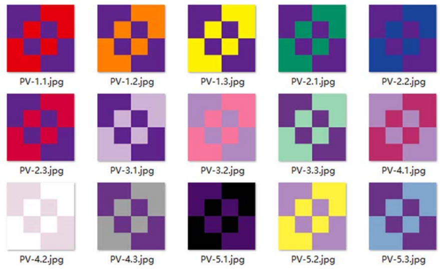
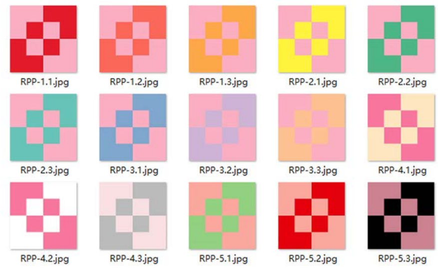
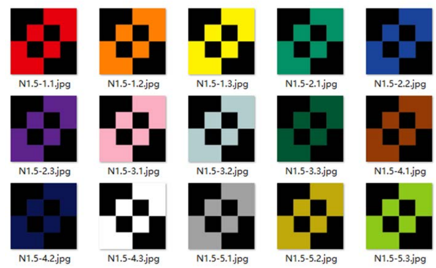
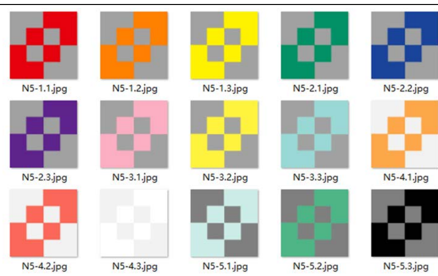
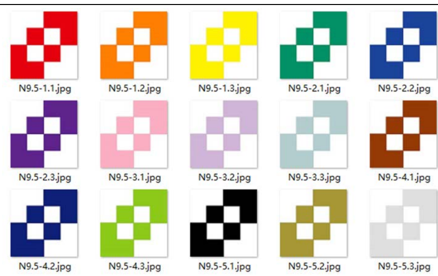
PB/Dk	 PBDk-1.1.jpg PBDk-1.2.jpg PBDk-1.3.jpg PBDk-2.1.jpg PBDk-2.2.jpg PBDk-2.3.jpg PBDk-3.1.jpg PBDk-3.2.jpg PBDk-3.3.jpg PBDk-4.1.jpg PBDk-4.2.jpg PBDk-4.3.jpg PBDk-5.1.jpg PBDk-5.2.jpg PBDk-5.3.jpg
P/V	 PV-1.1.jpg PV-1.2.jpg PV-1.3.jpg PV-2.1.jpg PV-2.2.jpg PV-2.3.jpg PV-3.1.jpg PV-3.2.jpg PV-3.3.jpg PV-4.1.jpg PV-4.2.jpg PV-4.3.jpg PV-5.1.jpg PV-5.2.jpg PV-5.3.jpg
RP/P	 RPP-1.1.jpg RPP-1.2.jpg RPP-1.3.jpg RPP-2.1.jpg RPP-2.2.jpg RPP-2.3.jpg RPP-3.1.jpg RPP-3.2.jpg RPP-3.3.jpg RPP-4.1.jpg RPP-4.2.jpg RPP-4.3.jpg RPP-5.1.jpg RPP-5.2.jpg RPP-5.3.jpg
N1.5	 N1.5-1.1.jpg N1.5-1.2.jpg N1.5-1.3.jpg N1.5-2.1.jpg N1.5-2.2.jpg N1.5-2.3.jpg N1.5-3.1.jpg N1.5-3.2.jpg N1.5-3.3.jpg N1.5-4.1.jpg N1.5-4.2.jpg N1.5-4.3.jpg N1.5-5.1.jpg N1.5-5.2.jpg N1.5-5.3.jpg
N5	 N5-1.1.jpg N5-1.2.jpg N5-1.3.jpg N5-2.1.jpg N5-2.2.jpg N5-2.3.jpg N5-3.1.jpg N5-3.2.jpg N5-3.3.jpg N5-4.1.jpg N5-4.2.jpg N5-4.3.jpg N5-5.1.jpg N5-5.2.jpg N5-5.3.jpg
N9.5	 N9.5-1.1.jpg N9.5-1.2.jpg N9.5-1.3.jpg N9.5-2.1.jpg N9.5-2.2.jpg N9.5-2.3.jpg N9.5-3.1.jpg N9.5-3.2.jpg N9.5-3.3.jpg N9.5-4.1.jpg N9.5-4.2.jpg N9.5-4.3.jpg N9.5-5.1.jpg N9.5-5.2.jpg N9.5-5.3.jpg

TABLE 9. The values of L^*, a^*, and b^* in the CIELAB color space of main and assistant colors.

	Main color			Assistant color		
	L_1^*	a_1^*	b_1^*	L_2^*	a_2^*	b_2^*
RV-1.1	49	74	60	68	46	75
RV-1.2	49	74	60	94	-10	91
RV-1.3	49	74	60	53	-42	13
RV-2.1	49	74	60	30	13	-53
RV-2.2	49	74	60	28	42	-48
RV-2.3	49	74	60	0	0	0
RV-3.1	49	74	60	66	0	0
RV-3.2	49	74	60	79	31	2
RV-3.3	49	74	60	37	37	47
RV-4.1	49	72	48	66	-6	-24
RV-4.2	63	57	48	100	0	0
RV-4.3	46	71	34	28	42	-48
RV-5.1	63	57	38	95	-9	81
RV-5.2	49	72	48	68	-39	63
RV-5.3	28	51	39	10	17	-39
YRDp-1.1	37	37	47	49	74	60
YRDp-1.2	37	37	47	68	46	75
YRDp-1.3	37	37	47	94	-10	91
YRDp-2.1	37	37	47	53	-42	13
YRDp-2.2	37	37	47	30	13	-53
YRDp-2.3	37	37	47	28	42	-48
YRDp-3.1	37	37	47	44	-26	41
YRDp-3.2	37	37	47	6	-10	5
YRDp-3.3	37	37	47	79	31	2
YRDp-4.1	66	24	39	100	0	0
YRDp-4.2	42	27	41	49	72	48
YRDp-4.3	42	27	41	63	-25	-4
YRDp-5.1	27	31	38	60	32	-19
YRDp-5.2	27	31	38	6	-10	5
YRDp-5.3	12	15	16	68	46	75
YRV-1.1	68	46	75	49	74	60
YRV-1.2	94	-10	91	68	46	75
YRV-1.3	68	46	75	75	-37	70
YRV-2.1	68	46	75	53	-42	13
YRV-2.2	68	46	75	30	13	-53
YRV-2.3	68	46	75	28	42	-48
YRV-3.1	68	46	75	93	4	21
YRV-3.2	68	46	75	79	31	2
YRV-3.3	68	46	75	37	38	47
YRV-4.1	76	27	60	76	15	-14
YRV-4.2	76	0	0	100	15	-14
YRV-4.3	83	18	33	81	-26	12
YRV-5.1	83	18	33	95	-9	81
YRV-5.2	28	51	39	61	53	70
YRV-5.3	75	6	26	27	31	38
YV-1.1	94	-10	91	49	74	60
YV-1.2	94	-10	91	68	46	75

TABLE 9. *(Continued.)* The values of L^*, a^*, and b^* in the CIELAB color space of main and assistant colors.

YV-1.3	94	-10	91	75	-37	70
YV-2.1	94	-10	91	53	-42	13
YV-2.2	94	-10	91	44	-22	-20
YV-2.3	94	-10	91	30	13	-53
YV-3.1	94	-10	91	28	42	-48
YV-3.2	94	-10	91	79	31	2
YV-3.3	94	-10	91	37	37	47
YV-4.1	95	-7	58	63	57	38
YV-4.2	95	-7	58	81	-26	12
YV-4.3	95	-9	81	10	17	-39
YV-5.1	98	-6	32	76	0	0
YV-5.2	70	-1	70	17	22	-53
YV-5.3	79	-1	28	0	0	0
GV-1.1	54	-46	25	49	75	61
GV-1.2	54	-46	25	67	47	74
GV-1.3	54	-46	25	94	-10	91
GV-2.1	54	-46	25	75	-37	70
GV-2.2	54	-46	25	73	-31	-3
GV-2.3	54	-46	25	30	13	-53
GV-3.1	54	-46	25	28	42	-48
GV-3.2	54	-46	25	79	31	2
GV-3.3	54	-46	25	82	-21	-5
GV-4.1	94	-14	37	17	22	-53
GV-4.2	75	-37	70	95	-7	58
GV-4.3	75	-37	70	62	24	-23
GV-5.1	20	-22	18	67	-24	49
GV-5.2	20	-22	18	44	5	47
GV-5.3	17	-16	-3	0	0	0
PBV-1.1	30	13	-53	49	74	60
PBV-1.2	30	13	-53	69	46	75
PBV-1.3	30	13	-53	94	-10	91
PBV-2.1	30	13	-53	67	-40	15
PBV-2.2	30	13	-53	73	-31	-3
PBV-2.3	30	13	-53	76	15	-14
PBV-3.1	30	13	-53	66	-6	-24
PBV-3.2	30	13	-53	79	31	2
PBV-3.3	30	13	-53	37	37	47
PBV-4.1	82	-21	-5	10	17	-39
PBV-4.2	57	-39	-1	95	-9	81
PBV-4.3	57	-39	-1	53	0	0
PBV-5.1	17	22	-53	0	0	0
PBV-5.2	17	22	-53	28	51	39
PBV-5.3	38	5	-39	76	27	60
PBDk-1.1	10	17	-39	49	74	60
PBDk-1.2	10	17	-39	68	46	75
PBDk-1.3	10	17	-39	94	-10	91
PBDk-2.1	10	17	-39	53	-42	13
PBDk-2.2	10	17	-39	30	13	-53
PBDk-2.3	10	17	-39	28	42	-48

TABLE 9. ***(Continued.)*** **The values of L^*, a^*, and b^* in the CIELAB color space of main and assistant colors.**

PBDk-3.1	10	17	-39	79	31	2
PBDk-3.2	10	17	-39	50	-12	10
PBDk-3.3	10	17	-39	5	23	7
PBDk-4.1	10	17	-39	95	-7	58
PBDk-4.2	10	17	-39	100	0	0
PBDk-4.3	30	1	-24	53	0	0
PBDk-5.1	8	23	-33	76	6	1
PBDk-5.2	4	8	-25	63	57	38
PBDk-5.3	17	22	-53	45	10	27
PV-1.1	28	42	-48	49	74	60
PV-1.2	28	42	-48	68	46	75
PV-1.3	28	42	-48	94	-10	91
PV-2.1	28	42	-48	53	-42	13
PV-2.2	28	42	-48	30	13	-53
PV-2.3	28	42	-48	46	71	34
PV-3.1	28	42	-48	76	15	-14
PV-3.2	62	23	-23	66	54	4
PV-3.3	32	36	-37	81	-26	12
PV-4.1	62	23	-23	44	59	1
PV-4.2	88	7	-3	100	0	0
PV-4.3	32	36	-37	66	0	0
PV-5.1	18	39	-41	0	0	0
PV-5.2	62	23	-23	95	-9	81
PV-5.3	32	36	-37	66	-6	-24
RPP-1.1	79	31	2	49	72	48
RPP-1.2	79	31	2	63	57	38
RPP-1.3	79	31	2	76	27	60
RPP-2.1	79	31	2	95	-9	81
RPP-2.2	79	31	2	67	-40	15
RPP-2.3	79	31	2	73	-31	-3
RPP-3.1	79	31	2	66	-6	-24
RPP-3.2	79	31	2	76	15	-14
RPP-3.3	79	31	2	83	18	33
RPP-4.1	66	54	4	93	4	21
RPP-4.2	66	54	4	100	0	0
RPP-4.3	91	10	2	76	0	0
RPP-5.1	77	31	19	78	-32	34
RPP-5.2	77	31	19	49	74	60
RPP-5.3	62	30	5	0	0	0
N1.5-1.1	0	0	0	49	75	61
N1.5-1.2	0	0	0	68	46	75
N1.5-1.3	0	0	0	94	-10	91
N1.5-2.1	0	0	0	53	-42	13
N1.5-2.2	0	0	0	30	13	-53
N1.5-2.3	0	0	0	28	42	-48
N1.5-3.1	0	0	0	79	31	2
N1.5-3.2	0	0	0	80	-9	-4
N1.5-3.3	0	0	0	31	-31	15
N1.5-4.1	0	0	0	37	37	47

TABLE 9. ***(Continued.)*** **The values of L^*, a^*, and b^* in the CIELAB color space of main and assistant colors.**

N1.5-4.2	0	0	0	10	17	-39
N1.5-4.3	0	0	0	100	0	0
N1.5-5.1	0	0	0	66	0	0
N1.5-5.2	0	0	0	70	-1	70
N1.5-5.3	0	0	0	75	-37	70
N5-1.1	66	0	0	49	75	61
N5-1.2	66	0	0	68	46	75
N5-1.3	66	0	0	94	-10	91
N5-2.1	66	0	0	53	-42	13
N5-2.2	66	0	0	30	13	-53
N5-2.3	66	0	0	28	42	-48
N5-3.1	66	0	0	79	31	2
N5-3.2	66	0	0	95	-9	81
N5-3.3	66	0	0	82	-21	-5
N5-4.1	95	0	0	76	27	60
N5-4.2	95	0	0	63	57	38
N5-4.3	95	0	0	100	0	0
N5-5.1	53	0	0	91	-12	-1
N5-5.2	53	0	0	67	-40	15
N5-5.3	53	0	0	0	0	0
N9.5-1.1	100	0	0	49	75	61
N9.5-1.2	100	0	0	68	46	75
N9.5-1.3	100	0	0	94	-10	91
N9.5-2.1	100	0	0	53	-42	13
N9.5-2.2	100	0	0	30	13	-53
N9.5-2.3	100	0	0	28	42	-48
N9.5-3.1	100	0	0	79	31	2
N9.5-3.2	100	0	0	77	15	-14
N9.5-3.3	100	0	0	80	-9	-4
N9.5-4.1	100	0	0	37	37	47
N9.5-4.2	100	0	0	17	22	-53
N9.5-4.3	100	0	0	75	-37	70
N9.5-5.1	100	0	0	0	0	0
N9.5-5.2	100	0	0	62	-2	51
N9.5-5.3	100	0	0	88	0	0

Note: The L^*, a^*, and b^* values presented in this article are the values in digital files.

The total correlation coefficient matrix is shown in Figure 15.

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