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INSTITUTE OF TEXTILES AND CLOTHING

A Quantitative Study on Color Harmony

By

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Certificate of Originality

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Abstract

In color vision, colors appear as interrelated visual sensations. Color harmony is about whether colors working together may produce a pleasing effect. It is a result of interaction between the external world and human's psyche. Apparently, it is a multidisciplinary research field, including perceptual and cognitive psychology, color vision, aesthetics, fashion, etc. This investigation examined what colors working together can invoke a harmonious feeling, how the color harmony is predicted, what the inner causation of color harmony is, and how color harmony models can be used in application.

To transfer real-life situation into laboratory, color patches or chips were used to simulate object and/or background colors in this investigation. Two kinds of the most general arrangement of two colors, one of which was two colors laid side by side (SS pattern), and the other was two colors in center-background relationship (CB pattern), were designed for two-color harmony evaluation. In order to estimate three-color harmony, two kinds of three-color arrangements, one of which was three colors laid side by side on a grey background (SSS pattern), and the other was two colors laid side by side on a chromatic background (SSB pattern), were devised. Rating scale method was used to evaluate preference levels of single colors and harmony levels of color patterns. Twenty Chinese students participated in this aesthetic evaluation.

By using multiple regression analysis, models of SS color pattern and CB color pattern were developed. 72.6% of total variance of SS patterns and 66.3% of total variance of CB patterns can be explained by their corresponding models.

Component color relationships and single color preference are the two main categories of factors affecting color harmony of both color patterns. Characteristics of each single color in the pattern are considered to be less important to the harmony of a color pattern.

Hue difference is the primary influential factor on color harmony of SS patterns, while lightness difference is of the most importance for CB patterns. A positive relationship between color harmony and total lightness was found in both kinds of patterns. In view of the strong positive dependence of single color preference on lightness, it is concluded that high harmonious levels of patterns with high total lightness might attribute to both their high total lightness and high single color preference.

For both kinds of three-color patterns, a positive correlation was found between harmony of three-color patterns and that of related two-color patterns. However, although it is feasible for SSS patterns to predict their harmony values from those of three related two-color patterns, it is difficult for SSB patterns possibly due to their complex structures.

By combining these color harmony results with sensation and perception theory, it is deduced that color harmony is a pleasing feeling evoked by color patterns which consist of preferred single colors and can satisfy people's expectation. Since the single color preference is related to the cultural background of observers, harmonious levels of color patterns may be different for peoples with different cultural background.

Finally, to apply the color harmony models to practical use, a flexible and general method to establish harmonious color patterns was developed which was applicable to all kinds of color pattern design. By progressively setting the constraints such as the function required by the situation, the emotion to be expressed, the influence of prevailing color, on color patterns, the most harmonious color combinations could be determined based on the color harmony models.

In conclusion, this investigation demonstrates that color harmony is a stable feeling and can be objectively quantified by aesthetic experiment. It provides a framework for further research on color harmony.

Publications

1. Referred journal articles:

1. GAO, X.P. and XIN, J.H. Investigation of human's emotional responses on colors. Color Research and Application. vol. 31, no. 5, pp. 411-417 (2006).
2. GAO, X.P. and XIN, J.H. (with SATO, T., et al.) Analysis of cross-cultural color emotion. Color Research and Application. vol. 32, no. 3, pp. 223-229 (2007).
3. GAO, X.P. and XIN, J.H. Color harmony modeling on two-color patterns. Color Research and Application. (2006). (submitted)
4. GAO, X.P. and XIN, J.H. The study of single color preference. Color Research and Application. (2006). (submitted)
5. GAO, X.P. and XIN, J.H. Color harmony modeling on three-color patterns. Color Research and Application. (2007). (submitted)

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Chapter 1

Introduction

1.1 Background

Color appears everywhere in our daily life. It appears in natural objects such as flowers, rocks, and woods, and in industrial products such as textile fabrics, cars, bubble-gum, and balloons. The question of which color is beautiful and which is ugly in various context, is of great interest to many people. Many attempts have, therefore, been made to study the preference of different colors as well as their associated meanings. In reality, it is inadequate to study the preference of single color as colors actually always work together. They appear as interrelated visual sensations, which are unpredictable from looking at colors in isolation. Therefore, questions, such as how colors work together, how they interact, and how they harmonize, are more interesting and relevant in color planning applications such as fabric design, environment design and advertisement design. In these practical applications, computers are now widely used and colors can be selected from almost unlimited range of possibilities, and are easily displayed on monitors. However, until now, the design of a color scheme is usually based on the skill and memory of trained color specialists and designers. The color scheme designed by this method may vary with individuals and even be affected by designers' psychological conditions. Therefore, only when a color harmony model is constructed by combining physical attributes of color stimulus with experience of "harmony", an accurate and useful tool for designing the most pleasing color combination can be possible.

Since the publication of Goethe's *Farbenlehre* in 1810, the notion of "color harmony" has attracted considerable interests in both philosophical and scientific aesthetics. At the beginning, some renowned theorists, such as Vinci (Zelanski and Fisher, 1999), Chevreul (1987), Itten (1970), Munsell (1905), Ostwald (Birren, 1969b) etc. postulated some color harmony "orders" based on their personal experiences. For example, Chevreul (1987) developed a systematic harmony law of 'contrast' and 'analogous'. Munsell (Birren, 1969a) attributed color harmony to balance, while Ostwald (Birren, 1969b) considered that order was more important. These traditional color harmony orders, however, are not convincing since they are based on personal experience and only represent personal desires without systematic observation of color phenomena.

Nevertheless, the aesthetic research on color harmony is still on primitive stage to date. Firstly, compared to the preference on single color, the research on color combination is quite limited. Secondly, only the simplest pattern, that is, two colors laid side by side on a grey background, has been studied. In many practical applications such as pattern design of textile fabrics, however, foreground-background color scheme as illustrated in Fig. 1.1 is frequently used. Finally, although the two factors influencing color harmony are clear, i.e., preference rating of component colors in color combination and the inter-relationship of perception attributes including hue, chroma, and lightness between component colors, the detailed relationship between the experience of "harmony" and these factors are still equivocal.

Fig. 1.1 Two foreground-background color schemes in textile fabric design.

This rather slow progress in the research of color harmony is mainly due to its complexity. The most difficult problem encountered is that there are almost infinite numbers of color combinations. As a result, it is really difficult to decide how to choose limited yet representative color combinations in the investigation. This has prevented many researchers from setting foot in this area. And the limited research focused only on the simplest patterns with small sample size while without considering factor interactions.

In conclusion, the research on color harmony is desired by its importance in practical applications, while hindered by its complexity encountered in investigations. This project is proposed to bring forward an effective method for color harmony study, based on which a color harmony model can be finally developed.

1.2 Research aim and objectives

The main aim of this research is to construct color harmony models that can be used in applications of product design. The detailed objectives are as follows:

- To propose an effective sampling method to minimize the sample size of color combinations.
- To evaluate how color harmony is established.
- To construct color harmony models for two kinds of basic two-color combinations.
- To develop a method for estimating the harmony of three-color patterns.
- To develop a methodology for producing harmonious color combinations in practical applications.
- To deduce the possible process occurring in the inner world of human beings during aesthetics evaluation.

1.3 Research delimitation

This research focuses on the aesthetic evaluation of color combinations. The two subjects, color appearance model and mechanism of color response, are beyond the scope of this study.

Color appearance model describes the phenomenon how the appearance of a single color is affected by colors surrounding it. Color harmony is the result of a plurality of colors taken as an ensemble, independent of how the appearance of individual color is established. The thorough discussion of color appearance model can be found in a book by Fairchild (1997).

It is well known that color vision is the result of a series of highly complex processes. The mechanism of color response is still not fully understood, and it is also not within the scope of this study although some assumptions are made based on the results of color harmony. We consider that using a black box approach to evaluate the aesthetics of color combination is appropriate because it allows responses to stimuli to be measured, independent of how the responses are produced (Skinner, 1974). The detailed discussion of color vision mechanism is provided in a book by Hubel (1988).

1.4 Significance and values

A quantitative color harmony model is very valuable due to the following issues:

It can provide an accurate and objective tool for color arrangement in applications such as textile fabric design, interior design, and advertisement design. In particular, the efficiency of product design can be significantly enhanced when the color harmony model is incorporated into computer-aided design (CAD) system.

Color harmony evaluation is an aesthetic appreciation process. Color harmony model reflects the nature of human's aesthetic perception and will benefit further research in this area.

1.5 Thesis layout

The contents of this thesis are organized in seven chapters. Chapter 1 is the introduction. In this chapter, the background, aim, objectives, research delimitation, significance and values of this work are presented.

Chapter 2 provides a detailed survey on the literature related to this study.

In Chapter 3, a three-step color harmony evaluation process is described and the causation of the arrangement of the experiment process is explained. The methodologies of color pattern design, color combination design, psychophysical experiment method, and the method of color sample display on a CRT monitor, etc. are depicted. Finally, the method of data collection and data analysis is explained.

Chapter 4 is devoted to the investigation of the influential factors on the color harmony of two-color patterns with different hues, but same lightness and same chroma.

Based on the results of Chapter 4, the main experiment is designed in Chapter 5 to evaluate the color patterns differing in hue, lightness and chroma. The data collected in the experiment are summarized and analyzed. Color harmony models for two kinds of two-color patterns are constructed which allows color harmony to be systematically specified and applied. The differences in the factors between the two kinds of two-color patterns are compared; and the inner causation leading to these differentiations are analyzed according to the sensation and perception theories.

Due to the complexity of the three-color patterns, an attempt is made to predict three-color harmony from two-color harmony in Chapter 6.

In Chapter 7 a methodology for establishing harmonious color patterns based on the constructed color harmony models is developed. Constraints in color pattern design are analyzed and a methodology for a comprehensive consideration of these constraints to the harmonious color pattern design is conceived.

Finally, all the results and the major contributions of this study are summarized in Chapter 8. The direction of future research work is also suggested.

Chapter 2

Literature Review

In this chapter, the definition of color is first explained from physical and psychological viewpoints. Then, previous research on color is discussed in a four-level hierarchy. Color harmony research, as one category at the top level, is critically reviewed in detail. In addition, the development of color preference is examined and the difference between color harmony and color preference is clarified. Finally, sensation and perception theories that may relate to the nature of the visual aesthetic response are surveyed.

2.1 Color conceptions

In dictionary, color is defined as “effect produced by a ray of light of a particular wavelength, or by a mixture of these” and “sensation produced in the eye by rays of decomposed light” (Hornby, 1989; Sinclair, 1995). The description of color must include both physical actions, such as producing a stimulus in the form of light, and subjective results, such as receiving and interpreting this stimulus in the eye and the brain or human visual system (Billmeyer and Saltzman, 1981). That is to say, a color impression is not only a mechanism of seeing, but also a sensation or feeling that simultaneously activates our thoughts and our cognitive mechanism (Mahnke, 1996).

2.2 Hierarchy of color models

Color is a vast, complex research area involving visible radiation, color sensation, and color psychology, etc (Sharpe, 1974). A hierarchy of color models was introduced by Jacobson and Bender (1996) as shown in Fig. 2.1.

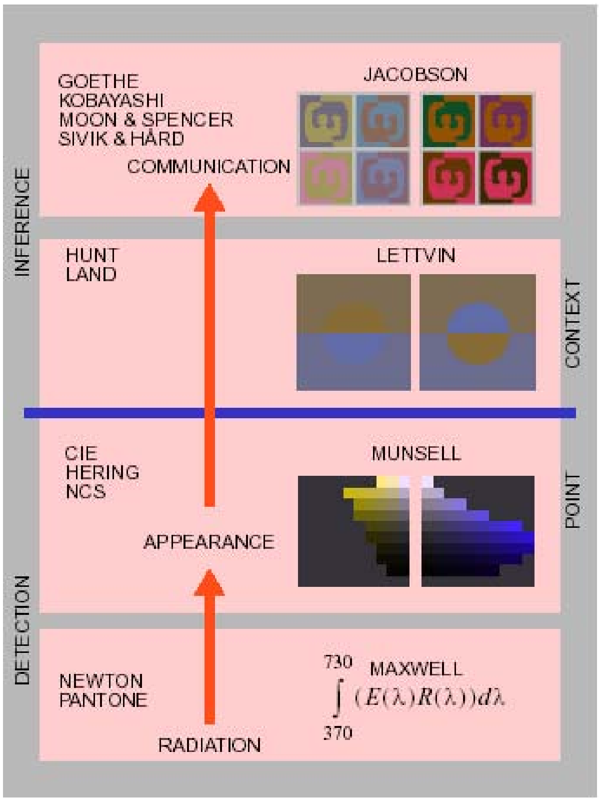


Fig. 2.1 A four level of color research hierarchy by Jacobson and Bender.

The bottom level is the detection of points of electromagnetic radiation. The wavelengths of photons to which the eye is sensitive are in the range of about 380 to 780 nm. The concept of visible radiation is principally used to describe energy external to human visual system. It is defined, discussed, and applied by using the language of physics. In radiation models, Newton established the principles of color mixing by using prisms.

The second level is to model the transformation of radiation by the human visual system into the sensation of color. Models in this level include those of the Commission International de 1'Eclairage (CIE), Munsell color system, and the Natural Color System (NCS). In these models, color is measured as isolated visual sensations, which are used for consistent and systematic specification. Furthermore, models such as CIELAB, Munsell color system, and NCS are approximately perceptual uniform. This characteristic is very important for color psychology research as perceptual difference of two colors could be represented by their distance in these uniform color spaces.

The limitation of these models is that they always ignore visual context. Their visual context, however, can produce large shifts in color appearance that cannot be accounted for by colorimetric specifications of isolated points of color (Fairchild, 1998).

The third level is color appearance models, which predict color shifts produced by visual context. Color appearance is not an attribute of objects but an attribute of representations within an individual's mind. Understanding color-appearance phenomena and developing models to predict them have been the focus of a great deal of research in the past fifteen years. The models involved in this field include the Hunt model (Hunt, 1991), the RLAB model (Fairchild, 1996), and the ATD model (Guth, 1994a, 1994b), etc.

Color appearance models, similar to colorimetric models in the second level, are used to describe the phenomenology of a single color. That is, they describe the processes how the appearance of a single color is affected by colors surrounding it.

In reality, human obtain meaning of the world from a “collection” of visual inference by “seeing” (Wandell, 1995). Seeing color involves more than just the sensation of isolated color appearance. It is the result of a plurality of colors taken as an ensemble, independent of how the appearance of the individual colors is established. This is the top level of color models, and reflects actual human experience on colors. In color experience research, there are two main categories: one deals with preference, pleasantness, or evaluative dimensions of colors, and the other primarily concerns descriptive dimensions. The former is often referred to as color harmony, and the latter is often referred to as connotation of colors.

2.3 Development on color harmony

Most early work on color harmony was done by philosophers and artists. They formulated their own color harmony orders based on their personal experience. The deficiencies of those works have motivated rigorous scientific investigations on color harmony. In this section, the definition of color harmony is first explained, and then, the historical development of color harmony is examined.

2.3.1 Definition of color harmony

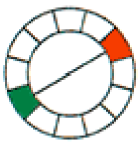
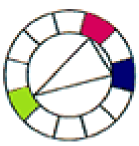
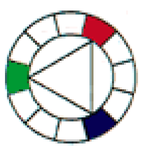
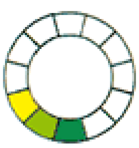
In American Heritage Dictionary, "harmony" is defined as "a pleasing combination of elements in a whole". In keeping with this definition, "color harmony" was described as "two or more colors seen in neighboring areas produce a pleasing effect" (Judd, 1975).

2.3.2 Color harmony based on hue

Color harmony, from its beginning, has been considered as a question of which colors go together harmoniously. Vinci was one of the first persons who considered the contrast colors as the most beautiful color combinations (Zelanski and Fisher, 1999; Kuehni, 1997). However, his remarks are rather vague as he had no idea on what colors are opposite to each other. Thompson first employed the term 'complementary color' in an essay written in 1794 (Venn, 1997). He claimed that two colors were harmonious if one color was balanced out by the compound of the two remaining primary colors.

During that time, it was realized that to classify all color values into a standardized, objective system was useful for constructing harmonious color combinations. Goethe described the diametrically opposed colors in his 6-tone color wheel as harmonious, and the alternate colors in the color wheel as characteristic (Kuehni, 1997, 2003). In 1893, Chevreul published more systematic laws of color harmony (1987). He probably is the first researcher to divide color harmony into harmonies of analogous colors and harmonies of contrast colors, based on his finely graded two-dimensional color circle. The rules of color harmony created by Chevreul (1987) are still adopted today and are very familiar to us: the harmony of adjacent or analogous, complements, split complements, and triads (Table 2.1). Further, “area” was qualitatively considered by Chevreul in color harmony. He recommended that colors with high contrast should be used in large juxtaposed areas for its making each other more brilliant, while analogous colors should be used in small, diffused amounts. In a 12 hues color wheel, Bezold (1874) and Brucke (1866) argued that colors with differences less than one step (neighboring hues) or large than one-third of the circle (almost complementary hues) could produce harmonious color schemes, while those in-between did not offer pleasing feeling.

Table 2.1 Color harmony rules created by Chevreul.

	**Complementary Colors** Complementary colors opposite each other provide high color contrast.
	**Split-Complementary Colors** Split-Complementary colors are those on either side of the complementary color. They contrast, but not as strongly as complementary colors.
	**Triad Colors** Triad color schemes use three colors equally spaced on the color wheel. To create harmony in triad color schemes, select one hue as dominant and mix a little of it with the other two.
	**Analogous Colors** Analogous colors are adjacent to each other on the color wheel. These colors share enough common attributes that they can work well with each other. They provide little contrast.

These earliest color systems were two-dimensional, using a circle, wheel, or polygon, to depict the sequence and some interrelations of hues (Kuehni, 1997, 2003; Chevreul, 1987). However, these color systems were not satisfactory and harmonious color combinations based on them are vague and incomplete. Subsequently, it was realized that color was determined by at least three attributes (hue, brightness, and saturation), and three-dimensional models were then introduced. A major reason for the development of early form of color space was to have a basis for discovering systematic rules of color harmony (Kuehni, 2003).

2.3.3 Color harmony based on three-dimensional color order systems

The Color Sphere proposed by Runge in 1810 was attempt to present color perception in a three-dimensional space, in which the relationship between colors was regarded as a sphere (Zelanski and Fisher, 1999; Kuehni, 2003). In the color sphere, pure hues were displayed around its equator, and the central axis was a gray value scale, from black at the bottom to white at the top. Harmonious color pairs were thought, first of all, to be those opposing each other on the circle. About 150 years later, Itten (1970) adopted and adjusted Runge's model. Itten thought that harmony was equilibrium, and two or more colors were harmonious when their mixture results in a neutral gray. Thus, very conveniently, it can be said that all complementary colors in the twelve-color circle with a relationship of an equal or an equilateral triangle, or a square, or a rectangle, are harmonious (Itten, 1970).

In the early twentieth century, Munsell (1905) used three color perception attributes (hue, value, and chroma), each graded in equal perceptual steps, to describe his color order system (Fig. 2.2). Munsell defined hue as the quality by which we distinguish one color from another. He selected five principle colors: red, yellow, green, blue, and purple; and five intermediate colors: yellow-red, green-yellow, blue-green, purple-blue, and red-purple. Munsell hue is expressed by a number and letter combination such as 5R or 10PB in which the letters are taken from the ten major hue names (for example, R for red, YR for yellow-red, Y for yellow etc.), and the numbers run from the divisions 1 to 10. Value is the quality by which a color can be classified as equivalent in lightness. It is defined in 11 steps from white to black. Chroma, a measure of the saturation (or purity) of a color, is an open end scale. These three dimensions form an irregular sphere, rather than the perfect sphere proposed by earlier theorists (Zelanski and Fisher, 1999; Itten, 1970). This is because he noticed that different hue reach maximum saturation at different steps of value, and they also differ in the number of equal steps from neutral gray to maximum saturation.

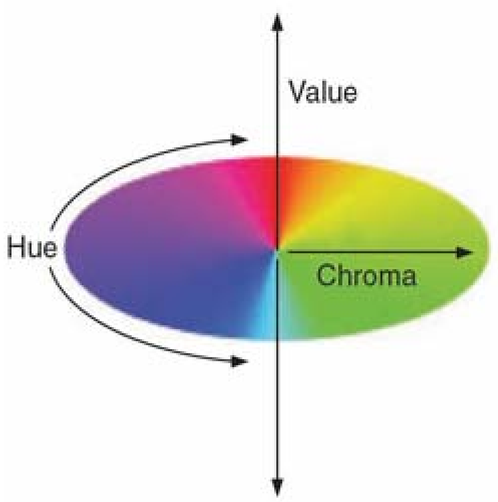


Fig. 2.2 Munsell color system

On the problem of color harmony, Munsell (Birren, 1969a) stated that “the sense of comfort is the outcome of balance”. As Field (Hope and Walch, 1990) argued that the area must be adjusted so that the mixture of colors on a rotating disk gave a neutral gray, and all color arrangements by Munsell were balanced to “N5”. In addition to opposite colors, Munsell also appreciated adjacent hues, split-complements, triads, and even all the hues of his color circle with careful adjustment of areas according to the following equation:

$$A_1(V_1C_1) = A_2(V_2C_2) \tag{2.1}$$

where A is area, V and C are value and chroma, respectively, and subscripts 1 and 2 denote two different colors. From Eqn. 2.1, it can be seen that area are inversely proportional to the product of value and chroma of the color involved. Munsell thought that a balance point could be reached for colors satisfying Eqn. 2.1.

Although his original intent was to represent a uniform color space, Munsell failed to work out a totally uniform space since the units of the three visual scales, hue, value, and chroma, are not identical in perceived magnitude (Kuehni, 2003).

Ostwald chose a double-cone model comprising a series of triangular cross-sections to develop his color order system (Birren, 1969b). In the system, white forms the upper pole of the triangles, black forms the lower pole, and 24 pure hues circled the equator. Color harmony in this system was established according to the law that harmony equals order. In this situation, order means regular distribution of color points on Ostwald color system. All possible harmonious combinations, therefore, can be found by mining all the possible arrangement in this color space. For example, one can find several harmonious combinations, including achromatic, constant hue, constant value, and a combination of these. However, it was noticed that Ostwald's color order system was derived from additive color mixture data, and thus was not uniform merely being regular.

From the works of Itten (1970), Munsell (Birren, 1969a), and Ostwald (Birren, 1969b), it is obvious that *order* is the main principle of color harmony. This leads to a demand of uniformly scaled color space so that color pairs with equal contrasts can be represented by point pairs of equal distances. The progress in color specification has indeed benefited the advancement of the theory of color harmony. However, developing a uniform color space is a nontrivial task. Although having been studied extensively, almost all of those color order systems are just regular or partially uniform. In addition, they do not provide a mathematical framework, and as a consequence, color harmony based on these systems is only qualitative.

2.3.4 Color harmony based on metric color spaces

To translate vague order of color harmony into scientific theory, a satisfactory metric color space is needed. In 1931, the Commission International l'Eclairage (CIE) recommended a standard colorimetric system, CIE1931 (Nimeroff, 1968). However, this colorimetric system is not suitable for the analysis of color harmony as it is not uniform. Equal distances in CIE1931 color space do not correspond to equal perceptual steps in color and thus distances in different directions are not comparable. The attempt to obtain equal steps between two colors was made based on the CIE1931 color space. In the 1940's, the colors of the Munsell space were examined in detail by the subcommittee on Uniform Spacing of Munsell Colors of the Optical Society of America (OSA) (Nimeroff, 1968). The committee confirmed many local irregularities in space revealed by the spectrophotometric studies and therefore adjusted them so that the color space was closer to perfection under normal conditions (adaptation to daylight, gray surrounding field, and so on), and named it as *Munsell renotation* (Newhall, Nickson, and Judd, 1943). This new standard system is close to equal visual steps, and every sample in this new system is specified not only by three dimensions of Munsell system, hue, value, chroma, but also by colorimatric coordinates of CIE1931 colorimetric system, Y, x, and y. This enables the color transformation between colorimetric coordinates and Munsell book notations.

In 1943, Moon and Spencer (1943a, 1943b) developed a metric color space by a nonlinear transformation of CIEXYZ based on *Munsell renotation*. In this space, curves of constant hue appear as nearly straight lines and curves of constant chroma appear as almost uniformly spaced circles. This color space is a simple and approximately uniform space, in which discrepancies are easily noticed, and thus can be used for geometrical formulation of color harmony. Based on this color space and according to the ideas that orderly schemed color combinations would be pleasing, Moon and Spencer introduced a geometric formulation of classical color harmony (1944a). They gave a numerical designation of identity, similarity, ambiguity and contrast and proposed two principles for pleasing combinations (1944a, 1944b). They argued that ambiguous interval between colors would lead to confused and displeasing feeling, which was unharmonious.

Furthermore, Moon and Spencer pointed out that the previous sharp division of color combinations into harmonies and disharmonies was not consistent with practice (1944b). They ranked color combinations on a continuous scale from very poor combinations to very good ones. An empirical approach of aesthetic measure *M* was defined as:

$$M=O/C \tag{2.2}$$

where *O* represents the number of elements of order, and *C* is the number of elements of complexity. The elements of order include (a) identity, similarity and contrast of hue, value and chroma, and (b) area balance. Ambiguity and area imbalance are elements of disorder. The number of elements of complexity *C* is defined as:

$$\begin{aligned} C= &\text{(No. of colors)} + \text{(No. of color pairs having hue difference)} \\ &+ \text{(No. of color pairs with value difference)} \\ &+ \text{(No. of color pairs with chroma difference)} \end{aligned} \tag{2.3}$$

From Equation 2.2, it can be seen that the relations between component colors in color combinations play the most important role in harmony rating.

Moon and Spencer's work has greatly propelled the color harmony research forward by translating a vague speculation into a systematic quantitative approach based on their metric color space. However, due to its weak theoretical basis and insufficient experiment supporting, the work of Moon and Spencer was not fully accepted by many artists and researchers. For example, Pope (1944), on his opinion as an artist, criticized that some statements about color harmony were over-simplified and not consistent with practice in art. He claimed that the aesthetic measure formula *M=O/C* was only the symbol of aesthetic principle, and could not be exactly used in design practice. Sivik and Hard (1994) commented on Moon and Spencer's theory that, it was based on classical color harmony rules, not on the scientific foundation, to construct a color harmony model. Realizing these deficiencies, the emphasis of subsequent studies on color harmony has been transformed from traditional deduction and speculation to experimental approach.

2.3.5 Investigating color harmony using experimental evaluation methods

One of the most commonly used methods to investigate aesthetic evaluation is to transfer real-life situation into laboratory. Using this method, suitable control can be exerted by a prior selection of stimulus characteristics or criteria upon which judgment has to be based. Statistically valid results can be obtained by averaging the responses from a large number of subjects. This method has been adopted in color harmony research by using color patches or chips as stimuli to simulate object and/or background colors.

Due to the complexity in the construction of color combination, experiments on color harmony are always conducted with the most simplified pattern; that is, two color patches laid side by side on gray background as shown in Fig. 2.3. The evaluation methods include rank order method (Granger, 1955a, 1955b, 1955c, 1957), paired comparison method (Nayatani, etc. 1967, 1969) and the most frequently adopted rating scales method (Morriss, etc. 1987, 1988; Hogg, 1969a, 1969b; Berlyne, 1971; Pieters, 1979; Sivik and Taft, 1992; Ou, and Luo, 2003). Munsell color space was used by many researchers to derive qualitative color harmony rules (Granger, 1955a, 1955b, 1955c, 1957; Nayatani, etc. 1967, 1969; Morriss, 1987, 1988). The CIELAB color space, as one of the most uniform metric spaces, was used by Chuang and Ou (2001) and Ou and Luo (2003) to develop a quantitative color harmony model.

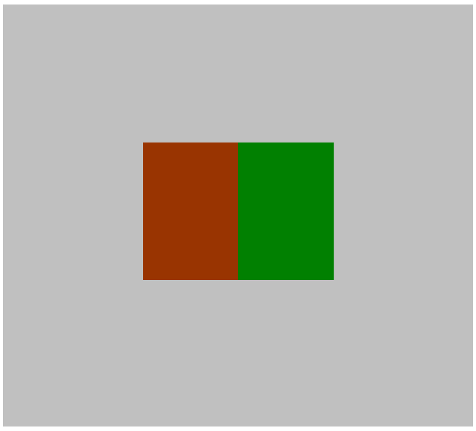


Fig 2.3 A frequently used color pattern in color harmony studies.

All these studies have constructed rules governing color harmony. However, the results are inconsistent. Granger (1955a, 1955b) claimed that preference on color combination tended to increase with the increasing of hue interval. As a result, complementary colors were the most favored. On the contrary, Nayatani etc. (1967, 1969), Sivik and Taft (1992), Chuang and Ou (2001), and Ou and Luo (2003, 2006) found that color pairs with similar hues were more harmonious. As to the lightness interval of two colors, Granger (1955a, 1955b), and Sivik and

Taft (1992) stated that small interval was more preferred, while Pieters (1979), and Levelt (Berlyne, 1971) observed higher preferences for larger lightness difference. Opposite to the above two opinions, Ou and Luo (2003, 2006) found that color pairs with median lightness difference and higher lightness summation were more favored. For chroma interval, Granger (1955a, 1955b) and Ou and Luo (2006) observed a higher preference on color pairs with lower chroma interval, whereas Levelt (Berlyne, 1971) and Pieters (1979) found that color pairs with higher chroma summation were more beautiful. In addition, many researchers (Granger, 1955a, 1955b, 1955c Nayatani etc. 1967, 1969, Chuang & Ou, 2001, Ou and Luo, 2003, 2006) observed a significant influence of single color preference on color harmony. However, Sivik & Taft (1992) found that the influence of single color preference is very little.

Nevertheless, based on these studies, it is natural to assume that there are two kinds of factors affecting color harmony. One is human's preference of component colors in color combination, and the other is the relationship between perception attributes (hue, chroma, and lightness) of component colors. This assumption is partially verified by Pieters' investigation (1979). He remarked that the evaluation of color combinations included a perceptual process and a motivational process. The perceptual process refers to the judgment of suitability of colors to each other. Thus, the relationship between perception attributes of component colors is very important to the degree of harmony. This perceptual process is objective and independent of any training in aesthetics or fashion. The motivational process, however, is much subjective, as the experience and cultural background of subjects and fashion may influence the observers' taste on colors and thus the aesthetic evaluation on color combinations. The preference on single colors has been studied by many researchers (Guiford, 1934, Smets, 1982, Guiford & Smith, 1959, Sivik, 1975, Wijk *et al*.1999, Eysenck, 1941, Granger, 1955a Saito, 1999, Washburn & Grose, 1921). Most of results obtained by these researchers are consistent. However, some inconsistencies are also observed, which could be attributed to different cultures of observers and different time periods. The details are discussed in section 2.4.

In addition, according to the previous experiments on color harmony, one can conclude that only certain interrelationships between component colors are related to color harmony. Hue Interval is the only factor in hue related variables. In lightness related variables, only Lightness Interval and/or Average Lightness should be considered. Similarly, in chroma related variables, only Chroma Interval and/or Average Chroma should be considered. Although it is certain that these factors do influence color harmony, detailed quantitative relationships are still unclear.

To summarize, Table 2.2 gives a concise introduction of experiment designs and their results of the studies discussed above.

Table 2.2 Summary of studies on color harmony.

	Authors	experiment		Results				
		adopted color space	method	Preference on Component color	Hue interval	Lightness interval	Chroma interval	remarks
1	Granger (1955a, 1955b, 1957)	Munsell color space	Rank order method	yes	high	small	low	---
2	Nayatani, et al. (1967, 1969)	Musnell color space	Paired comparison method	yes	small	yes	yes	Harmonious and inharmonious regions are different for each of different reference colors
3	Levelt (Berlyne, 1971)	hesselgren color system	Rating scale method	---	yes	high	High chroma summation	---
4	Pieters (1979)	hesselgren color system	Rating scale method	---	yes	high	High chroma summation	Color harmony = saturation harmony×(hue harmony + lightness harmony)
5	Morriss, et al. (1987, 1988)	Munsell color space	Adjusting the relative area of two colors	---	---	---	---	Background color has significant influence on area
6	Hirano, et al. (1992)	Munsell color space	Selecting harmonious color combinations	---	---	---	---	A neural network was constructed to predict the beauty of color combinations
7	Sivik, et al. (1989, 1992)	NCS	Rating scale method	no	small	small	---	Two sub-dimension of proposed color combination model, i.e., color parameter identities and complexity, are related to color harmony
8	Ou, etc. (2003, 2006)	CIELAB	Rating scale method	yes	small	Large lightness summation and median difference	small	---

Another important color pattern consists of a center color placed on a background. Few papers reported the results of color harmony on such kind of color patterns. The preference of this kind of color patterns was studied by some researchers, including Washburn and Grose (1921), Reddy and Bennett (1985), and Helson and Lansford (1970) et al. The results of these studies will be discussed in the section 2.4.2.

From the review of the literature, it can be concluded that:

1. Due to the complexity in the construction of color combination, there are only limited studies on color harmony and most are on two-color combinations. Three or more color combinations are so complex that they are seldom considered. Furthermore, most of the studies only investigated the simple pattern of two colors laid side by side.
2. Previous works suggest that any predictive model of color harmony must take into account at least two sets of factors: one is the preference on component colors and the other is the relationship between perceptual attributes among combination.
3. An unequivocal result from the analysis of these two sets of factors is that aesthetical evaluation on color combination cannot be predicted from component colors' preference. The inter-relationships between perceptual attributes of component colors seem to be more important.
4. Although the results about the interrelationship between component colors on color harmony are inconsistent, the variables can be grouped into three categories:
    i. Hue related ----- Hue Interval
    ii. Lightness related ---- Lightness Interval, Average Lightness
    iii. Chroma related ---- Chroma Interval, Average Chroma
5. In previous studies, each of these variables was considered as single variable and their interactions were not taken into account. This may be the reason why the reported relationships between influential variables and color harmony are inconsistent. Therefore, to describe color harmony

with reliability, both these factors and their interactions should be considered.

6. Another research gap is that most of the existing color harmony models are qualitative. However, in computer aided design, a quantitative model is needed.

2.4 The development of color preference

Previous studies have shown that preference of component colors may influence the harmony of color patterns. Therefore, the development on color preference is reviewed in this section. Preference for single colors and color combinations are surveyed and the relationship between color preference and color harmony are discussed.

2.4.1 Preference of single colors

Numerous studies on single color preference have been conducted to ascertain the dependence of color preference on stimulus characteristics, hue, lightness and chroma. Studies on color preference for single colors have long been focused on the hue effect. Later, it was realized that preference on single color couldn’t be considered simply in terms of hue. This resulted in much of the early work conducted in this field.

The studies on the dependence of single color preference on color characteristics is mainly related to three questions, that is, which of the color attributes may related to color preference, which one is the most important, and what the detailed relationship is.

Many authors reported that all three attributes might influence single color preference (Camgoz, et al, 2002; Granger, 1955d; Guilford and Smith, 1959; Guilford, 1934). Others have found different results. For example, Hogg (1969b) found that only hue and chroma might influence single color preference, Smets (1982) claimed that hue was almost irrelevant to color preference, and Ou, et al. (2004c) stated that chroma effect could be neglected.

For the predominant attribute on single color preference, different results were reported. Guilford (1934), Hogg (1969b), and Granger (1955d) all stated that hue was the most important factor on single color preference. Ou, et al (2004c) compared the color preference scales of 20 colors between British and Chinese observers. They found that hue was the most predominant attribute for British, whereas lightness was the most predominant attribute for Chinese. Smets (1982) found that variation in chroma primarily accounted for pleasantness judgment. A minor effect was due to value, while hue was almost irrelevant.

For the precise relationship between color attributes and color preference, the results are quite consistent. Guilford (1934), Eysenck (1941), Granger (1955c), Guilford and Smith (1959), and Wijk et al. (1999), all found that blue was preferred the most and yellow was preferred the least when isolated colors were presented. The same result was stated by Washburn and Grose (1921) and Camgoz et al. (2002) regardless of the background colors viewed. In their study of the role of spectral energy of the source and the background color in the pleasantness of object colors, Helson and Lansford (1979) stated that the hues of the highest-rated object colors over all sources and backgrounds were blue, purple blue, green and blue green. Yellow and purple were ranked low, so were colors with strong yellow components like green yellow and yellow red. For the influence of lightness and chroma, Guilford (1934), Smets (1982), Guilford and Smith (1959), Sivik (1975), Helson and Lansford (1979), Camgoz et al. (2002) all stated that brighter and more saturated colors were more preferred. One exception came from Hogg (1969b) who found no systematic relationship for value but detected a tendency for colors in the mid-chroma region to be highly preferred. Eysenck (1941) also stated a contradicting result that brighter colors were less preferred.

2.4.2 Preference of color combinations

Early work of the preference for color combinations focused on the prediction of preference of color combinations from that of component colors. Geissler (1917) was probably the first to investigate the relation between the preference of color combinations and that of the colors experienced singly. The result showed that the pleasantness of combinations increased directly with the pleasantness of the colors taken singly. Washburn, et al. (1921) repeated Geissler's experiment but use the method of "single stimuli" instead of paired comparison. They found that, to a very considerable extent, the pleasantness of a color combination depended upon the pleasantness of its components, but could not be explained entirely in terms of a mere summation of affect. Allen and Guilford (1936) presented 45 color combinations to 10 observers to judge the affective value by a rating scale method. They also concluded that the affective value of a combination was highly dependant on the affective values of its components; but there was also evidence that hue, lightness, and saturation differences between the components might influence the preference. Granger (1955c) obtained the same result and concluded that both preferences of components and intervals between the components influenced preferences of color combinations.

All these findings suggest that the influence of relationships between component colors cannot be neglected in preference of color combinations. Many previous authors have taken their efforts to clarify the dependence of the relationships between component colors and preferences of color combinations. Both Kansaku (1963) and Togrol (1967) studied the color patterns similar to the pattern shown in Fig. 2.3 and observed higher preference for large value difference, whereas the observation by Granger (1955a) was reverse. Granger (1955a) also found that hue difference was the most important influential factor and higher hue difference was more preferred. Washburn and Grose (1921), Reddy and Bennett (1985), and Helson and Lansford (1970) studied the preference of color patterns, which consisted of a center color placed on a background. They all demonstrated that the larger of the brightness contrast, the more the color combination were preferred.

2.4.3 Color preference, color pleasantness, and color harmony

It is quite difficult to distinguish the differences between color preference, color pleasantness, and color harmony. Granville (1987) considered color harmony as "the color usage that pleased people". Judd and Wyszecki (1975) defined color harmony as "when two or more colors seen in neighbouring areas produce a pleasing effect, they are said to produce a color harmony". These two statements suggest the same meaning for color harmony and color pleasantness. Judd and Wyszecki (1975) also declared that color harmony was a "matter of likes and dislikes". It indicates that there is a strong link between color preference and color harmony. Some previous investigations, for example, Granger (1955a, 1955b), treated color harmony and color preference with the same meaning. To clarify the relationship between these two terms, Ou et al. (2004c) compared the evaluating data of two scales, "like-dislike" and "harmonious-disharmonious". A very interesting result was obtained as shown in Fig 2.4.

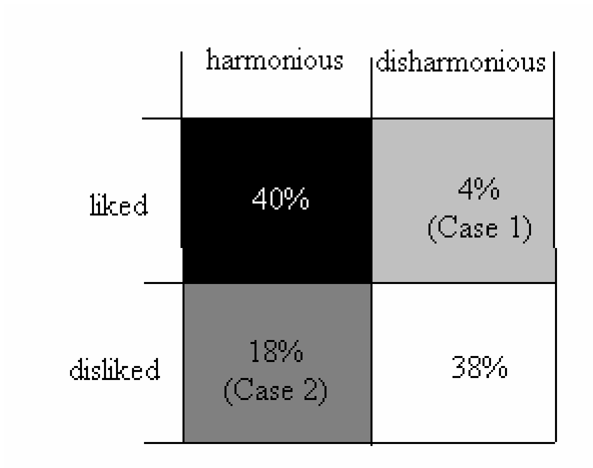


Fig. 2.4 The relationship between colour preference and colour harmony by Ou et al. (2004c)

From this figure, they observed that in most conditions, harmonious patterns were liked and disharmonious patterns were disliked. However, there was also a high possibility that observers dislike a color pair when they find it harmonious. Therefore, it was concluded that although color preference and color harmony had a strong correlation, they had different meaning and could not be substituted for each other.

2.5 Theory of sensation and perception

Humans are surrounded by a world of objects and events, and with no conscious effort humans sense their presence. But how all these pieces of information get into our heads and how all the qualities and features of objects in environment are represented and seemingly re-created in the minds is very important. In this section, many different theories relating to the sensation and the perception are summarized so that some insights into the nature of the visual aesthetic response may be obtained in the investigation.

2.5.1 Structuralism

While natural science focuses on discovering the structure of basic elements of matter, such as atoms, molecules, and cells, etc, psychology tries to discover the simplest, most basic elements of conscious experience according to a sensation and perception approach called structuralism. However, the early structuralism approach to perception is mainly of historical significance, and its strict elemental assumptions are not taken seriously today.

2.5.2 Gestalt psychology

The Gestalt theory of perception began from around 1910 and opposed the prevailing structuralism theory since it ignored a significant factor of perception: the relationship between stimuli. In Gestalt approach, it is believed that percepts are not formed out of unaltered elemental stimuli but from a grouping of features, which are determined by both the observer and the nature of the stimulus. This theory emphasized that people perceive the environment with respect to its inherent organizational and related properties. Therefore, people tend to perceive holistic, cohesive, meaningful forms. According to this theory, it is the innate organizing principles of the brain that determine how the world is seen.

2.5.3 Constructivist theory

The constructivist theory, which stemmed originally from Von Helmholtz, stresses the observer's active role in the perceptual process and derives in large part from the empiricist tradition. It proposed that what humans perceive is a mental construction based on their cognitive strategies, such as previous knowledge, biases, motives, and expectations, more than just the information in the stimulus input. Based on the past experience, internal hypotheses are formed which generate perceptual expectancy. This forms the basis of a "mental set" which determines both what will be looked for and partly how it will appear. In this process, ambiguity, uncertainty or conflicts of information may result in confusion, anxiety and raised tension or arousal and then lead to a negative response.

2.5.4 Direct registration theory

Different from the constructivist theory, in which perception is seen as the outcome of information processing, direct registration theory presumes that inner mental process plays little role in perception and an observer may directly pick up the information needed for effective perception (Gibson, 1950). According to this view, the information necessary to the accurate perception is already present in the environment; while additional stage of processing is unnecessary.

2.5.5 Computational theory

By considering the brain as analogous to a very complex computer, Marr applied his ideas to model the function of the visual system (Marr, 1982) and called it computational approach. This theory accepts the basic idea of direct registration that the environment directly provides all the information needed for perception. However, it also proposes that the perception of characteristics such as shape and form requires transforming or computing information of the stimuli into an internal representation. It works in the same way as a computer program allowing a machine to interpret selected sensory information for decision making.

2.5.6 Neurophysiological theory

The neurophysiological theory, proposed by Crick (1994), argues that sensory and perceptual phenomena are best explained by neural and physiological mechanisms serving sensory structures. Neurophysiological mechanisms play a very critical role in explaining phenomena at the sensory level. It has provided some definitive answers to fundamental problems of sensation and perception. However, it is not a separate and distinct approach of perception. It is just one step, that is, physiological mechanisms, in the chain of events between incoming sensory stimuli and a resulting conscious perceptual experience. Neurophysiological mechanisms alone cannot explain the whole process.

2.5.7 Summary

Applying these perception theories, it may be possible to clarify the cognitive process during aesthetic appraisal when concrete evidence of what is perceived is established. By combining these perception theories with the results of color harmony, the possibly process occurring in the inner world of human beings during aesthetics evaluation of color combinations can be deduced.

Chapter 3

Research Methodology

This chapter discusses the research methodology used in this experiment. Some important considerations relating to the experiment design are described. The experimental procedure is presented. Finally, the methods of data collection and analysis are given.

3.1 Design consideration

3.1.1 Research process

The first task in this study is to propose an effective sampling method to minimize the sample size of color combinations. According to the conclusions of the literature review, color combinations can be constructed based on three dimensions: hue-related dimension, lightness-related dimension and chroma-related dimension, as shown in Fig. 3.1.

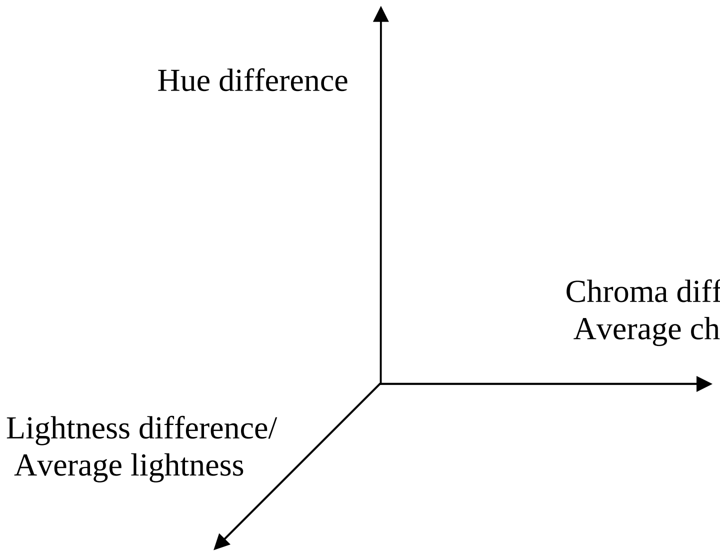


Fig.3.1 Three dimensional factors influencing color harmony

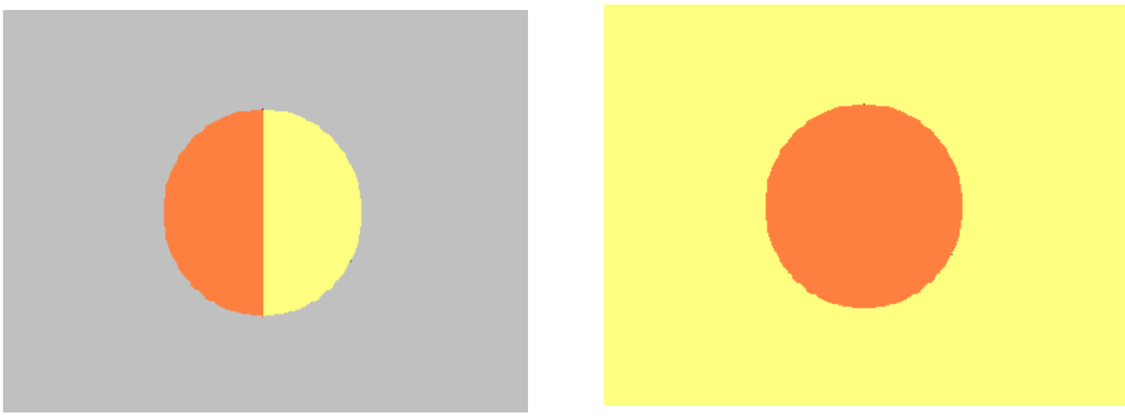
The influence of single color preference can be incorporated in the process of color harmony modeling. In these three factors, hue related variables are the most complex. Problems, such as (1) what hue should be selected and (2) how big the appropriate hue difference step should be, need to be decided first so that the size of color combinations can be controlled within the feasibility of this study. A preliminary experiment was designed to solve these problems. In the preliminary experiment, two-color combinations with different hues but same lightness and chroma were evaluated.

Based on the results of the preliminary experiment, the main experiment was designed to evaluate color harmony of two-color combinations with different hues, different lightnesses and different chromas. Two kinds of patterns discussed in Section 3.1.2 are studied.

A further experiment is designed to study harmony of three-color combinations. As we have discussed in Section 2.3.5, the interrelationships between component colors are the most influential factors on color harmony. In addition, it is known that three-color combinations can be decomposed into three two-color combinations with almost no relationship lost. Hence, the possibility of predicting color harmony of three-color combinations from that of two-color combinations is subsequently investigated.

3.1.2 Color patterns

Two types of color patterns as shown in Fig.3.2 were considered in this study. One is that two colors laid side by side on a neutral grey (Munsell N5) background (Fig. 3.2a), and the other is composed of a center color placed on a colored background (Fig. 3.2b).

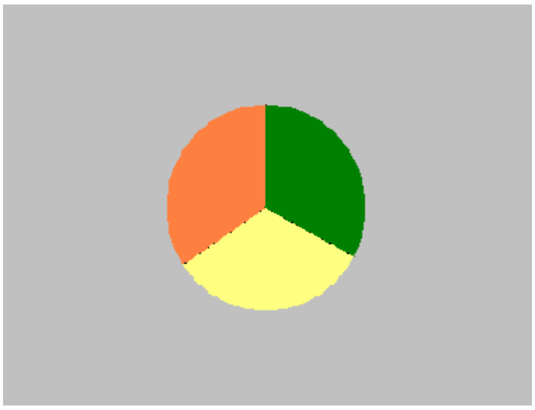


(a) (b)

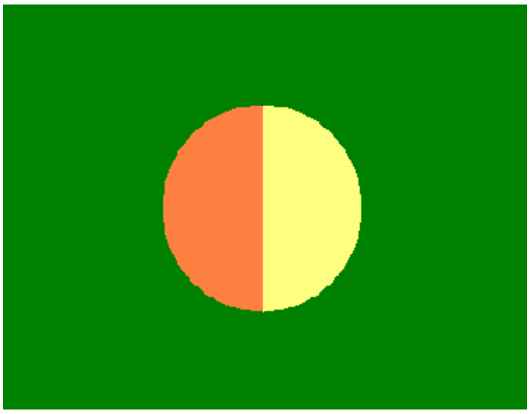
Fig. 3.2 Two kinds of two-color patterns. (a) color pattern with two colors laid side by side; (b) color pattern with two colors in center – background relationship

For simple, the former was named SS pattern and the latter CB pattern. Most color designs can be decomposed into these two basic patterns. Almost all previous studies on color harmony were based on SS patterns. In this study we also considered CB pattern since it was widely adopted in many practical applications such as design of printing textile patterns. Colors in these two types of patterns may have different interactions and thus both were considered in this color harmony study.

For three-color combinations, two kinds of patterns, as shown in Fig. 3.3, were considered in this study.



(a)



(b)

Fig. 3.3 Two kinds of three-color patterns. (a) Color pattern with three colors laid side by side; (b) Color pattern with two colors laid side by side on a colored background.

The pattern in Fig. 3.3a is three colors laid side by side with a 120^{o} covering angle each. This pattern can be decomposed into 3 SS patterns. For simplification, we call it SSS pattern. The pattern shown in Fig. 3.3b is the other kind of three-color pattern with two colors laid side by side on a colored background. This pattern can be decomposed into one SS pattern and two CB patterns. Therefore, we call it SSB pattern.

3.1.3 Evaluation variables and rating scales

Rating scale, as a method developed in psychophysics, has been frequently used to estimate the magnitude of individual dimensions of color (Fairchild, 2005). In psychological research, even though there is no objective external reference, relative scaling can be performed for reliable estimation (Lockhead, 1992). It has been adopted by many researchers in their color harmony studies (Morriss, etc. 1987, 1988, Hogg, 1969a, 1969b, Berlyne, 1971, Pieters, 1979, Sivik and Taft, 1992, Ou, and Luo, 2003). In this research, rating scale method was also used to evaluate preference levels of single colors and harmonious levels of color patterns.

A typical rating scale consists of pairs of antonyms placed at the two ends of the scale. For example, in this study, an "unpreferred-preferred" ratings scale

unpreferred -3 -2 -1 1 2 3 preferred

was used to evaluate the preference levels of component colors, and a similar "Unharmonious - Harmonious" rating scale was used to evaluate harmonious levels of color patterns. In the scales, the negative response descriptors ("unpreferred" or "unharmonious") appeared at the left end, and the positive response descriptors ("preferred" or "harmonious") appeared at the right end. Six ratings (from -3 to 3) were used as response magnitudes for evaluation.

3.1.4 Color combinations

In the preliminary experiment, in order to evaluate the influence of hue on color harmony, colors with different Munsell hues but the same lightness and chroma were used. The L*, C* values were 58 and 35, respectively, which were approximate to Munsell value 6 and Munsell chroma 8. The hues adopted in the patterns are shown in Fig. 3.3. In SS patterns, the two colors are symmetrical and exchangeable, and are denoted as Color1 and Color2, while in CB patterns, the two colors are unsymmetrical and non-exchangeable, and are denoted as background color and center color. There are 10 hues (from 5R to 5RP) in Color1 and background color column, respectively, and 20 hues (from 5R, 10R to 5RP, 10RP) in Color2 and center color column, respectively. We termed ten hues from 5R to 5RP as ‘5-series’ and 10R to 10RP as ‘10-series’. In Fig. 3.4, each of the ten colors in the left column would be combined with each of the twenty colors in the right column for SS and CB patterns.

Color 1/ Background color		Color 2/ Center color
5R	×	5R
5YR		10R
5Y		5YR
5GY		10YR
5G		5Y
5BG		10Y
5B		5GY
5PB		10GY
5P		5G
5RP		10G
		5BG
		10BG
		5B
		10B
		5PB
		10PB
		5P
		10P
		5RP
		10RP

Fig. 3.4 Hues of color samples used in preliminary experiment.

The number of SS patterns is calculated by subtracting the number of symmetrical pairs and the number of pairs with identical colors from the total number of combinations. As a result, the number of SS patterns is 145 (200 total pairs – 45 symmetrical pairs – 10 identical color pairs). In the CB patterns, as the Center color and Background color are not symmetrical, there are 190 (200 total pairs -10 identical pairs) color combinations.

The color samples used in the main experiment varied along the dimensions shown in Fig. 3.1. The variation along the hue related dimension was decided according to the result of preliminary experiment. Both the interval value and the average value were deemed to be very important in the lightness related and chroma related variables (Granger, 1955b, Pieters, 1979, Ou and Luo, 2006, Nayatani, et al, 1967, 1969). The selection of color pairs along the lightness and chroma dimensions is as follows. The lightness and chroma of each color were respectively classified into three levels: high, medium, and low. Hence for the two component colors in a pattern, 6 following combinations along lightness or chroma dimension are possible: high-high, high-medium, high-low, medium-medium, medium-low, and low-low. With different lightness combinations and chroma combinations, different color schemes were constructed for each hue pair. In this experiment, 35, 50, 65 were selected to represent low, medium, and high value of L*. It is known that the highest chroma achieved depends on the hue and lightness of the samples. For example, for 5B and 5BG, when lightness and chroma are 35, 30, or 50, 45, respectively, the colors may be out of gamut. Therefore, the chroma was selected based on the hue and lightness of the samples so that the whole color space can be covered as far as possible while still within the gamut of the display system. Table 3.1 shows the values of C* and L* which represent low, medium, and high level of chroma and lightness.

Table 3.1 Lightness and chroma of color samples used in main experiment.

Lightness	Chroma		
	low	medium	high
35	10	20	30
50	15	30	45
65	20	30	40

In order to predict the harmonious levels of three-color combinations from that of two-color combinations, we designed color combinations as follows. Patterns such as in Fig. 3.3a can be decomposed into 3 SS patterns and patterns such as in Fig. 3.3b can be decomposed into 1 SS and 2 CB patterns. Each two-color combination can be grouped into harmonious or unharmonious categories according to the results of main experiment. All possible three-color combinations are listed in Table 3.2.

Table 3.2 All possible three-color combinations.

	Category	Category of two-color patterns	
		harmonious	unharmonious
SSS pattern	1	All	None
	2	Two SS	One SS
	3	One SS	Two SS
	4	None	All
SSB pattern	1	All	None
	2	Two CB	One SS
	3	One SS, One CB	One CB
	4	One CB	One SS, One CB
	5	One SS	Two CB
	6	None	All

Based on Table 3.1, we investigated whether it was possible to predict the harmonious levels of three-color combinations from that of two-color combinations.

3.1.5 Objectives of the experiment

The objectives of the experiment are (1) to evaluate single color preference, and (2) to evaluate harmonious levels of color schemes. Since the color preferred as a background color may not be preferred as an object color, the evaluations of the preference of object color and background color were based on their real size in the two-color combination. Afterwards the color harmonies of SS patterns and CB patterns were evaluated. During each experimental session, colors/patterns appeared in a random order, with the time interval between sequential color/pattern being 10 seconds. The need of a time interval between the evaluations will be explained in the following section. Subjects were instructed to evaluate the preference/harmonious level of each color/pattern based on the 7-point rating scale. The detailed instructions of the experiment are listed in Appendix 1.

3.1.6 Adaptation

During the experiment, the adaptation process affects the judgment of the subject. That is, the evaluation of a pattern may be influenced by the appearance of previous patterns. Two levels of adaptation, the sensory level and the cognitive level (Fairchild, 2005), may occur.

On the sensory level, adaptation produces a shift of the colors towards the afterimage colors of the previous pattern. To reduce this effect, in the present study, subjects were asked to look at a gray screen for ten seconds between two observations. In addition, randomizing the order of presentation of patterns for each subject and across subjects was also applied to minimize the effect of this chromatic adaptation.

Cognitive adaptation refers to a progressive learning effect, by which subjects may respond more quickly and more proficiently at rating patterns during the experimental session progression. In this study, the order of presentation of patterns was randomized, so that cognitive adaptation might be different for each subject and its effect could be canceled out by averaging the results across subjects.

3.1.7 Management of experiment errors

In an observation process, two types of error, i.e., systematic bias and random error, may occur (Mitchell and Jolley, 2001). To obtain more reliable results, the following techniques were adopted to reduce the influence of these two errors:

1. Subjects with similar cultural background, education and age were selected and the sex of each subject was recorded, with 50% male and 50% female.
2. During the experiment, subjects were required to record their intuitional response to color patterns to reduce the influence of subjects' knowledge on judgments of color patterns.

3. Color patterns were observed one by one in random order so that the effect of order (practice and fatigue) could be reduced, and adaptation effects could be cancelled out.
4. Training steps were arranged before experiment to warm-up subjects and motivate them to be accurate.
5. Ten percent of duplicate color patterns were included in the experiment and only the data of those subjects with high consistence during observations were used.
6. Sufficient time was allowed between experiment sessions for memory of foregoing experiment to wear off.

3.2 Implementation

3.2.1 Setup

The experiment was conducted in a complete dark room and the influence of ambient illumination could be neglected. The experiment was conducted on a SONY Trinitron 21 inch CRT monitor. The monitor was calibrated and characterised using the gain, offset, and gamma (GOG) model with additive terms for ambient flare and interreflection (Berns, Motta, and Gorzynski, 1993, CIE, 1996). The lightness, chroma, and hue of each color were converted into RGB values via the GOG model, and then displayed on the CRT monitor. During the experiment, subjects were asked to sit in front of the CRT monitor at a visual field size of 10° from color patterns.

3.2.2 Subjects

Twenty subjects, half male and half female, participated in the visual assessments. They were all students from Chinese university aged from 25 to 35. Before experiment, the subjects were asked to take the Isihara color blindness test (Ishihara, 1976) to ensure they had normal color vision.

3.2.3 Training

Before experiment, subjects were required to go through a brief training period. That is, they were asked to evaluate a set of patterns representative of the wide variety of color combinations contained in the actual experiment. During this period, subjects became familiar with the procedure and thus the experiment could be performed more smoothly in the actual test.

3.2.4 Experimental procedure

The experimental procedure is described in the following. A color pattern was displayed on the screen. A rating was made by clicking a radio button labeled with a number from -3 to 3 along the rating scale. The rating was automatically recorded, together with the information of the color compositions in the pattern. By clicking the down arrow button, a neutral gray color was displayed on full screen for ten seconds. Then a new color pattern was displayed. This procedure was repeated until all patterns in the session were evaluated. The number of patterns in each session was between 200 and 800. Evaluation of each pattern took a few seconds, plus the ten seconds of gray screen between the patterns. Therefore time span of each test session was between 1 and 2.5 hours by the observers.

3.2.5 Data processing

The data was collected automatically by the computer as the experimental session proceeded. The data indicating the composition of patterns and their rating by each subject was stored in a multidimensional database. The data was averaged across subjects, plotted for interpretation, and fitted with parametric models. The results of the preliminary experiment are discussed in Chapter 4 and the results of the main experiment and the following experiment are discussed in Chapter 5.

Chapter 4

Results of Preliminary Experiment

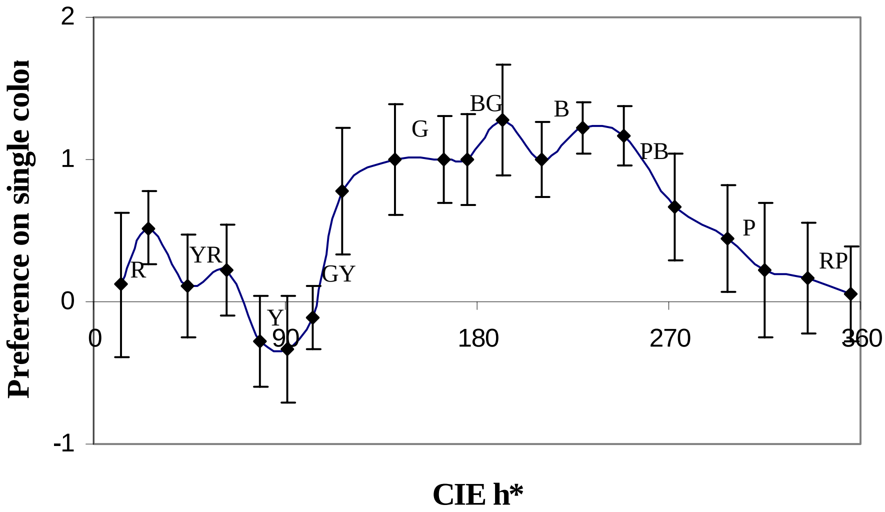
In the preliminary experiment, the preference of 20 object colors and 10 background colors were evaluated. 145 SS patterns and 190 CB patterns which covered a wide level of hue difference were evaluated based on seven-point "unharmonious-harmonious" scales. The preference of single color was analyzed, and the influences of single color preference and hue difference on color harmony were discussed. Based on these results, two quantitative color harmony models for SS and CB patterns were developed respectively.

4.1 Preference on single color

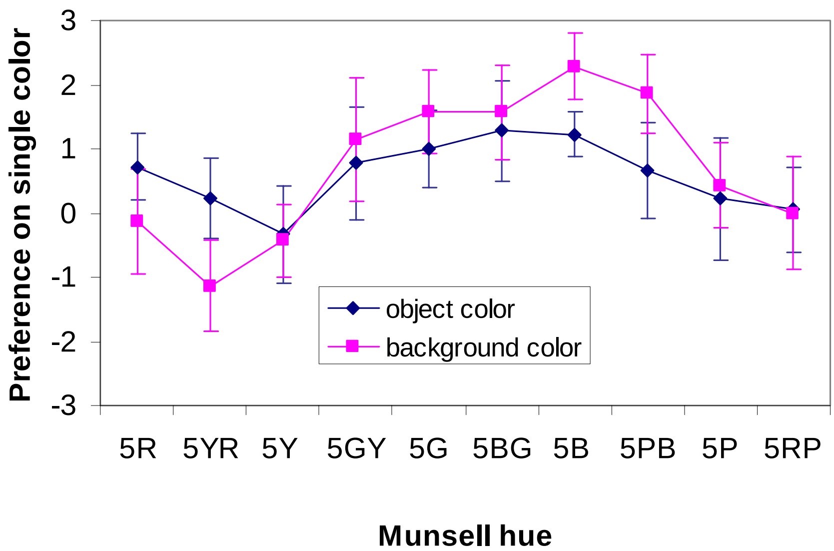
The variation of preference of object color against its CIE h^* is shown in Fig. 4.1(a). From this figure, it can be observed that colors containing Green or Blue are more preferred, while those containing Yellow or Purple are less preferred. This finding agrees with those by Eysenck (1941), Granger (1955d), and Guilford & Smith (1959), etc.

The preference of colors as background is shown in Fig. 4.1(b). The preference of corresponding colors as object is also shown in the same figure for comparison. The shape of two curves is very similar. It was also found that those containing Green or Blue are more preferred, while those containing Yellow or

Purple are less preferred for colors as background. In addition, the magnitude of response to colors as background, regardless of preferred or unpreferred ones, is higher than that as object. As the area of the color for background is larger than that for object, it is inferred that a larger area of color may activate a higher response than a smaller one.



(a)



(b)

Fig. 4.1 Average single color preference ± standard deviation of 20 subjects (a) for colors as object (b) for colors as background, compared with object color preference.

4.2 Color harmony modeling

4.2.1 Observer repeatability and agreement

To ensure that we are measuring a stable characteristic, observer repeatability and agreement were examined.

Observer repeatability is used to determine the variation of the visual assessment of a particular observer. In the preliminary experiment, 20 duplicated color patterns were used to test the repeatability of each subject. The results are shown in Table 4.1. It was found that, among 20 subjects, only 1 had correlation coefficient less than 0.7 ($p < 0.05$). Consequently, the evaluation results of the rest 19 subjects were adopted for further statistical analysis.

Table 4.1 The repeatability of each subject and the average repeatability.

No. of subject	1	2	3	4	5	6	7	8	9	10
r	0.75	0.83	0.77	0.86	0.78	0.75	0.84	0.82	0.80	0.77
No. of subject	11	12	13	14	15	16	17	18	19	20
r	0.76	0.71	0.59	0.79	0.84	0.78	0.83	0.78	0.77	0.79
Average *r*	0.78									

Observer agreement represents the average deviation of each individual observer from the mean visual results of all observers. The correlation between the color harmony values of each observer and the average color harmony values of all observers were calculated. The average correlation coefficients are 0.73 in SS patterns and 0.71 in CB patterns with the lowest individual figure large than 0.6. Table 4.1 illustrates that the average repeatability is 0.78. It seems that the repeatability is better than the agreement. This is reasonable since the former compare the evaluation results of the same person, while the later compare the results between different observers.

The results of observer repeatability and agreement indicate that color harmony is an unequivocal and stable feeling for most people.

The average color harmony for each color pattern was calculated among the 19 subjects and was then treated as dependent variable. Hue difference between the two component colors as discussed in section 4.2.2.1, and average preference on two component colors were treated as independent variables. Based on these variables, color harmony model was then constructed.

4.2.2 Color harmony of SS patterns

4.2.2.1 Effects of hue difference

To facilitate the investigation of the influence of hue difference, we define the hue difference in degree as follows:

Δh_{ab} = Hue1 - Hue2

Δh_{ab} = Δh_{ab} - 360, if Δh_{ab} large than 180 degree

Δh_{ab} = Δh_{ab} + 360, if Δh_{ab} less than -180 degree where Hue1 refers to the hue of Color1 and Hue2 the hue of Color2. This method keeps the hue difference in the range of [-180, 180]. For simplicity, the term "hue difference" or Δh_{ab} always refers to the values calculated by this method through out the thesis, unless stated otherwise.

Color harmony as a function of hue difference ($|\Delta h_{ab}|$) is shown in Fig. 4.2. 180 degree of hue difference corresponds to the most different or complementary hues, while 0 degree corresponds to the same hues. A negative relationship was observed between color harmony and hue difference. That is, patterns whose component colors have similar hues are more harmonious, while those have complementary colors are more unharmonious. This result is in agreement with those published by most of the previous researchers (Nayatani, etc. 1967, 1969, Sivik & Taft, 1992, Chuang & Ou, 2001, and Ou and Luo, 2003), who also found that color pairs with similar hues were more harmonious.

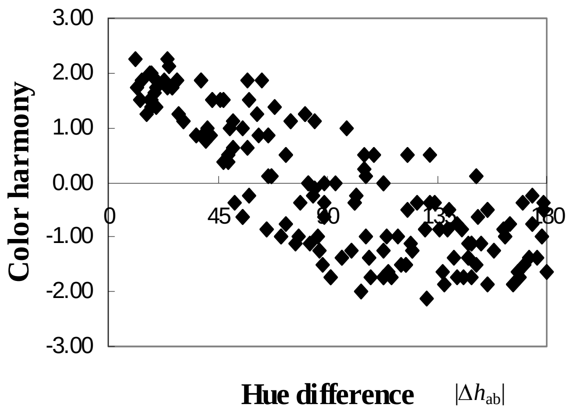


Fig. 4.2 The scattering of color harmony against the corresponding hue difference for SS patterns.

To examine the detailed relationship between hue difference and color harmony, ten 5-series colors as Color1 were fixed as reference color, and the hue difference Δh_{ab} between Color1 and Color2 were calculated. Fig. 4.3 shows the color harmony as a function of hue difference Δh_{ab} for 5R as a reference color. The plots for all reference colors are shown in Appendix 2.

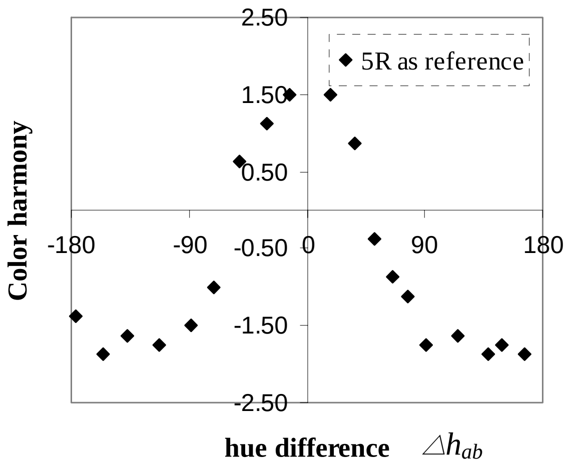


Fig. 4.3 The scattering of Color harmony against hue difference for SS patterns with 5R as reference color.

From these figures, the following observations can be found: firstly, color harmony for all reference colors has a similar bell-shaped trendline with respect to hue difference. Patterns with smaller hue difference are more harmonious, while those with complementary colors are more unharmonious. Secondly, the variation of color harmony against hue difference is very continuous and regular. Therefore, we can reduce the sample size by using a small number of Color2. In this study, we selected 5-series hues as Color2 in the subsequent main experiment, excluding the 10-series hues. This sample size reduction is very important for the main experiment, in which more dependent variables were considered and the sample size was very large. Finally, a small difference was observed between curves of different reference colors. This indicates that, in addition to hue difference, color harmony may also be influenced by the characteristics of the reference colors such as single color preference. The detailed analysis is provided in next section.

4.2.2.2 Effects of single color preference

To investigate the influence of single color preferences on color harmony, two hypotheses were made:

(1) Color patterns with a preferred color may be evaluated to be more harmonious.

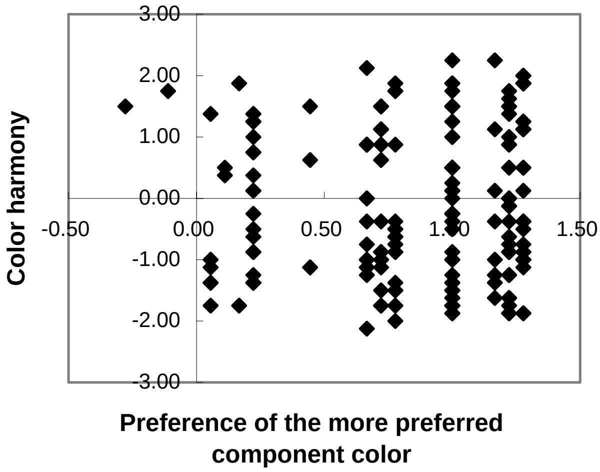
(2) The more the two component colors are preferred, the more harmonious the color patterns are evaluated.

To validate these two hypotheses, the following two corresponding relationships were examined:

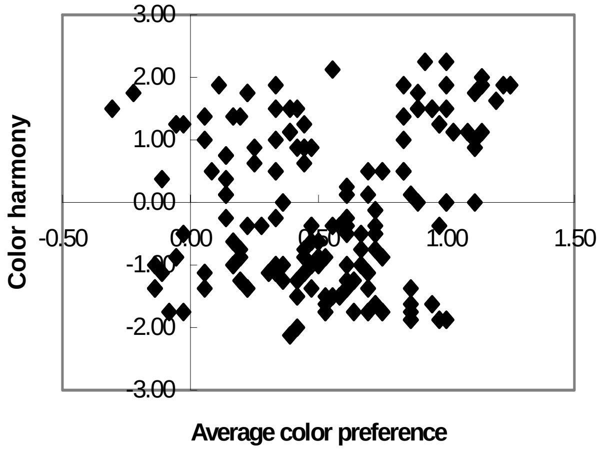
(1) The relationship between color harmony and the preference of the more preferred color in a pattern.

(2) The relationship between color harmony and the average color preference of component colors.

The distribution of color harmony against the preference of the more preferred color and the distribution of color harmony against average color preference are plotted in Fig. 4.4. No distinct relationship can be observed from both figures.



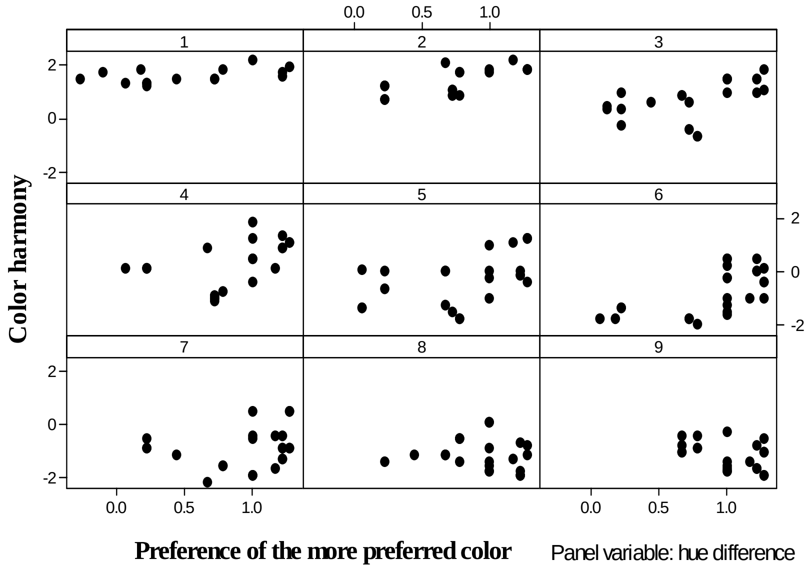
(a)



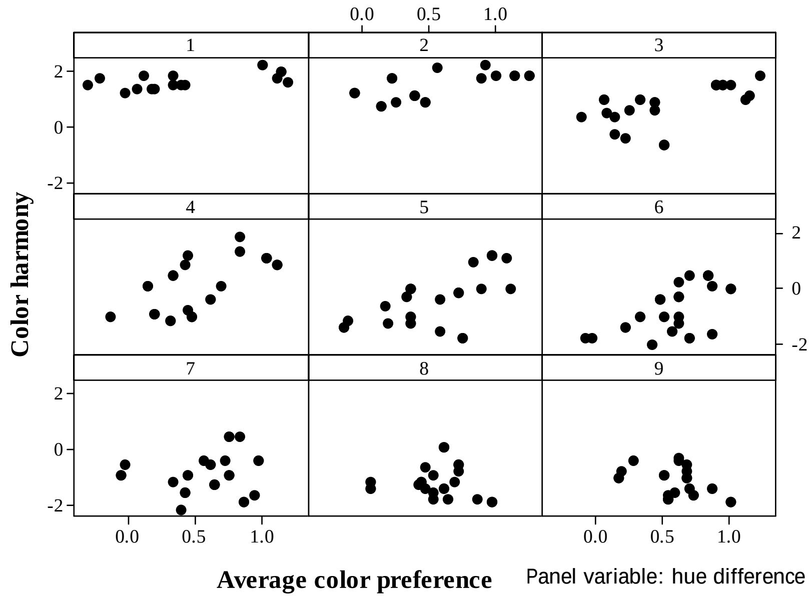
(b)

Fig. 4.4 The scattering of color harmony for SS patterns against (a) the preference of the more preferred component color and (b) the average color preference.

Since hue difference influences color harmony significantly, to show the effect of color preference, we need to compare the color harmony under a small hue difference range. Therefore, the whole hue difference was divided into 9 small sections. The change of color harmony against the preference of the more preferred color and that against average color preference were respectively plotted in Fig. 4.5(a) and Fig. 4.5(b) with each panel corresponding to a small range of hue difference. Nine panels in each figure correspond to 9 parts of hue difference from 0 to 180. For example, 1 represents the hue difference from 0 to 20, 2 represents hue difference from 21 to 40, etc. A very small positive relationship can be observed between color harmony and the preference of the more preferred color according to Fig. 4.5(a), while a more distinct positive relationship can be observed between average color preference and color harmony according to Fig. 4.5(b), especially when hue difference is of medium magnitude. This result indicates that average color preference is more influential than the preference of the more preferred color in a pattern on the harmony of SS color patterns.



(a)



(b)

Fig. 4.5 The scattering of color harmony of SS patterns against (a) the preference of the more preferred color and (b) the average color preference with hue difference was fixed in a small range in each panel.

4.2.2.3 Quantitative modeling of color harmony

According to the above analysis, two kinds of variables, i.e., hue difference and single color preference, should be considered in developing a quantitative color harmony model for SS patterns. Predictor variables, not only individual dimensions but also their interactions should be considered in modeling.

By using regression analysis, the following mathematical model for the color harmony in SS patterns was obtained:

$$y = 5.665 - 3.317x_1 + 0.886x_2 \tag{4.1}$$

with $R^2 = 0.720, p < 0.001$

where y is average color harmony, x_1 is $\log(|\Delta h_{ab}|)$, x_2 is average preference. Both hue difference and average single color preference are significant predictors ($p < 0.001$). The total variance explained by this model is 72%. $\log(|\Delta h_{ab}|)$ accounts for 65.6% of the variance, while average preference accounts for only 6.4%.

It is clear that hue difference is the main factor affecting color harmony for SS patterns, while the influence of single color preference is very small. This result is not consistent with most of previous studies, where they reported that single color preference was very important to color harmony (Granger, 1955a, 1955b, 1955c, Nayatani etc. 1967, 1969, Chuang & Ou, 2001, Ou and Luo, 2003, 2006). The logarithmic relationship between color harmony and hue difference shows that with the increasing of hue difference, the color harmony value decreases more and more slowly. When hue difference is equal to zero, the two colors are the same and two colors become one color. The color harmony in this situation is not covered by this work.

4.2.3 Color harmony of CB patterns

4.2.3.1 Effects of hue difference

The color harmony for CB patterns as a function of hue difference is shown in Fig. 4.6. Contrary to SS patterns, a strong positive relationship was observed between hue difference and color harmony of CB patterns. Patterns with small hue difference between background and center color were regarded to be unharmonious, while those with large hue difference were considered to be harmonious. This result is consistent with the research by Helson and Lansford (1979). They studied the preference of this kind of color patterns and found that higher frequency for most preferred combinations occurred at the hue difference from Munsell 7 steps to 10 steps, while most unpreferred combinations occurred at the hue difference from Munsell 2 to 3 steps, where 0 step represents similar hues, 10 steps represent complementary hues.

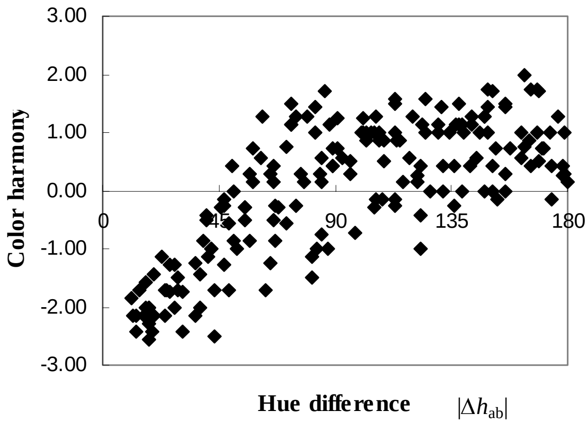


Fig. 4.6 The scattering of color harmony against the corresponding hue difference for CB patterns.

The detailed relationship between hue difference and color harmony is analyzed for each background color. Fig. 4.7 shows the color harmony as a function of hue difference for background color 5R. The plots for all background hues are shown in Appendix 3.

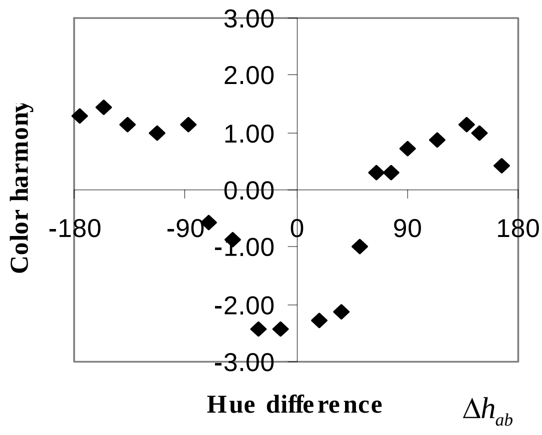


Fig. 4.7 The scattering of color harmony against hue difference for CB patterns with 5R as background color.

For different background, small differences in the shape of trendlines are found. That is, for a given hue difference, color harmony is dependent on the hue of background. In addition, as in the case of SS patterns, a continuous and regular variation of color harmony against hue difference was observed for CB patterns. Therefore, we can reduce the sample size by using a small number of center colors. In this study, we selected 5-series hues as center color in the subsequent experiment and excluded the 10-series hues.

4.2.3.2 Effects of single color preference

In SS patterns, the relationship between color harmony and the preference of the more preferred color as well as the relationship between color harmony and average color preference were examined. Considering the asymmetry of the two component colors of CB pattern, besides these two relationships, we further investigated their respective influences of background color preference and center color preference on color harmony.

As in SS patterns, no distinct relationship was observed between color harmony and the preference of the more preferred color in CB patterns. Furthermore, there was also no obvious relationship between average color preference of two component colors and color harmony in CB patterns, while a small positive correlation was observed in SS patterns. To investigate the influence of preference of background color and center color, the average color harmony ratings for each background color (with 19 center colors) and each center color (with 9 background colors) were calculated, respectively. Their relationships with single color preference are shown in Fig 4.8 and Fig 4.9, respectively.

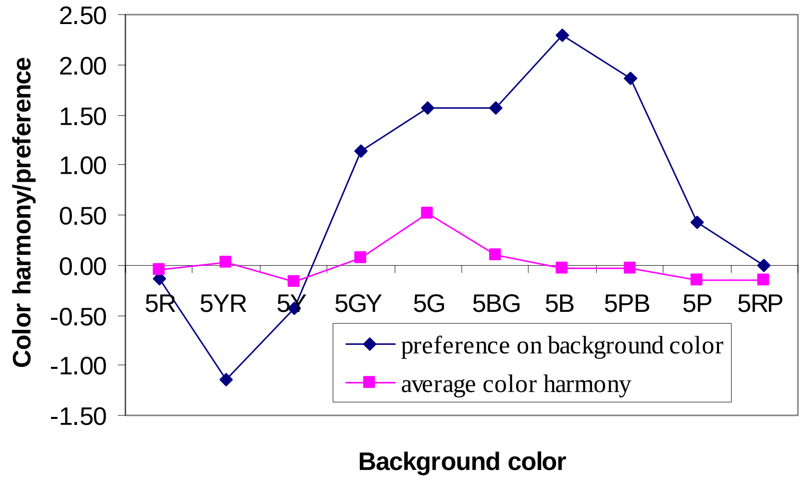


Fig. 4.8 The distributions of single color preference and average color harmony for ten background colors.

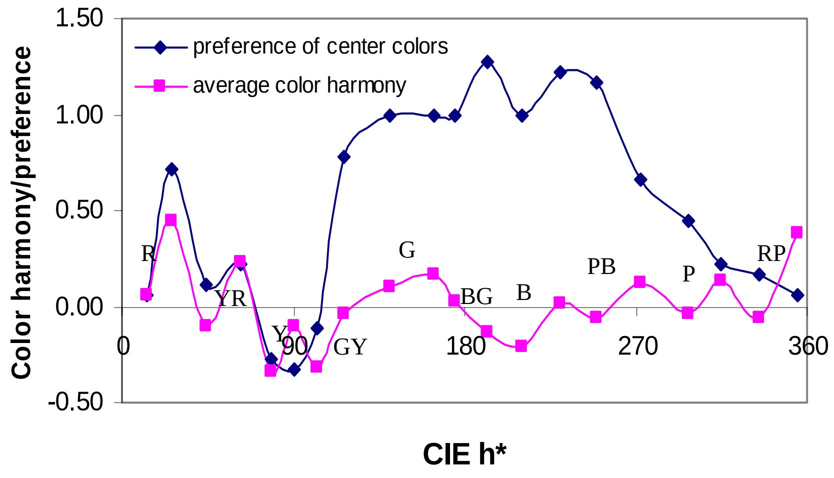


Fig. 4.9 The distributions of single color preference and average color harmony for 20 center colors.

In Fig. 4.8 and Fig. 4.9, there's no clear relationship between single color preference and average color harmony. By further examining the average color harmony, it can be seen that patterns containing 5G are ranked slightly high, while those containing Yellow color are ranked slightly low in both situations. As a whole, the influence is very slight for CB patterns.

4.2.3.3 Quantitative modeling of color harmony

By using regression analysis, we obtained the following model for color harmony in CB patterns:

$$y = -5.170 + 2.658x_1 + 0.554x_2 \qquad (4.2)$$

with $R^2 = 0.687, p < 0.001$

where y is average color harmony rating, x_1 is $\log(|\Delta h_{ab}|)$, x_2 is average color preference. Both hue difference and average single color preference are significant predictors ($p < 0.001$). The total variance explained by this model is 68.7% with $\log(|\Delta h_{ab}|)$ accounting for 66.1% of the variance. The contribution of average preference, only accounting for 2.6%, is so small and almost can be neglected.

Equation 4.2 indicates that hue difference is also the main factor influencing color harmony of CB patterns as for SS patterns. A positive correlation exists between color harmony and hue difference of CB patterns. The logarithmic relationship between color harmony and hue difference indicates that the variation of color harmony may slow down with the increasing of hue difference. The effect of single color preference on color harmony is significant, but very weak.

4.3 Conclusion

From the data analyzed above, we can draw these conclusions:

Firstly, hue difference is the most influential factor on color harmony, not only for SS pattern but also for CB pattern. The influence of the hues of two component colors was considered to be of minor importance. Based on this result, we can construct the sampling method by fixing one color while varying the other color to cover various levels of hue difference in the subsequent main experiment. By using this sampling method, the sample size can be largely reduced and therefore the size of color combinations can be controlled within the feasibility of this project, while the experiment results are still applicable to most color combinations.

Furthermore, the influence of hue difference is different for the two different patterns. More specifically, a positive relationship was found in CB patterns, while a negative relationship was found in SS patterns. This indicates that for different color patterns, different color harmony rules should be used.

Finally, it is found in this preliminary study that the influence of single color preference is not so important, which disagrees slightly with previous studies (Granger, 1955a, 1955b, 1955c Nayatani etc. 1967, 1969, Chuang & Ou, 2001, Ou and Luo, 2003, 2006).

These findings were considered in designing the main experiment described in chapter 5.

Chapter 5

Color Harmony of Two-color Patterns

Based on the results of the preliminary experiment, the main experiment was designed to evaluate the color patterns differing in hue, lightness and chroma. The data collected in the experiment were analyzed. Mathematical models for two kinds of two-color patterns were constructed so that color harmony can be systematically specified and applied.

5.1 Evaluation of color harmony on two-color patterns

In the preliminary experiment, color harmony of two-color combinations with different hues, but same lightness and same chroma were evaluated. To construct a general color harmony model of two-color combinations, the main experiment was designed to analyze the harmony of two-color combinations with different hues, different lightness values and different chroma values based on the preliminary experimental results. Two kinds of two-color patterns, which have been discussed in Section 3.1.2, were evaluated.

The color samples used in the main experiment varied along the dimensions shown in Fig. 3.1. It indicates that hue related, lightness related, and chroma related variables are three categories of factors which would be involved in color combination selection (Section 3.1.1). The variation along the hue related dimension was decided according to the result of preliminary experiment, which indicates that for both kinds of color patterns, the hue difference was the most important factor and the influence of hue itself was negligible. Therefore, we can fix the hue of one component color and change that of the other component color such that various levels of hue difference could be covered. By using this sampling method, sample size can be largely reduced, while the results may still be applicable to most situations. Furthermore, it was also observed in the preliminary experiment that the variation of color harmony along hue angle is very continuous and regular. Thus, fewer hue angles would be adopted and sample size can be further reduced. In main experiment, we selected Munsell hue 5G as one hue and ten 5-series Munsell hue as the other ones, as illustrated in Fig 5.1. Hence, there are totally ten hue pairs in each kind of patterns. In CB pattern, since two component colors are asymmetric, both hue pairs with 5G as background color and as center color were used. Therefore, there are totally 19 hue pairs in CB pattern.

$$\text{5G} \times \begin{bmatrix} \text{5G} \\ \text{5GY} \\ \text{5BG} \\ \text{5B} \\ \text{5PB} \\ \text{5P} \\ \text{5RP} \\ \text{5R} \\ \text{5YR} \\ \text{5Y} \end{bmatrix}$$

Fig 5.1 Hue pairs used in the main experiment

To test the generality of the result, other hue pairs, including 5R×5RP, 5R×5P, 5R×5B, 5GY×5BG, 5GY×5Y, were also selected in a random manner due to the very large number of evaluations involved. As a result, the additional 5 hue pairs for SS pattern and 10 hue pairs for CB pattern were involved in the evaluation experiment for reliability test of color harmony model.

The selections of lightness and chroma, as well as the selection of color combinations, have been explained in Section 3.1.4. Firstly, three levels (high level, median level, and low level) of lightness and chroma for single color were selected. For most hues, 9 color samples were selected with different combinations of chroma and lightness levels. For the hue 5B and 5BG, as two colors (L*=35, C*=30 or L*=50, C*=45) are out of the gamut of CRT display, only 7 color samples were used. According to previous studies, we have learnt that lightness difference, total lightness, chroma difference and total chroma are the main factors that influence the color harmony of color combinations. Lightness or chroma of single color was not considered serious for color harmony (Ou&Luo, 2003; Sivik, 1992; Pieters, 1979; Hogg, 1969a, 1969b; Nayatani etc, 1967, 1969; Grander, 1955a, 1955b). The selection of color combinations is therefore based on these previous conclusions. As there were 9 colors for each hue, when they were combined with 5G to form hue pairs, the number of color combinations for SS pattern is $C_9^2 + 9 = 45$, where the second term (9) represents the number of combinations with same lightness and same chroma. When 5G was combined with 5G, these 9 combinations was excluded since the two component colors are the same, thus we obtained 36 color combinations for 5G and 5G hue pairs. As there were only 7 colors for 5B or

5BG, 36 different color pairs were obtained for each hue pair in the combination with 5G. Consequently there are 423 (=45×7+36×3) different SS patterns. As a result, totally 630 SS patterns were evaluated in this experiment, with additional 207 (45×3+36×2) testing samples.

As the two component colors of CB patterns are asymmetrical, it is of our interest to investigate if exchanging the positions of these two colors may affect the harmonious level, although in preliminary experiment, we observed that exchanging the hues of the two component colors did not affect the result. The number of CB patterns is 423×2=846. With additional 414 (=207×2) test samples, totally 1260 CB patterns were evaluated in this experiment.

The procedure of the experiment and the data collection in this chapter are the same as those adopted in the preliminary experiment.

5.2 Color harmony of two-color patterns

5.2.1 Preference on single colors

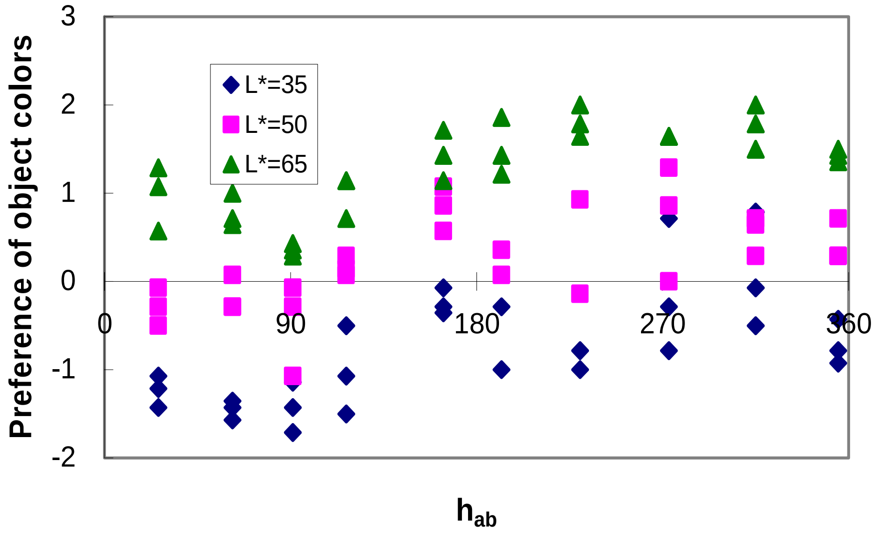
The influence of perceptual color attributes (hue, lightness, and chroma) on single color preference was examined by correlation analysis. Table 5.1 suggests that all three attributes have significant influence ($p < 0.01$) on the preference of single colors no matter it is an object or a background color, and lightness is the most important factor in both situations.

Table 5.1 Correlation coefficients between single color preference and color perceptual attributes.

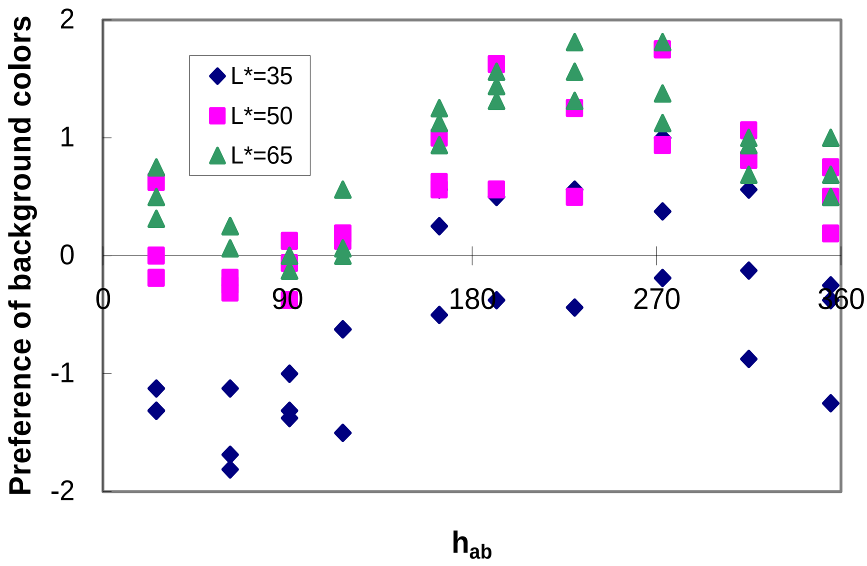
Single color preference	Color perceptual attributes		
	Lightness	Chroma	Hue
Color as object	0.837	0.398	0.355
Color as background	0.627	0.387	0.433

The detailed relationship was analyzed by using graphical representation. Fig. 5.2 shows the scattering of single color preference with respect to hue h_{ab} for different lightness L^*. Fig. 5.2(a) and Fig. 5.2(b) show the preference of single color as object and as background, respectively. It is found that:

1) The variation of preference of object color is similar to that of background color.
2) The variation of preference along the hue dimension is quite similar to the observation in the preliminary experiment. That is, colors containing Green or Blue were more preferred, while those containing Yellow or Purple were less preferred.
3) Lightness is a very important factor influencing preference of colors either as object or as background. A positive relationship between lightness and single color preference was observed. That is, for colors with the same hue, those with higher lightness are more preferred by observers.



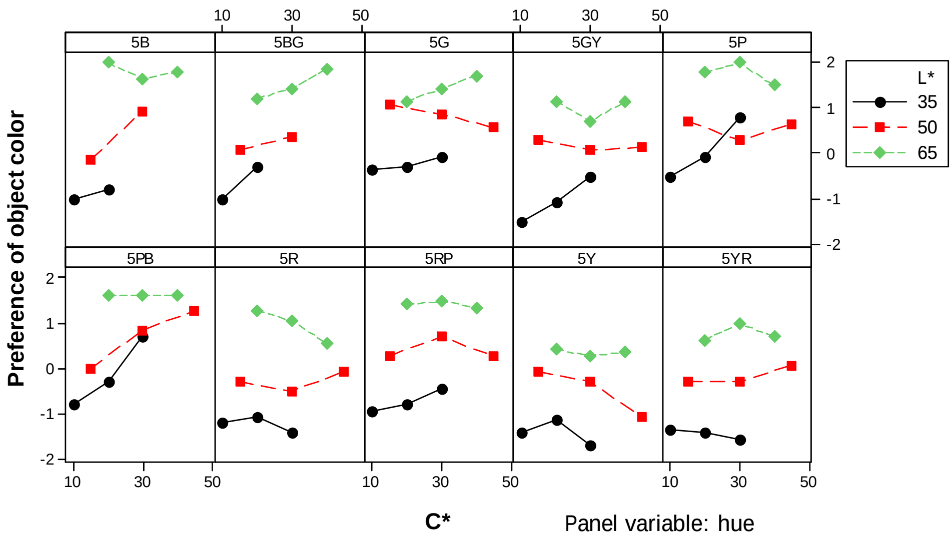
(a)



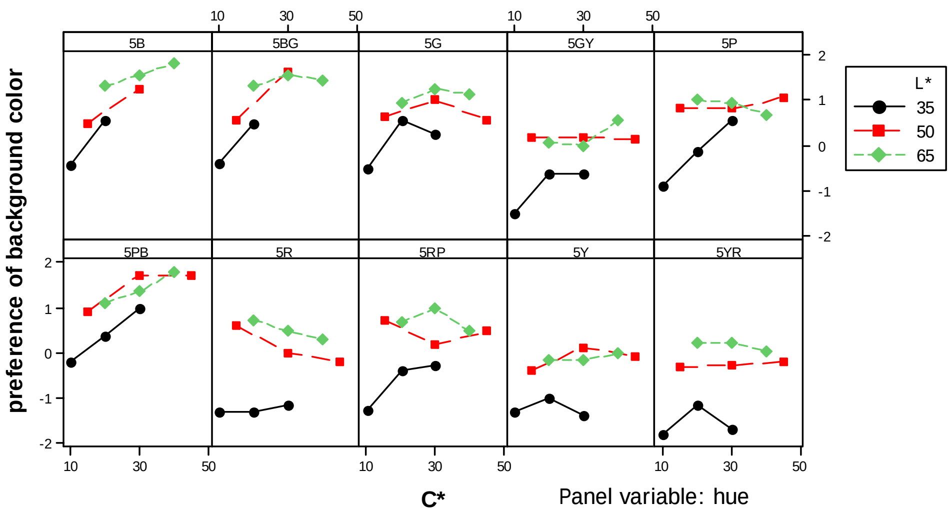
(b)

Fig. 5.2 Single color preference of (a) object color and (b) background color with respect to hue and lightness

The influences of chroma on preferences of object color and background color are shown in Fig. 5.3(a) and Fig. 5.3(b), respectively. There are 10 panels representing 10 different hues in each figure. In each panel, there are 3 curves with different lightness values. Each curve represents the variation of preference of colors with respect to chroma.



(a)



(b)

Fig. 5.3 The variation of single color preference of (a) object color and (b) background color with respect to chroma with hue fixed in each panel and different curves representing different lightnesses.

From these two figures, it can be observed that:

1) Generally, at the same lightness level, preference increases with the increasing of chroma. For the majority of hues, colors with lowest lightness and lowest chroma were evaluated to be the least preferred.
2) A distinct influence of lightness also can be observed by comparing their curves in each panel.

According to these results, we can conclude that:

1) All color perceptual attributes may significantly influence single color preference. This finding agrees with the results by Guilford & Smith (1959), Granger (1955d), Hogg (1969b), Sivik (1975), Guilford (1934), Smets (1982), and Camgoz (2002). They all have found that color preference was dominated not only by hue but also by lightness and chroma as well.
2) The most important factor affecting preference is lightness, not the hue. This result is in opposition to some early studies on color preference such as Guilford (1934). He used 40 colors to develop color-preference equations on the basis of hue, lightness, and chroma and suggested that hue was the dominant factor regardless of the gender of observers. Recently, Ou, et al. (2004) investigated the relationship between "like-dislike" feeling and the three perceptual attributes for British and Chinese. Similar to this research, he also found that lightness was the most predominant factor for Chinese. However, for British, hue seemed to be more important. This indicates that cultural background should not be ignored in color preference study.
3) For constant lightness and chroma, colors containing Green or Blue were more preferred, while those containing Yellow or Purple were less preferred.

This result is in good accordance with the findings by Helson & Lansford (1970). In addition, Washburn & Grose (1921) Eysenck (1941), Granger (1955d), and Guilford & Smith (1959), Camgoz, etc. (2002), Ou, etc. (2004) all stated that the blue was the most preferred color, while yellow was the least preferred.

4) Furthermore, similar to most studies (Guilford (1934), Guilford & Smith (1959), Sivik (1975), Smets (1982), Camgoz (2002)), we also found that bright and saturated colors were more preferred. The only exception was Eysenck (1941), who stated that brighter color was less preferred.

5.2.2 Observer repeatability and agreement

The observer repeatability and agreement were examined as in the preliminary experiment to ensure the stability and meaningfulness of the measured characteristics.

In the main experiment, 60 duplicated SS color patterns and 80 duplicated CB patterns were used to test the repeatability of each subject. It was found that, among the 20 subjects, 2 subjects and 1 subject had correlation coefficient less than 0.7 ($p < 0.05$) in SS pattern and CB pattern, respectively. Therefore, the evaluation results of the rest of 18 subjects in SS pattern and 19 subjects in CB pattern were considered reliable and were adopted for further statistical analysis.

Observer agreement represents the average deviation of each individual observer from the mean visual results of all observers. The correlations between the color harmony values of individual observers and their average values were analyzed. It was found that the average correlation coefficients are 0.65 in SS pattern and 0.69 in CB pattern with the lowest one being 0.57.

Similar to the preliminary experiment, we can also conclude here that color harmony is an unequivocal and stable feeling for most people.

The average color harmony was calculated from the most reliable 18 subjects for SS pattern and the most reliable 19 subjects for CB patterns.

5.2.3 Color harmony of SS pattern

In this section, the data collected in the main experiment for the SS pattern are analyzed. The relationships between color harmony and the variables including color perceptual attributes and single color preferences are examined. A mathematical color harmony model for SS pattern, which enable the harmonious color combinations to be systematically specified and applied in practice, is derived.

As in the preliminary experiment, we use Color1 and Color2 to denote the two component colors in SS pattern. The CIELAB color attributes of Color1 and Color2 are denoted as L_1 , C_1 , h_1, and L_2 , C_2 , h_2, respectively.

5.2.3.1 Effect of hue

To examine the influence of hue on color harmony, the average color harmony and its 95% of confidence interval (CI) for each hue pair were calculated. The variation of these values with respect to Hue2 (Munsell hue of Color2), with Hue1 (Munsell hue of Color1) fixed to 5G, were displayed in Fig. 5.4. The dashed-lines in the figure represent the positions of the Hue1.

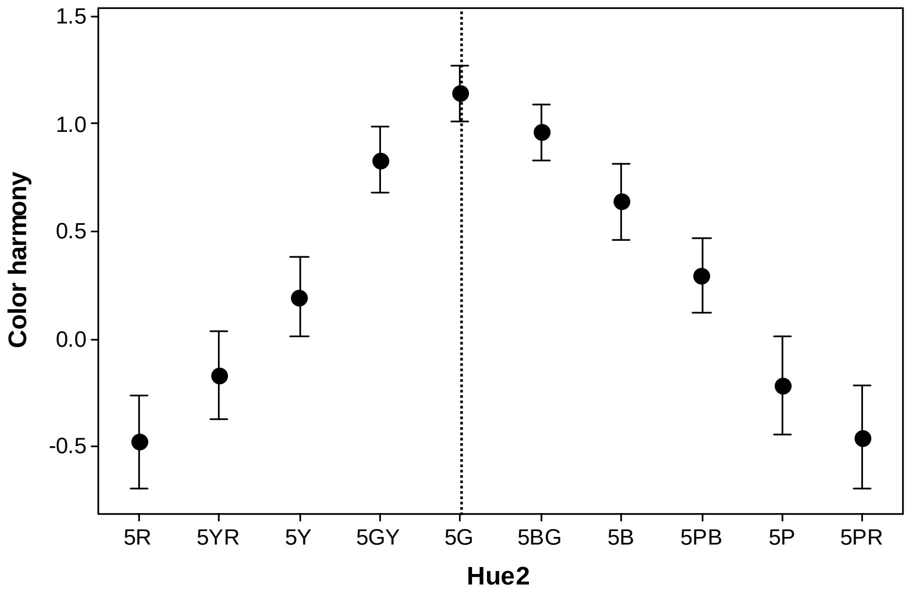


Fig 5.4 Average color harmony for each hue pair and its 95% of CI of SS patterns with respect to Hue2 with Hue1 fixed to 5G

From this figure, it can be seen that the average color harmony of the SS patterns decreases with the increasing of the distance between Hue1 and Hue2. This indicates that hue difference has a negative influence on color harmony of SS patterns.

5.2.3.2 Effect of lightness

Fig 5.5 shows the mean color harmony and its 95% of CI at 6 different lightness combinations for all SS patterns. "L_1/L_2" represents combinations of lightness levels of two component colors. LO, ME, and HI were used to represent low, medium, and high level of lightness. The figure shows that color patterns with "HI/HI" lightness pair are the most harmonious, followed by the "ME/HI" lightness pair. As there are some overlaps between the harmonious levels of other combinations, t-tests were used for comparison. It was found that, except for the color patterns with lightness pairs of "LO/HI" and "ME/ME", statistically significant differences ($p < 0.01$) in the means of color harmony were observed among the others. Compared with "LO/ME", "LO/HI", and "ME/ME" pairs, color patterns with "LO/LO" lightness pair are less harmonious. These results indicate that color patterns with higher total lightness are usually more harmonious.

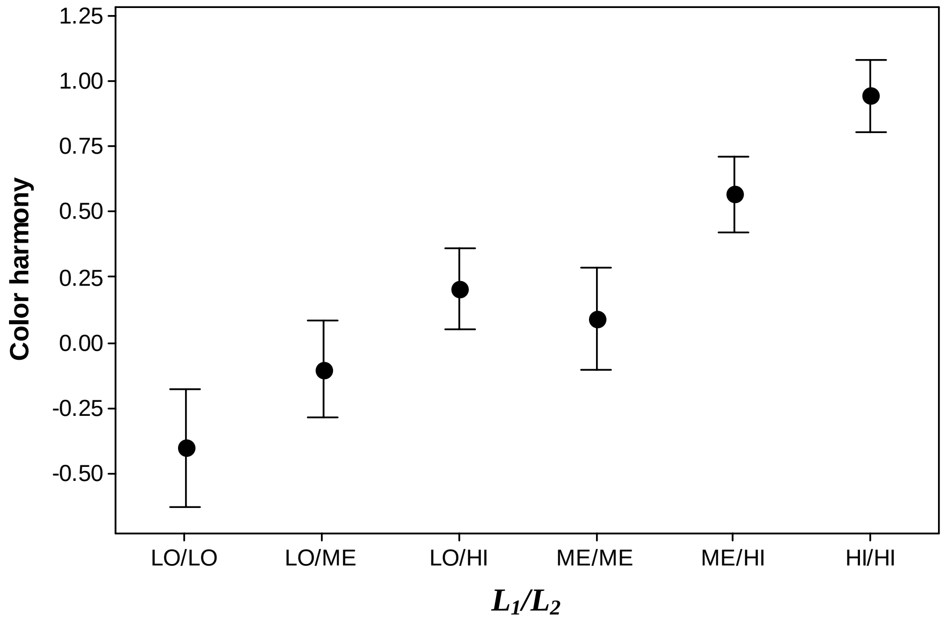


Fig. 5.5 Average color harmony and its 95% CI with respect to different lightness pairs.

5.2.3.3 Effect of chroma

The effect of chroma on color harmony seems not as distinct as that of hue and lightness. To investigate the influence of chroma, we fixed the lightness pair and hue pair to remove their influence on color harmony. Fig.5.6 shows the variation of color harmony against different hue pairs when lightness pair was fixed to "LO/ME". There are six panels in this figure with each panel representing a possible chroma of Color2. In each panel, points with different symbols and colors represent different chroma values of Color1. This figure shows that for each C_2, the color patterns with lower C_1 tend to be evaluated more harmonious.

Similar effects of chroma on color harmony were also observed in other conditions of lightness pair, as shown in Appendix 4.

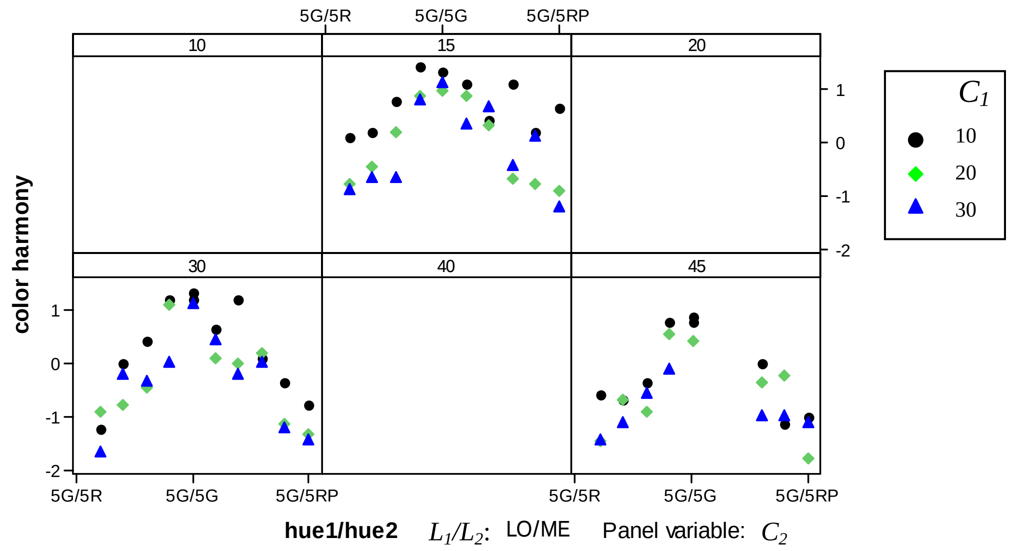


Fig. 5.6 The scattering of color harmony against hue pairs with lightness pair fixed to "LO/ME", C_2 fixed in each panel and different colors and symbols representing different C_1

5.2.3.4 Effect of single color preference

In Section 5.2.1, the influential factors on single color preference were examined. Lightness is the most important factor for single color preference, followed by hue and then chroma. Colors containing green or blue with high lightness and high chroma are more preferred, while those containing yellow or purple with low lightness and low chroma are less preferred. To investigate the effect of single color preference on color harmony, the relationship between color harmony and the preference of the more preferred color in a pattern, as well as the relationship between color harmony and average color preference of two component colors, were examined as we have discussed in Chapter 4. The correlation results are shown in Table 5.2.

Table 5.2 Correlation coefficients (*R*) between color harmony and single color preference related variables.

	Preference of the more preferred color	Average color preference
Color harmony	0.268	0.395

It is clear that average color preference has a higher correlation with color harmony than preference of the more preferred color, although both are of significant importance ($p<0.001$). It is also observed that the preference of the more preferred color and average color preference are highly correlated (R = 0.863). Therefore, it is reasonable to only consider the influence of average color preference. The distribution of color harmony with respect to average color preference of two component colors is plotted in Fig. 5.7. There are 15 panels with different hue pairs in the figure. Approximate linear relationship between color harmony and average preference can be observed in each panel. It is obvious that patterns consisting of colors with higher preference tend to be more harmonious.

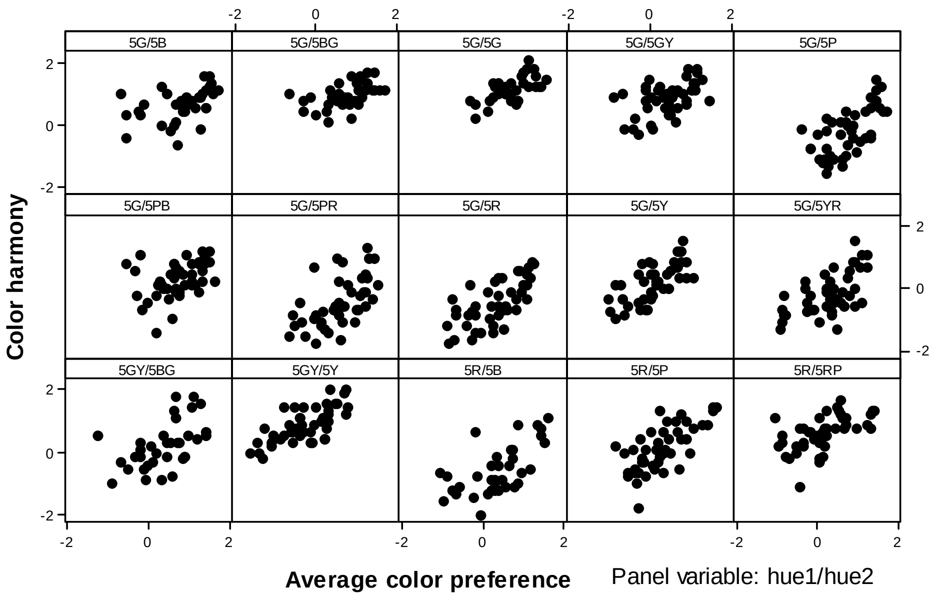


Fig. 5.7 Distribution of color harmony with respect to average color preference for different hue pairs.

This result seems inconsistent with the findings of the preliminary experiment. In the preliminary experiment, the influence of average preference on color harmony is very limited (about 6.4% of total variance); while in the main experiment, a linear relationship was observed between average preference and color harmony for each hue pair. This inconsistency may be due to the high correlation between lightness and single color preference. In the main experiment, a large variation of lightness from 35 to 65 leads to a large variation in single color preference, then leads to a large contributes on color harmony. In the preliminary experiment, the lightness are the same (L^*=58) for all colors, which may lead to a small variation in single color preference. Hence, a small contribution of color preference to color harmony was observed in preliminary experiment.

5.2.3.5 Quantitative modeling of color harmony

In previous sections, we have observed that hue, lightness, chroma, and single color preference all have influence on the color harmony of SS patterns. To clarify the exact relationship between them and the magnitude of contribution of each variable, multiple regression analysis (Kleinbaum, et al, 2003) was used for mathematical modeling of color harmony of SS patterns. In the following, we give the steps in selecting the best regression equation for color harmony.

Step 1: Specify the maximum model to be considered

The maximum model is defined to be the largest model or the one having all potential predictor variables considered in the process of model selection (Kleinbaum, et al, 2003). The following elements were included in the maximum model:

a. All conceivable basic predictors:

Although the results of previous researches on the interrelationship between component colors in color harmony are inconsistent, the variables can be grouped into four categories:

Hue related ----- Hue Interval

Lightness related ---- Lightness Interval, Average Lightness

Chroma related ---- Chroma Interval, Average Chroma

Preference of component colors

Let L_1 and L_2, and C_1 and C_2 be the CIE lightness and chroma of Color1 and Color2 respectively, Δh_{ab} be the CIELAB hue difference between two component colors, and P_1 and P_2 be the single color preference on Color1 and Color2 respectively. There are 6 basic variables as listed in Table 5.3.

Table 5.3 Variables and their meanings used for color harmony modeling in SS pattern

Variable	Meaning	Variable	Meaning
x_1	$\lvert L_1-L_2\rvert$	x_4	C_1+C_2
x_2	L_1+L_2	x_5	$\lvert\Delta h_{ab}\rvert$
x_3	$\lvert C_1-C_2\rvert$	x_6	$(P_1+P_2) / 2$

b. Quadratic terms of basic predictors:

x_1^2, x_2^2, x_3^2, x_4^2, x_5^2

c. First-order interactions between any two basic predictors

x_1x_2, x_1x_3, x_1x_4, x_1x_5, x_2x_3, x_2x_4, x_2x_5, x_3x_4, x_3x_5, x_4x_5

d. Other predictors

x_7 : $(L_1 - L_2)(C_1 - C_2)$

High correlations were observed between basic predictors and their polynomial terms and interaction terms. This may cause near collinearity problem and consequently leads to very unstable and often uninterpretable results. To reduce such collinearity problem and increase numerical accuracy, Aiken and West’s (1991) mean centering method was used on five basic variables. By using this method, a set of scores $\{X_{ij}\}$ is centered by subtracting the mean $\overline{X_j}$ of the scales for each predictor from each individual score for that predictor, giving

$$X_{ij}^* = X_{ij} - \overline{X_j} \tag{5.1}$$

in which $\overline{X_j} = \sum_{i=1}^{n} X_{ij} / n$, for the *j*th predictor. Therefore, centered scores have zero mean. Table 5.4 shows the mean and standard deviation of five basic variables. The values after centering are shown in Table 5.5.

Table 5.4 Descriptive statistics of five basic variables before centering

Variable	Mean	S.D.
x_1	12.36	11.276
x_3	10.62	9.381
x_2	50.46	9.034
x_4	26.39	7.941
x_5	84.07	50.775

Table 5.5 Descriptive statistics of five basic variables after centering

Variable	Mean	S.D.
x_1	0	11.276
x_3	0	9.381
x_2	0	9.034
x_4	0	7.941
x_5	0	50.775

In the following analysis, x_1, x_2, x_3, x_4, x_5 denote centered variables.

Step 2: Specifying a strategy for selecting variables

This step is to specify the strategy for selecting variables. Such a strategy is to determine how many variables and which particular variables should be included in the final model. A forward selection method focuses on deciding whether a variable should be added to a model, while a backward elimination method focuses on deciding whether a variable should be deleted from a model.

Stepwise regression method was selected to derive the best model in this study. This method, a modified version of forward regression, permits reexamination, at each step, of the variables incorporated in the model in previous steps. A variable that enters at an earlier stage may become superfluous to subsequent stages. To check this possibility, a partial F test is made for each variable currently in the model. The variable with the smallest nonsignificant partial F statistic is removed. The whole process continues until no more variables can be entered or removed. The process was conducted by using SPSS® and Mintab® and the result is shown in Table 5.6.

Table 5.6 Variables added/removed in each step of color harmony modeling for SS patterns.

Modeling steps	Variables Added	Variables Removed	R^2 (%)	R^2 increased (%)
1	x_5		36.8	36.8
2	x_2		59.8	23.0
3	x_4		72.6	12.8
4	x_6		74.1	1.5
5	x_4^2		74.8	0.6
6	x_1		75.3	0.5

In Table 5.6, “variables added” refers to the variables added into the model, while “variable removed” refers to the variables removed from the model when it was examined to be superfluous. The variables with probability of F (*p*) less than 0.001 are added into the model while those with *p* larger than 0.01 are removed. “R^2 increased” refers to the variance explained by the corresponding variable. R^2 refers to the total variance explained by the variables included in the model in the corresponding step. Table 5.6 shows that six variables were added step by step with the criteria of $p<0.001$. The total variance explained by the largest model is 75.3%. Variables x_5, x_2, and x_4 are the most important factors which increase 36.8%, 23.0%, and 12.8% R^2 values, respectively. Variables x_6, x_4^2, and x_1 also have statistically significant influence on color harmony, but contribute very little to total variance. As practically unimportant but statistically significant predictors can greatly confuse the interpretation of regression result, we focused on certain important variables in a small model. It is reasonable to assume that the variable increasing R^2 less than 5% offers unimportant improvement in predictive power. Consequently, the model with the first three variables (x_5, x_2, and x_4) was the best one considering the contribution of variables and model simplicity. Table 5.7 lists the ANOVA results of the model. This table illustrates that x_5, x_2, and x_4 are of significant importance to color harmony with 72.6% of total variance.

Table 5.7 The ANOVA results of the selected model of SS pattern.

Source	d.f.	SS	MS	F	Sig.	R^2
x_5	1	134.054	134.054	563.252		
x_2	1	83.784	83.784	352.034	P<0.001	72.6%
x_4	1	46.627	46.627	195.912		
Residual Error	419	99.812	0.238			
Total	422	364.277				

Table 5.8 shows the coefficients and their 95% Confidence interval of these three variables.

Table 5.8 The coefficients of the variables in the model.

Variables	Coefficients		95% Confidence interval for $\hat{\beta}$	
	$\hat{\beta}$	Std. Error	Lower Bound	Upper Bound
Constant	0.258	0.017	0.224	0.292
x_5	-0.010	0.000	-0.011	-0.009
x_2	0.059	0.002	0.055	0.063
x_4	-0.041	0.002	-0.046	-0.036

The regression equation is

$$y = 0.258 - 0.010x_5 + 0.059x_2 - 0.041x_4 \tag{5.2}$$

where y is the color harmony of SS pattern. When replaced by their original variables, the equation is

$$HARMONY_{SS} = -0.796 - 0.010\left|\Delta h_{ab}\right| + 0.030(L_1 + L_2) - 0.021(C_1 + C_2) \tag{5.3}$$

where the subscript “SS” denotes SS pattern. Using this model, 72.6% of total variance of color harmony can be explained. Hue difference is the most important factor to color harmony. This result is similar to the observation in the preliminary experiment, in which a negative relationship was found between hue difference and color harmony in SS patterns. Average lightness is also very important, accounting for 23.0% of total variance. In addition, average chroma also has a quite influential contribution (12.8%) to the color harmony. According to this model, it seems that SS patterns with higher total lightness, lower hue difference and lower total chroma are more harmonious. The influence of the interactions between basic variables on color harmony was insignificant. Furthermore, although we have found that average single color preference is highly correlated to color harmony, it is not included in this model. This may be due to the high correlation between lightness and single color preference. That is, colors with higher lightness are always more preferred. This suggests that a high harmonious level of color patterns with high total lightness may attribute to their high color preference. To confirm this assumption, total lightness was excluded from the variable list (Table 5.3) in multiple regression analysis. It was found that average color preference took the place of total lightness and accounted for 21.9% of total variance. However, considering the easiness of measurement of lightness and difficulty in estimating color preference, we selected total lightness rather than average color preference as variables included in the SS color harmony model. The influence of average color preference on color harmony was included in terms of total lightness in the model.

Step 3: Evaluation reliability with split samples

Once the best model has been chosen, we should further evaluate the generality of the model. A split-sample approach (Kleinbaum, et al, 2003) was used to assess the reliability of the model. In this approach, training samples for model construction and testing samples for reliability assessment were assigned before any analysis was conducted. In the experiment design, we selected 423 SS color patterns as training samples for model construction and 207 patterns as testing samples for assessment of the reliability of the model. Here we use symbol 1 to denote the training group and use symbol 2 to denote the testing group. Cross-validation analysis was conducted by using the regression equation estimated from training data to predict the values for testing data. The shrinkage on cross-validation (Kleinbaum, et al, 2003) is used to judge the model reliability, which is defined as:

$$SH = R^2(1) - R_*^2(2) \tag{5.4}$$

where SH represents shrinkage. $R^2(1)$ denotes the sample squared multiple correlation of training data, and here it equals 0.726. $R_*^2(2)$ denotes the cross-validation correlation, which is given by:

$$R_*^2(2) = r^2(Y_2, \hat{Y}_*^2) \tag{5.5}$$

where Y_2 is the observed values of the testing samples. $\hat{Y}_*^2$ is the predict value for the testing samples by using the prediction equation. Therefore, $R_*^2(2)$ represents the univariate correlation between predicted values and the observed values in the testing sample. In this experiment, its value is 0.674. As a result, *SH* equals to 0.054. Since a *SH* value less than 0.10 indicates a reliable model (Kleinbaum, et al, 2003), the *SH* in this experiment is quite small, and indicates a quite high reliability of estimation. Therefore, this color harmony model for SS pattern is acceptable and can be reliably applied to other samples.

According to this model, we can conclude that for SS patterns, hue difference is the most influential factor on color harmony. Single color preference as a lightness related variable may also influence the evaluation. In addition, the influence of average chroma can not be neglected.

5.2.4 Color harmony of CB pattern

In this section, we analyze the effects of color attributes and single color preference on color harmony of CB pattern. A color harmony model for CB pattern is constructed. For abbreviation, in this investigation, the CIELAB color attributes of background and center colors are denoted as L_b, C_b, h_b, and L_c, C_c, h_c, respectively.

5.2.4.1 Effect of color exchange

Different from the SS pattern, the two component colors of the CB pattern are unsymmetrical. Therefore, it is interesting to investigate if exchanging the positions of these two colors affects its harmonious level. In the preliminary experiment, we have found that hue difference is the main factor affecting the color harmony. That means the exchange the hues of background color and center color may not influence the harmonious levels of color pattern. Previous works (Ou&Luo, 2003, Sivik, 1992, Pieters, 1979, Hogg, 1969a, 1969b, Nayatani etc, 1967, 1969, Grander, 1955a, 1955b) indicated that lightness related variables (lightness difference and average lightness) and chroma related variables (chroma difference and average chroma), were related to color harmony. From these results, it can be deducted that exchanging the position of the two component colors of the CB patterns may not affect its harmonious levels.

To test this assumption, color harmony of CB color patterns and their corresponding patterns after exchanging the center and the background color, were examined. In Fig. 5.8, the term “Harmony1” represents the harmonious level of color patterns with 5G as background, and “Harmony2” represents the harmonious level of color patterns with 5G as center color. A positive linear relationship with correlation coefficient R=0.826 ($p<0.01$) between the color harmony of these two groups of color combinations was observed. A T-test was used to compare the means of color harmony of these two groups of color combinations and no significant difference was observed ($p<0.05$). This result indicates that exchanging component colors of CB patterns will not significantly affect their harmonious levels.

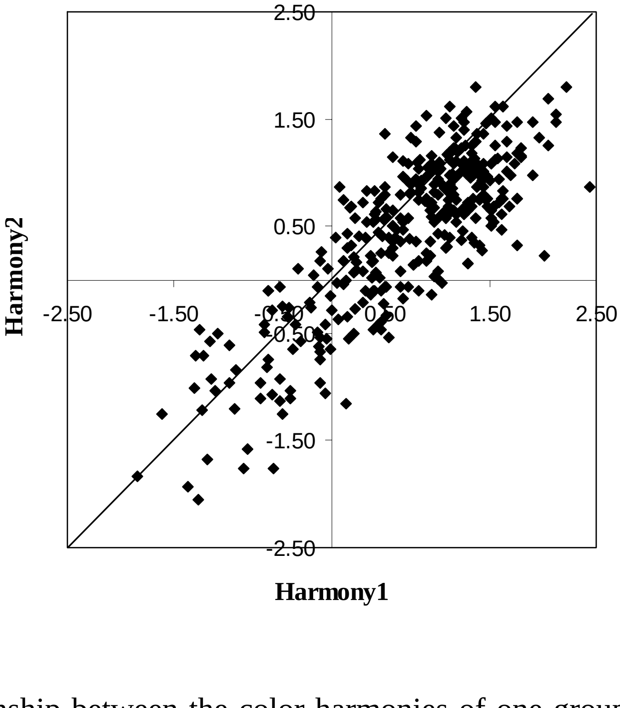


Fig. 5.8 Relationship between the color harmonies of one group of CB patterns and their corresponding patterns after exchanging centre and background colors. Color 5G is the background color for “Harmony1” and is the center color for “Harmony2”.

5.2.4.2 Effect of hue

To examine the relationship between color harmony and hue difference, the variation of color harmony with respect to the hue of center color h_c is plotted in Fig. 5.9 with a fixed background color 5G. Similarly, the variation of color harmony with respect to the hue of background color h_b is plotted in Fig.5.10 with a fixed center color 5G. Each figure consists of 18 panels, in which the chroma of center color (or background color) and the lightness of two component colors are fixed. In these panels, the chroma of center color, C_c (or chroma of background color, C_b) is represented by colored symbols so that the variation of color harmony against h_c (or h_b) can be clearly observed. The “V” shapes in panels indicate that harmonious levels increase with the increasing of hue difference between component colors. It can be found that when two component colors were both 5G, the color patterns were always judged to be the most unharmonious. On the contrary, the color patterns with hue combinations of (5G and 5R) or (5G and 5RP) were usually evaluated to be very harmonious.

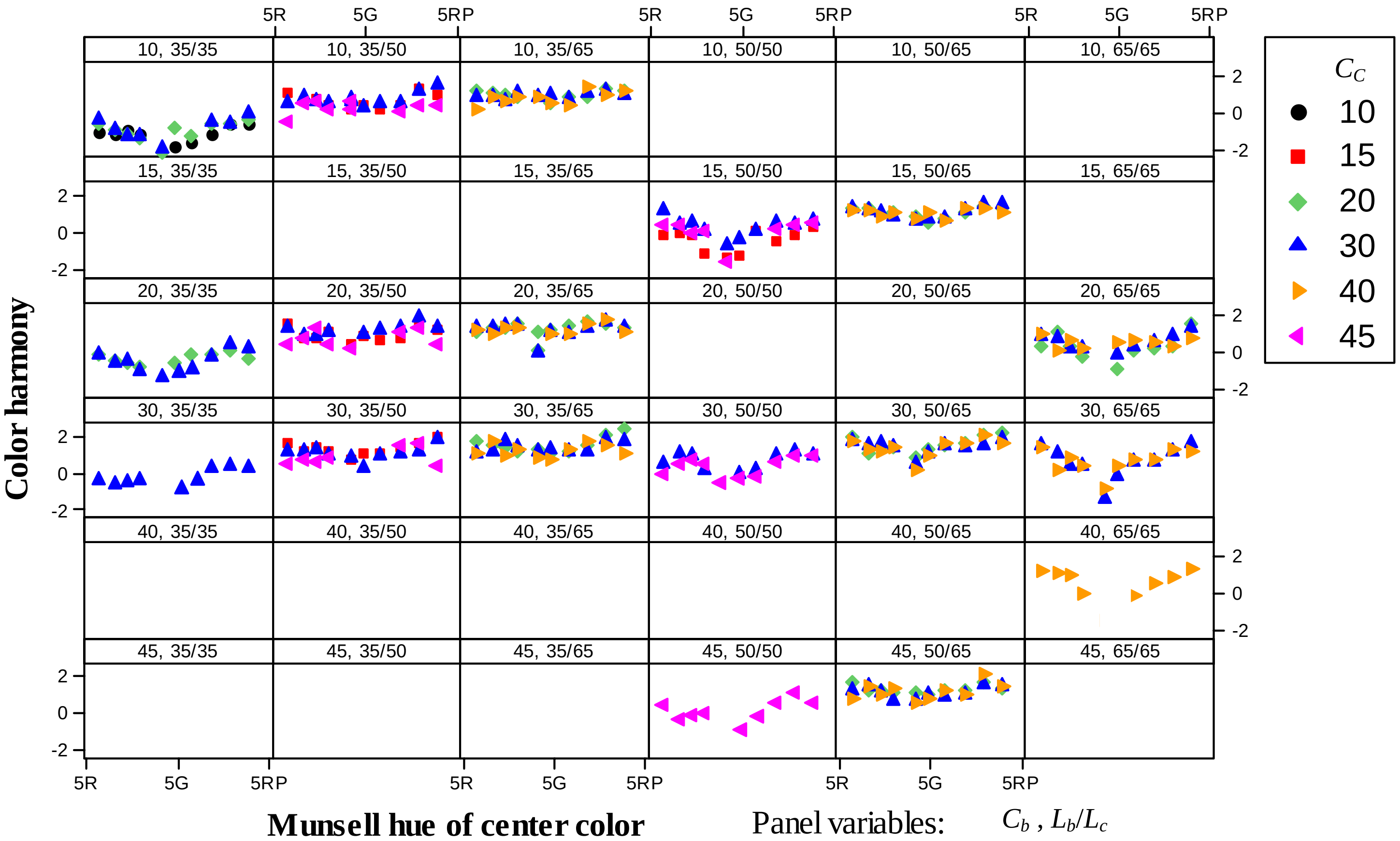


Fig. 5.9 The plot of color harmony against the hue of center color, where C_b and L_b/L_c are panel variables and C_c is categorical variable

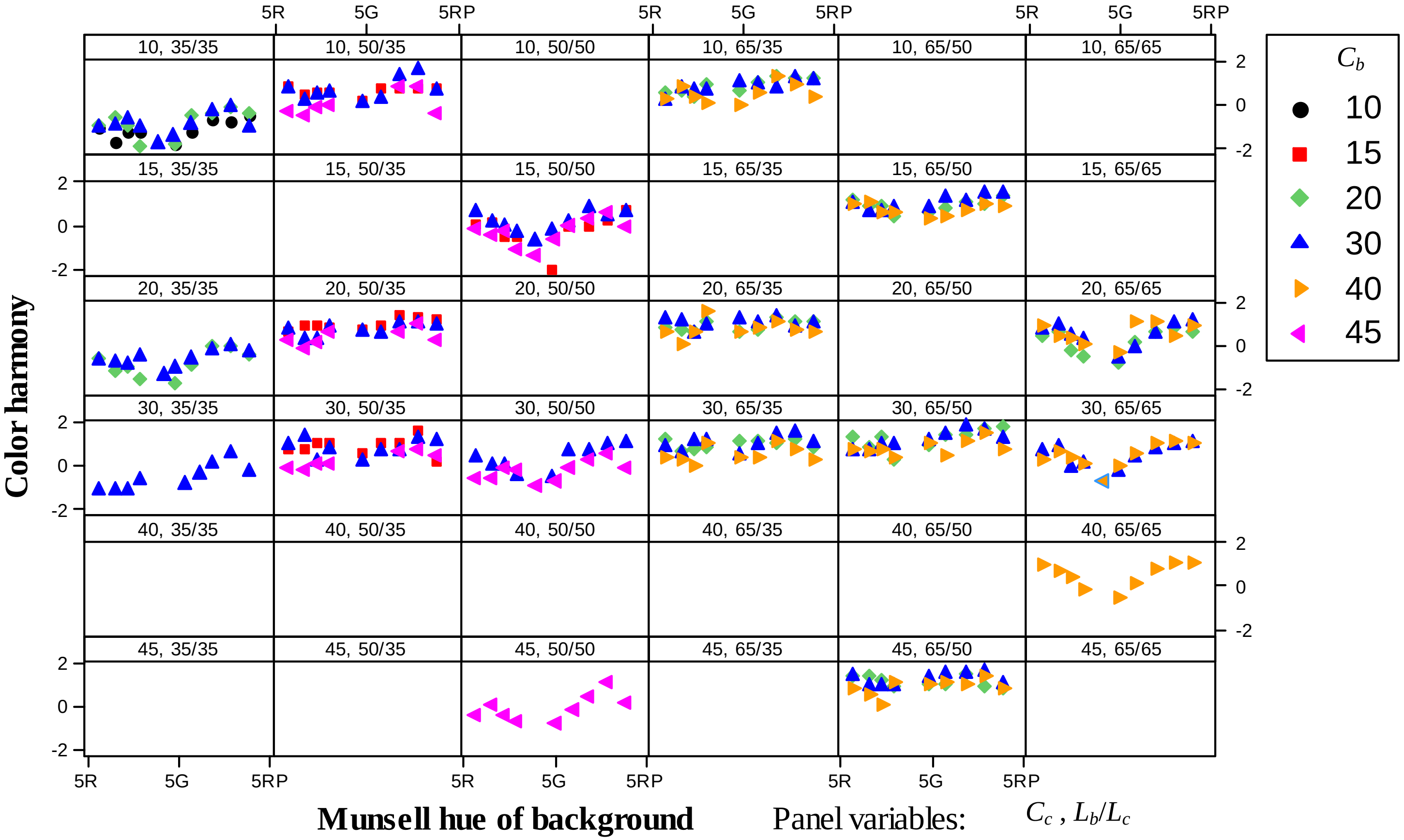
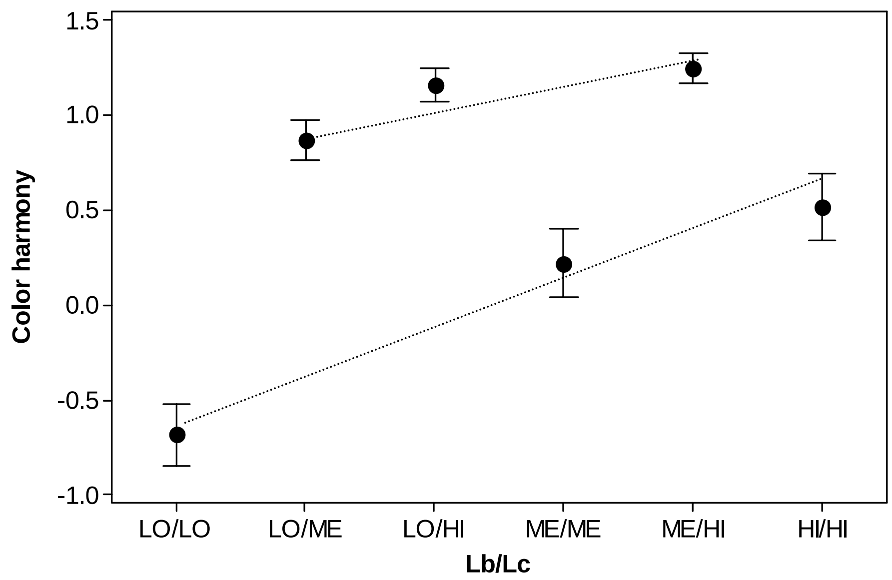


Fig. 5.10 The plot of color harmony against the hue of background color, where C_c and L_b/L_c are panel variables and C_b is categorical variable.

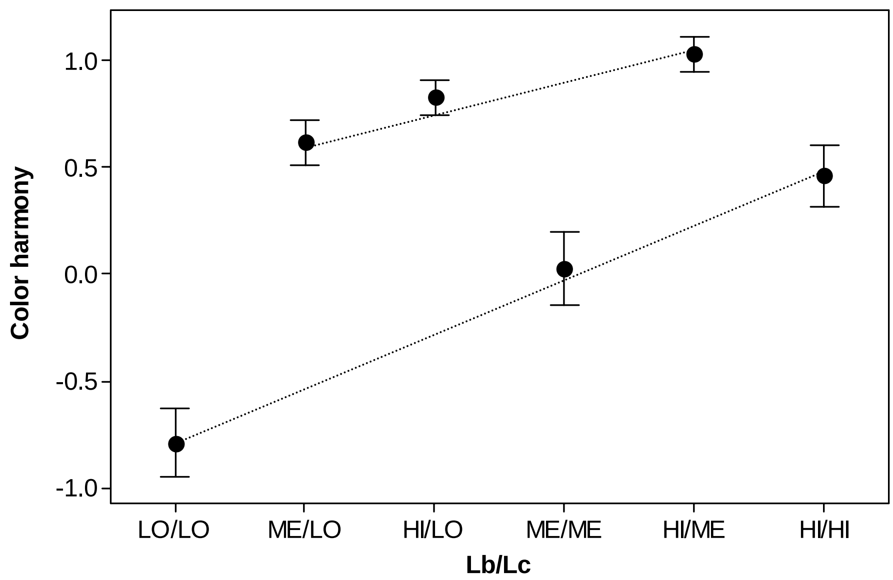
5.2.4.3 Effect of lightness

Fig 5.11(a) and Fig 5.11(b) show the average color harmony and its 95% of CI at six different lightness combinations for color patterns with 5G as Background color and 5G as Center color respectively. From this figure, it can be found that:

1) The variations of color harmony with respect to L_b/L_c are very similar for these two kinds of CB color patterns.
2) Color patterns with different lightnesses (including LO/ME, LO/HI, and ME/HI) were evaluated to be more harmonious than those with equal lightness (including LO/LO, ME/ME, and HI/HI)
3) For patterns with same lightness difference (for example, LO/ME and ME/HI), those with higher total lightness (that is, ME/HI) were more harmonious.
4) There are some overlaps between color patterns with lightness pair “LO/HI” and those with lightness pair “ME/HI”. This may due to a higher lightness interval, yet a lower total lightness in “LO/HI” color combinations, as compared to “ME/HI” color combinations.



(a)



(b)

Fig. 5.11 Average color harmony and its 95% CI with respect to L_b / L_c when (a) 5G is background color and (b) 5G is center color

To clearly illustrate these relationships, lightness interval and average lightness were calculated and the histograms of color harmony are plotted for six groups color patterns with different lightness intervals and average lightness values (Fig. 5.12). Each group is fitted with the normal distribution. The mean and standard deviation for each group are shown in the corresponding panels in Fig. 5.12. It is obvious that color patterns with similar lightness and lower total lightness have lower scores in color harmony evaluation, while those with higher lightness interval and higher total lightness always possess higher scores.

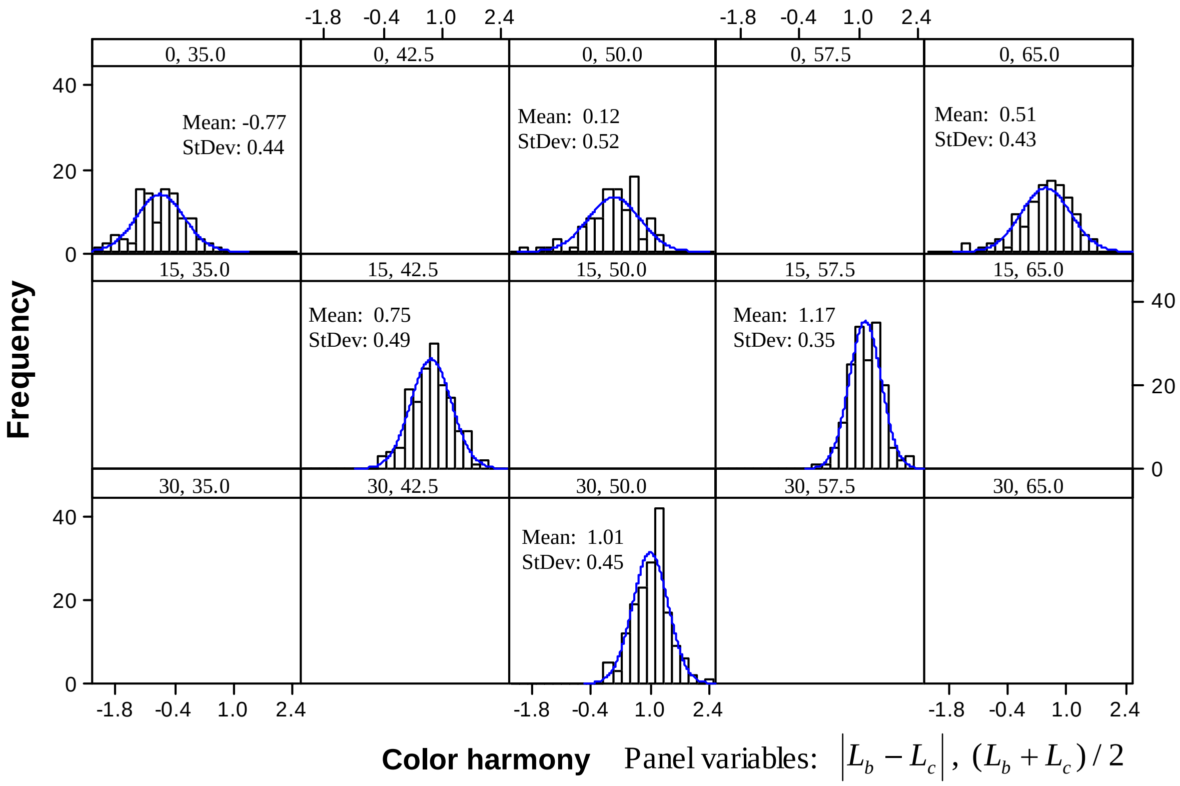


Fig. 5.12 Histogram of color harmony for six groups of color patterns with different lightness intervals and average lightness values.

5.2.4.4 Effect of chroma

For the effect of chroma on color harmony, we can refer to Fig. 5.9 and Fig. 5.10. In each panel of these two figures, points with different symbols and colors represent different chroma values of the center color (in Fig. 5.9) or different chroma values of the background color (in Fig. 5.10). In the panels, color harmony levels of most groups with different chroma values are overlapped and no distinct relationship can be observed between color harmony and chroma of component colors.

5.2.4.5 Effect of single color preference

In addition to the relationship between color harmony and the preference of the more preferred color in a pattern, we further investigated the respective influences of background color preference and center color preference on color harmony of CB patterns.

As in SS patterns, a smaller correlation coefficient was observed between the preference of the more preferred color and color harmony, compared with the multiple correlation between color harmony and the preferences of center color and background color. Therefore, it is reasonable to only consider the influence of the preferences of background color and center color. Table 5.9 shows the results of correlations between the preference of background color (P_b) or center color (P_c) and the harmony of color patterns with 5G as background (Harmony1) or center color (Harmony2). The results indicate that single color preferences of the two component colors are both significantly important (p<0.001) to color harmony. It was also observed that P_c was more important in the patterns with 5G as background color, but less important in the patterns with 5G as center color. This may be due to small variation in single color preference of 5G colors, compared with the range of the single color preference of all ten hues. In addition, it was also observed that the influence of P_b was slightly more important than that of P_c.

Table 5.9 Correlation coefficients between single color preferences and color harmony

Color harmony	Single color preferences	
	P_b	P_c
Harmony1	0.264	0.515
Harmony2	0.526	0.125

5.2.4.6 Quantitative Modeling of color harmony

As discussed in the above sections, the variables including hue difference, lightness interval, total lightness, and preference on component colors, etc. may influence color harmony of CB patterns. Similar to Section 5.2.3.5, multiple regression analysis was used for color harmony modeling of CB pattern. The steps in selecting the best regression equation for color harmony of CB patterns are described as follows:

Step 1: Specify the maximum model to be considered

a. All conceivable basic predictors:

Table 5.10 lists the basic variables used in CB pattern. L_b and L_c, and C_b and C_c are CIE lightness and chroma of background color and center color respectively. The calculation of Δh_{ab} is given in section 4.2.2.1. P_b and P_c are single color preference on background color and center color respectively. As in the case of SS pattern, the variables x_i (i = 1…5) denotes their centered counterparts in the following analysis.

Table 5.10 Variables and their meanings used for color harmony modeling in CB pattern

Variable	Meaning	Variable	Meaning
x_1	$\|L_b-L_c\|$	x_5	$\|\Delta h_{ab}\|$
x_2	$(L_b+L_c) / 2$	x_6	P_b
x_3	$\|C_b-C_c\|$	x_7	P_c
x_4	$(C_b+C_c) / 2$		

b. Quadratic terms of basic predictors:

x_1^2, x_2^2, x_3^2, x_4^2, x_5^2

c. First-order interactions between any two basic predictors

x_1x_2, x_1x_3, x_1x_4, x_1x_5, x_2x_3, x_2x_4, x_2x_5, x_3x_4, x_3x_5, x_4x_5

d. Other predictors

x_8: $(L_b - L_c)(C_b - C_c)$

All these variables were considered in the modeling process.

Step 2: Specifying a strategy for selecting variables

Stepwise regression method was selected to choose the best model. Using SPSS® and Mintab®, the results are as follows:

Table 5.11 Variables added/removed in each step of color harmony modeling for CB patterns.

Modeling steps	Variables Entered	Variables Removed	R^2	R^2 increased
1	x_1		30.2%	30.2%
2	x_2		48.5%	18.3%
3	x_5		57.6%	9.1%
4	x_1^2		66.3%	8.7%
5	x_6		69.1%	2.8%
6	x_8		71.2%	2.1%
7	x_1x_5		73.1%	1.9%
8	x_7		74.8%	1.7%

Table 5.11 shows that eight variables were entered step by step with the criteria of $p < 0.001$. The total variance explained by the largest model is 74.8% with x_1 and x_2 being the most important factors, which contribute to 30.2% and 18.3% of total variance respectively. x_5, accounting for 9.1% of total variance, and x_1^2, accounting for 8.7%, are of considerable influence. x_6, x_8, x_1x_5, and x_7 although significant, they were abandoned due to their very small contributions and practically unimportant. Therefore, a small model with four factors was

selected for color harmony of CB patterns. The ANOVA table and the coefficients for these four variables are as follows:

Table 5.12 The ANOVA results of the selected model for CB patterns.

Source	d.f.	SS	MS	F	Sig.	R^2
x_1	1	146.740	146.740	752.513		
x_2	1	88.989	88.989	456.354	$P < 0.001$	66.3%
x_5	1	44.312	44.312	227.241		
x_1^2	1	41.359	41.359	212.097		
Residual Error	841	163.73	0.195			
Total	845	485.130				

Table 5.13 The coefficients of the variables in the model.

Variables	Coefficients		95% Confidence interval for $\hat{\beta}$	
	$\hat{\beta}$	Std. Error	Lower Bound	Upper Bound
Constant	0.404	0.040	0.326	0.482
x_1	0.047	0.002	0.044	0.050
x_2	0.038	0.002	0.035	0.041
x_5	0.005	0.000	0.004	0.005
x_1^2	-0.002	0.000	-0.002	-0.002

The regression equation is

$$y = 0.404 + 0.047x_1 + 0.038x_2 + 0.005x_5 - 0.002x_1^2 \tag{5.6}$$

where *y* is color harmony of CB pattern. Or in another form

$$HARMONY_{CB} = -1.246 - 0.002(|L_b - L_c| - 24)^2 + 0.019(L_b + L_c) + 0.005|\Delta h_{ab}| \tag{5.7}$$

Using this model, 66.3% of total variance of color harmony on CB patterns can be explained. As in the preliminary experiment, a positive relationship was found between hue difference and color harmony, which is contrary to the results in SS patterns. It was also inspected that lightness interval and average lightness are more influential, which contribute to 30.2% and 18.3% of total variance respectively.

As for the influence of lightness interval, when the lightness interval between two component colors is equal to 24, the harmony of the color pattern reaches its maximum. More or less than this value, the harmonious levels of color pattern will decrease.

As for the influence of total lightness, the same effect was observed in CB patterns as in SS patterns, that is, increasing the total lightness improves their harmonious levels. Because of the relationship between color preference and lightness, a high harmonious level of color patterns with high lightness may partially attribute to high single color preference. In fact, it was observed that single color preference may enter the model and totally 23.2% of variance can be explained by the effects of single color preference of center color and background color when total lightness was excluded from the predictor variables. As in SS pattern, we also selected total lightness, not average color preference as one of the variables included in the CB color harmony model. The influence of average color preference on color harmony was included through total lightness in the model. In addition, it was observed that the contributions of total lightness in SS patterns and CB patterns were quite similar (23.0% in SS pattern and 18.3% in CB pattern). This result indicates that the total lightness is a common factor independent of constructions of color patterns.

Step 3: Evaluation reliability with split samples

In the experiment design, we selected 846 CB color patterns as training samples for model construction and 414 patterns as testing samples for model reliability assessment. Since the squared multiple correlation between predicted values and observed values for testing data ($R_*^2(2)$) is 0.587, $R^2(1)$ = 0.663 for training data, and thus shrinkage is 0.663-0.567 = 0.096. It is less than 0.10 and indicates that the model is reliable.

According to this model, it can be concluded that for CB patterns, lightness interval is the most important factor influencing color harmony. Color patterns with lightness interval equals to 24 are most harmonious. Hue difference is also quite influential. Color patterns composed of complementary color seems more harmonious. In addition, single color preference that relates to lightness, also plays a very important role in color harmony.

5.2.5 Discussion

In this chapter, two different color harmony models for two-color combinations with SS pattern and CB pattern were developed. It is noted that there are some common characteristics in these two models. Despite of the configuration of the color pattern, component color relationships and single color preference are the two main categories of factors affecting color harmony. This result is in accordance with the Gestalt theory, which states that the nature of response is determined by the elements connected and especially by their inter-relations to one another, not by individual elements (Schiffman, 1995). Furthermore, we also find that the relationships of color attributes are always the dominant factor, followed by single color preference.

For the detailed relationship between color harmony and these variables, it is observed that hue difference is the primary factor for SS patterns. This result is quite similar to the “Equal-hue principle” by Ou & Luo (2003, 2006). Nayatani et al. (1967, 1969) and Sivik (1992) also suggested that colors with similar hue were more harmonious. Under the experimental conditions (Chinese observers, same SS color patterns) similar to ours, Ou and Luo (2003, 2006) also revealed a “high lightness principle”, which indicated that people tend to feel pleasant when seeing lighter color combinations. However, this principle is not found in the results of all other color harmony experiments. The cultural background of the observers might be the causation of this disagreement. In this study, we have verified that single color preference, which is closely related to lightness, is one of dominant factors affecting color harmony. This factor may be influenced by the cultural background of observers and so is the color harmony. Ou et al. (2004) also stated that “hue was found to be the most predominant attribute for British, whereas lightness was the most predominant for Chinese.” Similar to our finding, Ou et al. also found that total lightness is significantly important to color harmony for Chinese observers. Therefore, it is presumable that different color harmony rules may be associated with observers of different culture backgrounds.

In contrast to the SS patterns, there are very limited studies related to the color harmony of CB patterns. Some researchers, such as Washburn and Grose (1921), Reddy and Bennett (1985), and Helson and Lansford (1970) et al. have studied the preference of this kind of color patterns. All of them found that lightness interval had the strongest impact on color combination preference for this kind of patterns. In this study, we also found that lightness interval is the most influential factor on color harmony for CB patterns. This may indicate a strong link between color preference and color harmony. In addition, these researchers stated that the larger was the brightness contrast (or lightness interval), the more preferred was a color combination, while we observed that lightness interval close to 24 is evaluated to be the most harmonious.

Comparing the color harmony principles in these two kinds of color patterns, a very interesting phenomenon was observed. A negative relationship between color harmony and hue difference exists in SS patterns, while a positive relationship exists between color harmony and hue difference in CB patterns and a quite large of lightness interval (near 24) are required for harmonious CB color patterns. It seems that, in observer’s feeling, the component colors in SS pattern should be similar, while those in CB pattern should be different. This can be successfully explained in view of sensation and perception.

People are surrounded by a world of objects and events whose existences are not influenced by human's consciousness. How the features of objects in our environment get constructed and how they are recreated in our minds so that we perceive them and even feel pleased or uncomfortable, are very fundamental towards the understanding of color harmony.

It is known that perception is not only based on physical stimulus, but observers' inner mental process as well. That is, the perception is based on more than just the information in the stimulus input. According to Constructivist theory, perceptions are constructed or even inferred by the observers based on their past experiences, biases, expectations, motives, etc. Gregory (1979) argued that seeing is composed of an assemblage of guesses, with the senses providing evidence by which an "internal hypothesis" can be checked. When the internal hypothesis is satisfied, a pleasing feeling may be evoked. Ambiguity, uncertainty or conflicts of information result in confusion, anxiety and raised tension (Osbourn, 1988). In color harmony experiment, two kinds of patterns were required to be evaluated. One is SS patterns with two colors laid side by side on neutral gray background, and the other is CB patterns with two colors in center-background relationship. Taking interior design for example, the color scheme of furniture and walls (or floor) may be represented by CB patterns, while the color arrangement between different pieces of furniture (such as sofa and chair) may be represented by SS patterns. According to intuitive experience, observers consider two colors displayed in SS pattern should form a plane, while two colors displayed in CB pattern should form a three-dimensional space. These effects can be achieved when two colors in a SS pattern are similar and two colors in a CB pattern are in large discrepancy. Thus, a pleasing feeling is evoked in these situations. On the contrary, when what one see is in conflict with his/her experience, negative responses will occur. In interior design, it was observed that if the color of furniture was similar to that of walls and floor, the effect would not be aesthetically pleasing as the three dimensional figure-ground concept would be destroyed (Sharpe, 1974). Therefore, it is unsurprising to obtain the results in this study that SS patterns with similar component colors are evaluated more harmonious, while CB patterns are preferred when two component colors have a large discrepancy.

5.2.6 Conclusion

Based on the experimental results, we confirmed that color harmony is an unequivocal and stable feeling for most people. Component color relationships are the most important factors on color harmony and the effect of single color preference is also influential. For SS pattern, similar component colors seem to form a plane and were evaluated to be more harmonious. On the contrary, for CB patterns, only those with different component colors which seem to form a three-dimensional space were evaluated harmonious. These two different color harmony rules provide an important evidence for understanding of color harmony. When relating these results with sensation and perception theory, we deduced that color harmony is a pleasing effect evoked by color patterns when human's inner hypothesis was satisfied. In addition, we also found that single color preference has a prominent effect on color harmony. It seems that color harmony as a aesthetics related topic, may associated with subjective preference, that is, single color preference.

Chapter 6

Color Harmony of Three-color Patterns

A further experiment is designed to study color harmony of three-color combinations. As the relationships between component colors in three-color patterns are very complicated, it is quite difficult to predict three-color harmony by using the same method as in two-color patterns. Nevertheless, we know that the interrelationships between component colors are the most important factors on color harmony, and that three color combinations can be decomposed into three two-color combinations with almost no relationship lost. Hence, it is attempted to predict color harmony of three-color combinations from that of two-color combinations.

6.1 Evaluation of color harmony for three-color patterns

Two kinds of three-color patterns shown in Fig. 3.3 were evaluated in the further experiment. One is SSS pattern which can be decomposed into three SS color patterns; the other is SSB pattern which can be decomposed into one SS and two CB color patterns.

Four kinds of SSS patterns and six kinds of SSB patterns as shown in Table 3.2 were designed. To obtain these color combinations, the harmony scores of two-color patterns from evaluation experiment were first sorted in an ascending order, and were then partitioned into three bins with an approximately equal number of color patterns in each bin. The color patterns in three bins were categorized into unharmonious group, median group, and harmonious group according to their harmony scores. This categorization was conducted in both SS and CB patterns (Table 6.1). Then, 13 color combinations in each kind of SSS pattern and 15 combinations in each kind of SSB pattern were selected. Consequently, 52 SSS patterns and 90 SSB patterns were obtained and evaluated using the same method in two-color patterns.

Table 6.1 The harmony ranges of three bins for SS and CB color pattern

Color patterns	Bins		
	unharmonious	median	harmonious
SS pattern	[-2.00, -0.63)	[-0.63, 0.74]	(0.74, 2.11]
CB pattern	[-2.15, -0.62)	[-0.62, 0.91]	(0.91, 2.44]

6.2 Color harmony of three-color patterns

6.2.1 Color harmony of SSS patterns

6.2.1.1 The relationship between harmony of SSS pattern and that of three related SS patterns

Fig. 6.1 shows the average harmonious levels and their 95% CI from experiment for four categories of SSS patterns. In Table 3.2, “1” represents the category of SSS patterns with 3 harmonious SS patterns; “2” refers to the category composed of 2 harmonious and 1 unharmonious SS patterns; “3” refers to the category with

1 harmonious and 2 unharmonious SS patterns; "4" represents the category with 3 unharmonious SS patterns. Fig. 6.1 suggests that SSS patterns of category "1" are the most harmonious, followed by category "2", and category "3" and "4" are the most unharmonious. This result indicates that SSS patterns composed of harmonious SS patterns are more harmonious than those composed of unharmonious SS patterns.

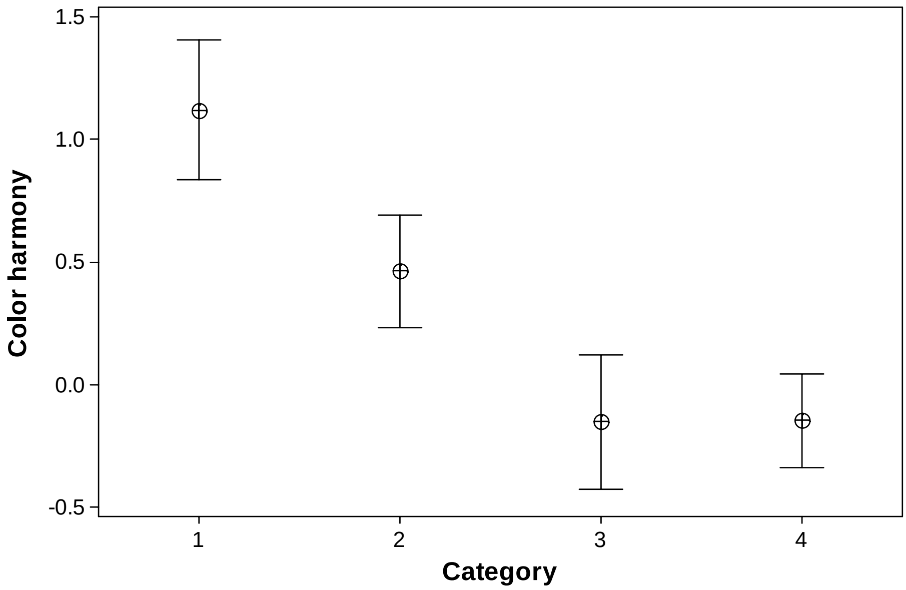


Fig. 6.1 The average color harmony levels and their 95% CI for four kinds of SSS patterns.

Since the three related SS patterns are almost of equal importance to the corresponding SSS pattern, the influences of their harmonious levels on the harmony of the SSS pattern are nearly the same. The average color harmony of evaluation results for three related SS patterns were calculated, and the relationship between this average value and the evaluated color harmony of corresponding SSS pattern was illustrated in Fig. 6.2. From this Figure, a strong positive relationship between the average color harmony of three related SS patterns and the color harmony of SSS patterns was observed.

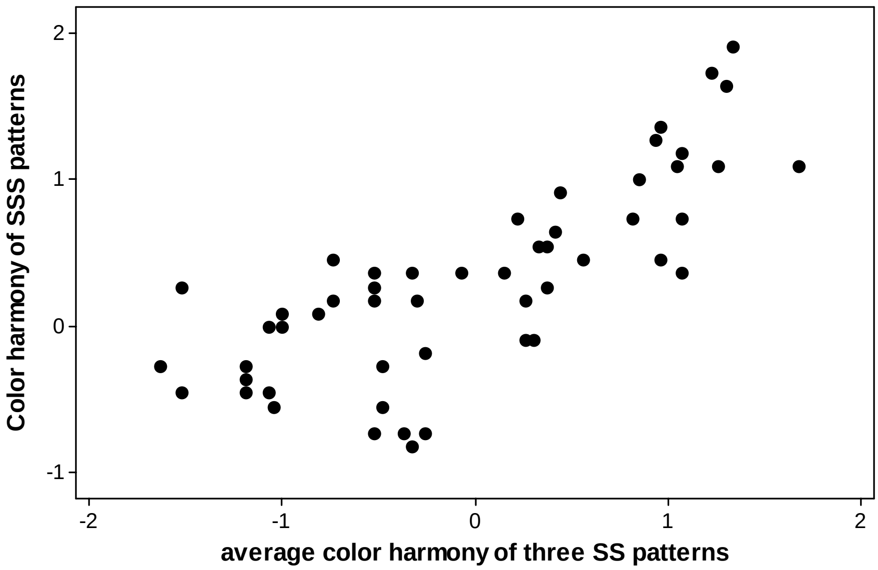


Fig. 6.2 The relationship between color harmony of SSS pattern and average color harmony of related three SS patterns.

The multiple regression method, as in two-color harmony, was used to model the color harmony of SSS pattern from that of SS pattern. h_1, h_2, h_3 were used to represent the color harmony values of three related SS patterns obtained from the evaluation experiment. Average color harmony $(h_1+h_2+h_3)/3$, average of the first-order interactions $(h_1h_2+h_1h_3+h_2h_3)/3$ and second-order interaction $h_1h_2h_3$ were calculated and included in the predict variables. Equation 6.1 shows the regression result between these variables and color harmony of SSS patterns.

$$Harmony_{SSS} = 0.212 + 0.194(h_1 + h_2 + h_3) + 0.070(h_1h_2 + h_1h_3 + h_2h_3) \qquad (6.1)$$

It was found that 67.8% of total variance of harmony of SSS pattern can be explained by the harmony of the related three SS patterns. Average value is the most important factor which accounts for 59.8% of total variance. 8% of variance is attributed to the average of the first-order interactions among the three related SS patterns, while the second-order interaction almost has no influence. It seems that predicting harmony value of SSS pattern from those of three related SS patterns is possible. This model provides a very convenient tool for estimating the harmonious levels of SSS patterns.

6.2.1.2 The influence of color perceptual attributes on harmony of SSS pattern

The influence of color perceptual attributes on harmony of SSS pattern was examined in this section since it is very useful for the design of harmonious SSS patterns. However, as the sampling method used in this experiment is based on the harmonious levels of related two-color patterns, not the perceptual attributes of the component colors, the model constructed on the color perceptual attributes can only be used in the conditions similar to this experiment.

In view of the equal role of three related SS patterns, four kinds of variables, i.e., (1)average hue difference, (2)average lightness difference and average lightness, (3)average chroma difference and average chroma, and (4) average single color preference, were calculated. The meaning of each variable is shown in Table 6.2.

Table 6.2 The variables and their meaning for color harmony modeling of SSS pattern. The subscripts, 1, 2, and 3, represent three colors in SSS pattern.

Variable	Abbr.	Meaning
Average hue difference	A_HD	$(\lvert\Delta h_{12}\rvert+\lvert\Delta h_{13}\rvert+\lvert\Delta h_{23}\rvert)/3$
Average lightness difference	A_LD	$(\lvert L_1-L_2\rvert+\lvert L_1-L_3\rvert+\lvert L_2-L_3\rvert)/3$
Average lightness	A_L	$(L_1+L_2+L_3)/3$
Average chroma difference	A_CD	$(\lvert C_1-C_2\rvert+\lvert C_1-C_3\rvert+\lvert C_2-C_3\rvert)/3$
Average chroma	A_C	$(C_1+C_2+C_3)/3$
Average single color preference	A_P	$(P_1+P_2+P_3)/3$

The correlation results between these variables and the color harmony of SSS pattern are listed in Table 6.3.

Table 6.3 Correlation coefficients between the color perceptual attributes related variables and color harmony of SSS patterns

Number	Variables	Correlation coefficients
1	A_HD	-0.633*
2	A_LD	0.000
3	A_L	0.318*
4	A_CD	-0.039
5	A_C	-0.386*
6	A_P	0.236*

*: Correlation is significant at the level 0.05 (2-tailed).

This table illustrates that average hue difference is the most important factor on SSS pattern. This is quite similar to the results of SS pattern in which hue difference is the decisive factor on color harmony. In addition, average lightness and average chroma as the main factors on color harmony of SS pattern also significantly correlate with color harmony of SSS patterns. Average preference of component colors is also very important.

Considering the six variables in Table 6.2 as well as their second-order terms and interaction terms, the following model is given by using the same multiple regression method as in main experiment:

$$Harmony_{sss} = 2.246 - 0.012A\_HD + 0.448A\_P - 0.036A\_C \qquad (6.2)$$

58.3% of total variance can be explained by this model. Three variables, i.e., average hue difference, average preference, and average chroma, are the most important factors on color harmony of SSS patterns, which account for 40.1%, 7.1%, and 11.1% of total variance, respectively. This result is quite similar to those obtained in the SS pattern. It implies that a simple arithmetical relationship exists between SSS pattern and its three related SS patterns. It further suggests that it is possible to derive the harmonious level of SSS pattern from those of related SS patterns.

6.2.2 Color harmony of SSB patterns

6.2.2.1 The relationship between harmony of SSB pattern and that of three related two-color patterns

SSB pattern can be decomposed into one SS pattern and two CB patterns. The two CB patterns is equivalent in SSB pattern. Hence, totally 6 kinds of SSB patterns were designed in this experiment as shown in Table 3.2. For briefness, we use “1” to represent the category of SSB patterns composed of 3 harmonious patterns, “2” and “3” to represent the categories with 2 harmonious patterns, “4” and “5” to represent the categories with 1 harmonious pattern, and “6” to represent the category with 3 unharmonious patterns. Fig.6.3 shows the average color harmony levels and their 95% CI from experiment for 6 categories of SSB patterns. From this Figure, the harmonious levels of category 1, 2 and 3 are apparently larger than those of category 4, 5, and 6. It means that SSB patterns composed of harmonious two-color patterns were also evaluated more harmonious than those composed of unharmonious two-color patterns.

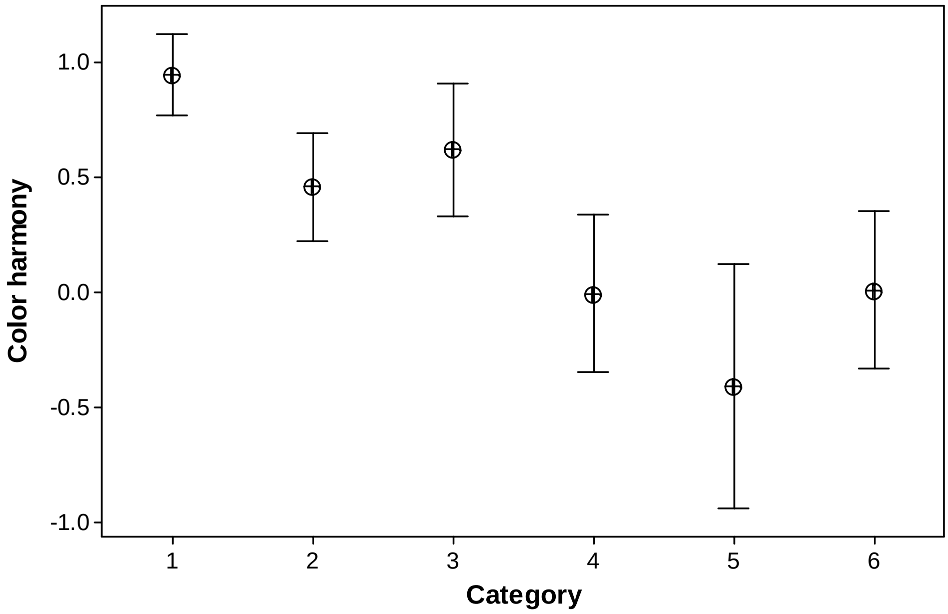


Fig. 6.3 The average color harmony levels and their 95% CI for 6 categories of SSB patterns.

To model the color harmony of SSB pattern from those of three related two-color patterns, four variables including (1) average harmony of two CB patterns, (2) harmony of SS patterns, (3) interaction between above two variables, and (4) interaction between harmony values of two CB patterns, were considered in multiple regression analysis as used in two-color harmony. However, the model is not very satisfactory since only 36.2% of total variance can be explained by the harmony of related two-color patterns. Average harmony of two related CB patterns, which accounts for 33.1% of total variance, is the most important factor on harmony of SSB patterns. This low prediction rate may be due to the relative complicated configuration in this kind of color patterns.

6.2.2.2 The influence of color perceptual attributes on harmony of SSB pattern

To examine the influence of the perceptual attributes of component colors on color harmony, the variables were divided into four groups as shown in Table 6.4.

Table 6.4 The variables and their abbreviation in SSB patterns.

Groups	Variable	Abbr.
Hue related variables	Average hue difference of two related CB patterns	AHD_CB
	Hue difference of related SS pattern	HD_SS
Lightness related variables	Average lightness difference of two related CB patterns	ALD_CB
	Lightness difference of related SS pattern	LD_SS
	Average lightness of related SS pattern	AL_SS
Chroma related variables	Average chroma difference of two related CB patterns	ACD_CB
	Chroma difference of related SS pattern	CD_SS
	Average chroma of related SS pattern	AC_SS
Single color preference related variables	Average single color preference of related SS pattern	AP_SS
	Single color preference of background color	P_B

The correlation results between these variables and color harmony of SSB patterns are shown in Table 6.5.

Table 6.5 Correlation coefficients between the color perceptual attributes related variables and color harmony of SSB patterns

Number	Variables	Correlation coefficients
1	AHD_CB	-0.206
2	HD_SS	-0.357**
3	ALD_CB	0.640**
4	LD_SS	-0.126
5	AL_SS	0.626**
6	ACD_CB	-0.018
7	CD_SS	-0.122
8	AC_SS	-0.078
9	AP_SS	0.502**
10	P_B	0.526**

**: Correlation is significant at the 0.01 level (2 tailed).

It was observed that average lightness difference of two related CB patterns (ALD_CB) and average lightness of related SS pattern (AL_SS) have the highest correlation with color harmony of SSB patterns. Single color preference related variables (AP_SS, P_B) are all observed to have a similar moderate correlation with harmony of SSB patterns. It indicates that the preference of two center colors and one background color of SSB pattern have the same influence on its harmonious level. A low yet significant correlation coefficient (p<0.01) was observed between hue difference of SS pattern (HD_SS) and harmony of SSB pattern. These results are consistent with the findings in two-color patterns, where lightness difference is the most important factor in color harmony of CB pattern and hue difference is the most important factor in SS pattern. Since SSB pattern can be decomposed into two symmetrical CB patterns and one SS pattern, it is logical that the average lightness difference of two related CB patterns and hue difference of SS pattern may be the two main factors on color harmony of SSB patterns. The single color preference of each component color, as in two-color patterns, may significantly influence the harmony of SSB patterns. Considering ten basic variables shown in Table 6.4, multiple regression analysis was conducted to derive a color harmony model for SSB pattern:

$$\begin{aligned} Harmony_{SSB} &= 0.068 + 0.022ALD\_CB - 0.005HD\_SS \\ &\quad + 0.026AL\_SS - 0.028AC\_SS + 0.279P\_B \end{aligned} \tag{6.3}$$

Using this model, 70.6% of total variance can be explained by five significantly influential factors. The contribution of each factor is shown in Table 6.6.

Table 6.6 Contributions of five significantly influential factors on color harmony of SSB patterns.

	Variables	R^2
1	ALD_CB	40.9%
2	HD_SS	14.8%
3	AL_SS	7.1%
4	AC_SS	3.4%
5	P_B	4.4%
Total		70.6%

As the most important factor of CB pattern, lightness difference of two related CB patterns, accounting for 40.9% of total variance, is also the determinant on color harmony of SSB pattern. Hue difference, average lightness, and average chroma are the main factors of SS pattern. These three factors of related SS pattern also may significantly influence the harmony of SSB pattern. For the influence of single color preference, 4.4% of total variance can be explained by the background color preference, while the influence of the center color preferences is included through average lightness of related SS pattern. Based on these results, harmonious SSB patterns can be conveniently designed.

Similar to SSS patterns, the sampling method of SSB pattern is based on the purpose to predict the three-color harmony from two-color harmony, but not to predict from the color perceptual attributes of component colors. Therefore, the color combinations of SSB patterns were not selected systematically in CIELAB color space. Consequently, the model based on color perceptual attributes is not general and can only be used in the situations similar to this experiment.

6.3 Conclusion

Two kinds of three-color patterns, one is three colors laid side by side on a neutral grey background (SSS pattern) and the other is two center colors laid side by side on a colored background (SSB pattern), were evaluated in this experiment. Four kinds of SSS patterns and 6 kinds of SSB patterns, which are composed of two-color patterns with different harmonious levels, were designed and evaluated in an attempt to find the relationship between the harmony of three-color pattern and that of three related two-color patterns. The results show that qualitatively a distinct relationship exists between harmony of three-color pattern and two-color pattern. It means that three-color patterns composed of harmonious two-color patterns are always evaluated to be harmonious. From the viewpoint of quantitative analysis, for SSS patterns, possibly due to their simple configuration, it was feasible to predict their harmony values from those of three related SS patterns. For SSB patterns, however, due to their relative complicated structure, it is difficult to obtain the harmony values from those of three related two-color patterns. The relationship between three-color harmony and color perceptual attributes of the component colors was also examined. Two models were constructed with influential variables consistent with those obtained in the two-color harmony.

Chapter 7

Color Harmony in Application

The previous two chapters analyzed the influencing variables on color harmony of two-color, and three-color patterns. Color harmony models， which allow harmonious color patterns to be specified， were constructed. This chapter focuses on the development of a methodology for designing and constructing harmonious color patterns using the color harmony models. Constraints in color pattern design are analyzed, and a methodology for comprehensive consideration of these constraints in the harmonious color pattern design process is conceived.

This Chapter includes three parts. The first part presents the visualized dimensions of color harmony based on the models constructed in previous chapters so that harmonious regions can be easily navigated. The second part describes the constraints that should be set on the dimensions of color harmony in order to select a more appropriate harmonious color patterns. The third part develops a framework for the application of color harmony.

7.1 Visualizing the dimensions of color harmony

By using Equations (5.3) and (5.7), the dimension of color harmony can be visualized using a multi-dimensional space in which color harmony levels can be represented. In this space, the harmonious levels of a given combination of dimensions can be indicated. Consequently, how color harmony levels are distributed in the space, how the variables influence the harmonious levels, and which one may produce the greatest variability in color harmony, can be determined.

Based on Equation (5.3) and (5.7), the color harmony of SS patterns and CB patterns was illustrated in Fig. 7.1 and Fig. 7.2 respectively. To visualize the color harmony space, $|\Delta h_{ab}|$ was fixed to 10°, 90° and 180° to respectively represent analogous, medium, and complementary hues; the color harmony was represented in six equal-width levels (Han and Kamber, 2001) from -3 to 3. Therefore, a two-dimensional space was obtained to exhibit the distribution of color harmony. The harmony region in which the harmonious value is in the range of 0 to 3 was enclosed by red line. By this way, we can easily figure out which region is evaluated to be harmonious.

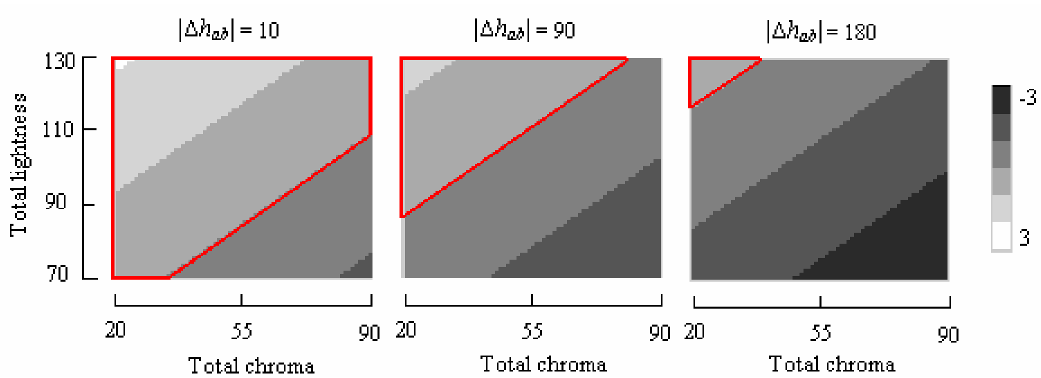


Fig. 7.1 Color harmony space of SS color patterns with $|\Delta h_{ab}|$ was fixed to 10°, 90° and 180°.

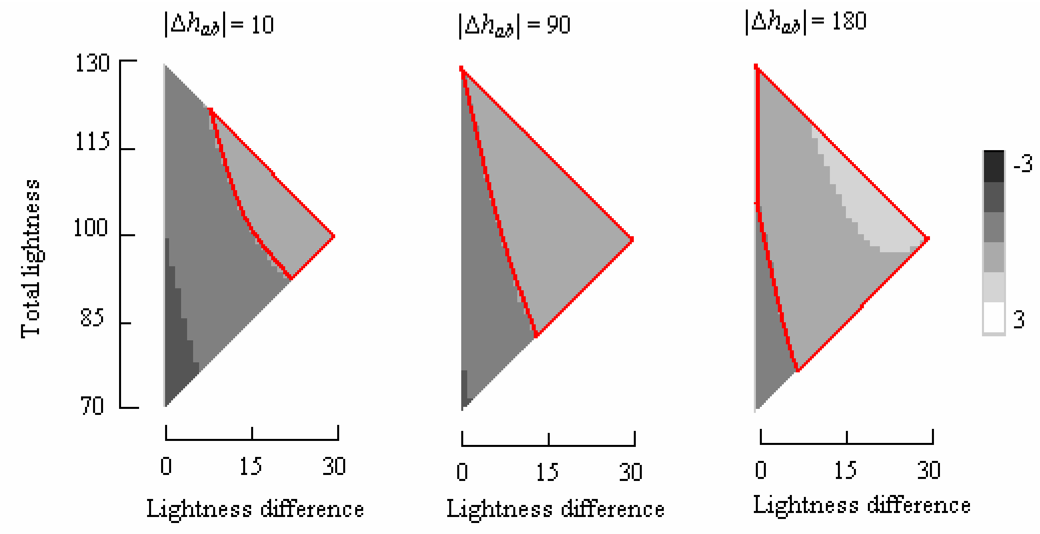


Fig. 7.2 Color harmony space of CB color patterns with $|\Delta h_{ab}|$ was fixed to 10°, 90° and 180°.

From Figure 7.1 and 7.2, it can be found that:

The area of harmony region decreases quickly with the hue difference for SS patterns, while for CB patterns, it increases with the hue difference. For SS patterns, those with similar hues were almost always considered to be harmonious, while for complementary hues, only the patterns with very high total lightness and very low total chroma were evaluated harmonious. On the contrary, for CB patterns, contrast colors were highly appraised except for a small region of patterns with similar low lightness in two component colors. For CB patterns with similar hues, only a very small region was rated harmonious.

It is also observed that the harmony region of SS pattern, regardless the magnitude of hue difference, locates in the top-left corner, where color patterns has high total lightness and low total chroma. For CB pattern, those with small lightness difference were almost always rated unharmonious, especially when total lightness was also very small.

Another feature can be observed from these two figures is that an equivalent harmonious level can be obtained for color patterns with different composition. For example, for SS patterns, in terms of hue difference, total lightness, and total chroma, different color patterns may be rated in the same harmonious level. Similarly, for CB patterns, by adjusting the value of hue difference, lightness of background and center color, same harmonious level can also be obtained. In product design, it seems very difficult to determine a unique color scheme since so many combinations were rated harmonious. In practical application, many constraints as discussed in Section 7.2 should be set. These constraints may confine the harmonious color patterns to a unique harmonious color combination.

7.2 Constraints in color pattern design

In practical applications, colors appeared as interrelated sensations are required to be harmonious to please people observing it. Except for this very important but basic requirement, color patterns may serve many other purposes. For example, it may be used as identification, symbolism, or to deliver some specific emotion. In this section, four kinds of constraints in color pattern design are discussed.

7.2.1 Function

7.2.1.1 Formatting

Depending on the required effect, sometimes the purpose of using color is to segregate and group objects of the same color or to quickly locate an object of a novel color in a crowded display (Travis, 1991). The former application is called *Grouping*, while the latter is called *Highlighting*.

- Grouping

Objects of similar hue tend to align themselves together. However, despite the fact that people can distinguish thousands of different colors, only eleven colors are never confused (Boynton etc, 1989, Smallman and Boynton, 1990). Therefore, when the number of category is eleven or less, different hues can be used to distinguish them. Thus, large hue difference as an effective dimension can be used for grouping.

- Highlighting

When an object is sufficiently different in color from the surrounding objects, it instantly segregates, or pops out of the background. Jacobson and Bender (1990) found that a large hue-to-hue alignment serves for maximum discrimination between background and object when there is little contrast of value and sufficient chroma. When there is a greater contrast of value, hue-to-hue alignment is less important. Perception research by Ware (1999) also affirms that brightness contrast is important for distinguishing objects from one to another.

Hence, the utilization of large lightness difference invites the opportunity for accent or highlight.

7.2.1.2 Coding

Colors can be used for coding to identify categories, or to show trends and relationships in information. As a general guideline, categories or names are better coded by large difference in hue to emphasize its categorical nature. Small steps in hue and logically related hues such as red, red-purple, purple, purple-blue, and etc, can be used to represent interval information. Saturation also can be used to code such kind of quantitative information (Travis, 1991). Therefore, according to the type of information, large hue difference, small hue difference, or chroma difference may be utilized for coding.

7.2.1.3 Legibility

Many studies on color legibility have found that legibility depends solely on the luminance differences between the color of the words and the color of the background (Knoblauch, etc, 1991, Legge and Rubin, 1986, Tinker, 1963). Jacobson, *et al* (1991) have reported that the legibility of value contrast between text and background is at least 2.0 Munsell units. Recently, measuring legibility by the number of visual pathways needed for legibility reveals the contribution of hue (Nilsson, 2005). In color design, if legibility is required, then a large lightness difference can be utilized.

7.2.2 Emotion

People do not live in a black-and-white world. Rather, they live in an increasingly colorful world that is filled with emotions, feelings and associations. For example, interior designers or artists may be asked to design an office with minimal stress and optimal comfort, or to design a residential space with visual homeliness and visual pleasantness. To exploit these effects, many efforts were contributed to discover and quantify the links between color perceptual attributes and the emotional response of observers.

The interests focusing on this field can be divided into two broad categories. One is about the experimental aesthetics of color or color preference, which deals with evaluative dimensions of colors, such as “comfortable” or “uncomfortable”, “good” or “bad” etc. (Granger, 1955d, Sivik and Taft, 1992, Ou, etc, 2004a). The other is concerned primarily with descriptive dimensions, such as “warm” or “cool”, “light” or “dark”, “heavy” or “light” etc. (Wright and Rainwater, 1962, Hogg, 1969a, 1969b, Sivik, 1970, Xin, etc, 2004a, 2004b, Gao and Xin, 2006). A majority of researchers agreed that the conformity between different people about the general cognitive characteristic of colors is considerable (Hardin and Maffi, 1997). However, they considered that the color preference is cultural related. The constraints relating to cultural background are examined and discussed in Section 7.2.4. In this section, we mainly concern the issues of descriptive, but not evaluative dimensions of colors.

The efforts in color emotion research were mainly contribute to extracting the factors in color emotion space and relating them to the color perceptual attributes.

7.2.2.1 Common factors for description color emotion

A psychophysical experiment was conducted by the authors to investigate the issues related to color emotion (Gao and Xin, 2006, Gao, et al, accepted). Totally 214 color samples were evaluated on 12 emotional variables by subjects from four Asia regions, including Hong Kong, Taiwan, Thailand, Japan, and three Western regions, including Italy, Sweden, and Spain. Four factors, i.e., activity, potency, definition, and temperature were concluded in the experiment. As in our studies, Sivik (1970) also found excitement/activity, forcefulness/potency, and temperature factors in his color emotion study on Greeks and Swedes. Kunishima and Yanase (1985) studied the visual effects of wall colors and also found two similar factors, i.e. activity and warmness/temperature. Ou et al. (2004a) also identified three factors, i.e. color activity, color weight, and color heat, in British and Chinese subjects. From these results, considerable similarities were observed in these findings, despite of different emotional variables, different color samples, and subjects with different cultural background.

7.2.2.2 Determinants on color emotion factors

For the determinants on each factor, this holds particularly for the relation of activity (also called "excitement" or "dynamism") and chroma (Gao and Xin, 2006, Sato, et al, 2000, Sivik, 1974, Hogg, et al, 1979), as well as potency (also called "forcefulness") and lightness (Gao and Xin, 2006, Sato, et al, 2000, Sivik, 1974, Wright, 1962). The inconsistency mainly comes from the variable "warm-cool" or called "temperature" or "Warmness" factor. Some researchers reported that "warm" or "cool" of a color was mainly dependent on its hue (Sato, et al, 2000, Kunishima and Yanase, 1985, Sivik, 1970, Wright, 1962). Sivik (1970) and Wright (1962) found that the variation of the color temperature was also considerable for colors of the same hue. Recently, Ou et al (2004a) reported a significant influence of chroma on "warm-cool". In our studies (Gao et al, accepted), it was observed that people from different regions may have different feelings on "warm" or "cool" of a color. Hue is a decisive factor for the observers in Japan, Taiwan, Sweden, and Spain, while chroma is more important for those in Hong Kong and Italy. For Thai people, chroma and hue are almost of same importance. According to these results, it seems that the temperature of a color, which is determined by hue or chroma, may lie on the cultural background of the observers.

7.2.2.3 Emotion of color combinations

The emotion of single color has been widely studied in the literature. However, in daily life colors are never seen in isolation, but always presented together with other colors. Therefore, it is necessary to clarify the color emotion of color combinations.

A few works have been carried out to investigate the emotion of color combinations. Hogg (1969a, 1969b) and Sivik (1989) have take efforts in identifying the factors in emotion space of color combinations. Ou et al (2004b) have found an additivity relationship between the emotion of color pair and the emotions of the component colors. Using this relationship, the emotion of a color pair can be easily predicted by averaging the emotions of the individual colors of the pair.

7.2.2.4 Application of color emotion theory in color design

To accurately deliver the emotion of an image is meaningful for a designer so that the customers may be attracted by the product. To achieve this purpose, the designer can follow the steps listed below:

1) To identify the emotion of the product that he/she wants to deliver;
2) To determine the category, for example, potency, activity, or temperature, etc, to which the emotional variables may belong to;
3) Then based on the theory of color emotion mentioned above, such as potency by lightness, activity by chroma, temperature by hue for Spain, etc, to determine the dimension that the category depending on;
4) Finally, to determine the total value of the dimensions of color combinations by using the Ou et al's additivity theory, so that the feeling that the designer wants to express may be arrived.

7.2.3 Prevailing fashions

Consumers of modern fashion goods are very sensitive to fashion trend. To attract customers, fashion goods designers may attempt to roll out products that match the current fashion trends as closely as possible. Color is a very important element in product design and fashion color is pursued by designers insistently, especially in the fashion products industry, such as textile design (Choo and Kim, 2003). It is certain that fashion color should be primarily considered in fashion product design.

7.2.4 Culture background

The cultural significance of color is particularly interesting. It was observed that how people react to color and how they interpret color are often relating to their cultural background (Ou, etc, 2003). For example, white represents purity in the West and is thus used in wedding dresses as traditional color, while in some Eastern countries, wearing a white wedding dress would be considered a serious breach of etiquette. Therefore, designers should be very carefully in the usage of colors when exploring the possible color schemes for such kind of products.

In addition, it was observed that the color preference was subject to strong cultural differences (McElroy, 1952, Choungourian, 1968, Ou, etc, 2004c). For example, Ou, etc (2004c) have found that lightness is the most predominant factor on color preference for Chinese, while hue seems more important for

British. On the other hand, as discussed in previous chapters, a considerable contribution of the color preference on color harmony was observed. Therefore, to design a harmonious image, it is important to consider the cultural background of the customer or user of the goods.

7.2.5 Maintaining original color

In some color design, such as advertisement, certain hues are used to maintain the original color of objects. For example, in a coffee house poster, rich browns and dark blue are used for coffee and night sky respectively (Meier, Spalter, and Karelitz, 2004). In such a situation, the color of object and background are almost constrained.

In some other situations, the regularly-used colors are appreciated. For example, in interior design, Munsell YR and Y are the most frequently used colors. A small number of RP and GY colors are also included in residential space, while some PB and B show up in both office and commercial space interior design (Lee, Chang & Kim, 2005). In these situations, the selection of the dominant color is restricted in a narrow range.

7.3 Methodology for practical color pattern design

In any situation utilizing colors, such as graphic design, textile manufacturing, advertising, product packaging, etc, it is very useful to construct a typical procedure for effective color harmony model application. The methodology for practical color pattern design is discussed in the following.

Given an application, the function of the color pattern should be first considered. For example, similar hues can be used for grouping, and large lightness interval for legibility.

Designers should then focus on the emotion that they want to deliver. This is very important and also quite difficult since the emotion the color patterns evoked may determine the popularity of the product. Blue-green and a warm yellow may evoke the feeling of the tropics; saturated colors may deem to be exciting and gaudy; and light colors may be felt soft and represent weak. Using these theories, the emotion of product may be correctly expressed.

Next, the color harmony model should be used on the basis of the constraints mentioned above. Before the usage of color harmony model, the category of the color pattern (SS pattern or CB pattern) should be determined according to the structure of the designed product so that the appropriate color harmony model can be applied. Considering the constraints, a limited number of color patterns may be selected by adjusting the parameters of the harmony model.

Finally, other constraints may be set, such as fashion color, culture background of the consumers, even the personal preference of the designer. Fashion color is influential to adapt Zeitgeist, to guard against consumer boredom, and consequently to increase sales of certain products, especially for fashion and consumer products.

When all these constraints are satisfied, a harmonious and appropriate color patterns may be selected and used in product design.

7.4 Summary

This chapter focuses on developing a methodology for establishing harmonious color patterns. By progressively setting the constraints on harmonious color patterns, such as the function required by the situation, the emotion to be delivered, the influence of prevailing color, etc, a unique harmonious color pattern can be determined. Flexible is the first important feature of this methodology. It allows additional dimensions to be incorporated in the selection process and the order of the consideration of the constraints can be easily adjusted according to their importance. Generality is the second important feature since this methodology can be utilized in any application situations.

In the constraints examining process, we have also outlined various ways of application of color harmony models.

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Chapter 8

Conclusion and Future Work

This investigation attempts to analyze the influential factors on color harmony, to construct basic color harmony models which can be very useful for accurate and objective color pattern design, and finally to explore the potential causation of color harmony.

To fulfill these objectives, a three-step experiment was carried out using two-color and three-color patterns. In the preliminary experiment, two kinds of two-color patterns with different hues but same lightness and chroma were evaluated. This step deals with the questions including (1) which hue should be selected, and (2) how large of hue step is appropriate. Based on the results of preliminary experiment, an appropriate number of color combinations with different hues, different lightnesses and different chromas, were designed to investigate the determinants on color harmony in the second step. Color harmony models were constructed on the two kinds of two-color patterns. Finally, an attempt was made to predict three-color harmony from harmony values of related two-color patterns. The influences of two kinds of factors, one is the physical attributes of color itself, and the other is the subjective response (personal preference) on single colors, were examined to clarify the influential factors of color harmony.

In this chapter, the findings of the investigation are concluded and the issues deserve further investigations are suggested.

8.1 Conclusion

8.1.1 Determinants of single color preference

Consistent ratings on single color preference were observed among the subjects who have similar cultural backgrounds, same educational levels, and the same age group. For colors as object or background, same results were obtained and summarized as follows:

Firstly, similar to the results of most previous studies, not only hue, but also lightness and chroma are the influential factors on color preference.

Secondly, lightness is the most important factor on single color preference, while hue is of the secondary importance. This result is contrary to some early studies, in which the researchers claimed that hue is the determining factor on color preference. However, it was noted that Ou et al (2004) also found the same results for Chinese subjects as those in this study. This may indicate that cultural background can not be ignored in color preference evaluation.

Thirdly, for the detailed relationship between preference and hue, we have observed that colors containing green or blue are more preferred, while those containing yellow or purple are less preferred with constant lightness and chroma value. This result is in complete accordance with the findings in most of the previous studies.

Finally, for the relationship between preference and lightness as well as between preference and chroma, it was found that brighter and saturated colors are more preferred, while dark and low chroma colors are less preferred.

8.1.2 Determinants of color harmony

Color harmony of two kinds of patterns, i.e. SS pattern and CB pattern, were evaluated by 20 Chinese observers. The observer repeatability and agreement were examined and the results indicate that color harmony is an unequivocal and stable feeling for most people and is meaningful for further investigation.

On this basis, models for SS color pattern and CB color pattern were developed. 72.6% of total variance of SS patterns and 66.3% of total variance of CB patterns are explained by their corresponding model. Component color relationships and single color preferences are the two main categories of factors affecting color harmony of both color patterns. Characteristics of each single color in the pattern are considered to be less important to the harmony of a color pattern.

For SS patterns, hue difference is a primary influential factor which accounts for 36.8% of total variance. SS patterns with similar hues are harmonious, while those with complementary hues are unharmonious. For CB patterns, color harmony largely depends on lightness interval which accounts for 30.2% of total variance. Those patterns with lightness difference close to 24 in CIELAB system were found to be the most harmonious.

Positive correlations between color harmony and total lightness were observed in both kinds of patterns. For SS and CB patterns, 23% and 18.3% of total variance of color harmony can be explained by total lightness respectively. In view of the strong positive dependence of single color preference on lightness, it can be concluded that high harmonious levels of patterns with high total lightness may be due to high single color preference.

Two kinds of three-color patterns, that is, SSS pattern and 1SS2CB pattern, were evaluated in this investigation. The results show that qualitatively there is a distinct relationship between the harmony of three-color pattern and two-color pattern. This indicates that three-color patterns composed of harmonious two-color patterns can always be evaluated as harmonious, while those composed of unharmonious two-color patterns may be considered unharmonious.

From the viewpoint of quantitative analysis, it is feasible to predict the harmony value of SSS patterns from those of three related SS patterns. However, this kind of prediction is very difficult for SSB patterns possibly due to their complex structures.

8.1.3 Psychological viewpoint on color harmony

Color harmony is a pleasing response of human to color patterns. It is a result of interaction between the inner feelings of human beings and the external world. According to the results of color harmony, some inner cautions which lead to color harmony were deduced.

Different configurations between SS pattern and CB pattern lead to different criterion on color harmony. Similar colors are perceived as harmonious for SS patterns, while large difference in two component colors is favored for CB patterns. This may due to the fact that similar colors satisfy observers' expectation of seeing a plane in SS patterns, while a figure-background relationship can be easily observed for CB patterns with large color difference. All these indicate that color harmony is a pleasing response evoked by color patterns when an expectation is satisfied.

Single color preference is also very important to color harmony for both kinds of patterns. This indicates that color harmony, as an aesthetics related topic, is associated with the subjective preference. Furthermore, since single color preference may be influenced by cultural background, it is presumable that different color harmony rule would be obtained from observers with different cultural backgrounds.

8.2 Issues for future work

To increase the generality of the color harmony rules developed in this investigation, there are a number of fundamental issues which can be considered in future investigation.

- Smaller steps

In order to simplify the experiment, each attribute was selected in relatively large steps in this study. Further investigation using smaller steps in the selection of perceptual attributes of each component colors is suggested so that some subtle relationships can be examined. In addition, the color harmony of color patterns when hue difference is around zero should also be evaluated and analyzed carefully.

- More colors

Two-color patterns have been studied intensively in this research and the harmony of three-color patterns have been attempted to be predicted from the harmonies of two-color patterns. The results indicate that it is difficult to quantitatively predict the harmony of 1SS2CB patterns from those of related two-color patterns due to the complexity of the configuration of this pattern. Therefore, the influential factors on the harmony of this kind of three-color patterns need further analysis. Furthermore, harmony of patterns with more colors, such as four-color and five-color patterns, should be evaluated since our real world is a complex combination of many colors.

- Real images

In this study, two simple patterns were used in the evaluation to simulate the images in the real world. These simple patterns may conceal the influence of subjective connotations of objects in real world. Therefore, real images are more appropriate in investigations related to product color design.

- Color appearance

Colorimetric attributes were used to specify colors in this study. However, as we have known that the appearance of a color may be influenced by its surrounding colors, it is reasonable to consider the color appearance shifts produced by visual context in further investigation.

- Different cultural background

In this study, only Chinese students were chosen as observers. As it was found that cultural background may influence single color preference and consequently affect color harmony principles, observers with different cultural background should be involved in color harmony evaluation to generalize the rules for color harmony.

- Mechanism of color harmony perception

According to the results of color harmony on two kinds of two-color patterns and theory of sensation and perception, we deduced the possible mechanism of how the aesthetic responses are produced on color patterns. This deduction is worthy of verification by further experiments.

In conclusion, this investigation developed some simple color harmony principles which are worthy of further theoretical and applied research.

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Appendix 1

Color harmony experiment

1. Objectives and tasks

There are four tasks in this test:

1. To evaluate the preference of single color as object color. In this case, colors will be displayed in small size.
2. To evaluate the preference of single color as background color. In this case, colors will be displayed in full size.
3. To evaluate the harmonious level of color pattern in which component colors are arranged side by side.
4. To evaluate the harmonious level of color pattern in which component colors are in center-background relationship.

By the term of "color harmony", it refers to a pleasing effect produced by two or more colors seen in neighboring areas. During evaluate color harmony, you should keep in mind that what we are interested in is your intuitive "pleasing" or "unpleasing" response from the interaction between component colors in patterns. Any deliberate result is undesired and any color design knowledge should be disremembered.

2. Evaluating scale

Verbal descriptions "Unpreferred - Preferred" "Unharmonious - Harmonious" are used to rate single color preference and to evaluate color combinations, respectively. The rating scale is as follows:

Unpreferred	-3	-2	-1	1	2	3	Preferred
Unharmonious	-3	-2	-1	1	2	3	Harmonious

For example, upon presentation of a pattern, you should evaluate the color harmony levels based on this scale. If you think it is VERY HARMONIOUS, then click the radio button labeled with "3"; if, on the other hand, you think it is VERY UNHARMONIOUS, click the radio button labeled with "-3". You may find that the color pattern is HARMONIOUS, or UNHARMONIOUS, but is not very, then you can click the radio button labeled with "2" or "-2", respectively. If you think it is only A LITTLE HARMONIOUS, or A LITTLE UNHARMONIOUS, then you should click the radio button labeled with "1" or "-1", respectively. Zero, which represents a neither harmonious nor unharmonious response, does not appear in this scale. You are forced to make a judgment, harmonious or unharmonious. There is no right or wrong answer. You are simply providing you evaluation on color pattern, and as you go on, you will develop your own method for doing so.

3. Mechanics

You will run through a series of 20 trial combinations to get you familiarized with the mechanics of the experiment. During this training series, you will observe typical combinations that may see during the actual experiment. During this stage, it is important for you to establish some sort of mental scale for rating the combinations that you will see during the actual experiment. This is how you will calibrate your range.

Next is how the test works:

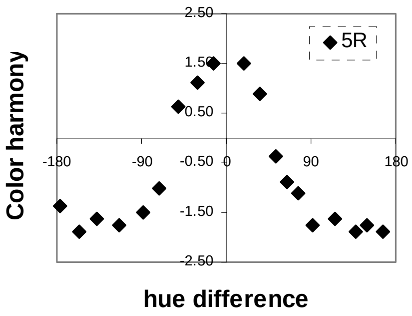
- A color pattern (or single color) will be displayed on the screen.
- A pair of descriptors with six scales from -3 to 3 will appear on the right bottom of the screen.
- You should rate the pattern (or color) based on these scales and click the radio button labeled with the number you select.
- Hit the down arrow button, and a neutral gray color will be displayed on the full screen.
- During this time, you are asked to look at the screen.
- After 10 seconds, a new color pattern (or single color) will appear, and the experiment repeats.

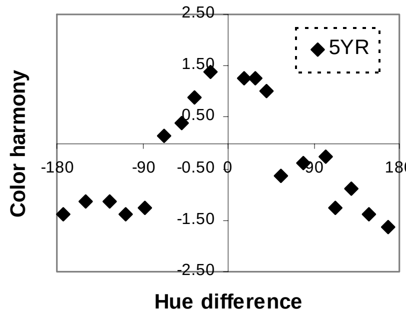
4. Duration of experiment

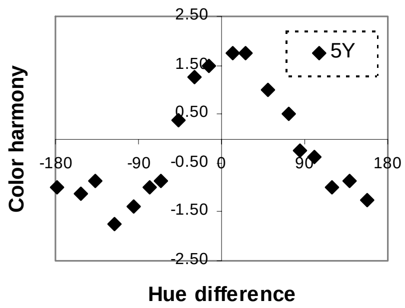
You are not being timed in this experiment. So you may establish your own pace. However, you are required to response quickly, typically 3 to 5 seconds per sample, so that an intuitive response can be obtained. The entire test should take you between one to two hours and a half to complete. You may take a break at any time during the experiment.

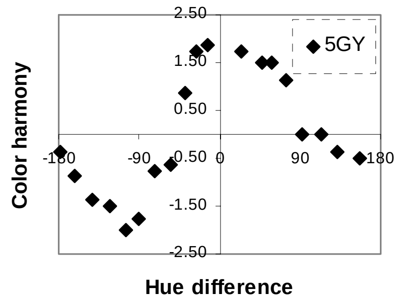
Thanks for your participation!

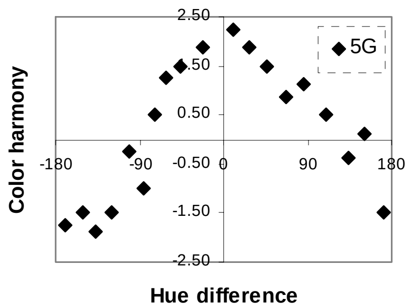
Appendix 2

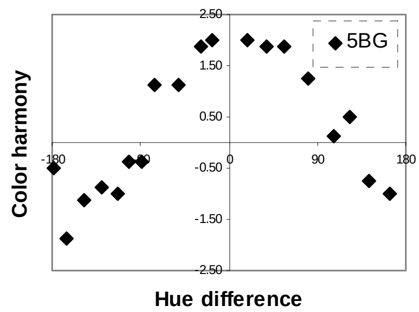

5R
Color harmony
hue difference

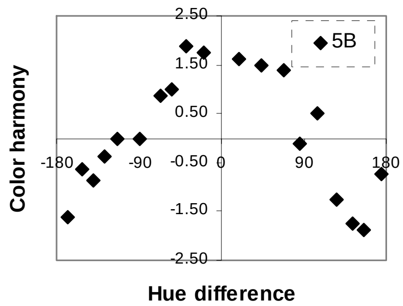

5YR
Color harmony
Hue difference


5Y
Color harmony
Hue difference


5GY
Color harmony
Hue difference


5G
Color harmony
Hue difference


5BG
Color harmony
Hue difference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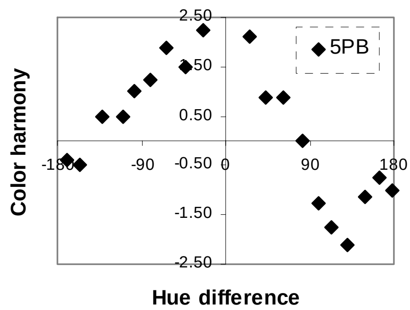
Color harmony
Hue difference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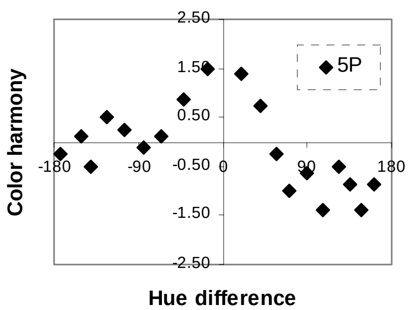
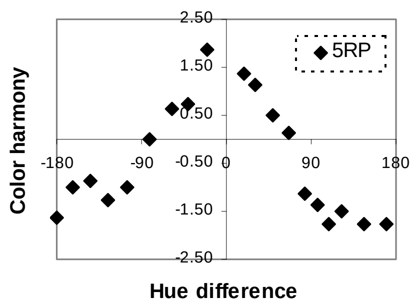
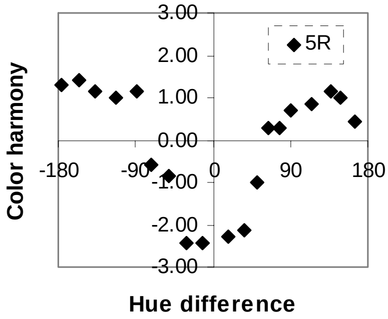
Color harmony
Hue difference

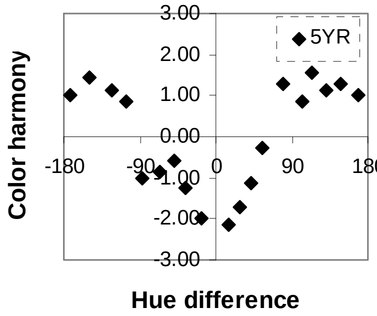

5P
Color harmony
Hue difference


5RP
Color harmony
Hue difference

Appendix 3



5R
Color harmony
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference



5YR
Color harmony
3.00
2.00
1.00
0.00
-1.00
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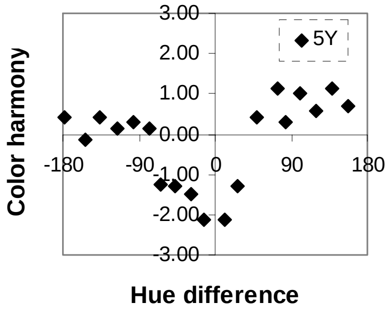
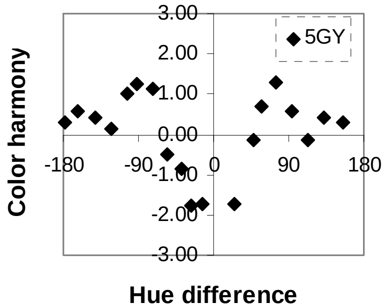
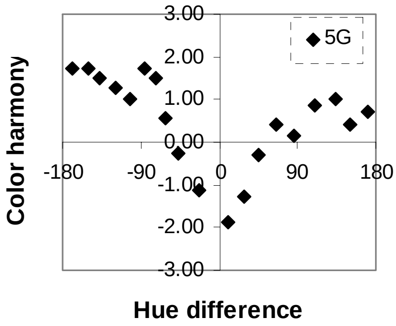
-3.00
-180
-90
0
90
180
Hue difference



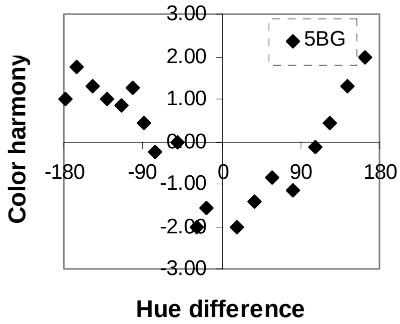
5Y
Color harmony
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference



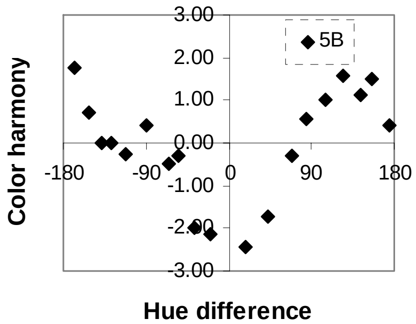
5GY
Color harmony
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference



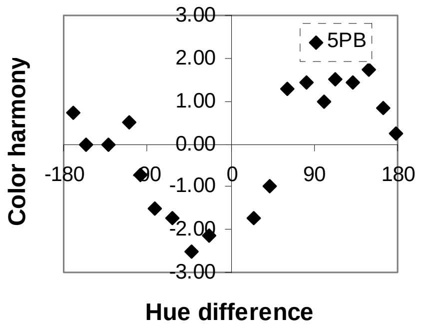
5G
Color harmony
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference



5BG
Color harmony
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference



5B
Color harmony
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference



5PB
Color harmony
3.00
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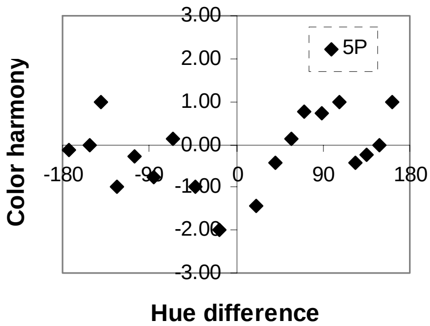
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference



5P
Color harmony
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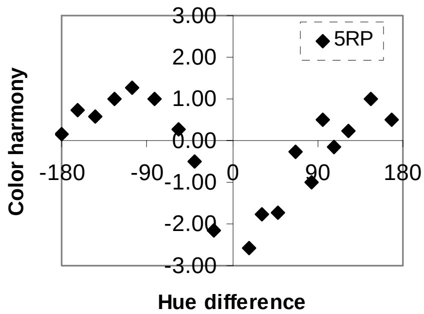
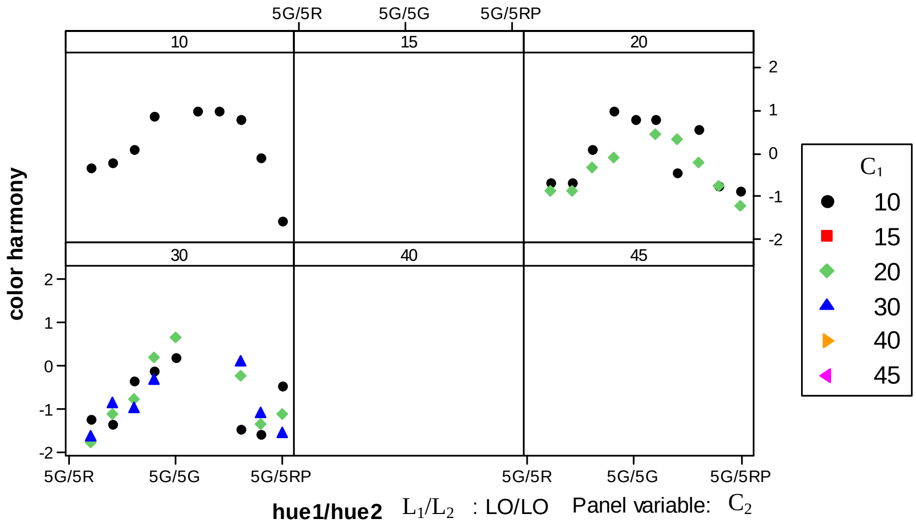
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference

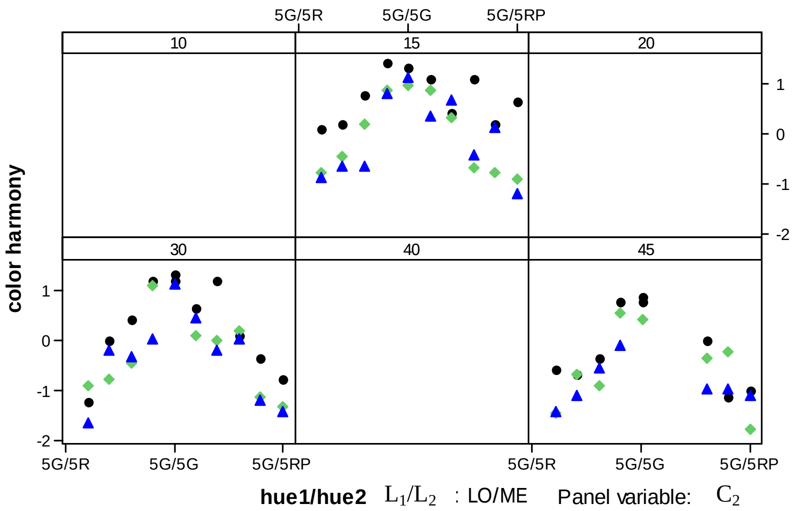


5RP
Color harmony
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-180
-90
0
90
180
Hue difference

Appendix 4



5G/5R 5G/5G 5G/5RP
10
15
20
30
40
45
color harmony
2 1 0 -1 -2
C1
10
15
20
30
40
45
5G/5R 5G/5G 5G/5RP
hue1/hue2 L1/L2 : LO/LO Panel variable: C2



5G/5R 5G/5G 5G/5RP
10
15
20
30
40
45
color harmony
1 0 -1 -2
5G/5R 5G/5G 5G/5RP
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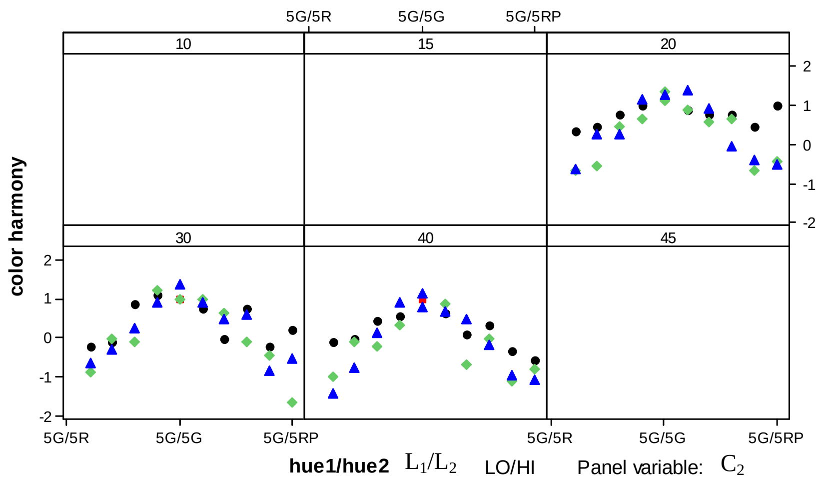

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15
20
30
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color harmony
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5G/5R 5G/5G 5G/5RP
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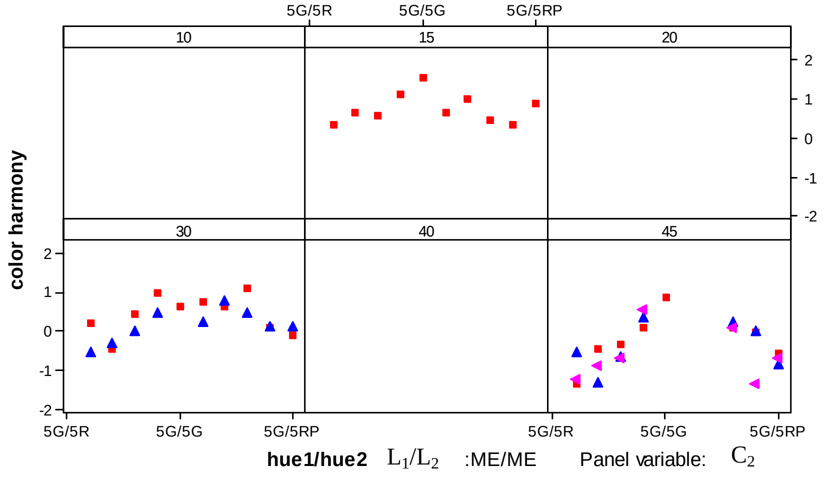
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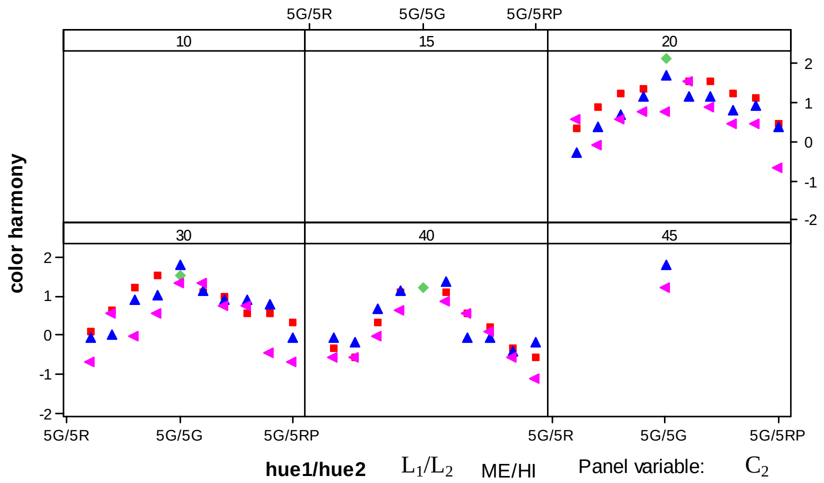
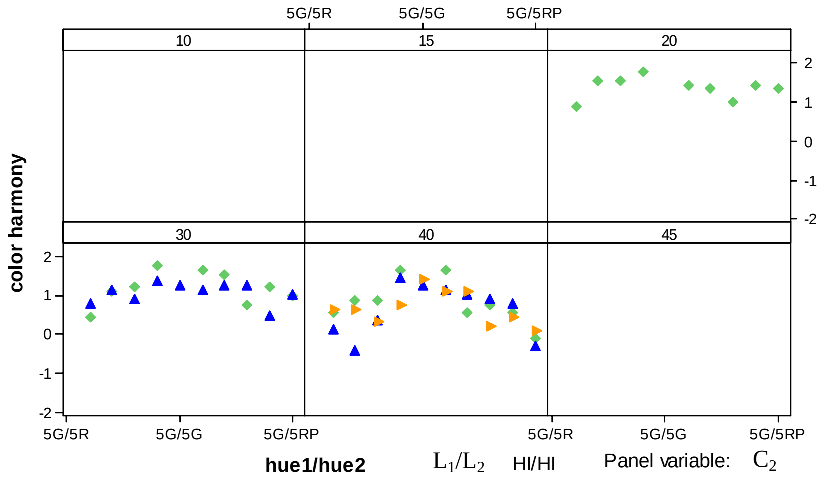
hue1/hue2
L_1/L_2 :ME/ME
Panel variable: C_2


5G/5R
5G/5G
5G/5RP
10
15
20
30
40
45
color harmony
hue1/hue2
L_1/L_2 ME/HI
Panel variable: C_2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hue1/hue2
L_1/L_2 HI/HI
Panel variable: C_2