Quantifying the Dimensions of Color Experience

by

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Submitted to the Media Arts and Sciences Section,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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Abstract

In visual experience, colors appear as interrelated visual sensations, unpredictable from looking at colors in isolation. This investigation examines *experience of color*: the response to colors as they *relate* to each other. It is proposed here that humans can make consistent evaluation of the *magnitude* of any given color experience, based on the type of interaction between the colors. The investigation addresses how color experiences are *established*, how experiences are *described*, and how experiences are *quantified.*

The investigation is interdisciplinary in nature. A model of color experience was developed utilizing research methods from fields such as perceptual and cognitive psychology, linguistics, experimental design, and visual aesthetics. The model describes experience of color with directly observable features of the colors, such as the *chromatic dimensions* of hue, value, chroma, and their contrasts, as well as the *spatial* dimensions of size, and proportion.

The interactions between the dimensions were uncovered through a series of experiments. Semantic differential scales were used to evaluate systematic variations in the relationships between the colors. It was found that distinct color experiences can be described with a single scale of magnitude, so that seemingly disparate visual sensations can be made commensurate with each other.

The results of this investigation directly apply to a wide variety of disciplines. For instance, in interface design, color can reinforce information by providing visual "counterpoint." In image reproduction, "color matching" becomes a matter of "preserving" the experience of color. In graphic design, a wide variety visual experiences can be established and "transposed." In multi-media applications, sensations produced by different modalities can be integrated.

In conclusion, the investigation demonstrates that experiences of color are governed by well defined objective principles that can be quantified with experimental methods. The methodology developed here provides the framework for further research in the field.

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I had a box of colours -
Other colours, pleasant, beautiful;
I had a box of colours
Some warm, others cold;

I had no red for the blood of the wounded;
I had no black for the mourning of orphans;
I had no white for the face of the dead;
I had no yellow for the sun-drenched sands.

I had orange for the joy of living;
I had green for blossoms and buds;
I had blue for cloudless, clear skies;
I had pink for dreams and tranquility.

I sat
And painted
Peace

written by Sorek, a 13-year-old from Beersheva, Israel.

provided by Rabbi Alvin Lieberman.

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This thesis is dedicated to the memory of two people:

my uncle *José Feldman*

and my cousin *Balfour Meerovici*.

They served as models of scholarship in the arts, and in science from very early on. They would have been very proud of me on completing this degree.

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Chapter 1

Experience of Color

1.1 Introduction

For most, color constitutes a routine aspect of everyday life. Color appears everywhere in natural objects such as flowers, fish, and rocks, and in fabricated objects such as athletic shoes, toothpaste, clothing, automobiles, soft-drinks, and bubble-gum. The use of color has been made even more widespread with the advent of computer driven displays, which can show images with colors selected from a wide range of possibilities. However, even in such sophisticated display systems, color selection is usually based on the skill and memory of trained color specialists and designers, who, in general, treat colors as *isolated* visual phenomena.

In reality, though, colors appear as interrelated visual sensations, unpredictable from looking at the colors in isolation. For instance, certain colors, when placed next to each other, can look "exciting," as if vibrating at their boundaries. Other colors can look "subdued" when placed next to each other; still some other colors can look somewhere along a continuum between "subdued" and "energetic." Thus, color experiences have a magnitude associated with them, which can range between *low* magnitude and *high* magnitude. *Experience of color* is the *response* to color relationships, as determined by the magnitude of the interaction between colors.

This investigation is about quantifying experiences produced by interactions between *two* colors in patterns encompassing a *wide-field* of view. It is proposed here that humans can make consistent evaluation as to where in the range of magnitude any given color experience lies. Thus, the premise of the investigation is a simple one: experience of color is *universal*. That is, humans have an ability to make judgements about *magnitude* of interaction of colors based on how colors relate to each other. Features of the colors, such as chromatic composition and spatial configuration determine the magnitude of the interactions. These features constitute the *dimensions* of color experience, hence, the title of the investigation.

1.2 Varieties of Experience

In visual communication, a wide variety of color experiences can be established. For example, Figure 1.1 shows several patterns made up of two colors arranged in different configurations. Each pattern constitutes an experience of color; each with its own unique "character." However, even among such varied experiences, it is possible to identify features which are common among the experiences: some of the experiences are *energetic* and some are *weak*. Therefore, when viewing colors what is most revealing is to determine how colors relate to each other. It is the relationship between colors which determines magnitude of experience. For instance, the experiences in Figure 1.1 can be organized by magnitude of experience, as shown in Figure 1.2.

1.3 Correspondence

The patterns in Figure 1.2 have been arranged so that the least energetic patterns are on the left hand side, the most energetic on the right, and all others in between. This arrangement by magnitude of experience suggests that experience of color transcends chromatic composition or spatial configuration, in that patterns of very different colors and shapes can be grouped together and, in effect, can be considered *equivalent* in terms of magnitude of experience. It is proposed here that there is *correspondence* between magnitude of experience and formal features such as color composition and spatial configuration of the patterns. Correspondence implies that a specific relationship between colors produces a given experience; and conversely, given an experience, the specific color relationships which established the experience can be determined.

1.4 Phenomenology of Color Experience

The focus of this investigation is on the *phenomenology* of color experience; that is, on how humans *respond* to color *interactions*, independent of *how* the response is produced. Unlike color appearance studies, the intent of this investigation is not to describe how a given color is affected by its surround colors, but rather, the intent is to evaluate the color and its surround, as a whole. Therefore, when evaluating experience of color, what matters is the type of interaction, and its magnitude.

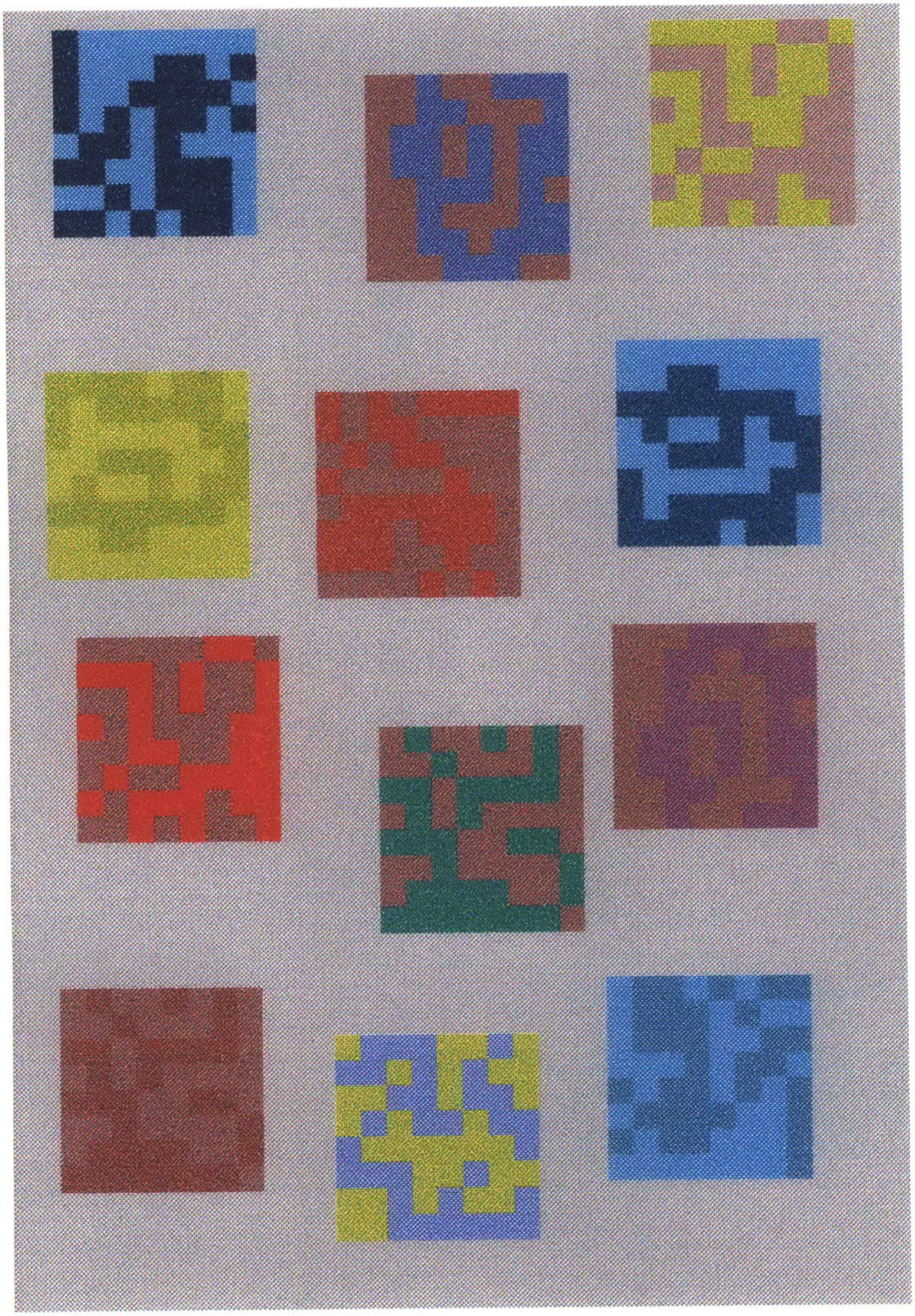

Figure 1.1: Varieties of color experience.

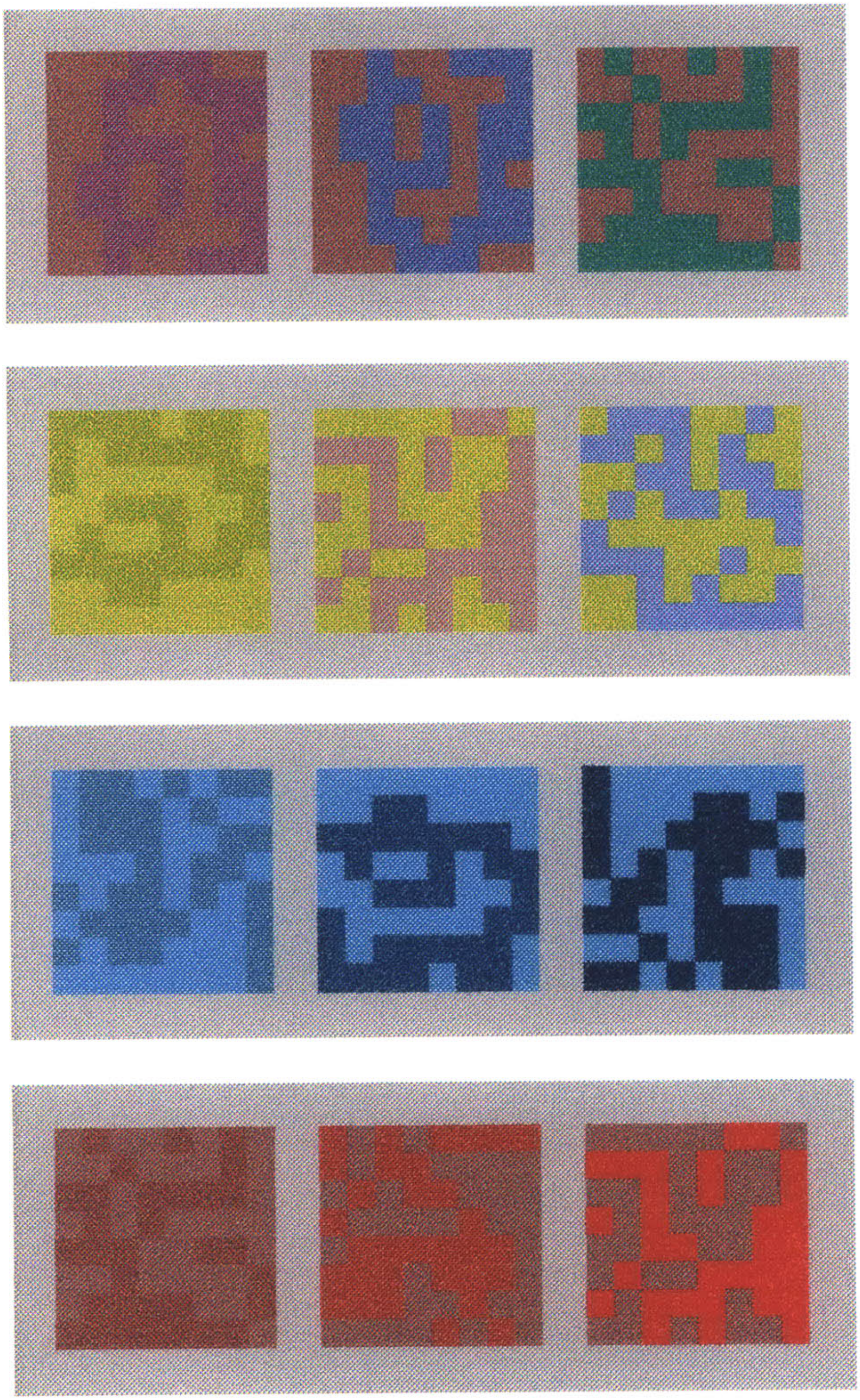

Figure 1.2: Varieties of color experience. From left to right, magnitude of interaction increases.

1.5 "Black box" approach

Color vision is the result of highly complex processing, as of yet not fully understood; therefore, evaluating experience of color with a "Skinnerian" approach is appropriate because it allows responses to stimuli to be measured, independent of how the responses are produced (Loeb, 1992). Namely, the human subject is treated as a "black box," which takes color experiences as input and produces a response as output (Skinner, 1974). The processes which produce the response are hidden inside the black box. Therefore, the mechanisms which produce the response are not the focus of this study, so they are not covered here. For a current and thorough discussion of the mechanisms of color vision refer to a book such as "Eye, Brain, and Vision," by Hubel (1988).

1.6 What Experience of Color is Not

When evaluating experience of color, agreement between people is large; that is, judgements of magnitude of experience constitute an *invariant* aspect of human response to color. Beyond such invariant response lie more *personal* and *subjective* issues of judgement, such as whether an experience is "pleasing" or not. The problem with assessing personal preferences is that there is no consensus among people, even less across people in different cultures, as to which colors are "beautiful" or "ugly" together. Therefore, subjective evaluation of color is deliberately avoided in this investigation. A complementary study by Green-Armytage (1992) evaluates the role of personal preferences on color experience. However, the role of personal preferences in selecting among equivalent experiences is discussed in Section 6.2.4.

1.7 Purpose and Scope

In summary, the objective of this investigation is to evaluate how color experiences are *established*, how experiences are *described*, and how experiences *relate* to each other. The investigation is interdisciplinary in nature. A model of color experience is developed utilizing research methods from disciplines such as perceptual and cognitive psychology, linguistics, experimental design, and visual aesthetics. The model has numerous applications in several disciplines. For instance it can provide answers to questions such as: "What information are color experiences providing?", "Can color experiences enhance the information being displayed?", "Can experience of color be preserved?", "How do experiences relate to each other?", and "Can experiences be transformed?"

Chapter 2

From Colorimetry to Color Experience

In this chapter experience of color is traced back to studies on the phenomenology of color. These related studies can be classified into five categories. The first category includes studies on *colorimetric* specification of colors, in which colors are treated as isolated visual sensations. The second category includes studies on color *appearance*, in which color is treated as it interacts with its surround. The third category includes studies on color *harmony*, in which patterns and symmetries in color relationships are described. The fourth category includes studies on *expressive* aspects of color, in which connotations of color are evaluated. The fifth category includes studies which develop *mathematical* models of color relatedness.

The model of color experience developed in this investigation differs from most previous studies in that color sensations are treated as *wholes*; that is, experience is evaluated for an ensemble of colors, independent of colorimetry and appearance of the individual colors. As the chapter proceeds, singular features of the model developed here are indicated.

2.1 Colorimetry

Colorimetry is the science of measuring color as *isolated* visual sensations (Billmeyer, 1981) (Wyszecki, 1963). The reason it is important to measure colors as isolated visual sensations is that there is a need for consistent and systematic specification of color to answer questions such as: "Do the colors of all parts of the body of a car match?", "Are paints produced today the same color as paints produced eight years ago?", "Is the color (and taste?) of the cola soft drink the same in Peru as it is in the United States?" Colorimetry provides the mechanisms for individual colors to be specified and matched with precision.

2.1.1 Small-distance Metrics

Metrics, such as ΔE, or "delta E", have been developed to evaluate the accuracy of a color match (Billmeyer, 1981). These metrics indicate the difference between colors with a single number, independent of which dimensions is producing the difference. That is, the metric does not distinguish between difference in hue, difference in value, or difference in saturation; but rather, the metric consolidates differences into a single number, which indicates the overall difference between colors.

Such metrics are referred to as *small*-distance metrics because they are accurate for computing differences between colors which are very similar to each other; namely, colors which differ in chromatic composition by a few *just-noticeably-differences*. However small-distance metrics can be misleading when attempting to describe differences between colors which are very distant from each other, because changes along different chromatic dimensions produce perceptually distinct changes. For example, for a given ΔE, a large difference in hue is *experientially* very different from a large difference in value, or a large difference in chroma, because the dimensions of color are not commensurate with each other. That is, a unit change in hue looks different from a unit change in value and from a unit change in chroma. Therefore, specifying differences between colors with colorimetric formulations is inaccurate when differences between colors are large.

In this investigation, a metric which makes the dimensions of color commensurate with each other, is developed. This single metric allows experiences to be related to each other.

2.1.2 Limitations of Colorimetry

One fundamental limitation of colorimetric models is that they do not indicate how a color appears once it is viewed in its visual context. That is, visual context can produce large shifts in color *appearance* which cannot be accounted for by colorimetric specification of the color; appearance of color is the result of an interaction of colors. For example, Figure 2.1 shows three identical yellow fields on backgrounds of different colors. Because of the interaction with the surround, the yellow fields *look* different, even though, *colorimetrically*, they are identical. Therefore, colorimetric specification of a color does not predict its appearance when viewed in its visual context.

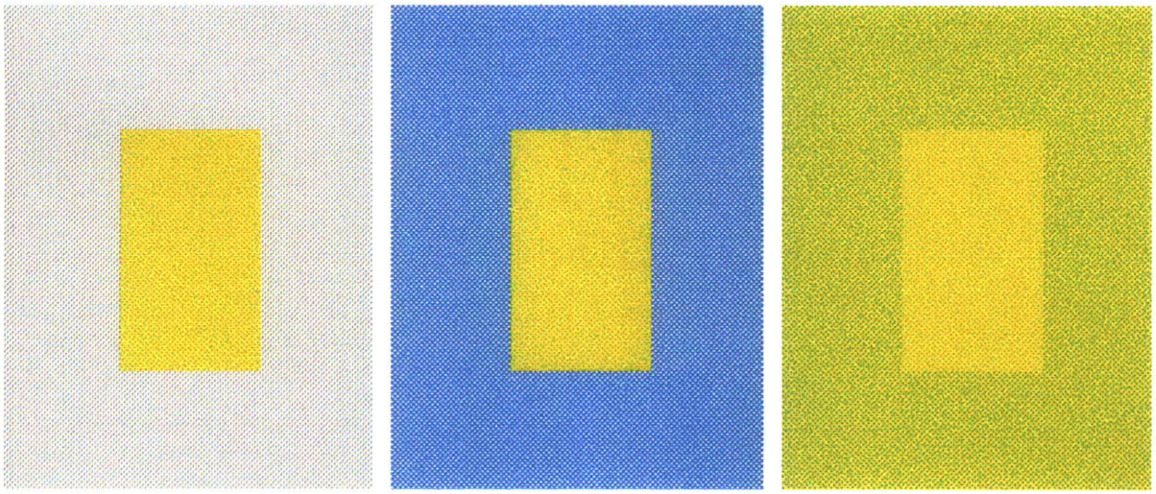

Figure 2.1: Identically colored yellow fields with different surrounds. The yellow fields are equivalent colorimetrically, yet, *experientially*, they look different from each other.

2.2 Color Appearance

There have been many studies on color appearance, in which indicate color shifts produced by interactions between color and its surround have been modeled.

2.2.1 Retinex Theory

One of the first theories of color vision to treat colors in visual context is Edwin Land's *Retinex* theory (1977). In essence, Retinex theory states that each set of cone cells in the retina generates an achromatic image of the scene, as if viewed through the filter of its own photopigment. The color of any single surface is obtained by comparing its lightness among each of those three differing achromatic images (Rock, 1990). Colors of the scene are determined based on ratios of luminosity between adjacent regions, regardless of the type of illumination, or state of adaptation (Labrecque, 1988). Retinex theory is a manifestation of *color constancy* (Boynton, 1979).

2.2.2 "The colors of things"

Lettvin and colleagues performed a fascinating study on the effects of spatial configuration on appearance of color (Lettvin, 1986). By evaluating factors such as shared boundaries, enclosure, and extensibility, they determined how color appearance is affected by the distribution of reflectance ratios across boundaries and around vertices.

2.2.3 Chromatic Induction

Interestingly, both Retinex theory and Lettvin's study rely on computing spatial interactions between neighboring colored regions. In fact, spatial interactions between adjacent color fields can be attributed, in large part, to the phenomenon of *chromatic induction*. Buchsbaum (1988) modeled chromatic induction for circular color-surround configurations with a set of exponential equations. These equations indicate the amount of perceived chromatic shift for any given circular color-surround configuration.

2.2.4 Global Interactions

In a related study, Arend investigated color interactions for stimuli more complex than the simple "disk-of-light-in-a-dark-surround" of traditional color research. His research was motivated by the limitations of traditional color appearance approaches, which cannot describe the phenomenology of color in images of real scenes. Thus, Arend takes a global or "wide" field-of-view approach at modeling the interactions between colors (Arend, 1990).

2.2.5 Limitations of Color Appearance Models

Color appearance models, just like colorimetric models, ultimately describe the phenomenology of a *single* color. That is, they describe the processes by which the appearance of a single color is affected by the color of its surround; be it by contrast effects, or by spatial configuration. In this investigation, the intent is to model the phenomenology of colors as an *ensemble*, independent of how the appearance of the individual colors is established.

2.3 Color Harmony

In color harmony studies, “harmony” refers to combinations of color which are perceived as “pleasing”. Such a definition is based on the notion that there exist certain immutable relations between objective stimulus properties of color and the perception of harmony.

2.3.1 Early Studies

From early on in the course of color science, models of color harmony have been proposed by artists and scientists alike. For instance, Leonardo considered that difference in hue or contrast in lightness between two colors produces a particularly *harmonious* effect (Granger, 1955a). Years later, researchers such as Goethe (1970), and Chevreul (1967) proposed alternate theories of color harmony. For a comprehensive evaluation of color harmony studies refer to Whitfield and Slatter (1979).

2.3.2 Color Order Systems

Some renowned color scientists, among them Munsell and Ostwald, have developed color order systems suitable for the specification of color harmony (Munsell, 1954) (Birren, 1969). The systems of Munsell and Ostwald were developed independently in America and in Germany.

Ostwald’s basic idea of color harmony is that any “orderly” geometric arrangement of colors, in the color order system he developed, should constitute a harmony. Ostwald considered the simplest harmonies to be made up of colors spaced uniformly along the neutral axis or of colors spaced uniformly in a radial direction. According to Ostwald’s formulation, combining these simple harmonies, more “complex” harmonies can be established.

Munsell developed concepts such as *area*, *balance*, and *paths* to describe color harmony (Munsell, 1954). For instance, harmonies may be established by following prescribed paths along color space. To achieve balance between colors in juxtaposition, he developed the *Law of Inverse Ratios of Areas*, which states that the area of a color in juxtaposition with another color should be inversely proportional to the product of the color’s value and chroma. For example, a “small” area of “high” chroma is *balanced* by a “large” area of “low” chroma. Validity of this law has been disputed because, as defined by Munsell, it is based on balance to a neutral color, rather than to any arbitrary color.

As a whole, Munsell's magnificent treatise on color set the foundations for later work on color harmony, including aspects of this investigation. When discussing the possibilities of color harmony, Munsell points out that:

> "As this constructive imagination gains power, the [color] solid may be laid aside. We can think of color consecutively. Each color suggests its place in the system, and may be taken as a point of departure for the invention of groups to carry out the desired relationship."

2.3.3 Preference Models

One of the first systematic evaluations of interaction of colors was performed by Cohn in 1894 (Granger, 1955b). In his study on the "harmony of hue" in two-color configurations, Cohn observed that combinations of colors which approach the *complementary* relationship tended to be seen as more "pleasing." The observations of Cohn agree with results of more recent studies. For instance, Granger (1955c) found that the degree of *preference* for a particular hue in combination with other hues is positively correlated with the size of the *interval* between the hues, so that complementary colors are seen as "most pleasing;" that is, hues which are farthest apart from each other tend to be described as most "harmonious" when viewed together.

2.3.4 Limitations: Boundaries and Indeterminacy

A fundamental problem with models of color harmony such as the ones mentioned above, is that they are prescriptive; that is, they designate specific color combinations as producing either "good" harmonies or "bad" harmonies.

This assumption that all color combinations can be divided into two distinct classes seems to be taken for granted throughout color harmony studies. There is supposed to be a perfectly sharp dividing line between *harmony* and *disharmony*, and every color combination must lie in one class or the other. Obviously the sharp division into two classes is not in accordance with fact, because boundaries between classes are not clearly defined; the boundaries are indeterminate. As Moon and Spencer wisely observed:

> "there are no forbidden combinations, there is no dividing line" (Moon, 1944a).

Therefore, color experiences are not bipolar, but rather, they span a continuum. There aren't just "good" or "bad" experiences, but there are a wide variety of experiences ranging between good and bad. In practical applications, this continuum of color experiences sets up a wide variety of *expressive* possibilities of color (Feldman, 1991).

In fact, this investigation demonstrates that not only a wide variety of experiences can be established, but also that any given experience of color can be produced in several different ways by adjusting the dimensions of color experience.

2.4 Expressive Color

2.4.1 Tension and relief with color

There have been many studies on the expressive aspects of color, by researcher such as Birren (1969), and Hård and Sivik (1989). Kreitler and Kreitler (1972) performed a study to determine which color combinations are "tension-provoking" and which "tension-relieving." They found that any two colors which are maximally distant in hue, such as *complements* or *off-complements* are "tension-laden"; whereas colors which are similar in hue, such as *monochrome* or *analogous* colors, are "tension-relieving". With respect to saturation, they found that highly saturated colors are experienced as more "tension-laden" than combinations of less saturated colors; that is, there is correspondence between color *relationship* and color *experience*, in that specific relationships between colors establish specific experiences (Feldman, 1991).

2.4.2 Color Image Scale

Kobayashi developed the *Color Image Scale* to describe specific color relationships using common adjectives (Kobayashi, 1990). In this way every color combination can be described along scales defined by three pairs of attributes: "warm or cool," "soft or hard," and "clear or grayish." These three scales correlate with the chromatic qualities of hue, value, and chroma of the colors, respectively. The color combinations utilized in his study are presented as a series of wonderful books of color combinations. In these books, color relationships are organized by their description (Kobayashi, 1984).

2.4.3 Limitations of Color Image Scale

The color image scale is useful in many design applications, however, it is limited because it is confined to the color samples contained in the books; that is, the color image scale does not provide a mechanism for establishing an experience with color combinations not in the books. As is shown in Chapter 6, it is possible to establish the *same* experience in many different ways, independent of which colors are utilized. For instance, "energetic" experiences can be produced around colors which are generally not considered "energetic," such as pink; when placed against a saturated olive or dark-yellow-green, pink is seen as "robust" and "energetic" (Jacobson, 1991a). Therefore, establishing experience of color becomes a matter of adjusting the relationship between colors and their dimensions.

2.5 Mathematical Formulation of Color Harmony

A mathematical model of color harmony would try to represent the relationship between color "specification" and color "harmony" with a set of equations. There have been only a few investigations attempting to achieve such a goal. Namely, Saunderson and Milner developed the "Zeta" space to find an analytical transformation between color differences in a uniform color space, so that harmonies may be determined (Saunderson, 1946). Glasser and his colleagues developed the cube-root model for a similar purpose (Glasser, 1958).

2.5.1 Moon and Spencer

The most significant study aimed at describing color relationships with a mathematical model is that of Moon and Spencer, performed in the nineteen-forties (Moon, 1944a). According to Moon and Spencer:

> "the basis of color harmony is that any arrangement of colors that can be described as an *orderly combination*, will be sensed as *pleasing*" (Moon, 1944b).

Their approach is based on mapping colors into a space in which color relationships are represented by regular geometrical figures such as lines, triangles, and circles. Formulas which account for *area* of color fields were developed for computing "balance," "identity", "similarity," and "contrast" in color relationship (Moon, 1944c).

2.5.2 Aesthetic Measure

To systematically evaluate color relationships, Moon and Spencer derived a formula for computing "aesthetic value" of a given color combination (Moon, 1944b). This formula is based on the concept of *aesthetic measure*, developed earlier by Birkhoff (Birkhoff, 1933). The formula states that the aesthetic measure is equal to the number of elements of *order* divided by the number of elements of *complexity* of an image. Harmonies of types such as "regularity," "similarity," "contrast," and "ambiguity" were evaluated by means of experiments in which observers organized color samples in order of *preference* (Moon, 1944b).

Application of the formula to color images requires determining the number of elements of order and the number of elements of complexity in the image. To this date, however, the formula hasn't been conclusively validated—and it might never be verified. Aesthetic measure, by definition, is determined by sampling a large population of people as to which color relationships are pleasant, and which unpleasant. However, when evaluating subjective aspects of color, such as personal preference, there is no consensus. Therefore, aesthetic measure is not a universal metric for evaluating phenomenology of color.

2.5.3 Single Metric Approach

As a whole, though, the work of Moon and Spencer can be considered as visionary in scope; it represents a significant attempt at describing color relatedness with a systematic mathematical model. Most importantly, the model introduces the notion of quantifying a wide variety of visual sensations with a *single* metric. Quantifying experience of color with a single metric is useful because it allows seemingly distinct sensations to be related to each other. That is, the metric becomes a unit for comparing experiences established in many different ways.

2.5.4 Criticism of Moon and Spencer model

The work of Moon and Spencer has been criticized by many. Pope accused them of reducing a process as complex as visual perception down to a set of generic mathematical formulas (Pope, 1944). Others have said that Moon and Spencer had a naive view of color science—their mathematical construct is "too contrived;" or that "reality does not conform to simple geometric models" (Whitfield, 1979) (Sivik, 1989).

Such accusation may have some validity, although most of the criticism tends to focus on details of the formulation, and not on the fundamental principles. As Moon and Spencer stated:

> "a simple formulation, even though imperfect, is better than no formulation" (Moon, 1944d).

In general, thus, their work represents not only a very significant contribution to the field of color-harmony, but also serves as a starting point for developing any new model of color relatedness. More specifically, it shares a fundamental feature with this investigation, the use of a *single* metric to quantify experience of color.

2.6 Color Experience

With the exception of the Moon and Spencer model, none of studies described above considers the phenomenology of color relationships as ensembles. The studies on colorimetry describe single colors as isolated sensations; the studies on color appearance describe the sensation of a single color as it interacts with its surround. Unlike traditional color harmony prescriptions, color experiences are not confined to harmonies or disharmonies, but rather, they span a wide range of magnitude. Thus, in essence, color experience describes the phenomenology of color relationships, as wholes.

2.7 Relationships of Color Relationships

This investigation develops a structure which relates all color experiences. Such a structure allows experiences to be established with any two colors by adjusting the relationships between their dimensions. This structure allows, for instance, experiences to be *transposed*, so that the same experience is established with two different colors; it is the relationship between colors that is maintained. In practice, a designer may be able to navigate within the space of all possible experiences and find experiences which are equivalent, as well as experiences which are different. Thus, in a general sense, this investigation is about finding the "relationship of color relationships."

Chapter 3

The Dimensions of Color Experience

> "*single channel psychophysics is an artifact of laboratory methodology*"
> (Lockhead, 1992).

Experience of color is determined by several factors. Namely, the number of colors, the brightness of the colors, their intensity, the size and shape of colored regions, etc. Thus, when evaluating color experience, it is not any one factor that is attended to, but rather, it is the interaction between factors that is experienced. Therefore, to describe experience of color, not only must several factors be considered, but also their interactions.

In this investigation, seven factors, or *dimensions*, were selected to describe experience of color. The choice of dimensions is based on previous studies by researchers such as Munsell (1954), Albers (1975), Itten (1970), Moon and Spencer (1944b), and more recently, Jacobson and Bender (1989). In these studies, chromatic dimensions such as hue, value, chroma, hue contrast, and value contrast, as well as spatial dimensions such as relative area, and size of color patterns, were identified as being major determinants of interaction of color.

However, in every study on interaction of color, with the exception of Jacobson and Bender's, the effect of each of the dimensions on interaction of color was evaluated individually, without taking into consideration the inter-relationships between the dimensions. For instance, hue contrasts were evaluated independently of value contrasts, when, in fact, there is a strong interaction between these two dimensions (Jacobson, 1991). One of the reasons why these studies evaluated dimensions individually is that it is difficult to evaluate the interactions between the dimensions because the dimensions are not commensurate with each other. For instance, a contrast in the hue dimension looks very different from a contrast in the value dimension, and different from a contrast in the chroma dimension; therefore, it is difficult to compare them to each other.

This investigation develops a metric which makes the dimensions of color experience commensurate with each other. This metric is an indicator of the overall experience, and allows variations along different dimensions to be compared to each other. The metric is obtained by including not only the contributions of individual dimensions to the overall experience, but also e contributions of the interactions between the dimensions.

3.1 Chromatic Dimensions

The dimensions of color experience evaluated in this investigation can be grouped into two categories: *chromatic*, and *spatial*. In this section chromatic dimensions of experience, such as hue, value, and chroma, as well as their contrasts, are described.

3.1.1 Color Specification

Every color sensation can be described by three distinct dimensions defined as *hue*, *value*, and *chroma*.

- *Hue* is the quality which distinguishes one color family from another, such as "red" from "yellow," or "green" from "blue."

- *Value* is the dimension which describes the lightness or darkness of a color. For instance, a *low-value*, or "dark" yellow is commonly called "brown." Black, white, and gray are achromatic or neutral colors, and thus, have only one dimension—value, which indicates its lightness or darkness.

- *Chroma*, or *saturation* is the purity or intensity of a color. It indicates the degree of departure of a color from a neutral color such as gray or white. For instance, "pink" is a red of "low-chroma" and "high-value". "Fire engine" red is a color of "high-chroma" and "low-value."

3.1.2 Color Order Systems

Colors, as described by their hue, value, and chroma, can be systematically arranged into a *color order system*. Color order systems are useful in specifying *individual* colors because every color is described by a unique set of hue, value, and chroma.

Many different color order systems have been developed; namely Munsell (1954), Ostwald (Birren, 1969), and NCS (Hård, 1981). In this investigation, the Munsell system of color was adopted.

3.1.3 Munsell System

The Munsell system of color is made up of a collection of samples which are arranged in a "tree-like" three-dimensional structure. One important feature of the Munsell system is that it was developed in accordance with visual perception; the samples are spaced in perceptually uniform steps along each dimension, or equivalently, the samples are an equal number of "just-noticeable-differences" apart from each other, along each of the dimensions. Thus, hue steps are equal to each other, value steps are equal to each other, and chroma steps are equal to each other. However, the dimensions are not commensurate with each other; that is, hue steps are *NOT* equal to value steps or to chroma steps.

Another important feature of the Munsell system is that its notation is not linked to, or limited by existing samples. Any conceivable color can be described by a unique combination of hue, value, and chroma, whether it can be produced with current technology or not (Billmeyer, 1981).

Dimension 1 ⟹ Reference Hue

In the Munsell system, hues are arranged along a continuous circular loop, so that there is a gradual and continuous change from one hue to the next. The Munsell hue "circle," shown in Figure 3.1, is divided into ten hue categories, one for each of the *basic* hues. Each basic hue is placed at the center of each category; each of those categories is subsequently partitioned into ten sub-divisions. This results in a circle which is broken up into 100 hue steps.

When comparing two hues, one of the hues is designated as the *reference* hue, the other as the *related* hue, as shown in Figure 3.2. In this investigation, each of the ten basic hues was selected as a reference hue. Distance between the hues is indicated by the number of steps between them. For instance, hues which are near each other are separated by just a few steps; whereas hues which are farthest apart from each other—diametrically opposite each other in the hue circle—are 50 hue units apart from each other. Jacobson and Bender refer to the separation between hues as *hue alignment* (Jacobson, 1989).

Dimension 2 ⟹ Hue Alignment

Hue alignment is defined as the *distance* in hue between any two colors. Hue alignment corresponds to the type of relationship between hues; in fact, researchers such as Jacobson and Bender (1990), and Moon and Spencer (1944a), have defined categories of hue alignments. For instance, hues such as "yellow" and "orange", are similar—but not identical—hues, hence they belong to the family of *analogous* colors. Hues such as "yellow" and "blue-purple" are called *complementary* because, in the Munsell system, they are farthest apart from each other. Thus, from a structural point of view, alignment corresponds to symmetries and other regularities in the spacing of colors (Feldman, 1990).

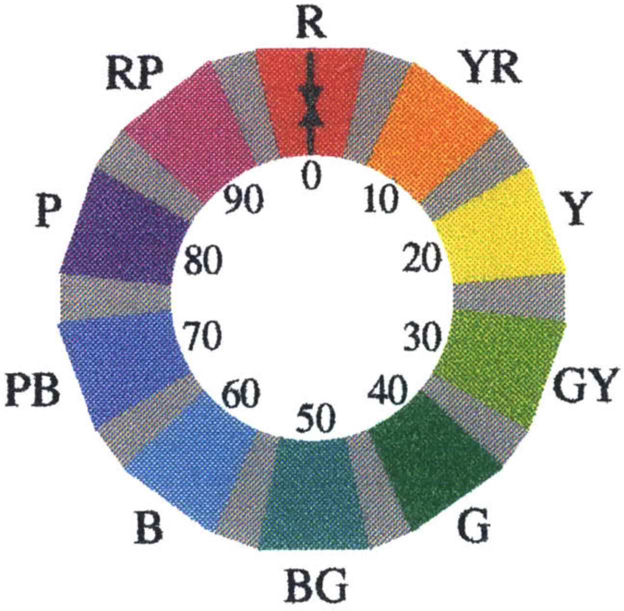

Figure 3.1: Munsell hue circle divided into ten "basic" hues. Hues are designated by either letters (outside), or by numbers ranging between 0 and 100 (inside). In this investigation, each of the ten basic hues serves as a *reference* hue.

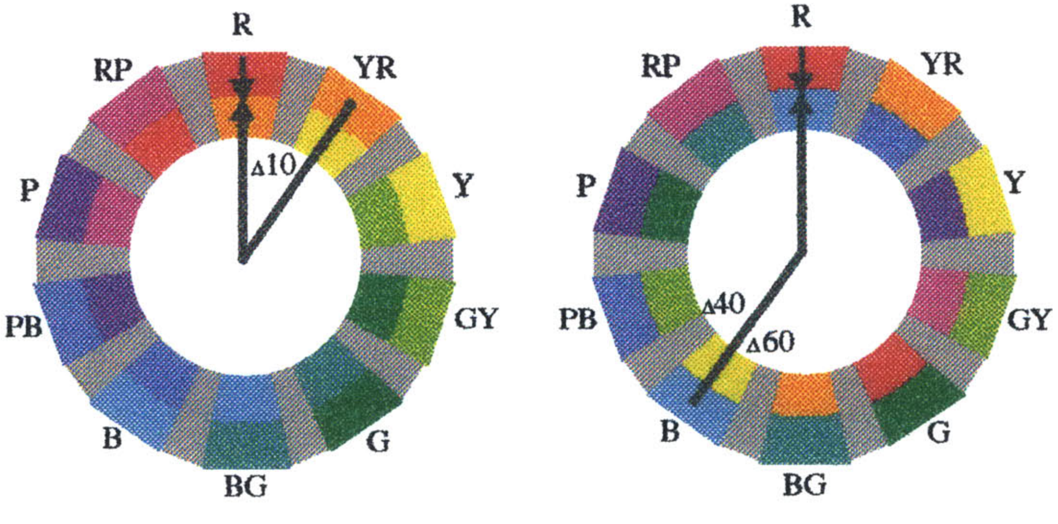

Figure 3.2: Two series of alignments with the same reference hue. Outer ring indicates *reference* hue; inner ring indicates *related* hue. Circle on the left shows alignments of hues spaced 10 units apart from each other. Circle on the right shows alignments of hues spaced 60 units apart from each other (or 40, if traversing hue circle in opposite direction). In terms of hue alignment, all color pairs in each circle are equivalent to each other.

3.1.4 Symmetry in Hue Alignment

Hue alignments appear as symmetric pairs. For any given reference hue, there are two equivalent alignments; one in each direction of traversal of the hue circuit. For instance, alignment of 10 is equivalent to alignment of 90, so is 20 with 80, 30 with 70, and so forth. These alignments are equivalent because the related hues are the same number of steps away from the reference hue; they are just on opposite sides of the reference hue. Thus, alignment is a measure which indicates *relative distance* from a reference hue, independent of what the reference hue is.

3.1.5 Alignment Computation

When computing hue alignment, as indicated in Figure 3.2, a number of steps greater than 50 measured in one direction, is equivalent to a number of steps less than 50 measured in the opposite direction. By convention, in this investigation, all alignments are measured by traversing the Munsell hue circle in the "clock-wise" direction, so that alignments are indicated by a number between 0 and 100.

Another convention, due to the circular nature of the hue circuit, is that there is "wrap-around," so that hue equal to 0 is identical to hue equal to 100. Similarly, alignment of 0 is the same as alignment of 100.

Dimension 3 ⟹ Reference Value

The Munsell color system can be visualized as consisting of planes of samples of equal *value*, which are stacked perpendicularly to a central achromatic core. When comparing two colors, as shown in Figure 3.3, the value of one of the colors is designated as the *reference value*. With respect to the reference value, the related color may be of either "equal" value, "higher" value, or "lower" value.

Dimension 4 ⟹ Value Contrast

Value contrast indicates the difference in lightness between colors. It is computed by measuring the distance in value between colors. In Munsell notation, value contrast is a number ranging between 0 and 10 units.

In an earlier study, Jacobson, Bender, and I evaluated the interaction between hue alignment and value contrast (Jacobson, 1991). It was observed that value contrast

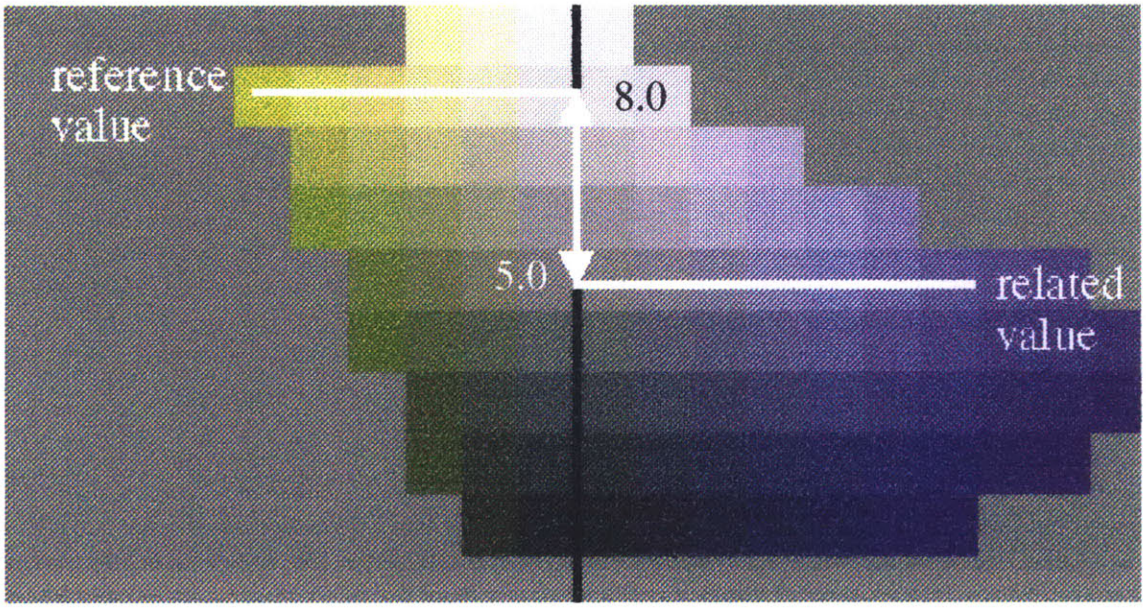

Figure 3.3: Two Munsell hue "slices;" Yellow on the left, Blue-Purple on the right. Colors increase in *value* from bottom to top, and in *chroma*, from the center outward. Note that each *hue* reaches its maximum chroma at a different value. *Value contrast* is defined as the difference between *reference* value and *related* value, as indicated by the arrows.

modulates hue alignment. For instance, hue alignment becomes predominant in determining experience when value contrast is "low;" whereas when value contrast is "high" experience becomes independent of hue alignment. The implications of this interaction between hue alignment and value contrast are significant in applications; for instance, when displaying text, high value contrast ensures *legibility*, independent of hue alignment; whereas, when color is to be used for *highlighting*, then value contrast should be low, so that hue alignment can predominate. Thus, value contrast and hue alignment are important dimensions of color experience.

***Dimension* 5 ⟹ Chroma**

Chroma indicates the degree of departure of a color from a neutral of the same value. In Figure 3.3, chroma corresponds to the distance from the achromatic core. In Munsell notation, neutrals are defined as having chroma equal to 0. Chroma of a color increases up to a maximum—a number which varies depending on the Hue and Value of the color. That is, due to its perceptual nature, the Munsell system does not constrain colors into "tidy" symmetrical constructs, but rather it "lets colors be" (Feldman, 1992). That is, each hue reaches its maximum chroma at a different value (Jacobson, 1990). For instance, "yellow" is a “light” color, and thus, reaches its maximum saturation at a “high” value; whereas “blue” is a “dark” color, and reaches its maximum saturation at a “low” value. Therefore, maximum chroma varies depending on the Hue and Value of the color. In this investigation, chromas were selected at levels ranging between 2 units and the maximum attainable chroma for a given Hue-Value position.

3.1.6 Effects of Chroma

Kreitler and Kreitler found that there is correlation between visual “tension” created by color patterns and chroma of the colors involved (Kreitler, 1972). Morriss and Dunlap found that increasing chroma of a color increases its “visual prominence,” independent of the hues involved (Morriss, 1988). These findings suggest that chroma contributes to experience of color, and its effects are, therefore, evaluated here.

3.2 Spatial Dimensions

In this investigation, two spatial dimensions were chosen: size of color element, and relative area of colors in the overall composition, for simple configurations. These two dimensions describe features such as “how large” the color patterns are, and “how much” each color is contributing to the overall experience.

***Dimension* 6 ⟹ Block Size**

Colors may be assembled in any size and configuration. For simplicity, in this investigation colors were confined to square blocks arranged in a matrix configuration. Size of the blocks is measured in *degrees of visual angle*. The size of the blocks was sufficiently large so that they were well beyond the range of optical mixing, which occurs for sizes less than 0.25 degrees; that is, blocks spanned angles of 0.5 degrees and greater (Rogowitz, 1983).

Dimension 7 ⟹ Area Ratio

When two or more colors are juxtaposed, the *area ratio* between the colors affects their visual prominence. The effect of area ratio on color “balance” has been addressed by researchers such as Munsell, and Moon and Spencer. In essence, it was observed that “small” areas of “high” chroma balance “large” areas of “low” chroma. Munsell considered “balance” of relative areas to be the most important factor in establishing harmony, thus, he developed a quantitative rule for determining relative areas in terms of value and chroma of respective colors (Munsell 1954). Whereas Munsell derived his rule from his observations as a painter, Moon and Spencer developed a formula based on mathematical relationships between colors (Moon, 1944c). In their formula, *value contrast* and *chroma* were used to compute *area ratio*.

3.2.1 “Balance” in Color Experience

This investigation departs from the notion of balance, and develops the more general notion of “establishing” an experience. That is, when selecting colors, the intent is not only to balance colors, but also to “tip” the balance by adjusting the dimensions of experience such as block size, and area ratio. Therefore, the contributions of the dimensions to experience of color are significant, and thus, need to be evaluated.

3.3 Proposed Model

To summarize, the dimensions chosen were:

- reference hue
- hue alignment
- reference value
- value contrast
- chroma
- block size
- area ratio

These seven dimensions are sufficient to describe the phenomenology of color experience, for simple color configurations. However, additional dimensions, such as separation between colors, or enclosure of colors, and temporal dimensions, may be added. Further examples of additional dimensions are given in Chapter 7. A methodology which allows any additional dimensions to be incorporated into the model of color experience is described in section 6.2.5.

3.3.1 Decomposition of Color Experience

The dimensions of color experience define the structure by which experience of color can be analyzed. Namely, experience of color can be *decomposed* into its dimensions, so that contributions of individual dimensions, as well as their interactions, can be identified. Variations in the experience become a matter of adjusting the contributions of each of the dimensions to the overall experience.

Chapter 4

Quantifying the Dimensions of Color Experience

This chapter describes a series of experiments performed to quantify experience of color. The experiments were designed to measure variations along the dimensions of color experience described in the previous chapter. The main consideration in designing the experiments was to measure color experience without invoking personal-subjective connotations of color, such as color preferences and shape associations. To achieve this, several design choices had to be made; primarily the choice of stimuli, and the choice of metric for evaluating the experience. The design process is the focus of the first part of the chapter. The second part of the chapter describes implementation and experimental procedure.

4.1 Design Considerations

4.1.1 Why "boggles?"

The goal of this investigation has been to evaluate experience of color in a way which is free from subjective connotations. However, in an image, as in nature, colors are usually bound up with forms, objects, meanings, situations, and memories; all of which may affect the experience of color (Kreitler, 1972). To dissociate color experience from shape connotations, abstract patterns of color, or "boggles," were chosen as stimuli (Jacobson, 1985).

A boggle is made up of colored squares arranged in a matrix pattern, as shown in Figure 4.1. The boggle is a configuration suitable for evaluating experience of color for the following reasons:

- On the average, every color shares a boundary with all other colors, allowing chromatic interactions to take place.
- There are no figure/ground ambiguities.

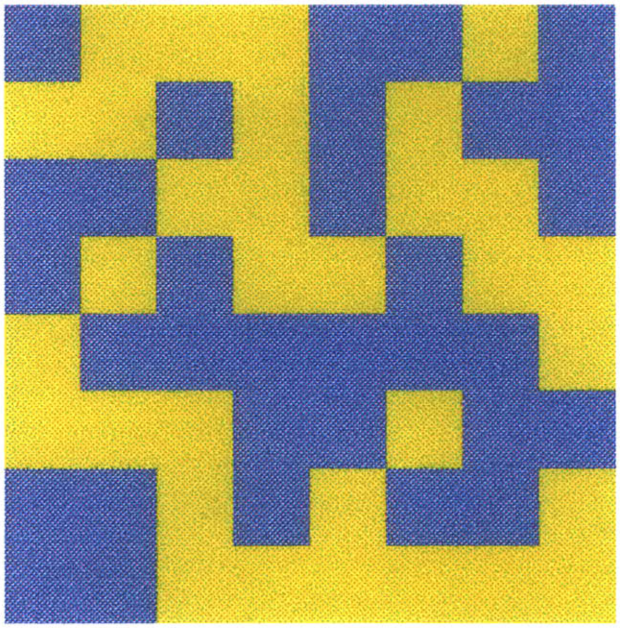

Figure 4.1: Sample boggle.

- Patterns inside boggles have indefinite shapes. The greater the number of blocks in the boggle, the more indefinite the shape. In fact, boggles can be described by an entropy measure, which is proportional to the number of blocks in the boggle; that is, the larger the number of blocks, the higher the entropy (Dorfman, 1966).

- For a given block size and area ratio, boundary length is, on the average, constant for all boggles.

- When shown in quick succession and in random order, boggles are effective in minimizing adaptation, as discussed in Section 4.1.9.

4.1.2 Dimensions of Meaning

There is no formal language for describing color experience. When talking about color, we resort to descriptions such as colors being cool, passive, exciting, ugly, sour, masculine, tense, and so forth. Cultural, as well as personal biases also play a role as to how colors are described.

Studies in the semantics of meaning have shown that seemingly distinct descriptive words tend to fall into only a few *dimensions of meaning* (Sivik, 1986a). Most notably, Osgood and colleagues (Osgood, 1957a) showed that descriptive words can be of three types:

- *Activity* type, such as: tame, wild, blatant, muted, still, vibrant.

- *Evaluative* type, such as: pleasant, unpleasant, ordered, chaotic.

- *Potency* type, such as: quiet, loud, weak, strong.

These results were confirmed by Hård and Sivik (1989b), who also found a fourth type:

- *Warmth*: hot, cold.

For this investigation, three pairs of antonyms were chosen to describe color experiences. Two pairs were from the activity scale: tame-wild, and still-vibrant; and one pair from the potency scale: quiet-loud. No descriptors were chosen from the evaluative category because words such as ordered, chaotic, pleasant, and unpleasant tend to be more judgemental than words from the other scales. The intent here was for the evaluations to be as non-judgemental as possible.

4.1.3 Hue Invariance

A premise of this investigation is that color experience is hue invariant. Therefore, descriptors from the *warmth* category were not chosen because warmth is dependent on reference hue and not on the relationship between colors (Kobayashi, 1990). However, warmth descriptors can play a role when selecting among equivalent experiences, as discussed in section 6.2.4.

4.1.4 Rating scales

Methods developed in psychophysics, such as rating scales, have repeatedly been applied to estimation of magnitude of individual dimensions of color. Even though there is no objective external reference against which to compare these subjective rating scales, relative scaling can be performed dependably to yield estimates of the magnitude of experiences (Lockhead, 1992). Thus, in the experiments, boggles were evaluated using rating scales.

A typical rating scale consists of pairs of antonyms placed at the ends of scales:

word 1 2 3 4 5 6 7 antonym

The chosen descriptors served as the ends of the scales: the low magnitude descriptors, "quiet-tame-still," appeared on the left end of the scales; whereas the high magnitude descriptors, ``loud-wild-vibrant," on the right end of the scales. The scales were divided into seven levels, a number typically used when performing absolute judgements of magnitude, as suggested by George Miller (1956) in his classic article titled "The Magical Number Seven, Plus or Minus Two."

4.1.5 Magnitude-of-Experience

In the analysis, the three scales were considered equivalent because of the assumption that in color experience it is the *magnitude* of the experience that matters, not the words used to describe it. Thus, effectively, the three scales constitute a single scale of magnitude of the form:

low magnitude 1 2 3 4 5 6 7 high magnitude

This reduction of the three *word* scales into a single *magnitude* scale is based on an implicit sense of magnitude built into the scales. The descriptor words themselves are relative—"quiet" is possible only because it is "not loud." Hård and Sivik (1989a) address this issue of *semantic relativity*, when describing the paradox inherent in selecting "bipolar" versus "unipolar" rating scales. They claim that any kind of rating scale is inherently bipolar because on one extreme there is a descriptor in its full magnitude, and the descriptor in its lowest magnitude on the opposite end. Effectively, these opposite magnitudes constitute an antonym pair. Therefore, in the analysis performed in this investigation, the scales are considered to be equivalent. This assumption was validated with a pilot experiment, in which a series of boggles were evaluated using the three rating scales.

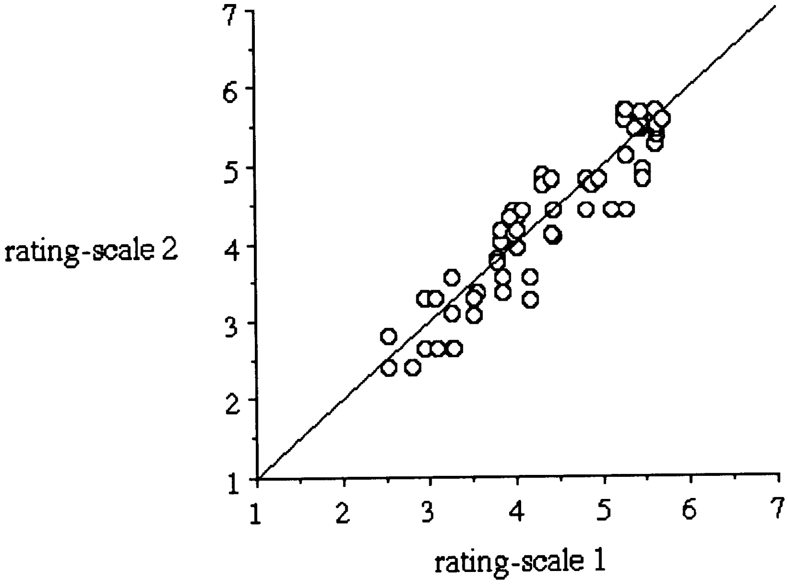

Figure 4.2: Scatterplot of response for a set of boggles evaluated using different rating scales. Diagonal line represents line of equal response.

Figure 4.2 shows a scatterplot of responses obtained with any two of the three rating scales. Each axis represents response along one of the three rating scales. The scatterplot shows how all points cluster along the diagonal. Since a point on the diagonal is equidistant from both axes, it, consequently, has the same value on both axes. This indicates that the responses were the same along both scales. In fact, a t-test revealed that there was agreement between the scales with a confidence level of ($p<0.001$). For the remainder of this document, agreement among rating scales is assumed; therefore, experiences are referred to by their magnitude, and not by any descriptor in particular.

4.1.6 Task

The task of the experiment consisted of evaluating boggles with rating scales. For each boggle, one of the three rating scales was selected, at random. During the experimental session, the boggles appeared in quick succession, changing in shape and color from trial to trial. Subjects were instructed to interpret each boggle by the way "the colors interact with each other." For instance, do the colors "pacify" each other, or do they "vibrate" together. To indicate the strength of the interaction they utilized the seven point rating scale. The actual instructions to the experiment are included as Appendix 1.

4.1.7 Task Design

The task described above was designed with two requirements in mind: first, that *difficulty* of the task be maintained for the duration of experiment; and second, that boredom and *monotony* be minimized. These two requirements were satisfied by *randomizing* the order of presentation of the patterns, so that each pattern appeared as a new and unexpected experience, requiring attention and careful evaluation. The experiment was self-paced, so each subject was in control of the time for making the evaluations, helping to minimize monotony.

4.1.8 Randomization

The following are the factors which were randomized throughout the experiments:

- The distribution of the colors in the boggle was random to eliminate patterns in the boggles.
- The order of presentation of the boggles was random.
- The descriptor words for the rating scale were chosen at random from the set of three pairs of descriptors.

All these randomizations amounted to increasing the robustness of the data by making the patterns less predictable. Randomization was also essential in neutralizing the effects of adaptation.

4.1.9 Adaptation

During the course of the experiments, it was noticed that evaluation of a boggle was influenced by the appearance of the previous boggles. This effect can be attributed to an adaptation process taking place in the subject. This adaptation occurred on two levels: a chromatic level, and a cognitive level.

On the *chromatic* level, adaptation produces a shift of the colors towards the afterimage colors of the previous boggle. However, this shift is in the same chromatic direction for both colors in the boggle, so that, in effect, the colors of the boggles shift as an ensemble, preserving the relationship between the colors. However, randomizing the order of presentation of the boggles across subjects minimized the effects of chromatic adaptation.

From observations made during the experiments, it was noticed that as the experimental session progressed, subjects responded more quickly. *Cognitive* adaptation refers to this progressive *learning* effect, by which subjects become more proficient at rating boggles as they are exposed to more of them. Since the order of presentation of boggles was random, cognitive adaptation was different for each subject. Thus, when averaged across subjects, the effects of cognitive adaptation canceled out.

4.1.10 Boggle Selection

The boggles utilized in the experiments constitute a systematic sampling of combinations of the dimensions of experience:

- *reference hue*: the hue from which hue alignment is computed.
- *hue alignment*: the distance in hue between colors.
- *reference value*: the Munsell value of the reference color.
- *value contrast*: the light-dark contrast between colors.
- *chroma*: the saturation of colors, in Munsell units.
- *block size*: the size of the individual blocks within overall pattern.
- *area ratio*: the relative surface area of each color in the boggle.

The experiments were designed for “hue invariance” because of the assumption that in color experience it is the relationship between the colors that matters, not what the actual hues are. Hue invariance was tested by generating boggles with hue alignments around ten different reference hues—the ten Munsell basic hues.

4.1.11 Boggle Composition

The specific composition of the boggles is presented in Appendix 2.

4.2 Implementation

4.2.1 Experimental Procedure

The procedure was as follows: A boggle was displayed on the screen for a few seconds. A rating was made by entering a number between one and seven along the rating scale provided with the boggle. The rating was automatically recorded, together with the information on the color composition of the boggle. The screen was cleared and a new pattern and rating scale appeared. This procedure was repeated until all boggles in the test series were evaluated. Each test series contained somewhere between 300 to 600 boggles. Evaluation of each boggle took a few seconds, so the entire experimental session took somewhere between 30 to 45 minutes for each subject to complete.

4.2.2 Setup

The experiments were performed at the Computer Graphics Laboratory at Boston University. The laboratory is typical of a modern computational facility, with several workstations distributed around the room. The lighting consisted of diffuse indirect light provided by fluorescent lamps.

4.2.3 Size of Stimuli

Subjects were seated 18 inches away from the screen, a distance at which the boggles encompassed about 16 degrees of visual angle. Depending on the experiment, the blocks inside the boggles ranged in size between 0.5 to 8 degrees of visual angle. These sizes are well beyond the range of optical mixing, which starts to occur for blocks smaller than 0.25 degrees of visual angle (Rogowitz, 1983).

4.2.4 Equipment

The experiments were performed on Sun 3/50 mini-computers with a Hitachi HM4119 color monitor. The monitor and color transformation software were calibrated with CIE Illuminant D6500 as the reference. The background screen color for all experiments was Munsell Neutral Gray of Value 5.0.

4.2.5 Subjects

Participants in this study were 170 Boston University Undergraduate Students, most of them between the ages of 17 to 25 years; all with normal color vision. For their participation, students received one unit of "participation credit" as part of a course requirement. Subjects had to sign a consent form in compliance with the regulations set by the MIT Committee on the Use of Humans as Experimental Subjects. This form is included as Appendix 3.

4.2.6 Training

Subjects went through a brief training period during which they evaluated a sequence of boggles representative of the wide variety of experiences contained in the actual experiment. In this way, subjects became familiar with the procedure and, most importantly, developed an individualized method for evaluating the boggles that appeared later in the actual test.

4.2.7 Data Processing

The data were collected automatically by the computer as the experimental session proceeded. The format of the data consists of a string of numbers, indicating the color composition of the boggle and its rating. Each response was entered individually and constituted an independent trial. The data were stored in a custom-made multi-dimensional database, which permitted direct access to any element of the data. The data were averaged across subjects, plotted for interpretation, and fitted with a parametric model. Chapter 5 describes, in detail, the results of the experiments, and the resultant model.

4.3 Supplementary Experiments

Three additional experiments were performed to evaluate experience of color for specific conditions. These supplementary experiments were prompted by observations made by subjects during the trials of the investigation.

4.3.1 "Dark" reference value

During the course of the experiments, it was observed that subjects became "confused" evaluating boggles with colors of Value 5.0 using the "still-vibrant" scale. It seemed contradictory to describe a "dark" boggle as "vibrant." To investigate this apparent contradiction, a series of boggles in which all colors were of Value 5.0 were evaluated. The composition of the boggles for this experiment are presented in Appendix 2.

4.3.2 Text as Stimuli

Another supplementary experiment was designed to determine the effects of using text, rather than boggles, as the stimuli. In this experiment, colored text was presented against a colored background. The task was the same as in the experiments involving boggles: to evaluate the "interaction between the colors." Characters in the text were randomized, to make it illegible; after all, the intent of the experiment was not to evaluate legibility of the text, but rather, to evaluate the interaction between the colors. The color composition of the test patterns is summarized in Appendix 2.

4.3.3 Three-color interactions

All experiments presented so far were designed to evaluate interactions between two colors. In general, though, colors appear in configurations which involve more than two colors. Following an inductive approach, an experiment to evaluate interaction between *three* colors was designed. Due to the increased complexity, this was only a preliminary experiment, in which a limited number of stimuli were used. To perform a comprehensive evaluation, the number of stimuli would have to be extremely large, due the large number of combinations of dimensions required to represent the relationships between three colors.

Task and procedure were the same as in the two-color experiments: to evaluate the magnitude of experience, in this case, between three colors. Preliminary results are given in section 7.1.2

Chapter 5

A Model of Color Experience

The experiments performed in this investigation measured experience of color as a function of the dimensions of experience. In this chapter, the data collected in the experiments are summarized and analyzed. The chapter concludes with a parametric model which allows experiences to be systematically specified and analyzed.

5.1 Data format

The data are presented as "curves" which indicate the response as a function of variations along a given dimension of experience. In fact, all the response curves are related to each other because they represent cross-sections of a *response space*. This response space is spanned by the dimensions of experience: reference hue, hue alignment, reference value, value contrast, chroma, block size, and area ratio. This response space encompasses all experiences produced by combinations of variations of all those dimensions. The structure and features of the response space are described in Chapter 6.

5.1.1 Data interpretation

The way to interpret a response curve is to correlate its features with the relationship between the dimensions of its corresponding boggle. The main features to examine are:

- The *mean response* of the curve.
- The *spread* of the responses: what is the swing in responses from minimum to maximum.
- The *shape* of the curve: which way does it curve; where does it peak.
- When viewing composite graphs, what is the *trend* in the response: does the response move up, down, or does it stay in the same place.

Each response curve is accompanied by a series of boggles showing sample variations along the dimension being analyzed. This is to aid in visualizing the features in the data.

5.2 Hue Alignment

The response as a function of hue alignment is shown in Figure 5.1. The horizontal axis indicates hue alignment; the scale "wraps around," so that alignment 100 is equal to alignment 0; also, alignment 50 corresponds to hues which are farthest apart from each other, or complementary. The vertical axis indicates the magnitude of the response, as measured by the seven point scales.

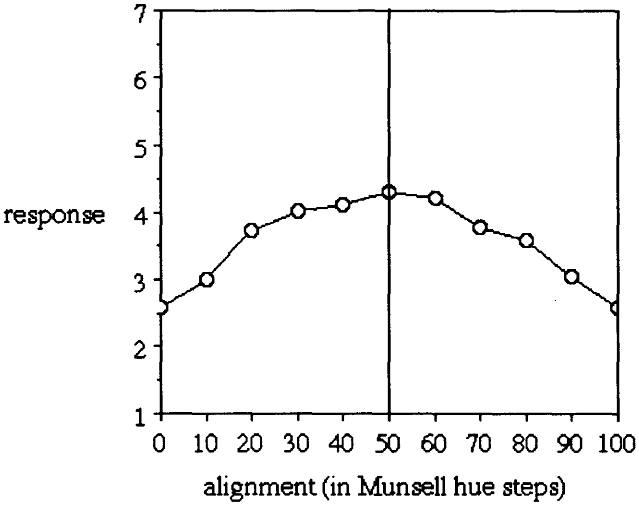

Figure 5.1: Response as a function of hue alignment. Vertical line is axis of symmetry around peak.

In figure 5.1, for the fixed conditions of value contrast 0.5, chroma 6.0, and block size of 2.0 degrees per block:

- the response ranged between 2.69 and 4.40.
- the mean response was 3.635.
- the spread was 1.71 with a statistical significance of $t(398) = 4.556$ ($p < 0.001$).
- the curve is concave-down.
- the curve has bilateral symmetry about the peak, corresponding to symmetrical alignments around reference hue.
- response is lowest at the endpoints, which correspond to hues which are near each other.
- response *peaks* near the midpoint of the curve, which corresponds to hues which are far apart from each other.

Figure 5.2 shows boggles corresponding to various hue alignments.

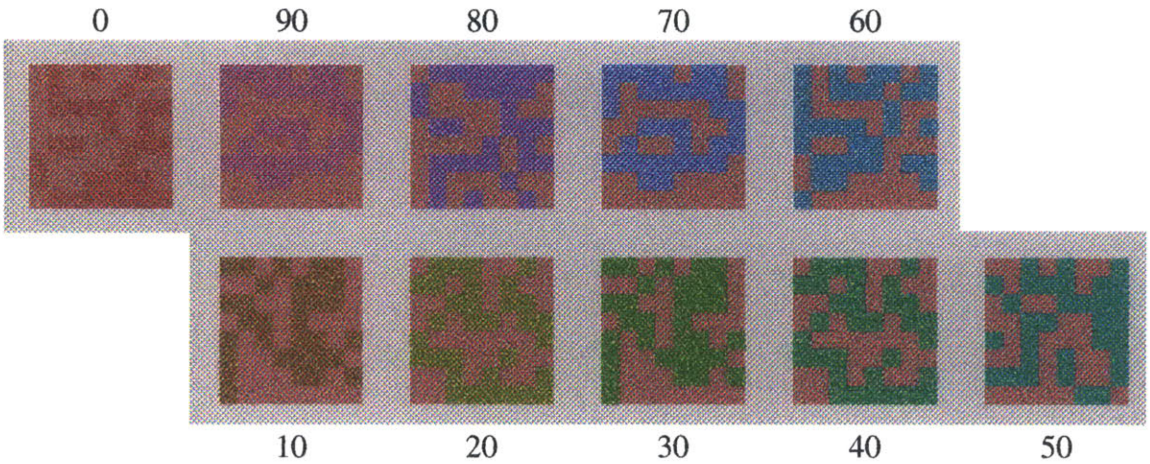

Figure 5.2: Boggle series. Alignments around single reference color: 5R 6/6.
Related colors are: Hue(0-100) 5.5/8.0.

5.2.1 Hue Alignment as Reference Dimension

In this investigation, hue alignment was the dimension along which the most samples were taken, and consequently, was chosen as the *reference* dimension. As the chapter proceeds, responses will be compared to this reference—Figure 5.1—to show the effects of each of the dimensions on the response as a function of alignment. Departures from the reference response will be indicated, as reference hue, reference value, value contrast, chroma, block size, and area ratio are varied.

5.3 Effect of reference hue

Figure 5.3 shows the response for five different reference hues, for the fixed conditions of value contrast equal to 0.5, chroma of 6.0, and block size of 2.0 degrees per block.

From the curves it can be observed that:

- all curves have the same concave-down shape.
- curves are symmetrical about the peak.
- the curves overlap.

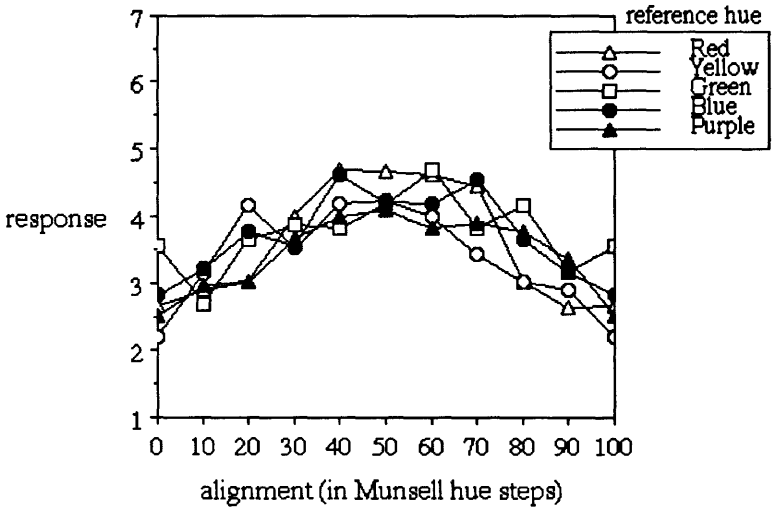

Figure 5.3: Response for five reference hues.

The mean response and spread for five reference hues are:

Reference Hue	mean	spread
Red	3.67	2.00
Yellow	3.48	2.02
Green	3.71	2.01
Blue	3.78	1.78
Purple	3.51	1.56

These measures indicate that mean and spread did not vary significantly across hue. In fact, t-tests along response curve indicates that there is no statistically significant difference between responses for the five reference hues, with a confidence level of ($p < 0.001$). Therefore the responses are considered *hue invariant* because, for any given hue alignment, the responses are comparable, independent of what the reference hue is. Thus, response is dependent on the relationship between hues; that is, on hue alignment.

Hue invariance is a feature which appeared consistently throughout the investigation. Therefore, *all* data presented here assume hue invariance.

Figure 5.4 shows two series of hue invariant boggles; that is, all boggles in each series were rated the same.

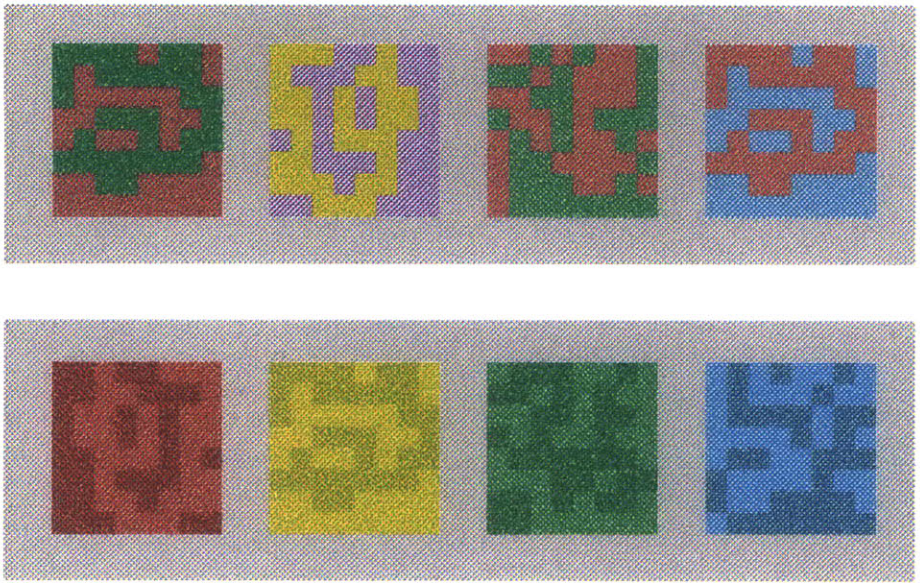

Figure 5.4: Hue invariant boggles.Top: high magnitude boggles. Bottom: low magnitude boggles.

5.4 Effect of Rating Scale

As mentioned in section 4.1.5, the three rating scales utilized to evaluate boggles were considered equivalent because of an implicit sense of magnitude built into the scales. Figure 5.5 shows the response for the three rating scales, in which it can be observed that:

- all curves have the same concave-down shape.
- the curves are symmetrical about the peak.
- the three curves overlap.

The mean and spread for each rating scale are:

Scale	mean	spread
still-vibrant	3.69	1.90
tame-wild	3.63	1.62
quiet-loud	3.54	2.03

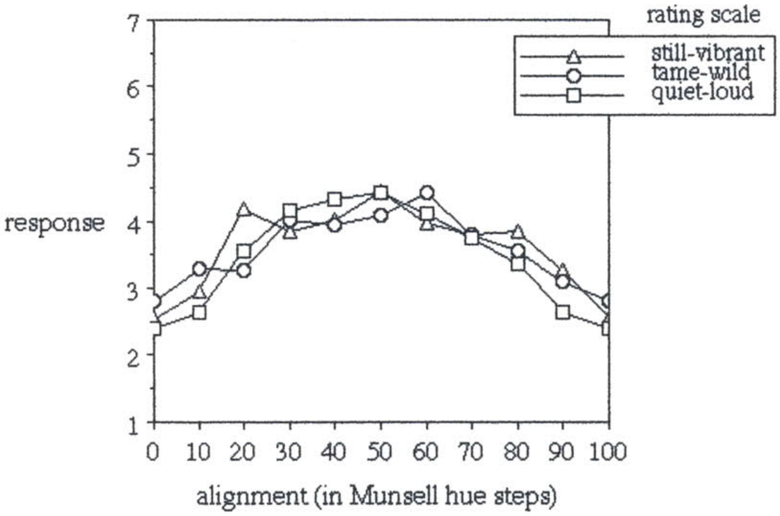

Figure 5.5: Response for three rating scales.

t-tests indicate that there is no statistically significant difference between the curves, with a confidence level of ($p < 0.001$). Therefore, the three rating scales can be considered equivalent. This justifies discarding the word designators, so that it is accurate to describe experiences by their *magnitude*, as a number between one and seven.

5.5 Chroma

Figure 5.6 shows boggles with chroma at levels of 2.0, 4.0, 6.0—the reference—and at maximum chroma attainable for any given hue-value. Figure 5.7 shows the response at those four chromas.

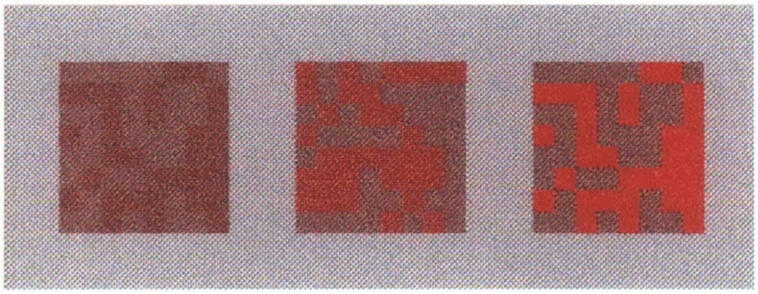

Figure 5.6: Boggle series; *chroma* of related color increases from left to right.

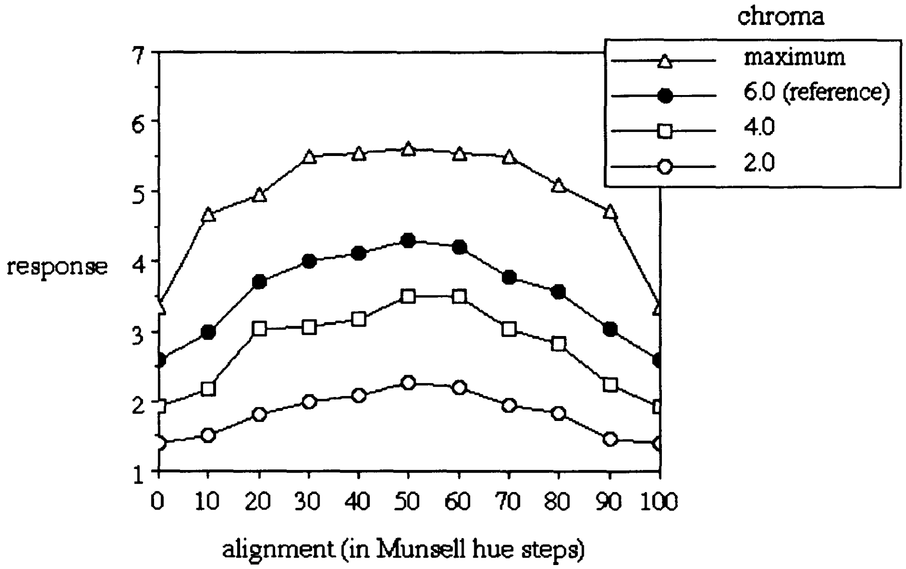

Figure 5.7: Response for four chroma levels.

The curves indicate that the shape of the curves is concave-down, and nearly symmetrical about the peak. The mean response and spread of the data are:

Chroma	mean	spread
2.0	1.86	0.87
4.0	2.85	1.59
6.0	3.64	1.71
maximum	5.05	2.26

These measures indicate that:

- mean response is *directly* proportional to chroma; as chroma increases, response increases.
- spread is *directly* proportional to chroma; as chroma increases, spread in response increases.

The effects of chroma on response were consistent for all conditions of value contrast, block size, reference hue, reference value, and area ratio. Relative to the reference, the mean response and the spread were greater for chroma greater than 6.0; they were less for chroma less than 6.0.

5.6 Value contrast

In this experiment, response as a function of value contrast was measured.value contrast was set at 0.0, 0.5, 2.0 and 2.5 Munsell Value units. Figure 5.8 shows examples of boggles with those value contrasts. The response, shown in Figure 5.9, indicates that the shape of the curves is concave-down, and symmetrical about the peak.

The mean response and spread of the data are:

Value contrast	mean	spread
0.0	3.60	1.70
0.5	3.64	1.71
2.0	3.99	0.95
2.5	4.09	0.92

The differences in the responses are statistically significant, and thus, these measures indicate that:

- mean response is *directly* proportional to value contrast; as value contrast increases, mean response increases.

- spread is *inversely* proportional to value contrast; as value contrast increases, the spread in the response decreases.

Therefore, as value contrast varies, mean and spread vary in opposite directions. Graphically, as value contrast increases, the ends of the curves move up, resulting in a "flatter" response. As value contrast increases, the flat response indicates that the effect of hue alignment is weakened because of diminished spread. This suggests a strong interaction between value contrast and hue alignment, as was found in a previous study (Jacobson, 1991).

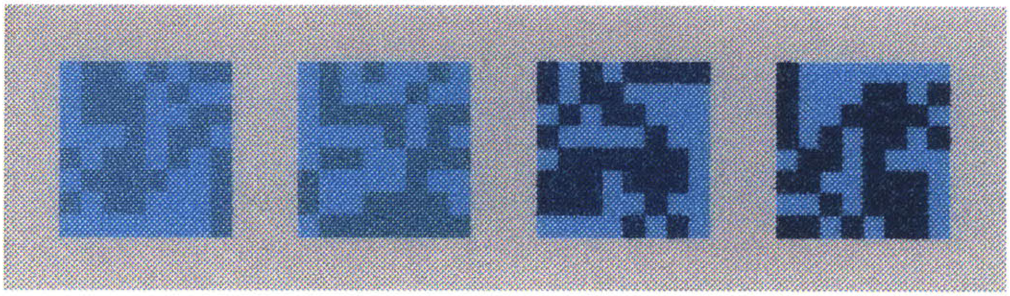

Figure 5.8: Boggle series: from left to right, *value contrast* of 0.5, 1.0, 2.0, and 2.5.

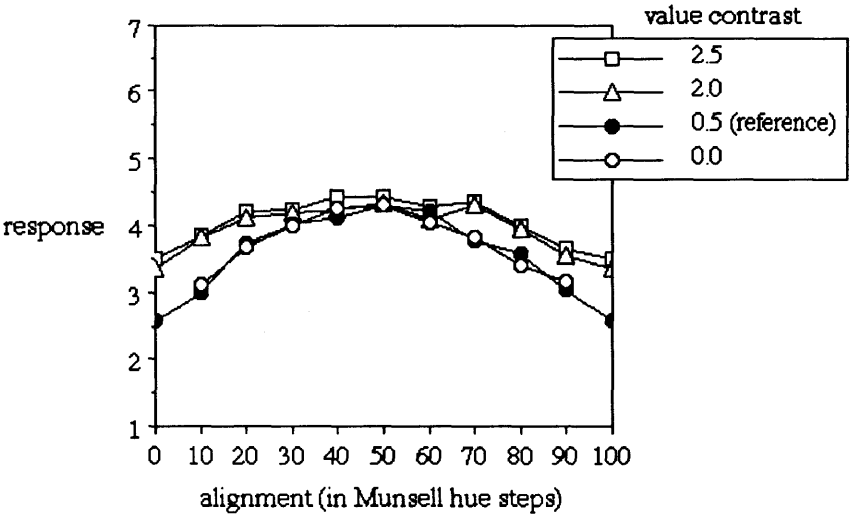

Figure 5.9: Response for different value contrasts.

An alternative view of the interaction between hue alignment and value contrast is shown in Figure 5.10, in which, as value contrast increases, the curves for the alignments of 0, 10, 20, and 30 slope upward, until, eventually, all the curves get close together, and flatten out. This confirms the observation that, as value contrast increases, response progressively becomes independent of hue alignment.

The effects of value contrast on response noted above were consistent for all conditions of hue alignment, chroma, block size, reference hue, reference value, and area ratio. Relative to the reference response, as value contrast increased from 0.0 to 2.5, the mean response increased, whereas the spread decreased.

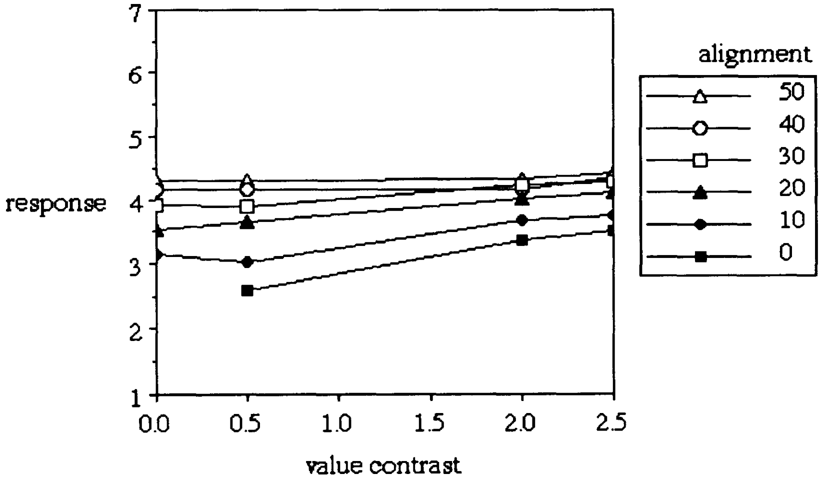

Figure 5.10: Response as a function of value contrast for various alignments

5.7 Reference Value

Figure 5.11 shows the response for three different reference values, for the fixed conditions of value contrast equal to 0.0, chroma of 6.0, and block size of 2.0 degrees per block.

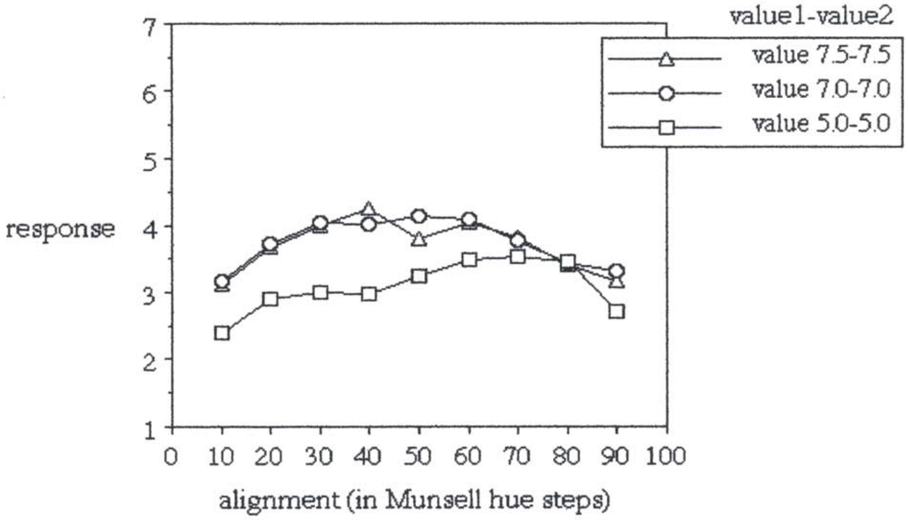

Figure 5.11: Response for three reference values.

The curves indicate that the shape of the curves is concave down. The mean response and spread of the data are:

Reference Value	mean	spread
7.5	3.70	1.13
7.0	3.75	0.98
5.0	3.07	1.14

These measures indicate that mean responses at reference values 7.0 and 7.5 are similar to each other; whereas response at value 5.0 is lower. Figure 5.12 shows sample boggles at the two reference values.

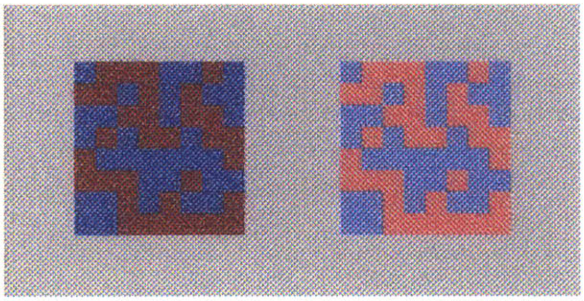

Figure 5.12: Boggles with hue alignment of 30, at reference values of 5.0, and 7.5.

5.8 Block size

Boggles containing blocks of various sizes are shown in Figure 5.13. In the experiments block sizes spanned 0.5, 1.0, 2.0, 4.0, and 8.0 degrees-of-visual-angle per block—well beyond the range of optical mixing, which occurs for block sizes of 0.25 degrees, or smaller.

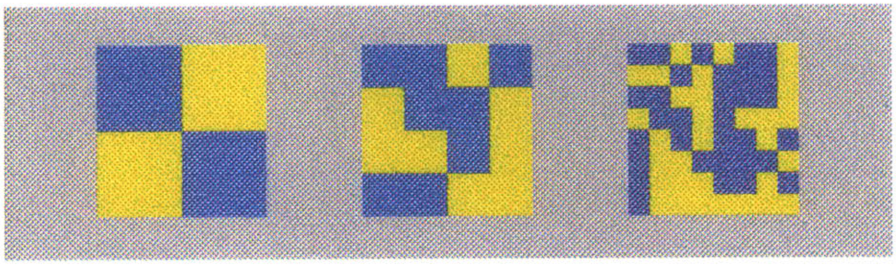

Figure 5.13: Boggle series: *block size* decreasing from left to right.

The response for different block sizes is shown in Figure 5.14. The curves indicate that the shape of the curves is concave-down, and symmetrical about the peak.

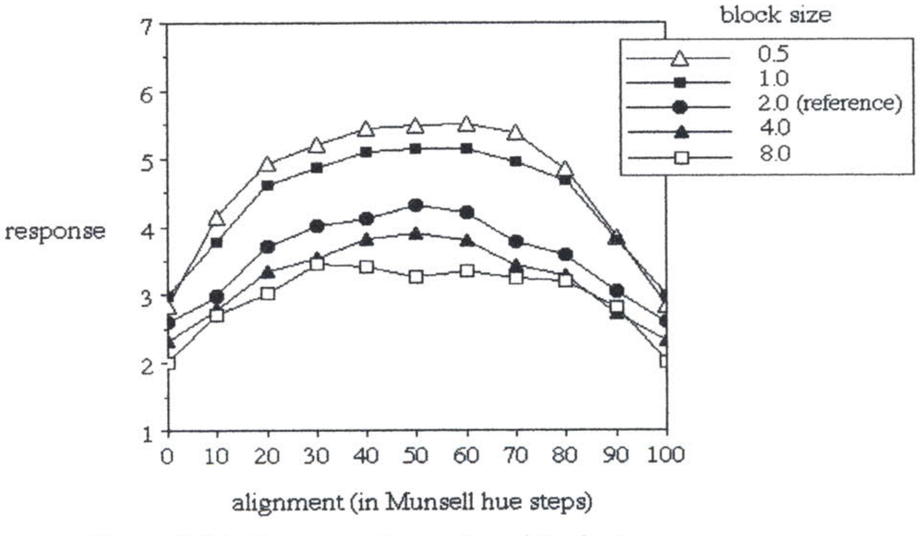

Figure 5.14: Response for various block sizes.

The mean response and spread of the data are:

Block size	mean	spread
0.5	4.76	2.67
1.0	4.50	2.16
2.0	3.64	1.71
4.0	3.29	1.57
8.0	3.05	1.35

These measures indicate that:

- response is *inversely* proportional to block size, in degrees-of-visual-angle per block; that is, as the blocks get smaller, response increases. Equivalently, as the *density* of the blocks in the boggle increases, the response increases.
- spread is *inversely* proportional to block size, in degrees-of-visual-angle per block; that is, as the blocks get smaller, the spread in response increases. Equivalently, as the *density* of the blocks in the boggle increases, the spread increases.

The effects of block size on response were consistent for all conditions of value contrast, chroma, reference hue, reference value, and area ratio. Relative to the reference, the mean response and the spread were *greater* for block size smaller than 2.0 degrees of visual angle; whereas they were *less* for block size larger than 2.0 degrees of visual angle.

5.9 Area ratio

All results presented so far have been for experiments in which the boggles contained an equal number of blocks of each of two colors. The "area ratio" experiment measured the response as the proportion of blocks between the two colors varied. The area ratios tested were 7:1, 6:2, and 5:3. Boggles with equal amounts of each color, with area ratio of 4:4, were not tested in this series, since they were tested in other series. Figure 5.15 shows a series of boggles representing the area ratios tested. In the experiments, the order of presentation of boggles was random.

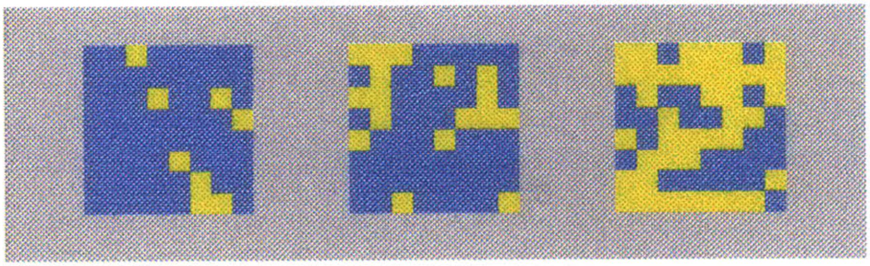

Figure 5.15: Boggle series; varying *area ratio*.

The response for different area ratios, shown in Figure 5.16, indicates that:

- all curves have a concave-down shape.
- the curves are symmetrical about the peak.
- the curves are "stacked" on top of each other; the closer the area ratio to unity, the higher the response; thus 3/5 is at the top, 1/7 at the bottom.

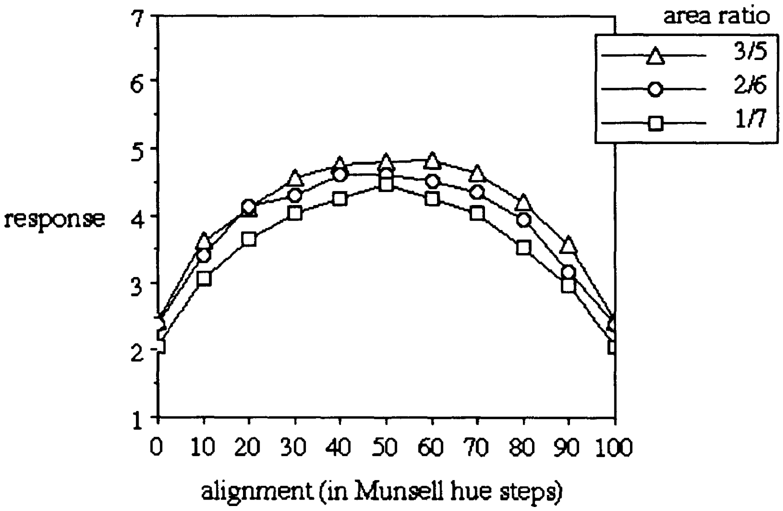

Figure 5.16: Response for various area ratios.

The mean response and spread as a function of area ratio are:

Area ratio	mean	spread
1:7	3.64	2.40
2:6	3.95	2.21
3:5	4.16	2.45

t-tests indicate that there is no statistically significant difference between the means, with a confidence level of ($p < 0.001$). Thus, apparently, area ratio does not have an effect on response, at least for the area ratios tested. However, it is likely that the effects of area ratio on experience are subtle and were not detected by the measurements performed in this investigation. However, for the purposes of this investigation, it is reasonable to assume that response is invariant with respect to area ratio because the task consisted of evaluating the interaction of colors independent of how much of each color appeared in the boggle. This dimension should be tested further.

5.10 Rating Scale: Dark Reference Value

A supplementary experiment to evaluate boggles with colors of Munsell value 5.0 was performed. This experiment was prompted by the apparent contradiction in evaluating "dark" colors using the "still-vibrant" rating scale.

For the fixed conditions of Value 5.0, value contrast 0.0, Chroma 6.0, and block size of

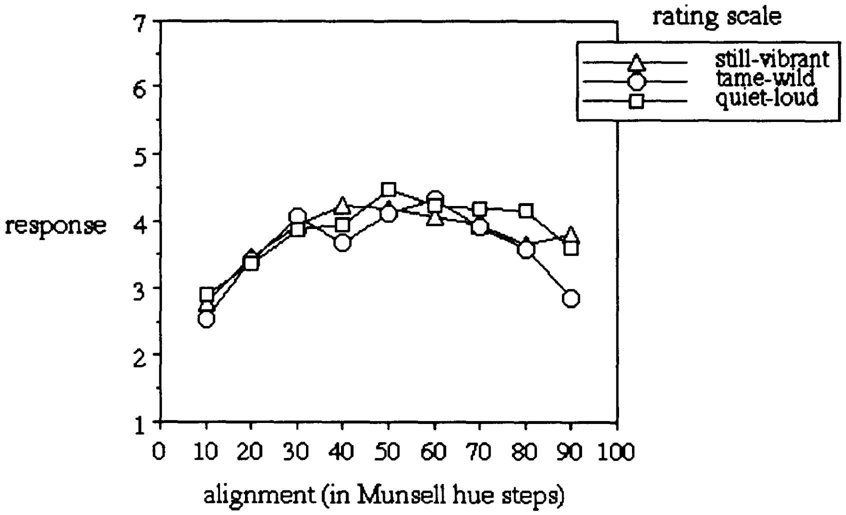

Figure 5.17: Response for "dark colors," evaluated with the three rating scales.

2.0 degrees-per-block, Figure 5.17 indicates that the three curves have concave-down shape. The mean response and spread are:

rating scale.	mean	spread
still-vibrant	3.78	1.44
tame-wild	3.61	1.78
quiet-loud	3.86	1.57

t-tests indicate that there is no statistically significant difference between the curves, with a confidence level of ($p<0.001$). Therefore, the three scales can be considered equivalent. This indicates that choice of rating scale does not affect response, even for "dark" colors. Therefore, it is reasonable to evaluate dark boggles using the "still-vibrant" scale, as well as with the other two scales.

5.11 Screens of Text as Stimuli

The response for screens of text as stimulus, rather than boggles, is shown in Figure 5.18. The response was measured at two value contrasts: 0.5 and 2.0. Value contrast of 0.5 corresponding to value contrast between text of value 7.5 and background of value 7.0; value contrast of 2.0 corresponding to value contrast between text of value 7.0 and background of value 5.0.

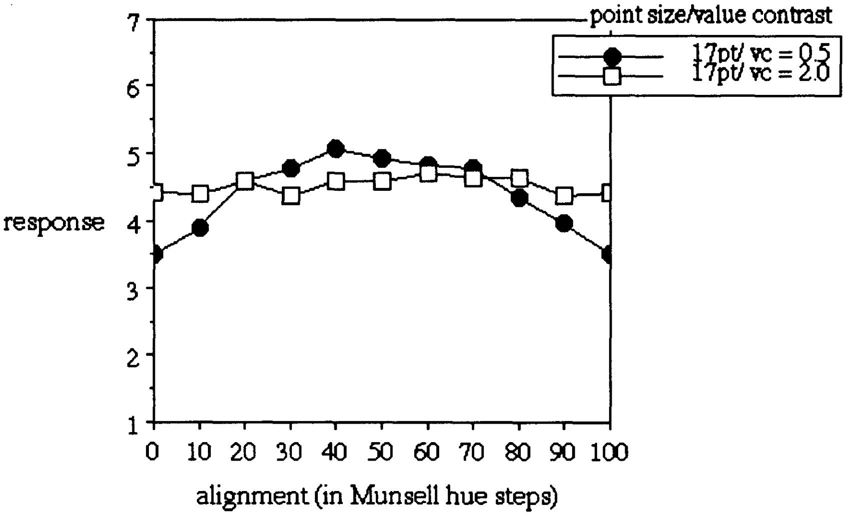

Figure 5.18: Response for *text* as stimuli

The data show that the response for large value contrast is flat, whereas that for low value contrast has concave-down shape. The mean response and spread of the data are:

value contrast	mean	spread
0.5	4.47	1.58
2.0	4.54	0.34

5.11.1 Discussion

The measures above indicate that as value contrast increases, the ends of the curves move up, resulting in a "flatter" response. A flat response indicates that text on background looks the same, independent of hue alignment. These observations agree with results of a previous study, which found that text becomes "legible" and independent of hue alignment, when value contrast is 2.0 Munsell units, or greater (Jacobson, 1991).

Therefore, the effects of value contrast on response for text-as-stimuli show trends similar to those for boggles-as-stimuli; that is, high value contrast flattens response, indicating that response is independent of alignment. When value contrast is low, alignment becomes predominant, as indicated by the curved response. One explanation for the flat response is that, perhaps, the presence of text makes it difficult to dissociate chromatic interactions from the task of reading the text. This remains as an issue for further investigation.

5.12 A Parametric Model of Color Experience

The data summarized above were fitted with a parametric model using multiple regression (Press, 1988). The parametric model takes the form of a sum of terms, each of which represents a contribution from either an individual dimension or from a cross-interaction between dimensions. The terms are presented in decreasing order of magnitude:

$$
\begin{array}{rrl}
response = & -36.94 & V_r \cdot K \\
 & +24.55 & K \\
 & +22.36 & K^2 \\
 & +12.17 & V_r^2 \\
 & -10.38 & V_r \\
\hdashline
 & +8.01 & Al \\
 & -5.02 & Al \cdot V_r \\
 & -4.27 & Al^2 \\
\hdashline
 & +2.12 & C \\
 & -2.04 & Al \cdot K \\
 & -2.03 & K \cdot C \\
 & -1.14 & V_r \cdot C \\
 & -0.79 & S \\
 & -0.55 & K \cdot S \\
 & +0.40 & Al \cdot C \\
 & +0.26 & V_r \cdot S \\
 & +0.10 & Al \cdot S \\
 & +0.05 & C \cdot S
\end{array}
$$

The largest five terms indicate that reference value and value contrast are the main contributors to the response.The next three largest terms indicate the contributions of hue alignment and of the interaction between alignment and reference value. The remaining terms indicate the contributions of the other dimensions and of their interactions. In applications, the parametric model allows responses to be determined by specifying the values of each of the terms in the equation. Conversely, the model allows contributions from individual dimensions to be determined by selecting a response and solving the equation in terms of the desired dimension.

5.12.1 Dimensional Coding:

Al = *hue alignment*; normalized to range 0.0 to 1.0.

V_r = *reference value*; range 5.0-7.5 Munsell value units.

K = *value contrast*; range 0.0 to 10.0 Munsell value units.

C = *chroma*; coded as 0 for chroma less than or equal to 6.0 Munsell units, 1 for chroma greater than 6.0 Munsell units.

S = *block size*; coded as 0 for block size 2.0 degrees of visual angle, 1 for block size of 8.0 degrees of visual angle.

5.13 Summary

This chapter has presented results of a series of experiments which evaluated experience of color as a function of variations along seven dimensions of experience. Trends in data were found, by evaluating features of response curves. Data indicated that five of the seven dimensions had an effect on experience: hue alignment, value contrast, reference value, chroma, and block size. The remaining two dimensions: area ratio, and reference hue were found to have no significant effect. The results are summarized below.

Dimension	Effect on response	To *increase* response	To *decrease* response
reference hue	No	—	—
hue alignment	Yes *	increase hue separation	decrease hue separation
reference value	Yes	raise reference value	lower reference value
value contrast	Yes *	increase value contrast	decrease value contrast
chroma	Yes	increase chroma	decrease chroma
block size	Yes	decrease block size	increase block size
area ratio	None detected	—	—

* Value contrast has a strong interaction with hue alignment. See Sections 5.6 and 5.11.

Chapter 6

Experience of Color in Applications

The previous chapter presented data which indicate the effects of the dimensions of experience on the response to color relationships. The chapter concluded with a parametric model of color experience, which allows experiences to be specified and analyzed. In this chapter, a methodology for establishing color experience, based on the data and model of the previous chapter, is developed. The methodology allows experiences to be established by adjusting the contributions of the different dimensions to the overall response. Examples which illustrate various ways of establishing color experience, are given.

The chapter is divided into three parts. The first part introduces the concept of *equivalent experiences*. The second part describes the *framework* for establishing experience of color. The third part develops the methodology for utilizing experience of color in *applications*.

6.1 Equivalency in Color Experience

6.1.1 Dimensions of Color Experience

Experience of color is the result of an interaction of several dimensions; in this investigation, *seven* dimensions were evaluated:

- reference hue. ×
- hue alignment. ✓
- reference value. ✓
- value contrast. ✓
- chroma. ✓
- block size. ✓
- area ratio. ?

The results presented in the previous chapter indicated that five of those dimensions had an effect on experience (✓): hue alignment, reference value, value contrast, chroma, and block size. The remaining two dimensions: reference hue (×), and area ratio (?) were found to have no significant effect. In the case of reference hue, experience was invariant, although reference hue can play a role when selecting among equivalent experiences, as shown in Section 6.2.3. In the case of area ratio, no effects were noticed, at least for the range of area ratios evaluated, and for the task of the rating experiment. Therefore, the number of significant dimensions of experience was conclusively reduced from seven to five.

6.1.2 Visualizing the Dimensions of Color Experience

The dimensions of color experience can be visualized as spanning a multi-dimensional space, in which all experiences are represented. In fact, experiences comprise a response "space," which indicates the magnitude of the response for a given combination of dimensions. Thus, conceptually, the objective of this investigation is to determine the features of this response space. In particular, how experiences are distributed in the space; how experiences relate to each other; and which dimensions produce the greatest variability in response.

6.1.3 Magnitude of experience as "metric"

The experiments performed in the investigation consisted of evaluation of boggles. The boggles were selected by systematically sampling the space along each dimension, so that all regions of the space were represented. In this way, correspondence between a boggle and a region in the space was established.

One unique feature of the approach utilized in this investigation was that all dimensions were made *commensurate* with each other because all boggles were rated using the same metric; that is, a number along a seven-point rating scale. In this way, the metric establishes the ways in which experiences, corresponding to different regions of the space, relate to each other. The metric serves as a type of "exchange currency" among experiences, so that comparisons can take place. For example, an experience produced by variations in chroma can be compared with an experience produced by variations in block size; in terms of boggles, a boggle with "small low-chroma" squares can produce an experience comparable to that produced by a boggle with "large high-chroma" squares.

6.1.4 Equivalent experiences

Data from the experiments indicated that, in fact, a wide variety of boggles were rated the same; namely, boggles with *different* composition, in terms of hue alignment, value contrast, chroma, block size, reference hue, reference-value, and area ratio, produced the same experience. All such boggles, which were rated the same, are considered *equivalent* experientially.

Equivalency has great theoretical as well as practical significance. On a theoretical level, equivalency provides the way by which responses along distinct dimensions of experience can be related to each other. On a practical level, equivalency allows experiences to be analyzed and synthesized for applications. Therefore, *equivalency in color experience constitutes one of the most significant findings of this investigation.*

6.1.5 Equivalency in Hue Alignment

Referring to the response as a function of hue alignment, replicated in Figure 6.1, it was noted that the curve has bi-lateral symmetry. This symmetry indicates that for any given magnitude of response, there are *two* equivalent experiences, represented by two points at symmetrical positions along the curve. These two ways of establishing the same magnitude of experience are a consequence of the response being hue invariant.

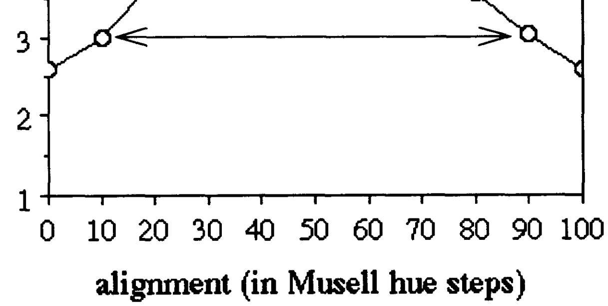

Figure 6.1: Bi-lateral symmetry in response. Arrows indicate two equivalent responses.

6.1.6 Equivalency across Experiential Space

Equivalency is not confined to hue alignment, but rather, a given magnitude of experience can be extended across the space, as if encompassing a region of equivalent response. Such a region, encompasses many equivalent experiences, all produced by different combinations of the dimensions. In terms of the parametric model, equivalent experiences are obtained by holding the response constant, and adjusting the dimensions accordingly.

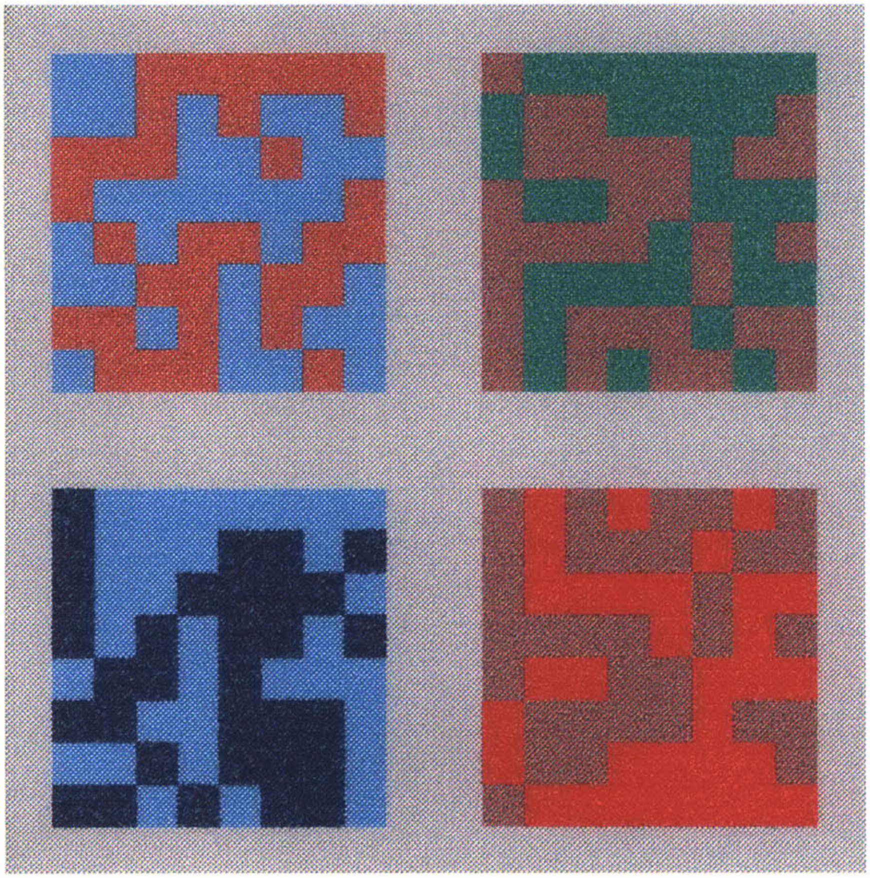

Figure 6.2: Equivalent boggles; they were all rated the same.

6.1.7 Establishing Equivalency

Figure 6.2 shows four boggles corresponding to four experiences which produced the same response. The boggles look very different from each other in terms of their dimensions, yet, they are *equivalent experientially.* One way to visualize why these experiences are equivalent is to establish how the experiences relate to each other; that is, how one experience is *transformed* into another equivalent experience.

6.1.8 Transformation of experiences

Equivalency between the four boggles above can be visualized by observing how the boggles *relate* to each other. Figures 6.3, and 6.4 are two examples of progressive adjustment to the dimensions of experience until an *experiential match* was established; that is, the dimensions of experience were adjusted until the boggles became equivalent *experientially.*

In both examples, the transformations are performed by *decreasing* the magnitude of response by adjustment of one dimension. This decrease is *compensated* by an *increase* in the magnitude of response by adjustment of another dimension.

These two examples show not only the range of possibilities for establishing experience of color, but also the degree of control provided by the methodology developed here.

6.1.9 Value contrast versus hue alignment

Figure 6.3 shows, along the horizontal dimension, from left to right, the progressive decrease in the magnitude of response by decreasing *value contrast* between the colors; hue alignment and chroma remain constant throughout the transformation. The decrease in magnitude of response was compensated by adjusting *hue alignment* until the hues get far apart from each other, as shown along the vertical direction, from bottom to top; value contrast and chroma remain constant throughout transformation.

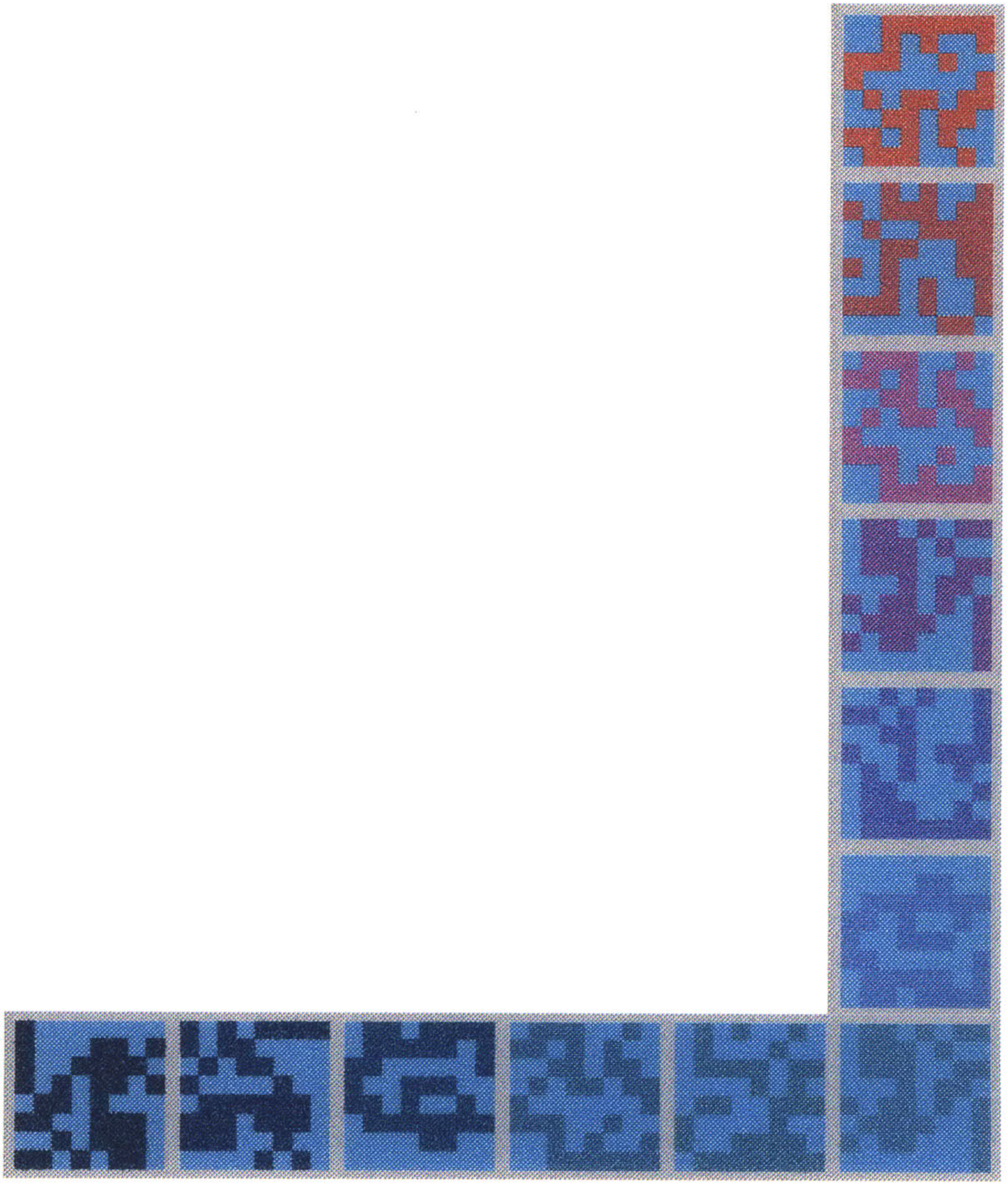

Figure 6.3: Transformation between equivalent experiences. As *value contrast* decreases from left to right, magnitude of response decreases. On the right hand side, from bottom to top, *hue alignment* is adjusted until hues get far apart from each other, so that magnitude of response increases.

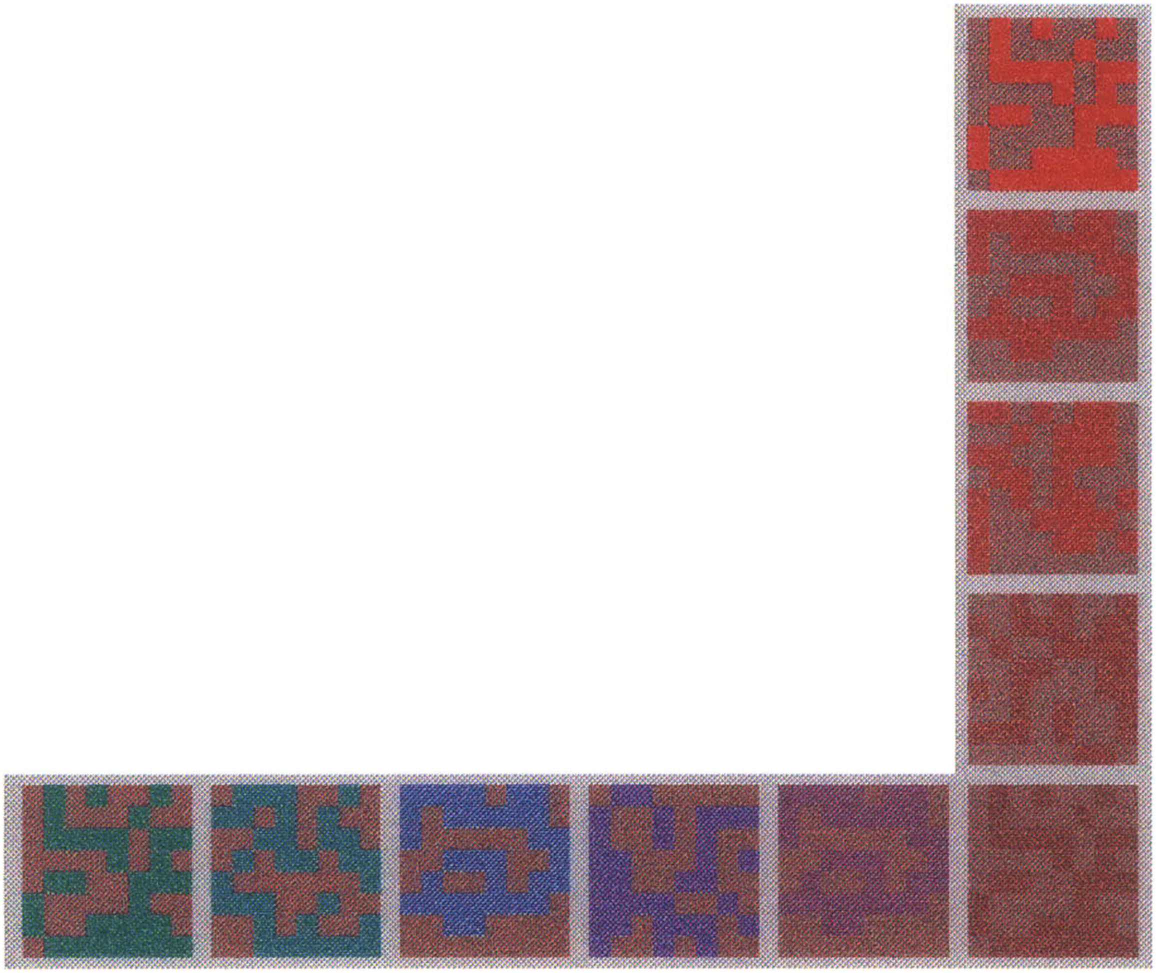

Figure 6.4: Transformation between equivalent experiences. From left to right, *hue alignment* is adjusted until hues get close together, and magnitude of response decreases. From bottom to top, on the right hand side, magnitude of response increases as *chroma* is increased.

6.1.10 Chroma versus hue alignment

Figure 6.4 shows the progressive decrease in the magnitude of experience by bringing the *hues* close together, until they establish a *Monochromatic* hue alignment. Magnitude of experience was increased back to its original level, by increasing *chroma* of the colors.

The transformations above demonstrate the power of adjustments along the dimensions of experience for *preservation* of the experience; that is, preserving the experience amounts to making compensatory adjustments along different dimensions of experience, so that the response level is maintained. However, adjustments to dimensions of experience can be used not only for preserving experience, but for establishing any experience of color, by selecting a response level accordingly.

6.2 Space as Framework for Establishing Color Experience

The space spanned by the dimensions of experience provides the framework for establishing any color experience because it indicates how experiences *relate* to each other. In fact, establishing color experience amounts to a form of "navigation" in the space. For instance, traversing the space along a region of constant response results in experiences which are equivalent to each other. *Navigation* is performed by adjusting the contributions of each dimension to the overall experience, and varying the position in the space.

6.2.1 Constraining the Dimensions of Experience

Establishing experience of color can be viewed as what is known in mathematics as an *underconstrained optimization problem* (Strang, 1980); that is, given a magnitude of experience, there are many equivalent experiences to choose from, and not enough information as to which to select. In terms of the parametric model, for a given level of response, there are many combinations of values of the dimensions which produce the same response. Thus, to select an experience, constraints on the dimensions of experience must be set, until a unique experience results. In terms of the multi-dimensional space, setting constraints on the dimensions can be visualized as confining the response to a single region of the space; a region in which only one of many equivalent experiences exists. In practice, constraints on the dimensions of experience are set by applications, or by the designer.

6.2.2 Selecting an Experience

The boggles shown previously in Figure 6.2, represent four out of many possible equivalent experiences. Suppose that in an application one of the four boggles must be chosen; how is that selection made?

Selection is made by setting constraints on the dimensions of experience, until a unique boggle is selected.

6.2.3 Constraints in Applications

The following are all examples of practical situations in which the dimensions of color experience are utilized to establish the functionality required by the situation. The examples show how certain dimensions are constrained, and how other dimensions are left unconstrained, so as to establish the visual conditions required by the application. These examples come from many disciplines, and thus, demonstrate the versatility of the methodology developed in this investigation.

• *Classification*: utilizing Hue Alignment

A typical application in visual design is *categorization*, in which graphical elements are grouped into distinct categories. When the number of categories is ten or fewer, *hue alignment* is an effective dimension to use (Boynton, 1990) (Derefeldt, 1981). Thus, in this case, hue alignment should be utilized, while other dimensions are constrained.

If the intent of the application is to *highlight*, so as to draw attention to a feature in the display, then a hue alignment which produces a high magnitude of response, such as a *complementary* alignment, is suitable. A high magnitude hue alignment serves for maximum discrimination between background and highlight (Jacobson, 1991).

• *Legibility*: constraining Value contrast

Legibility of text requires value contrast between text and background of at least 2.0 Munsell units (Jacobson, 1991) (Pastoor, 1990). Therefore, if legibility is a requirement, then value contrast needs to be constrained to value contrast of 2.0 units, or greater. Low value contrast is detrimental to legibility.

• *Reproduction*: limiting Chroma

In natural images, the range of chroma is wide. Thus, when reproducing natural images with existing technologies, chroma needs to be constrained to accommodate the range of chromas allowed by the reproduction processes. To adjust experience of color, other dimensions must be utilized.

• Block size in Typography and Environmental Design

Constraints on size occur frequently in applications; for instance, in certain computer displays, the size of the font might be fixed; to make text legible, other dimensions must be adjusted. In large-scale applications, such as architecture, area of surfaces is generally fixed, so adjustments to experience conveyed by an environment have to be made using other dimensions, primarily by adjustment of chromatic dimensions (Burling, 1992). For instance, if a room needs to be made "quiet," then color relationships which establish a low magnitude of experience must be chosen.

• "Maintaining product image" with reference hue

Industries, such as advertising and textile manufacturing, require that certain hues be used to maintain "product" image. In such a situation reference hue is constrained. To modify experiences, other dimensions can be adjusted around reference hue.

6.2.4 Alternative Constraints

• Accommodating personal preference

One alternative way of selecting from among equivalent experiences is to utilize personal preference; that is, select the boggle which is most "pleasant." This is what is commonly done when shopping for clothes; one chooses the colors one likes best, or one may also look for colors that "go" with other colors.

In graphic design, when establishing an experience, the colors people like best can be chosen; in which case, it is possible to maintain functionality while accommodating personal preference.

• Warmth Scale

One additional way of choosing among alternative experiences is to utilize the "cool-warm" scale. For instance, in interior design, when the intent is to establish the sensation of "warmth," then wood might be chosen over concrete. That is, wood, besides its thermal properties, is “redder” than concrete, and, therefore, it is a “warmer” color. Thus, decisions of coolness and warmth are based on reference hue; that is, the cool-warm scale has direct correspondence with the hue circle: there are “warm” hues—red, yellow; and “cool” hues—blue, green (Kobayashi, 1990). Since experience is hue invariant, cool and warm hues can be accommodated by model because equivalent experiences can be established around any reference hue.

6.2.5 Accommodating New Dimensions

The selection process described here is of great generality because color experience is not confined to the dimensions chosen in this investigation.; but rather, new dimensions can be integrated into the model of color experience, as long as the new dimensions are commensurate with the current dimensions of the model. That is, variations along all dimensions have to be evaluated using the same metric, using a scale, such as the seven-point rating scale.

Therefore, establishing experience of color can be guided not only by the compositional guidelines developed here, but also by additional dimensions, such as personal preference, warmth, and others which may arise in future applications. This investigation provides a mechanism for incorporating new dimensions into model.

6.3 Establishing Experience of Color in Applications

The general approach for establishing color experience is to determine the color *intent* of the application (Cowan, 1989). The color intent determines the visual relationships required by the application. In this discussion, “application” refers to any situation which utilizes color as a way of conveying a message, such as graphic design, computer graphics, painting, display design, textile manufacturing, advertising, cinematography, etc.

6.3.1 Prototypical Experiences

Experiences corresponding to specific visual relationships are referred to as *prototypical* experiences. For example, in graphic design, if the intent is to *highlight* or *draw attention* to a feature, then a *high-magnitude* prototypical experience is required. (Jacobson, 1991).

- **Finding Cursor**

The methodology developed here provides several ways of finding the cursor appearing on the screen; for instance highlighting can be established by utilizing, for instance, hue alignment, chroma, or block size. Which of the three dimensions is chosen is determined by the requirements of the application, by limitations of the display, or by preference of the designer. However, all three ways of highlighting achieve the same functionality because they all establish the prototypical experience required by the application. Therefore, there are several alternative ways of establishing the prototypical experience of finding the cursor.

Thus, in general, for effective use of color in applications, correspondence between task and prototypical experience must be established. In this way, the methodology will indicate alternatives for establishing the desired experience.

6.3.2 Response Level

In terms of the model of color experience, the choice of prototypical experience amounts to selecting a *response level* which corresponds to the prototypical experience. Selection of such a prototypical experience is made by constraining the dimensions of experience until the required visual conditions are established.

6.3.3 Transposing the Experience

If the intent of the application is to *preserve* the experience, then magnitude of experience is maintained. If, on the other hand, the intent is to *transpose* the experience, then magnitude of experience is varied. Thus, the model of color experience provides the ways for not only selecting among equivalent experiences, but also for selecting completely different experiences.

In an application such as hard-copy reproduction, the intent is to "preserve" the experience. In terms of the space, the objective is to maintain the response level. In graphic design, however, the intent might be to produce a variety of experiences, in which case, the space provides the paths to depart from an experience, by adjusting the contribution of the individual dimensions to the overall experience.

6.3.4 Adjusting Magnitude of Experience

When establishing experience of color in applications, there are alternatives. For instance, an *increase* in magnitude of experience can be achieved by either raising chroma, reducing size of blocks, reducing hue alignment, or reducing value contrast. Further, based on data from the experiments, changes in magnitude of experience occur at different rates, as indicated by the relative magnitude of the coefficients of the parametric model.

Changes can occur along more than one dimension simultaneously, as well. For instance, if rapid increase in magnitude of experience is required by an application, simultaneously increasing chroma, decreasing block-size, and maximizing distance between hues, will achieve that change most rapidly. On the other hand, if changes in magnitude of experience need to be more gradual, then progressive change in fewer dimensions will achieve that. However, the changes must be made along the dimensions which are not constrained.

6.4 Methodology for Establishing Experience of Color in Applications

The methodology that follows, is typical of a procedure which can be applied to any situation which utilizes color.

1. Given an application, determine prototypical experience required for the application. This is the *desired* experience.

2. Prototypical experience determines response level in space of color experiences.

3. Once response level of equivalent experience is selected, alternatives for establishing experience are identified from among all equivalent experiences.

4. Based on color composition and graphical configuration of application, *current* experience is located in space.

5. Determine how current experience relates to desired experience. If current experience is not equivalent to desired experience, then determine a path which leads from current experience to desired experience, by adjusting dimensions of experience.

6. Once path is identified, desired experience is established by setting constraints on dimensions of experience. Constraints are set either by application or by designer until desired experience is established.

7. Desired experience is established; it specifies conditions required for conveying color intent of application.

6.5 Summary

This chapter has developed a methodology for establishing color experience. The methodology is based on selecting among equivalent experiences by progressively setting constraints on the dimensions of experience. The methodology allows additional dimensions, such as personal preference, to be incorporated into the selection process. The methodology is of great generality, and it can be utilized in any application involving communication with color.

Chapter 7

Beyond Experience of Color

In this investigation, a methodology for describing experience of color was developed. This methodology is based on describing the phenomenology of color experience with directly observable features of the colors, such as the chromatic dimensions of hue, value, chroma, and their contrasts, and the spatial dimensions of area ratio and block size. The data presented in this document provide empirical support to the approach.

Although the features of the methodology originate in previous studies, this investigation is original in that it describes the interrelationship among the dimensions of color experience with a single metric. Having a single metric makes the dimensions commensurate with each other, so that seemingly disparate experiences can be related to each other. The power of this metric becomes apparent in applications, in which establishing experience of color becomes a matter of adjusting the metric, so that it matches a response level. Adjustments to the response are then performed by varying the contributions of individual dimensions to the overall experience, as dictated by the guidelines developed in the investigation.

7.1 Issues for further investigation

The methodology developed here describes experience of color in two-color patterns. Ultimately, however, the methodology should be capable of describing experience of color in complex *multi-color* images. Thus, to increase the generality of the approach developed here, a number of fundamental issues demand further investigation. Two types of issues come to mind: experimental issues, and dimensional issues. Some examples follow.

7.1.1 Experimental Issues

- *Pattern configuration*: evaluate patterns of different shapes, such as boggles with circular elements, polygons, irregular shapes, etc.

- *Rating scales*: utilize different descriptors for rating scale. Include "like-dislike," and "warm-cool" scales to evaluate subjective aspects of experience.

- *Envelopment*: or the enclosure of colors. Blocks inside boggles are, on the average, fully enclosed by related color. In natural images, however, colors are not always fully "enveloped" by just one color. As Lettvin and colleagues demonstrated in their investigation on appearance of colors, chromatic shifts may be produced by neighboring colors even when the boundary between colors is small (Lettvin, 1986). Thus, the effects of envelopment on experience of color should be measured.

- *Extensibility*: the propagation of color interaction across surfaces has been investigated by Buchsbaum, who measured the spread of chromatic induction across surfaces (Buchsbaum, 1988). Lettvin and colleagues also evaluated the separation between colors and its effects in shifting appearance of colors (Lettvin, 1986). Thus, the effects of extensibility and of placing buffers between colors should be evaluated.

- *Natural images*: evaluate experience of color utilizing realistic images, rather than with abstract patterns. Although, as mentioned in Chapter 4, boggles were deliberately chosen to dissociate color interaction from shape connotations. Objects in natural images have subjective connotations associated with them, and hence, they may confound response. Nevertheless, experience of color should be evaluated with natural images.

7.1.2 Dimensional Issues

- *Chromatic dimensions*: increase the number of colors in the pattern. As the complexity of the image increases, so do the number of interactions, and consequently, so does the complexity of the model. A supplementary experiment of this investigation consisted of evaluation of three-color boggles. Preliminary results indicate that interactions between three colors can be decomposed into interactions between two-colors. In this way, response to three-color interactions can be predicted from the responses obtained for the two-color boggles.

- *Temporal dimensions*: evaluate temporal effects such as sequential presentation of colors, duration of exposure to image, and adaptation effects (Bender, 1992).

7.2 Areas of further application

This investigation has, by no means, examined all the possibilities of color experience, but rather, a lot of issues remain unresolved. Nevertheless, the model developed in this investigation provides the groundwork for application of color experience in many fields, including:

- *Image Understanding*: or *boggles as primitives*. Images may be analyzed by looking at the interactions between colors. Color interactions in complex multi-color images may be decomposed into all possible pair-wise interactions. Overall experience may be predicted by weighted combination of responses to individual pairs.

- *Color Reproduction*: or *preserving experience* (Feldman, 1991). In applications such as transfer from screen to "hard-copy," the intent is to perform a "colorimetric" match of all colors in the image. However, due to technological constraints, such as gamut limitations, some colors are "impossible" to reproduce. As an alternative, an "experiential" match may be performed, so that the experience is preserved without necessarily reproducing the individual colors. As demonstrated earlier, there are many options for establishing "equivalent" experiences, by adjusting the dimensions of color experience, to match a given response level.

- *Device independent representations*: a map of an image is derived from the relationships among the chromatic dimensions and among the spatial dimensions of the image. Such representations would be device independent, and would make images compatible with new technologies, as they develop.

7.3 Beyond Experience of Color

In conclusion, this investigation has demonstrated that experiences of color are governed by well defined objective principles which can be quantified by experimental methods. Thus, experience of color constitutes a representation suitable for describing phenomenology of color; worthy of further theoretical and applied research.

Based on the developments of this investigation, the field of color "relatedness," so long the realm of unverified speculation and intuitiveness, is at a stage where it can coexist alongside the more scientifically "respectable" fields of colorimetry and color appearance. The methodology developed in this investigation provides the framework for subsequent research in the field.

Appendix 1

Evaluating experience of color

In this test you will be presented with patterns of color for evaluation. The patterns, the shapes, the sizes, and the colors will vary throughout the investigation. At all times during the experiment you should keep in mind that what we are interested in is the way colors INTERACT with each other.

By interaction we are referring to what happens between the colors: do they relate to each other, do they blend together, do they clash, do they vibrate at their boundaries. We are asking you to give an evaluation of that interaction.

As an analogy, you may think of these color interactions the way you would think about music: certain types of music are energetic, loud, dynamic; other types of music are quiet, soft, and peaceful.

In this experiment, certain interactions may look energetic, forceful, or dynamic. Other color pairs may be seen as slow, peaceful, and quiet. Yet others may appear as in between quiet and loud. The color combinations you will see, should be interpreted along those lines.

Therefore, your task is to rate each color interaction based on a pair of verbal descriptions. For example, upon presentation of a pattern, you may be asked to rate the color interactions along the following scale:

QUIET 1 2 3 4 5 6 7 LOUD

If you think it is QUIET, then enter 1 on the keyboard followed by a return; if, on the other hand, you think it is LOUD, enter a 7 on the keyboard followed by a return. You may find that the interaction is neither quiet nor loud so you may want to enter a neutral value, such as 4. You can indicate intermediate levels of quietness and loudness by entering any of the other numbers, just as if you were placing weights on opposite ends of a weight scale. Just remember that in this example, the closer you are to 1 the more quiet the color interaction is; the closer you are to 7, the louder the interaction is. Thus, the levels on the scale can be assigned as follows:

1 = very QUIET.

2 = somewhat QUIET.

3 = a little QUIET.

4 = neither QUIET nor LOUD, just in between.

5 = a little LOUD.

6 = somewhat LOUD.

7 = very LOUD.

All levels are permissible and should be used freely, as needed. There is NO right or wrong answer. You are simply providing your evaluation of the color interactions; and as you go on, you will develop your own method for doing so. Keep in mind, once again, that we are interested in the interaction between the colors, and not necessarily in the pattern the colors appear in.

MECHANICS

- You will run through a series of 20 to 30 trial combinations to get you familiarized with the mechanics of the experiment. During this training series, you will observe typical combinations that you 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. Remember, you can use any number in the 1 to 7 range.

This is how the test works:

- A pair of descriptors will appear in white letters on the lower part of the screen.
- You will observe the color pattern in the center of the screen.
- To rate the pattern you are to type a number from 1 to 7 with end-points defined by verbal descriptions. They should be evaluated as described above.
- Hit return key on the right hand side of keyboard.
- Screen will clear momentarily.
- A new pair of descriptors will appear.
- A new pattern will appear.
- And so on.

NOTES

- BE CAREFUL TO READ THE NEW DESCRIPTIONS AND NOTE THEIR ORDER.

- YOU ARE RATING EACH PATTERN ON A DIFFERENT PAIR OF VERBAL DESCRIPTIONS, and in some cases the same descriptors may appear!

DURATION OF EXPERIMENT

There is a counter which tells you the number of samples left in the experiment. You are not being timed, so you may establish your own pace, although the pace should be relatively quick, a couple of seconds per sample. The entire test should take you between 30 to 45 minutes to complete. You may take a break at any time during the experiment.

Thanks for your participation!

Appendix 2

Boggle Composition

Boggles were selected by combining the dimensions outlined below. Two issues had to be considered in the computation process:

- *Repeats* refers to symmetrical pairs of colors. That is, composition of a boggle is obtained by combining two colors, designated as $Color_1$ and $Color_2$. Since every color is combined with every color, each color combination appears twice in the permutations; thus boggle with $Color_1$ and $Color_2$ is identical to boggle with $Color_2$ and $Color_1$. Such symmetrical pairs were discarded from the sequence.

- *Flat color* refers to boggles in which $Color_1$ and $Color_2$ are identical to each other; so that boggle becomes, in effect, a flat surface of a single color. Such boggles were discarded from the sequence.

Dimensional Coding

Hue_1, Hue_2 = Munsell hue; a number between 0 and 100, obtained by traversing the hue circle in increments of 10 units. In the outline presented here, hues are indicated by their Munsell "basic" hue designation.

$Value_1$, $Value_2$ = Munsell value; a number between 5.0 and 7.5.

Chroma = Munsell chroma; a number ranging between 2.0 and *maximum* chroma attainable for a given hue-value position.

Block Size = block size; in degrees of visual angle.

Area Ratio = elements of a boggle are generated in multiples of eight. The ratio of areas indicates the number of parts assigned to each color. For instance, a ratio of 3/5 indicates a proportion of 3 parts $Color_1$ to 5 parts $Color_2$.

Notation

In the following sections, the variations along each dimension of experience is indicated by a column of elements enclosed by brackets. The "X" symbol indicates that every element in one of the columns is combined with all the elements in the adjacent column. The notation used here should not be confused with standard matrix notation.

A2.1 Complete Series

$$\begin{array}{ccccccccccc} Hue_1 & & Hue_2 & & Value_1 & & Value_2 & & Chroma & & Block\ Size \\ \begin{bmatrix} 5R \\ 5YR \\ 5Y \\ 5GY \\ 5G \\ 5BG \\ 5B \\ 5PB \\ 5P \\ 5RP \end{bmatrix} & \times & \begin{bmatrix} 5R \\ 5YR \\ 5Y \\ 5GY \\ 5G \\ 5BG \\ 5B \\ 5PB \\ 5P \\ 5RP \end{bmatrix} & \times & \begin{bmatrix} 7.5 \\ 7.0 \\ 5.0 \end{bmatrix} & \times & \begin{bmatrix} 7.5 \\ 7.0 \\ 5.0 \end{bmatrix} & \times & \begin{bmatrix} 6.0 \\ max \end{bmatrix} & \times & \begin{bmatrix} 8 \\ 2 \end{bmatrix} \end{array}$$

$$\frac{10Hue_1 \times 10Hue_2 \times 3Value_1 \times 3Value_2 \times 2Chroma \times 2BlockSizes}{2} - 60 = 1740$$

$$Area\ Ratio = 1/1$$
$$Number\ of\ subjects = 80$$

In this series, the number of boggles was obtained by combining the dimensions indicated above. The factor of 2 in the denominator accounts for repeated pairs. The number 60 represents the pairs of colors in which both colors are identical to each other, when boggle becomes a “flat” color pattern.

The 1740 boggles were divided into four groups of 435 boggles each. Each subject evaluated one of the four groups, so that it took four subjects to evaluate all the boggles in this series.

A2.1 Chroma Series

$$\begin{array}{ccccc} Hue_1\ Value_1 & & Hue_2\ Value_2 & & Chroma \\ \begin{bmatrix} 5R & 7.5/ \\ 5YR & 7.5/ \\ 5Y & 7.5/ \\ 5GY & 7.5/ \\ 5G & 7.5/ \\ 5BG & 7.5/ \\ 5B & 7.5/ \\ 5PB & 7.5/ \\ 5P & 7.5/ \\ 5RP & 7.5/ \end{bmatrix} & \times & \begin{bmatrix} 5R & 7.0/ \\ 5YR & 7.0/ \\ 5Y & 7.0/ \\ 5GY & 7.0/ \\ 5G & 7.0/ \\ 5BG & 7.0/ \\ 5B & 7.0/ \\ 5PB & 7.0/ \\ 5P & 7.0/ \\ 5RP & 7.0/ \end{bmatrix} & \times & \begin{bmatrix} 2.0 \\ 4.0 \\ 8.0 \end{bmatrix} \end{array}$$

10 Hue_1Value_1 x 10 Hue_2Value_2 x 3 *Chromas*= 300 boggles
Area Ratio = 1/1
Block Size = 2.0 degrees of visual angle
Number of Subjects = 20

A2.2 Dark Reference Value Series

$$\begin{array}{ccccc} Hue_1\ Value_1 & & Hue_2\ Value_2 & & Chroma \\ \begin{bmatrix} 5R & 5.0/ \\ 5YR & 5.0/ \\ 5Y & 5.0/ \\ 5GY & 5.0/ \\ 5G & 5.0/ \\ 5BG & 5.0/ \\ 5B & 5.0/ \\ 5PB & 5.0/ \\ 5P & 5.0/ \\ 5RP & 5.0/ \end{bmatrix} & \times & \begin{bmatrix} 5R & 5.0/ \\ 5YR & 5.0/ \\ 5Y & 5.0/ \\ 5GY & 5.0/ \\ 5G & 5.0/ \\ 5BG & 5.0/ \\ 5B & 5.0/ \\ 5PB & 5.0/ \\ 5P & 5.0/ \\ 5RP & 5.0/ \end{bmatrix} & \times & \begin{bmatrix} 6.0 \\ max \end{bmatrix} \end{array}$$

10 Hue_1Value_1 x 10 Hue_2Value_2 x 2 *Chromas* - 20 *repeats* = 180 boggles
Area Ratio = 1/1
Block Size = 2.0 degrees of visual angle
Number of Subjects = 31

A2.3 Area Ratio Series

$$\begin{array}{ccccc} \mathit{Hue}_1\ \mathit{Value}_1 & & \mathit{Hue}_2\ \mathit{Value}_2 & & \mathit{Area\ Ratio} \\ \begin{bmatrix} 5R & 7.5/ \\ 5YR & 7.5/ \\ 5Y & 7.5/ \\ 5GY & 7.5/ \\ 5G & 7.5/ \\ 5BG & 7.5/ \\ 5B & 7.5/ \\ 5PB & 7.5/ \\ 5P & 7.5/ \\ 5RP & 7.5/ \end{bmatrix} & \times & \begin{bmatrix} 5R & 7.0/ \\ 5YR & 7.0/ \\ 5Y & 7.0/ \\ 5GY & 7.0/ \\ 5G & 7.0/ \\ 5BG & 7.0/ \\ 5B & 7.0/ \\ 5PB & 7.0/ \\ 5P & 7.0/ \\ 5RP & 7.0/ \end{bmatrix} & \times & \begin{bmatrix} 1/7 \\ 2/6 \\ 3/5 \\ 5/3 \\ 6/2 \\ 7/1 \end{bmatrix} \end{array}$$

10 $\mathit{Hue}_1\mathit{Value}_1$ x 10 $\mathit{Hue}_2\mathit{Value}_2$ x 6 *Ratios*= 600 boggles
Chroma = 6.0
Block Size = 2.0 degrees of visual angle
Number of Subjects = 29

A2.4 Block Size Series

$$\begin{array}{ccccc} \mathit{Hue}_1\ \mathit{Value}_1 & & \mathit{Hue}_2\ \mathit{Value}_2 & & \mathit{Block\ Size} \\ \begin{bmatrix} 5R & 7.5/ \\ 5YR & 7.5/ \\ 5Y & 7.5/ \\ 5GY & 7.5/ \\ 5G & 7.5/ \\ 5BG & 7.5/ \\ 5B & 7.5/ \\ 5PB & 7.5/ \\ 5P & 7.5/ \\ 5RP & 7.5/ \end{bmatrix} & \times & \begin{bmatrix} 5R & 7.0/ \\ 5YR & 7.0/ \\ 5Y & 7.0/ \\ 5GY & 7.0/ \\ 5G & 7.0/ \\ 5BG & 7.0/ \\ 5B & 7.0/ \\ 5PB & 7.0/ \\ 5P & 7.0/ \\ 5RP & 7.0/ \end{bmatrix} & \times & \begin{bmatrix} 0.5 \\ 1.0 \\ 4.0 \end{bmatrix} \end{array}$$

10 $\mathit{Hue}_1\mathit{Value}_1$ x 10 $\mathit{Hue}_2\mathit{Value}_2$ x 3 *Block Sizes* = 300 boggles
Area Ratio = 1/1
Chroma = 6.0
Number of Subjects = 17

A2.5 Text as Stimuli Series

$$\begin{array}{ccccc} \textit{Background} & & \textit{Text} & & \\ Hue_1\ Value_1 & & Hue_2 & & \begin{array}{c}\textit{Text}\\ Value_2\end{array} \\ \begin{bmatrix} 5R & 7.5/ \\ 5YR & 7.5/ \\ 5Y & 7.5/ \\ 5GY & 7.5/ \\ 5G & 7.5/ \\ 5BG & 7.5/ \\ 5B & 7.5/ \\ 5PB & 7.5/ \\ 5P & 7.5/ \\ 5RP & 7.5/ \end{bmatrix} & \times & \begin{bmatrix} 5R \\ 5YR \\ 5Y \\ 5GY \\ 5G \\ 5BG \\ 5B \\ 5PB \\ 5P \\ 5RP \end{bmatrix} & \times & \begin{bmatrix} 7.0 \\ 5.0 \end{bmatrix} \end{array}$$

$$\frac{10Hue_1Value_1 \times 10Hue_2 \times 2Value_2}{2} = 100$$

Chroma = 6.0
Font Size = 17 point Adobe Times
Number of Subjects = 30

Appendix 3

Informed Consent Form

An investigation to evaluate the "experience of color" will be performed. Experience of color refers to the interaction between colors and their visual context. A wide variety of experiences are possible depending on the types of relationships between colors. It is believed that color experiences can be described objectively. We are interested in finding out how consistent these descriptions are.

Procedure

The investigation consists of evaluation of color patterns displayed on a computer screen. The patterns may take the form of checkered configurations, or screens of text. The experiences produced by any given color pattern will be evaluated using a rating scale and a list of descriptors provided to you. The data will be recorded automatically by the computer. The experiment is self-paced and should take you between 30 and 45 minutes to complete. You will be given one hour of credit for your participation. There are no apparent risks in performing these tests.

Guidelines

- Participation is voluntary and you may withdraw from the study at any time with no effects on your grade or credit.
- You may refuse to answer any questions.
- Your responses will be recorded in a file on a computer for later reference.
- Your name will not be used in any reports of the study.
- Your answers will be kept strictly confidential.
- Upon completion of the study you will be given an explanation of the study, at which time you will be entitled to ask questions about the study.

Consent

I willingly consent to participate in a study being conducted at Boston University by Boston University and Massachusetts Institute of Technology investigators.

Signature:____________________________________ Date:_______________

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