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Studies of effective color combinations in visualization

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STUDIES OF EFFECTIVE COLOR COMBINATIONS IN VISUALIZATION

by

SUSSAN EINAKIAN

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in
The Department of Computer Science
to
The School of Graduate Studies
of
The University of Alabama in Huntsville

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2017

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DISSERTATION APPROVAL FORM

Submitted by Sussan Einakian in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Computer Science and accepted on behalf of the Faculty of the School of Graduate Studies by the dissertation committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this dissertation. We further certify that we have reviewed the dissertation manuscript and approve it in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Computer Science.

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ABSTRACT

School of Graduate Studies
The University of Alabama in Huntsville

Degree Doctor of Philosophy College/Dept. Science/Computer Science

Name of Candidate Sussan Einakian

Title Studying Effective Color Combinations in Visualization

This dissertation research focuses on investigating the role of certain classes of color combinations in two classes of visualization. The certain classes of color combinations are color theories about harmonies, disharmonies, and opponencies. Our investigations concentrate in two classes of visualization: map-based visualization and surface-based volume visualization. The following research uses survey questionnaires to investigate the effect of color combinations in visualization.

The first concentration is on the overlay of data attributes in map-based information visualization. We examine the relative suitability and noticeability of color theories about harmonious, disharmonious, and opponent color combinations for feature overlays on map-based visualization. We also investigate the effectiveness of using high and low saturated, and high and low lightness colors for displaying attributes on a map.

The second area of concentration is on suitability of three classes of strategies governing color combination selection in surface-based volume visualization. These classes are harmonious, disharmonious, and opponent color combinations. Suitability is assessed via responses to survey questionnaires on the use of these color combinations in renderings of isosurfaces with multiple (nested) components.

The third area of concentration is to examine the existing rules and guidelines about color choices in visual presentations to determine applicability for isosurface-based volume renderings. Three guidelines are of special interest here: (1) guidelines based on rules of color harmony (from artistic color theory) introduced by Itten [49]; (2) guidelines based on color temperature introduced by Ebert et al. [27, 28]; and (3) guidelines for colors in layered translucent surface visualization introduced by House et al. [45].

The fourth area of concentration is to investigate the applicability of harmonious color combinations of the fashion industry in visualization. We also investigate the compatibility between color harmony in fashion industry and rules of color harmony by Itten [49, 50] and Munsell [37, 73].

Abstract Approval: Committee Chair Timothy S. Newman
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CHAPTER 1

INTRODUCTION

Visualization is a process of transforming data and information into a visual form with the aim to amplify the observers' capacity to study or explore the data and gain understanding and insights into it [54]. The visual display of information can allow an observer to become more easily aware of essential facts, to quickly see irregularities and outliers in the data, and therefore, to develop a deeper understanding of the data. Visualization often helps in the discovery of hidden or obscured information.

Visualization has been employed for centuries as a powerful way to present information. Visualization offers a method of seeing the unseen. Visualization was described by the National Science Foundation Visualization in Scientific Computing Workshop report [51] in 1987 as "a method of computing" that "transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. It enriches the process of scientific discovery and can foster profound and unexpected insight. The goal of visualization is to leverage existing scientific methods by providing new scientific insight through visual methods [51]." Ware [118] has stated that "visualizations have a small but crucial and expanding role in cognitive systems." He has indicated that humans obtain more information through vision than through any other sense. Ware has also referred to the definition of visualization in the 1972 Oxford English Dictionary. In that dictionary, visualization was defined as constructing a visual image in the mind. However, today visualization is sometimes used more as a graphical presentation of data or concepts. It has become a tool that supports decision making. Ware [118] has explained some of the advantages of visualization, such as (1) visualization could help in understanding large amounts of data; (2) it could help a viewer to perceive a pattern, possibly allowing a new insight; and (3) it could reveal features of data and improve the understanding of these features.

On the other hand, Card et al. [13] have defined visualization as the use of interactive visual representations of data to amplify cognition. Another definition of visualization was suggested by Kosara et al. [55]. They have defined visualization as a method of presenting data in an accessible, intelligible, and interesting manner. They believe visualization can transform data into visual forms that help people explore data and gain understanding and insights into the data (for example, about a trend). Once insights are gained, users could make decisions based on what they see in the data. Kosara et al. [54] have discussed that using connected stories in visualization could provide insights to users through discussions among users about a story. In fact, some of the earliest visualization examples use the power of storytelling (connecting facts together) to present data, such as Minard's visualization of Napoleon's Russian campaign of 1812 [55].

In the past, some visualizations have used grayscale or monochromatic displays of a dataset's dimensional or variable features or attributes (for example, display of features of CT data or of MRI data). These visualizations take advantage of one of the human visual system's sensitivities to variation or change, specifically to variations in grayscale (i.e., to lightness in a scene). However, a display (e.g., a visualization) that uses only grayscale could have limitations [31, 89, 114]. For example, Silverstein et al. [102] have discussed that using only grayscale in some types of visualizations, such as anatomical volume renderings, produces results that do not look realistic. Color also can be quickly observed by humans, so many visualizations instead have used color (or color with grayscale) to display the attributes of a dataset. Using color in visualizations could convey information effectively (which could facilitate visual search) including information about the underlying structure of the data. By conveying information effectively, color could also improve the presentation's usability. Since color differences can be detected by humans in milliseconds, using color to display variation for a number of objects or features can make differentiation of them less difficult.

Many data visualizations have used color as a visual cue, especially to represent one dimension of the data. Use of color has several advantages, including (1) allowing more attributes to be displayed than if only grayscale was used; (2) allowing more variation (or distinguishing levels) to be displayed; (3) possibly making structures or trends more readily discoverable; and (4) allowing annotations or labels in a different color than the rest of the visualization. Although color can be readily observed by standard observers, colors are often interpreted subjectively by visualization observers. Therefore, visualization may be more useful if color is used in a "safe" or prudent way. "Safe" usage has many aspects. One aspect is the need to put the right color in the right place, as described by Tufte [108]. For example, using the same color for the background and display of an attribute would not be a "safe" choice. The second aspect is the need to use a suitable theme in the right place. For example, if using the combination of a colorful foreground theme on a colorful background was visually stimulative but did not foster ready discovery of trends by visualization users, such a combination would be imprudent, or possibly even unsafe, for visualization.

Some research work in visual perception suggests that more than a thousand colors can be distinguished when colors are placed side by side [99] and other studies suggest that the human visual system can distinguish more than one million colors [29, 60, 121]. Using color effectively in visualization could require considering the following issues: (1) which colors are suitable choices for backgrounds and foregrounds; (2) which color combinations create effective (or ineffective) impressions of different types (or levels) of information for users; (3) which color combinations are suitable for legibility; (4) which color combinations are preferred by users; (5) which color combinations are most suitable to convey particular types of information, especially in consideration of cultural meanings related to some colors; (6) which color choices are effective (or not effective) when the observer is color-blind; etc.

In the past decade, some visualization researchers have considered using color combinations that are harmonious according to artistic color theory. A harmonious color combination can be defined as a set of colors that is aesthetically pleasing to the human visual system when used together. One of the focuses in my dissertation research has been to study whether using theories about color harmony and other theories of color combinations can be effective for certain visualizations. Another focus has been to study two alternative rules for color combinations: (1) disharmonious color combinations and (2) opposing (opponent) colors. The rest of this dissertation describes both focuses.

1.1 Dissertation Application Domain

In this research, the use of color in visualization of two types of data is considered. They are cartographic data and volumetric data. Volumetric data is extensively used in medical, scientific, and certain industrial applications. In some of these applications, data structure needs to be considered by visualization users. Proper choice of color can make the structure of the data clear, maybe even if the structure of the data is hidden or unclear. The dissertation work has application for deciding color attributes for word overlays on maps and for glyph overlays in map-based visualization. It also has application for helping to reveal shapes and surfaces or region boundaries in surface-based volume visualization.

1.2 Motivation and Contribution

This dissertation reports my research investigating if artistic and psychological theories about color combinations that have harmonies, non-harmonies (disharmonies), or opponencies can be useful in visualization, specifically in map-based and surface-based visualizations. The investigations for map-based visualizations focus on finding if some of these color combination guidelines can improve distinguishability of feature overlays (primarily word overlays, but also glyph overlays). The investigation for surface-based volume visualizations focuses on finding if some of these guidelines can improve distinguishability of nested isosurfaces in a single rendering. My long-term aim for the research was to help overcome challenges of color selection in two sorts of visualization. The findings might also be applicable to other discipline areas, such as computer graphics, web design, cartography, etc.

Use of color selection guidelines so far has not been considered widely in the visualization research.

My dissertation research attempts to answer a set of questions which helps in finding new guidelines for the use of color in visualization based on color theories. These questions are as follows:

- Are there guidelines about color combinations that form harmonious, disharmonious, or opponent color combinations useful for visualization?
- Can the application of one of the types of color combinations (i.e., harmonious, disharmonious, or opponent colors) in visualization help an observer to notice a phenomenon more easily?
- Can we determine guidelines about color combinations that form harmonious, disharmonious, or opponent colors which are useful in map-based visualization?
- Can using color combinations that form harmonious, disharmonious, or opponent colors lead to new sets of rules or guidelines about use of color combinations in visualization?

- Can using color combinations that form harmonious, disharmonious, or opponent colors be effective for surface-based visualization of volumetric data, such as CT data or MRI data?
- Can users easily distinguish nested isosurfaces in surface-based visualization of volumetric data utilizing one of these types of color combinations (i.e., harmonious, disharmonious, or opponent colors)?
- Can utilizing one of certain color combinations (i.e., harmonious, disharmonious, or opponent colors) help users in visualization to more easily distinguish multiple isosurfaces (each associated with a unique isovalue) in a surface-based volume visualization?
- Can fashion color harmonies be applicable to visualization?

1.3 Color and the Human Visual System

Knowing about the structure of the human visual system can help visualization designers understand how the brain reacts to visual stimuli. That understanding can guide visualization designers to improve the quality of the data display in a visualization. In this section the basics of the human visual system and the visible light spectrum are presented.

The human visual system consists of the eyes, the visual cortex of the brain, and the nerve connections between them. The primary visual cortex (known as V1) reacts to both motion and color. V1 and secondary visual cortex (known as V2) together are important centers for color vision. The brain's analysis of visual stimuli begins in V1 and V2 [35, 99]. On the other hand, the brain's processing of color depends on the input it gets. This input depends on how well the eyes can sense the light reflected or emitted from objects. The functioning of the eyes is explained in the next section.

1.3.1 Human Vision Basics

Human perception of color depends on different factors such as how well eyes can sense the light and on the color of the area surrounding the object. The human eye is sensitive to a very narrow range of frequencies in the electromagnetic spectrum (the wavelengths between 400 nm and 700 nm [99]). This range is known as the *visible light spectrum.* Figure 1.1 is a representation of a range of frequencies in the electromagnetic spectrum. It shows classifications of the wavelengths into the radio wave, infrared, ultraviolet, x-ray, gamma ray ranges, and the visible light spectrum. Each wavelength within the spectrum of visible light is associated with a particular color. One factor in human perception of color is how eyes sense the light, which is discussed next.

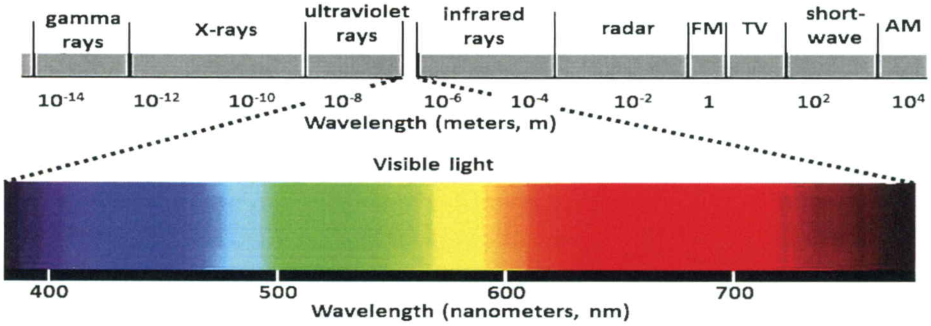


Figure 1.1: The Visible Spectrum, adapted from [99]

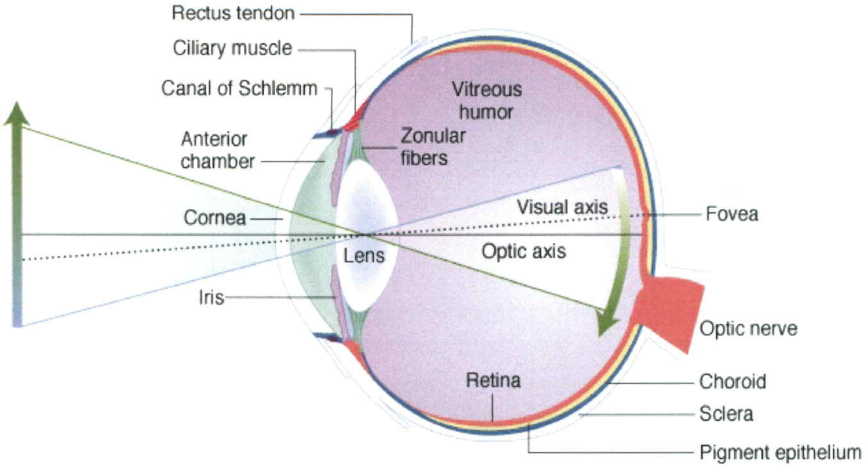


Figure 1.2: Anatomy of the Eye [40]

Basic anatomy of the human eye is presented in the Figure 1.2. In a number of ways, the human eye works like a digital camera [66]. Light is focused primarily by the cornea (i.e., the clear front surface of the eye) [66]. The cornea and lens are like compound lens and they act as a camera lens to focus the image. The lens of the eye helps the eye automatically focus on objects, even if the objects are moving. It is located behind the pupil (i.e., a hole located in the center of the iris that allows light to enter the eye's interior). The iris controls the amount of light reaching the back of the eye by automatically adjusting the size of the pupil. The iris acts like the aperture of a camera lens. The light passing through the lens then reaches the retina. The retina acts like an electronic image sensor of a digital camera, converting optical images into electronic signals. It consists of three layers of nerve cells and contains millions of photoreceptor cells known as rods and cones [46]. The detail of rods and cones are discussed in the next section. The optic nerve transmits these signals to the primary visual cortex of the brain (V1). The brain uses the processing in V1 and later interprets the scene being viewed [40].

1.3.2 Rods and Cones

The eye's retina has two types of photoreceptors, rods and cones, which are responsible for night and day vision, respectively. These two photoreceptors work independent from each other and each respond to the light differently. They are different in shape, structure, and location in the visual system [98].

The rods, which contain the visual pigment rhodopsin, are extremely sensitive to the light and are responsible for low light vision [98]. There is only one type of rod photoreceptor. Rhodopsin consists of a protein, known as opsin. Opsin is essential for vision in dim light. This protein contains a non-protein component, known as retinal [98]. Retinal changes its shape when it absorbs a photon of light. This change is transmitted to another protein, which eventually causes the propagation of a nervous impulse to the brain. The nervous impulse enables the brain to interpret and respond to the differences between light and dark and makes it possible for humans to detect movement and shape in dim light [30]. There are approximately 100 million rods in the retina, and they are mostly concentrated outside the fovea (i.e., the fovea is an area in the middle of retina). They provide low spatial resolution because each rod is connected to many cells in the optic nerve.

In the 18th century, Thomas Young and later Herman Von Helmholtz realized that there are three distinct sets of nerve fibers in the eye. They are activated by different wavelengths of light [98]. These three types of nerve fibers are called cones.

Human vision is called *trichromatic* because there are the three types of cones [30]. The cones respond to bright light and are sensitive to color. There are approximately 5 million cones. Their high threshold for detecting light and high acuity provide high spatial resolution. The cones are mostly concentrated in the fovea. The central fovea is the area of sharpest vision. Cone cells contain a light sensitive photopigment called photopsin and they are responsible for color vision. Cone cells are less sensitive than rods to light. When light levels decrease they cannot respond, thus the human visual system cannot recognizes colors in dark [92, 111]. The cones absorb wide range of wavelengths of light and generate nerve impulses on the optic nerve. The optic nerve transmits the nerve pulses to the brain for further processing of the color information [30].

The three types of cones are the L-, M-, and S-Cones. The cone types differ in their degree of sensitivity to particular wavelengths of light. Their sensitivity is determined by how they absorb photons of different wavelengths [30]. The S-cones absorb short wavelengths of light, with a maximum response at 430 nm (violet-blue). The M-cones mostly absorb medium wavelengths of light, with a maximum response at 530 nm (green). Finally, the L-cones mostly absorb long wavelengths of light, with a maximum response at 560 nm (slightly yellowish-orange) [99, 119]. These three cones have the different absorptions because they contain different photopsins that respond to the light differently [43,99]. The photopsins explain the differences in their peak wavelengths. The S-cones, M-cones, and L-cones are sometimes called the blue, green, and red cones, respectively [60, 99].

Figure 1.3 presents plots of the relative, normalized sensitivity response of each type of cone for the visible spectrum [119]. The ranges of sensitivity to light of the different cone types overlap. The L-cones and M-cones have a large amount of overlap in their range of response. The range of the S-cone's response has less overlap with the other cone types.

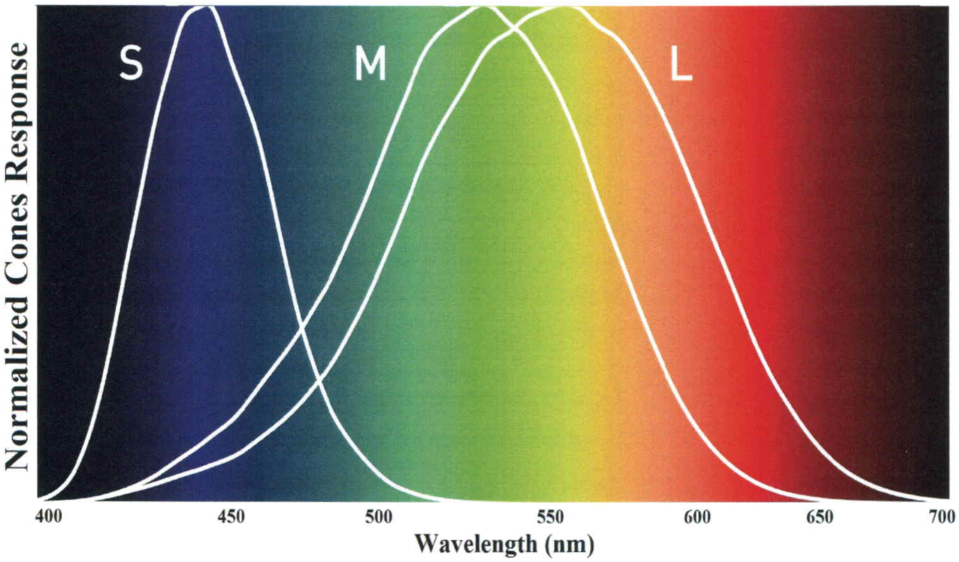


Figure 1.3: Normalized response spectra of human cone cells (S, M, and L cones) by light wavelength, duplicated from Ward et al. [119]

Each cone type absorbs a wide range of wavelengths. Cicerone and Nerger [30] have found out there are about 4 million L-cones, over 2 million M-cones, and under 1 million S-cones. The parts of the scene viewed with the center of fovea (in which the M-cones and L-cones are concentrated) are sensed with the highest level of spatial and color resolution and also sensed with maximum sensitivity in contrast. Contrast sensitivity describes the ability of an observer to detect difference in the qualities or intensities of the light [133]. The S-cones, which are not very prevalent in the area of sharpest vision, tend to result in human perception of blue objects to be less distinct than human perception of red and green objects [30].

If any cone has a deficiency in its response, color blindness can occur. To see an object in color at least two types of cones must be triggered and the perceived color will be based on the relative level of excitation of the different cones. For example, yellow results from moderate to high activity in both the L- and M- cones and small activity in the S-cones. White sensation results from activation of same degree of all three cone types [98].

1.3.3 Color Perception

Rods and cones are connected to retinal ganglion cells. The region of the retina (i.e. visual field) that ganglion cells respond to is called the receptive field. Each receptive field is divided into two regions, its "center" and the "surround" (of the center). Hubel and Wiesel [30, 46] have discovered that each of these regions can generate either an "on" (excited) or an "off" (inhibited) response. Each retinal ganglion cell has one of two types of receptive fields: on-center/off-surround or off-center/on-surround. If the center of receptive field excites the ganglion cell and the surround of receptive field inhibits the ganglion cell, the field is called off-surround [33, 46].

Figure 1.4 shows examples of receptive fields that have centers and surrounds. The figure shows four on-center and off-surround arrangements for the ganglion cells: (1) red center "on" (i.e., L-cone+S-cone) and green surround "off" (i.e., M-cone); (2) green center "on" (i.e., M-cone) and red surround "off" (i.e., L-cone+S-cone); (3)

blue center "on" (i.e., S-cone) and yellow surround "off" (i.e., M-cone+L-cone); and finally (4) yellow center "on" (i.e., M-cone+L-cone) and blue surround "off" (i.e., S-cone) [53]. For these arrangements, some wavelengths cause excitation in the center (i.e., on-center) cells and other wavelengths cause the inhibition in the surrounding (i.e., off-surround) cells. These center-surrounds are known as opponent processes since they are antagonistic. A detailed description of them is in Section 2.4.

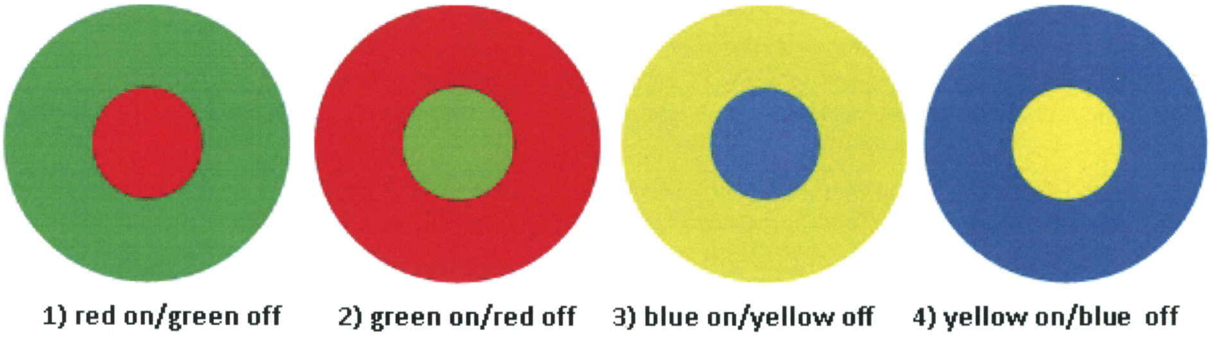


Figure 1.4: Example of Receptive Fields for Ganglion Cells, reproduced from Kolb et al. [53]

1.4 Dissertation Organization

This dissertation is organized into eleven chapters. Chapter 2 discusses related works about color representation and color models. That chapter also focuses on the development of color theories over time, including a discussion of color combinations that form harmonious, disharmonious, and opponent colors. Chapters 3, 5, 7 and 9 present the studies of effective color combinations in map-based visualization and isosurface-based volume visualization done for this dissertation. Chapter 3 describes user studies that explore certain aspects of harmonious, disharmonious, and opponent color combinations in map-based visualization. Chapter 5 discusses the user studies that explore use of color theories about harmonious, disharmonious, and opponent color combinations in isosurface-based volume visualization. Chapter 7 describes color selection guidelines in volume visualization and focuses on two guidelines which were suggested by Ebert et al. [27, 28] and House et al. [45]. Chapter 9 discuses the user studies that explore use of fashion color harmonies in visualization. That chapter also describes the results of experiments using different fabrics which follows harmonious color combinations suggested by designers and artists. Conclusions and future works are discussed in Chapter 11.

CHAPTER 2

BACKGROUND AND RELATED WORKS

This chapter discusses color representation and some common color models. It also considers color theories, in particular ones defining color harmony, and color opponencies.

2.1 Color Representation

Models for representing color are often called *color models*. They provide a standard way to identify colors by specifying the basic components that describe each color [121]. Each color model has a particular range of colors, which refer to a color space. Typical models represent identifiable colors as single points in the model's color space. Some common color models are the (1) Commission Internationale de l'Eclairage (CIE), (2) Red-Green-Blue (RGB), (3) Cyan-Magenta-Yellow-Black (CMYK), (4) Hue-Saturation-Value (HSV), and (5) Luma-Chroma (YUV) models.

2.1.1 Color Models

A color model is a simple way to define and present a color, usually by describing the color's basic components. Typically, the color is represented by a three- or four-tuple of numbers. Some color models are additive. Others are subtractive.

An additive color is created by mixing the light of two or more different colors. In additive color, the primaries are red, green, and blue, as shown in Figure 2.1 by R, G, B, respectively. The combination of two additive color primaries produces a complementary color (i.e., in the intersection of red and green, red and blue, and green and blue in Figure 2.1). The combination of red and green produces yellow, the combination of red and blue produces magenta, and the combination of green and blue produces cyan. The combination of fully intense additive primaries together produces white light, as shown in the center of Figure 2.1.

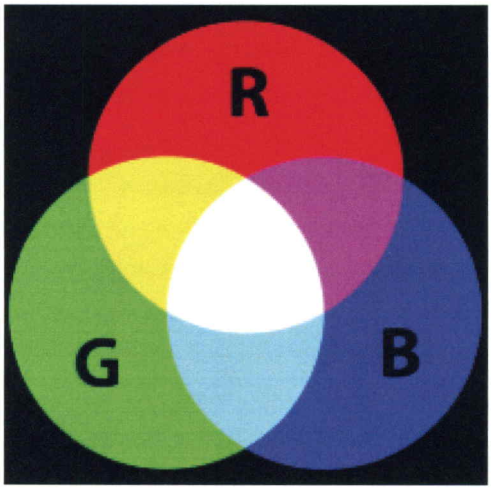


Figure 2.1: Additive Colors

Computer monitors, televisions, and other electronic display devices release light and produce additive colors. The range of colors that can be produced by a display is defined as its color gamut.

A subtractive color is created by mixing two or more pigment colors such as paints or dyes. The primaries of pigment are cyan, magenta, and yellow, as shown in Figure 2.2 by C, M, and Y, respectively. Pigments absorb selective wavelengths and prevent certain wavelengths of light from being reflected. When white light shines on colored paint only some of the wavelengths are reflected. As an example, cyan pigment absorbs red light but reflects green and blue light, and yellow pigment absorbs blue light but reflects green and red light. As a result, if cyan paint is mixed with yellow paint green paint can be seen, because red and blue light are absorbed and green light is reflected. The combination of equal amounts of primary subtractive colors produces black, as shown in the center of Figure 2.2.

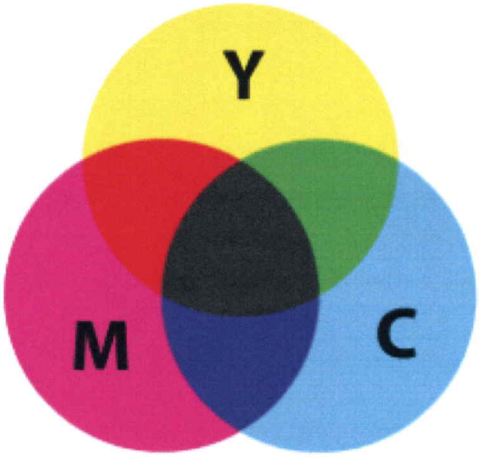


Figure 2.2: Subtractive Colors

The most common color models are CIE, RGB, and HSV. These three models are explained next.

2.1.1.1 CIE Color Model

The CIE color model, also known as CIE XYZ, is based on human perception and was developed by the Commission Internationale de l'Eclairage. The model was developed to be independent of any device and is considered to be very accurate. It is a three-dimensional model and is based on the chromatic response of the eye. It identifies colors based on the additive mixing of light [118].

The CIE model is based on three abstract primaries, X, Y, and Z. Combinations of these primaries can reproduce all the colors that the human visual system can perceive. These primaries do not directly correspond to red, green, and blue values, though. Instead, they were chosen because of their mathematical properties. The Y primary is related to luminance. The X and Z primaries are abstract dimensions. The Figure 2.3 shows the CIE XYZ dimensions. The diagram is known as the CIE chromaticity diagram [118]. The CIE color model space is shown in Figure 2.3. The gray horseshoe shape region in the center represents the part of the space the human visual system can perceive.

Since X and Z primaries of CIE model are not related to concrete dimensions, understanding them is difficult. Thus, subspaces of the CIE XYZ model that include some more concrete, derived dimensions are often used.

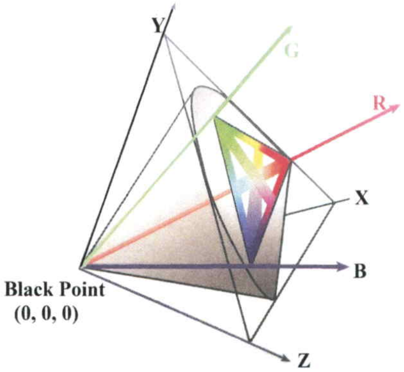


Figure 2.3: CIE XYZ chromaticity diagram, duplicated from Ware [118]

2.1.1.2 RGB Color Model

A RGB color model is an additive color model that represents each color with regard to red, green, and blue lights, which are its primaries. RGB color models are often used for representing and displaying images in electronic devices, such as televisions and computers. RGB models are device dependent; each device could reproduce RGB values differently [60].

One way to view a RGB color model is as a 3-dimensional color cube, where each axis is one of the primaries, as shown in Figure 2.4. Each color is presented as a three-component coordinate. Each coordinate component has an intensity value between 0 and 1. Using a RGB color model the location of any color (e.g., C) in the RGB color cube can be specified by the following equation using unit vectors R, G, and B that represent the primaries [11]:

$$C = (r, g, b) = rR + gG + bB, \tag{2.1}$$

where r, g, and b are the intensity values of each primary, specified in the range of 0 to 1. The unit vectors R, G, and B are, respectively:

$$\begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\1\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix}.$$

(0, 0, 0) in the color cube corresponds to the color black and (1, 1, 1) corresponds to the color white. Along the main diagonal between black and white are the gray shades, which are created when the r, g, and b components are equal [11].

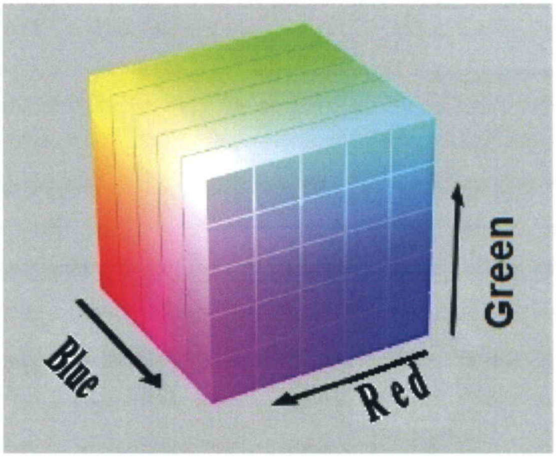


Figure 2.4: One view of the RGB Model

Some colors in the visible spectrum cannot be produced by combining the RGB's red, green, and blue primaries [10,70] (i.e., the RGB model's gamut of colors is much less than the colors the visual system can actually perceive). Various extensions to the RGB model, such as sRGB, Adobe RGB, Wide Gamut RGB, etc., have been defined over the years. Figure 2.5 shows a chromaticity diagram of the colors typical human eyes can perceive, as shown in the horseshoe shape versus the gamuts of the sRGB, Adobe RGB, Apple RGB, Color Match RGB, and Wide Gamut RGB color models [135].

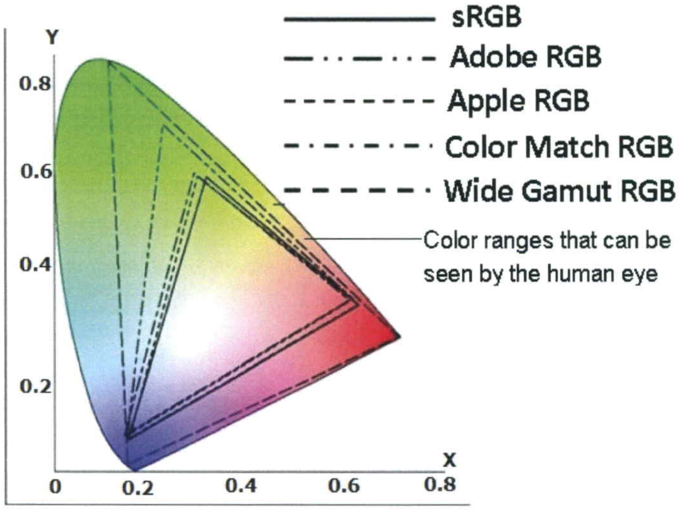


Figure 2.5: Chromaticity Diagram of RGB-related Color Models, duplicated from Canon [135]

2.1.1.3 HSB and HSV Color Models

The HSB color model describes color by the attributes of hue, saturation, and brightness. Hue describes the primary color (or colors) whose combination produces the color. For example, red, green, and blue are hues; and equal mixes of any two of those (secondary colors) are hues; and colors formed by mixing any secondary color and one of its component primaries is a hue. Saturation (or chroma) describes the vividness of a color [99, 100]. More-saturated colors appear more "pure" and less-saturated colors appear more "pale" [99]. Brightness describes the intensity of the light that forms the color, which represents lightness or darkness of the color. In the HSB model, black has 0% brightness and white has 100% brightness [99,100].

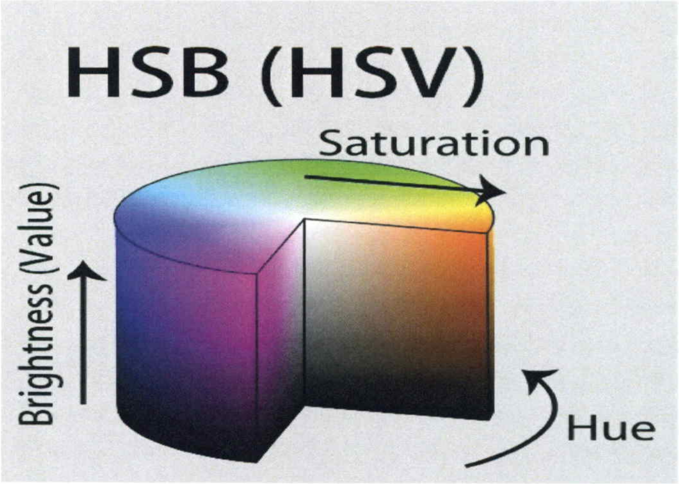


Figure 2.6: HSB (HSV) Color Model, duplicated from Pyimagesearch [130]

The HSB model is also known as the HSV color model. Both use the same attributes, except the HSV color model uses the term value to describe brightness. Value in HSV describes how dark a color is. It ranges from 0 to 100% (i.e., same as brightness in the HSB color model). The HSB (HSV) model can be viewed as a cylinder, as shown in Figure 2.6. Value (brightness) is represented as the fractional position on the vertical axis. It ranges from 0 to 1. Hue is represented as an angular position around vertical axis. It ranges from 0 to 360. Saturation is represented as the fractional position on a radial line directed outward from the vertical axis. It ranges from 0 to 1. The HSB (HSV) model is a nonlinear transformation of the RGB color model.

2.2 Color Theories

In this section, color categorization rules are discussed. Many rules about categorizing or arranging colors have been suggested by artists and psychologists. Many of those rules are part of color theories. One definition of a color theory is a collection of rules and guidelines that describes how combination of two or more colors interact with each other from design perspective and how these color combinations create specific visual effects. Another definition of a color theory is an ordering or arrangement of colors according to perception or logical rules. In this dissertation, I investigate application of some color theories in visualization.

One of the pioneers of color theory is Aristotle. He proposed a color theory with seven basic colors based on four elements of nature: water, air, earth, and fire. Its seven basic colors are white, yellow, red, purple, green, blue, and black. Since he viewed these colors as transitioning from brightness to darkness, he arranged them from light to dark. He described other colors as mixture of these basic colors [3, 36].

In the 16th century, Leonardo da Vinci proposed a color theory also based on Aristotle's ideas of colors being elements of nature. In his theory, white, yellow, green, blue, red, and black are representations of light, earth, water, air, fire, and darkness, respectively [62].

In the 17th century, Isaac Newton discovered that color is a property of light. He observed that light from the sun that passes through a prism produces a linear spectrum of colors. He also invented a hue circle that organized the colors in a circle, as shown in Figure 2.7, formed from bending the linear spectrum of colors produced by the prism [32, 101]. Newton's hue circle became a basis for many color theories in 18th and 19th centuries.

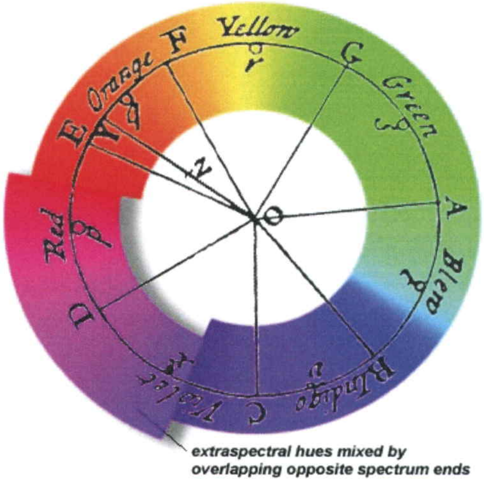


Figure 2.7: Newton Color Circle, duplicated from MacEvoy [63]

2.2.1 Goethe Color Theory

In 1810, Goethe focused on the psychological and physiological aspects of color [3]. His research was the beginning of modern color psychology [3]. Goethe's color theory was not based on physics and mathematical models. His idea came from the ancient Greek meaning for theoria, which is "contemplation," "inspection," "seeing," and "recognizing" [101].

Goethe believed in Aristotle's view that colors can be ordered transitioning from brightness to darkness [32]. He did experiments leading to knowledge about complementary colors.

Goethe's color theory was based on three primaries—red, blue, and yellow. All other colors were the results of the combination or mixture of these primaries. He arranged the colors in a wheel (or hue circle), shown in Figure 2.8. He categorized colors as positive or negative, and placed them on his hue circle according to his categorization. Goethe believed that two of his primaries, yellow (a positive or active color) and blue (a negative or passive color), were descriptions of the Earth. His color theory was based on experiments and his sense. For example, he sensed that yellow is an active color that creates excitement, warmth, and an agreeable impression. He also believed that blue is a passive color that gives an impression of cold, and that red and green were more neutral [32], with red giving an impression of gravity, dignity, and earthly power and green symbolizing heaven and hope [32].

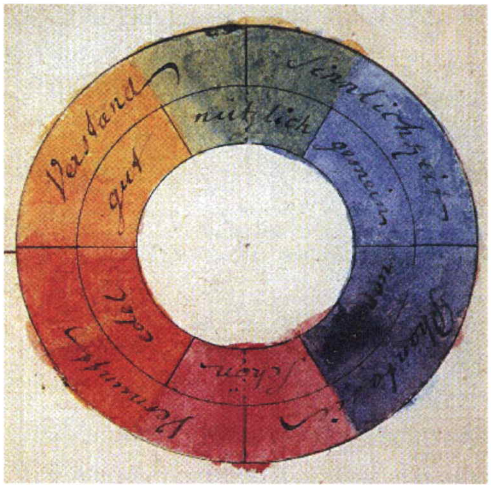


Figure 2.8: Goethe hue circle, duplicated from Sookoo [103]

Goethe believed that the sensations of color in the brain were shaped by human perception. Therefore, what is seen depends on more than lighting.

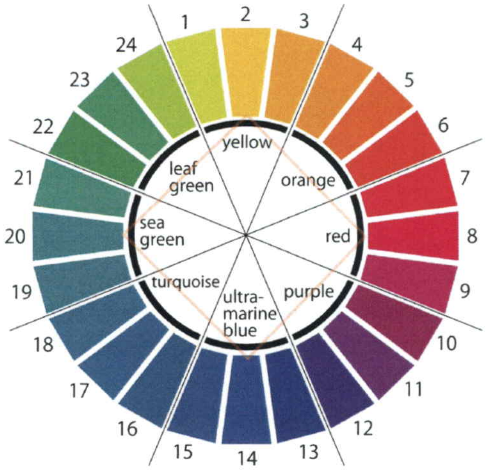


Figure 2.9: Ostwald hue circle, duplicated from Hernandez [42]

2.2.2 Ostwald Color Theory

Ostwald also proposed a color theory. It is based on the attributes of *hue, black*, and *white*. The hue of a color in his system is the dominant wavelength of the light that makes that color. He arranged hue in a hue circle that is divided into 24 color segments, as shown in Figure 2.9, based on four primaries—yellow, red, blue, and sea-green. The primary colors are equi-distance from each other and form a square, which is shown in orange in Figure 2.9. The 24 segments on this hue circle are made up of eight groups of three colors each. These groups are named the yellow, orange, red, purple, blue, turquoise, sea-green, and leaf-green groups. Other colors are formed by mixing a degree of white or black with a hue, and those colors are located in a three-dimensional space forming a double cone. The Ostwald hue circle is the equator of this double cone. All colors are located within, above, or below the hue circle. The colors on the equator are the most saturated ones. White is located at the upper apex of the double cone. Black is located at the double cone's lower apex. A vertical axis, called the gray or lightness axis, joins the apexes and passes through the center of the hue circle [60]. The amount of lightness for a color is the location of the color's projection onto the vertical axis. Colors are progressively lighter above the equator and progressively darker below the equator (in the direction of the vertical axis). Saturated colors in his theory were defined as colors without any gray. Amount of saturation for a color is its distance from the central axis of the cone.

2.2.3 Munsell Color Theory

Munsell also has a color theory [60, 73]. It is based on human perception. It uses attributes of *hue, value*, and *chroma* to model a color, as illustrated in Figure 2.10. It arranges hues in a circle. It defines hue as the (single) dominant light wavelength associated with the color. It arranges values in a vertical axis that passes through the center of the hue circle, as shown in Figure 2.10. It defines value as the degree of lightness that distinguishes light and dark colors. The axis for value describes the gray level of the color. Its midpoint is middle gray and is known as central point of balance. A color's value expressed the amount of lightness, with value 10 being totally white and value 0 being totally black [9]. The Munsell model defines chroma as the color "purity", which implies the degree to which a color is free of any achromatic color. It defines achromatic color as a color that lacks hue (i.e., is not characterized by a single wavelength). Examples are black, white, and gray. A color's chroma is expressed by its step position from the central axis. This position is the number of steps from central axis to the peak chroma of a color. These number of steps depend on the strength of pigments, which is not uniform for every hue. For example, color purple-blue with value attribute of 2 reaches peak chroma at 14 while color yellow with value attribute of 7 reaches peak chroma at 10 [20, 63]. Thus, each color in the Munsell model is represented in terms of its (1) hue segment, (2) amount of value, and (3) amount of chroma.

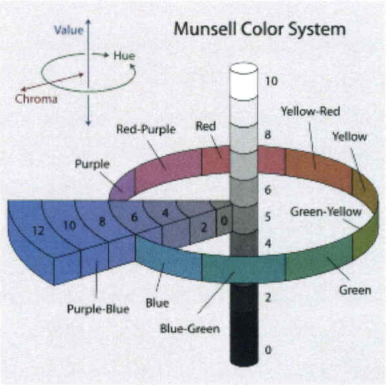


Figure 2.10: Munsell Color Model, duplicated from MacEvoy [63]

Munsell specified five colors, red, yellow, green, blue, and purple, as simple hues and identified them as R, Y, G, B, and P, respectively [73]. They are also known as the principal colors [20]. He specified five other colors—yellow-red, green-yellow, blue-green, purple-blue, and red-purple—as intermediate (compound) hues and identified them as YR, GY, BG, PB, and RP, respectively [20, 73]. All other colors were formed by mixing simple and intermediate hues. The original Munsell system divided each simple and intermediate hue into ten segments [73] (numbered 1 to 10). These segments are the variations of hue that a trained eye can recognize. In this model, each color is represented as a code in the form: $aH\frac{b}{c}$, where a is the segment number in the simple or intermediate hue denoted H, where H is one of the hue identifiers given above, and b denotes value and c denotes chroma. Thus, a $8\mathrm{Y}\frac{5}{2}$ indicates a color from segment 8 of hue yellow that has value 5 and chroma 2, which is about green-yellow [73].

The Munsell color theory also uses cylindrical charts to represent colors, as shown in Figure 2.11. Cylindrical charts are based on the simple and intermediates hues. They visualize the hue, value, and chroma of a color [73, 74].

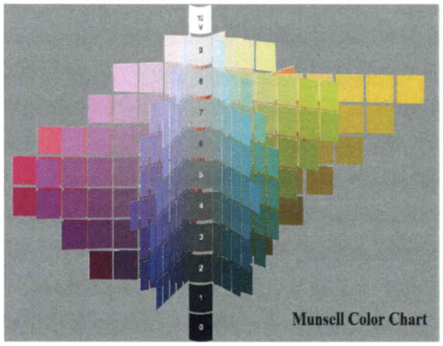


Figure 2.11: Munsell Color Chart, duplicated from Orian [84]

2.2.4 Itten Color Theory

Johannes Itten, an artist, designed a hue circle (color wheel) based on Goethe's color theory [36]. Itten's hue circle consists of twelve evenly spaced colors, as shown on the outer circle of the hue circle in Figure 2.12 [103]. It is based on three subtractive (i.e., color of pigments) primaries—red, yellow, and blue. The primaries form an equilateral triangle inside Itten's hue circle (as shown in the middle of Figure 2.12) with yellow at the top, blue at the lower left, and red at the lower right. Equally mixing two primary colors produces a secondary color. The secondary colors are orange (a mixture of yellow and red), green (a mixture of yellow and blue), and violet (a mixture of red and blue). The secondary colors are shown in Figure 2.12 between the circle and equilateral triangle. The mixtures of primaries and adjacent secondaries produce six other mixed colors (i.e., yellow-orange, red-violet, blue-green, red-orange, blue-violet, and yellow-green) [49]. In Figure 2.12, these mixed colors are shown on the outer circle of the hue circle between primaries and secondaries.

Figure 2.12: Itten's Hue Circle, duplicated from Sookoo [103]

Itten has also developed a color theory that describes seven types of contrast, including: (1) contrast of saturation, (2) contrast of light and dark, (3) contrast of extension (also known as contrast of proportion or size), (4) contrast of hue, (5) contrast of warm and cool (6) complementary contrast, and (7) simultaneous contrast [50]. The contrast of saturation is the difference between intense and dull colors. The contrast of light and dark is the difference between dark and light colors. The contrast of extension is the difference between large and small, long and short, wide and narrow, and thick and thin in relation to the visual weight of a color. The contrast of hue is the differences in color hues. Colors with greater distance on a hue circle have greater hue contrast. The contrast of warm and cool colors is the difference in warmth. The warmest colors are those from yellow to red-violet in the hue circle. The coolest colors are those from yellow-green to purple. Red-orange is the warmest color, and blue-green is the coolest color. The complementary contrast expresses the degree of complementarity the colors have. (Two colors are complements if mixing their pigments produces neutral gray.) The simultaneous contrast occurs between two colors that are not complements. It is caused when the human visual system simultaneously generates one color's complement as an after image, causing a sensation of contrast [50]. These contrasts were used by Sauvaget and Boyer [95] to determine the degree of harmony and then perform an automatic color adjustment on images to produce a harmonious image.

2.2.5 Nemcsics Color Theory

Another color model, which was created mostly for architects and visual designers (e.g., of web pages), is the ColorOid model of Nemcsics [76]. Its aim is to space colors in terms of vision system perception of viewers with normal color vision [128]. For example, colors C_1 and C_2 that are distance d apart in the Nemcsics' system are perceived by humans to have the same color difference as colors C_3 and C_4 that are also distance d apart. In addition, colors that are distance $2d$ apart in his system are perceived to have twice the color difference as colors that are distance d apart [128].

ColorOid views colors as having attributes of *hue, saturation,* and *luminosity.* It defines hue as the dominant wavelength of light, saturation as the degree of purity (colorfulness) of a color, and luminosity as the degree of brightness of a color.

The ColorOid was developed based on the results of a series of experiments that analyzed the perceptual properties of its attributes [80]. ColorOid models colors in a cylindrical space, as shown in Figure 2.13 [63]. The space's vertical axis, labeled V, is for luminosity, which represents the degree of whiteness. A direction quantity, labeled T, is for saturation. A color's distance from the vertical axis represents the amount of saturation, with the least-saturated colors placed at the vertical axis. The highest-saturated colors form the surface of the cylinder. The hue quantity, labeled A, expresses angular position, forming a hue circle on the base [57].

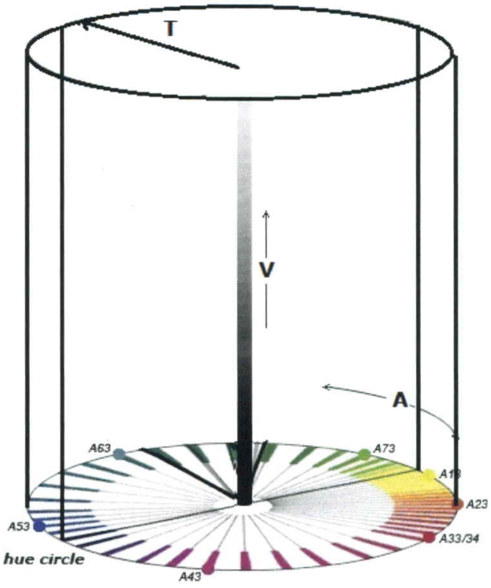


Figure 2.13: ColorOid Color space, duplicated from MacEvoy [63]

The ColorOid model has 48 basic hues, as shown in Figure 2.14. These hues have wavelengths between 450 and 625 nm [76]. Colors with a common hue but differing saturation and luminescence specify a half plane of constant hue. The 48 basic hues are partitioned into seven groups: yellow, orange, red, violet/purple, blue, cold green. and warm green. Each hue group has seven of the basic hues, except red, which has only six basic hues.

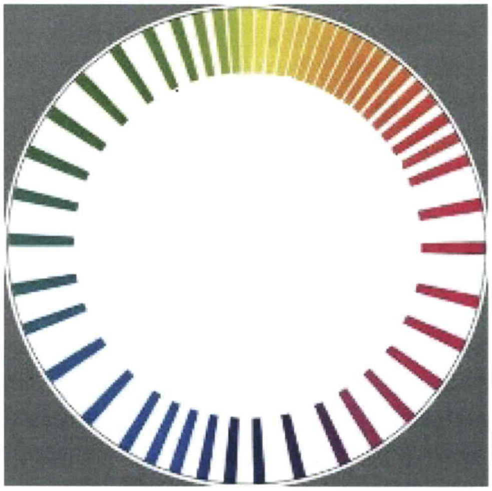


Figure 2.14: The ColorOid hue circle and its 48 basic hues, duplicated from Ahner [1]

2.2.6 Matsuda Color Theory

Matsuda's color model views colors as having attributes of *hue, brightness*, and *chroma*. The model uses idea from the Japanese PCCS color model, a two-dimensional model based on hue and tone, and Itten's hue circle. The PCCS tone dimension refers to intensity of a color and consists of value and chroma attributes. Matsuda pursued the Itten's ideas on two, three, four, and six combinations of colors on the hue circle to develop his hue templates [2]. Matsuda color model has four primary hues—red, blue, yellow, and green—which are located on opposite sides of Matsuda's hue circle. The hue circle has 24 segments, with colors arranged based on wavelength (i.e., yellow to green to blue to purple to red and to yellow again) [68].

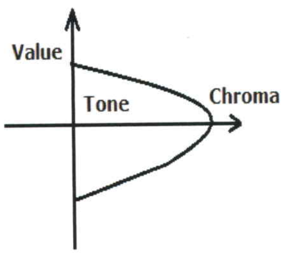


Figure 2.15: Matsuda's tone representation, reproduced from [81]

Matsuda color model is based on studies of people's preferences. In one study, Matsuda's students collected examples of their preferred color combinations in clothing, accessories, or backgrounds shown in fashion magazines. In the second study, Matsuda used color patterns (provided by fashion companies) that were popular in nine fashion seasons between 1979 and 1984 [68]. Matsuda plotted the hue of each color of a combination on his hue circle and plotted the tone of each of those colors on the tone dimension. Figure 2.15 shows the tone representation used by Matsuda. Its chroma and value are from Munsell's color model. Each tone distribution consists of colors whose tone falls within a range shown by shaded regions in Figure 2.16. Matsuda then categorized the color patterns into eight hue categories (named as hue templates) and ten color-tone distribution types, for a total of 80 classes of color patterns [21, 107]. Each hue template is a collection of hues sharing some radial relation on his hue circle. Therefore, any rotation of a given type of template is simply another instance of that template [21]. The tone distribution types are based on the value and chroma attributes. They are shown in Figure 2.16. He also formed groupings of colors based on the sensation each color elicited, such as vivid, bright, deep, and pale colors [68], but we do not focus on those groupings in this dissertation.

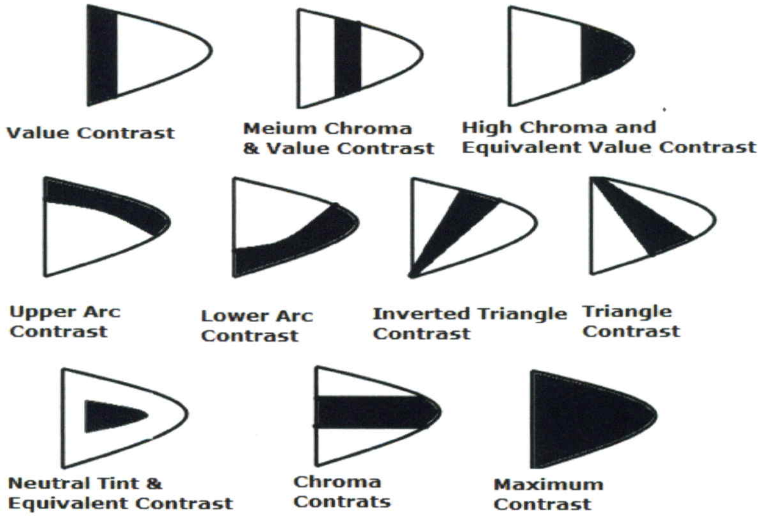


Figure 2.16: Matsuda's ten tone distribution types, reproduced from Tokumaru et al. [107]

2.3 Color Harmony

In this section, the definition of harmony and the color theorist point of view on color harmony are discussed. Harmony, in general, means a pleasing arrangement of parts. Harmony exists in many domains. For example, in music, harmony is an arrangement of musical notes or simultaneous combination of tones that are pleasing to the ear. A set of colors that creates an aesthetically pleasing perception when viewed together is called a harmonious color scheme (or a color harmony) [71]. Harmonious colors most likely are considered to be pleasing because of certain internal relationships between colors [21]. Such colors can deliver a sense of order and a balance to the visual experience [72].

Color harmony also has impact on how well human can perceive, remember, and recall color patterns. For example, experiments by Sanocki and Sulman [93] revealed that color patterns that have harmonious color combinations are 26% to 45% easier to perceive and hold in visual short-term memory than ones having non-harmonious colors. One visualization research team has also suggested that using harmonious color schemes may keep viewers engaged, thus promoting discovery of significant features or phenomena [115].

Color harmony is often defined based on some relations in color spaces, such as colors with equal hue, colors with equal chroma, and colors that have particular relative locations on the hue circle. For example, harmony based on relative location on the hue circle has been discussed by Goethe [32], Itten [49], Matsuda [68], and Lindner and Süsstrunk [61], and harmony based on equal hue and equal chroma has been discussed by Ostwald [85] and Munsell [73]. An overview of colormaps in visualization, including ones based on harmonies, has been presented by Zhou and Hansen [122]. Next, some key color harmony theories are discussed.

2.3.1 Goethe's Color Harmony

One early concept of color harmony, which is attributed to Goethe, uses Goethe's hue circle (as shown in Figure 2.8). We will call it Goethe's color harmony. In it, color harmony is related to the location of colors on his hue circle. His harmony concept was based on experience, empirical investigation, and his belief in the effect of colors on mood and emotion [32]. The concept considers any pair of colors located on opposite sides of his hue circle to be harmonious [82]. Therefore, the color pairs of (1) yellow and red, (2) blue and red, and (3) yellow and green are considered as having little or no harmony because they are not located on opposite sides of Goethe's hue circle.

2.3.2 Ostwald's Color Harmony

Another concept of color harmony is attributed to Ostwald. Ostwald's concept is based on his idea that any orderly arrangement of colors is harmonious [60, 71]. In his color model, colors are characterized by hue (color-content), white-content, and black-content. He believed color combinations with the equal hue (color-content) have harmony. He also believed that colors that lie in an orderly sequence in his color model are harmonious. His sequences can be colors of the same hue, colors of the same chromaticity, or colors of the same pleasing effect [60, 85]. He proposed his color-order as a "basic law" of color harmony [60, 85]. Ostwald color-order is defined using certain structures derived from the hue circle.

Monochromatic triangles are one of the structures that Ostwald used to describe his color-order. There is one monochromatic triangle for each hue of the Ostwald hue circle; there are a total of 24 monochromatic triangles (one per color segment on his hue circle) [60]. That hue is one vertex of the triangle. White and black are the two other vertices. The top side of the triangle is arranged in whiteness order and the bottom side of the triangle is arranged in blackness order. One triangle is shown in Figure 2.17. Each triangle has one side that arranges the achromatic colors from black to white in eight segments along the lightness axis (as shown on left side of Figure 2.17). Ostwald's law considers colors within a monochromatic triangle to be harmonious if they have equal white-content (which is called isotints) or equal black-content (which he named isotone—colors with the same degree of blackness). Also, in his view, a set of colors in different monochromatic triangles are harmonious if they have the same white-contents as well as the same black-contents [60].

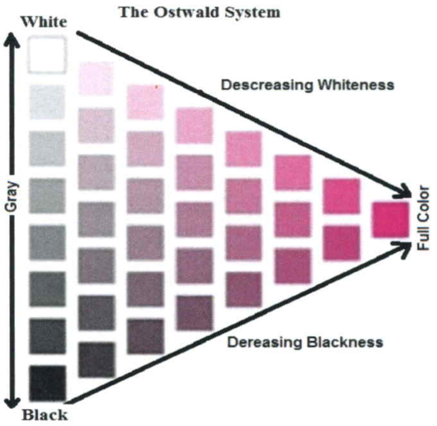


Figure 2.17: Ostwald Monochromatic Triangle, duplicated from Hernandez [42]

2.3.3 Itten's Color Harmony

Another color harmony concept is from Itten. His concept is based on an artistic point of view about color mixing (for example, if mixing two or more colors produces neutral gray, he believed those colors are harmonious). Itten also thought relationships between colors on his hue circle determined harmony [49, 50]. He described four types of these relations. They were the *dyads, triads, tetrads*, and *hexads* [49, 50]. Each of these relationships defines a different harmony. His *dyads* (or *complementaries)* involve two colors and occur when the two colors are on opposite sides of the hue circle. His *triads* involve three colors forming an equilateral triangle on the hue circle. His *tetrads* involve four colors forming a square, a rectangle (that also contains two complementary colors), or an isosceles trapezoid (from two adjacent colors (that we will call a and b) on one side of his hue circle and, on the side opposite to these, two other colors that are adjacent to a's complement and adjacent to b's complement [50]. His *hexads* involve six colors forming a hexagon (all sides with equal length) by connecting these colors on his hue circle [50]. Figure 2.18 presents examples of the Itten's harmonies. The concept of Itten's color model was used by Matsuda [68] and Tokumaru et al. [107], who introduced new sets of harmonious color combinations.

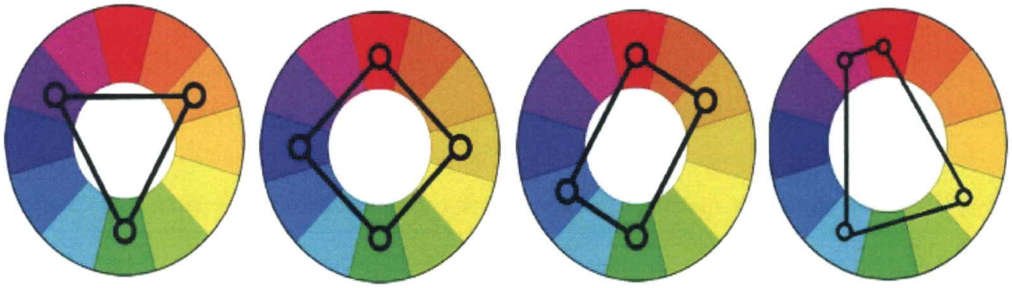


Figure 2.18: Triadic (Equilateral Triangle), Tetradic (Square), Tetradic (Rectangle), and Tetradic (Isosceles Trapezoid) Harmony Examples, reproduced from Itten [50]

2.3.4 Munsell's Color Harmony

Munsell's [73] color harmony is based on the idea of balance. Munsell believed two or more colors are harmonious if they are balanced in hue, chroma, and value. In contrast, he believed some paintings were unbalanced because their color combinations were “too weak or too strong” (unbalanced in chroma), “too light or too dark” (unbalanced in value), or “too hot or too cold” (unbalanced in hue). His idea of harmony is that the relationship between two components determines harmony: *strength*, which is the product of chroma (C) and value (V), and *area*, which is the amount of an image occupied by the color [37, 73]. His theory states that balance (harmony) between two colors in an image occurs when the product of *strength* and *area* of one color is equal to the product of *strength* and *area* of other color. A color is strong if it has a high product of value and chroma. Stated another way, balance for two colors occurs if the ratio of color areas is inversely proportional to the ratio of color strengths. In other words, harmonious colors satisfy:

$$\frac{A_1}{A_2} = \frac{V_2 \times C_2}{V_1 \times C_1}, \tag{2.2}$$

where A_1, V_1, C_1 are the area, value, and chroma, respectively, of the first color and A_2, V_2, C_2 are the area, value, and chroma, respectively, of the second color [63]. As an example, for a red color with C= 37.28 and V=6.16 (strength of 229.64) and a greenish-blue color with C=11.29 and V=7.66 (strength of 86.48) to be in harmony, the red part of the image must occupy a smaller area than the greenish-blue part of the image.

Like Itten, Munsell also believed that two colors are harmonious if their mixture produces neutral gray [20]. He called neutral gray the “central point of balance [20].”

2.3.5 Nemcsics' Color Harmony

The Nemcsics color harmony is based on contrast. In it, colors are harmonious when they have a contrast relationship in at least one of the three attributes of *hue, saturation,* or *luminosity.* It defined degree of hue contrast as the distance between colors in the hue circle. It also considered that colors harmonious based on hue contrasts had hue angles (hue expresses as angular position on the Nemcsics hue circle) between either 30 and 40 or 130 and 140 degrees [77,78]. It defined saturation contrast as the difference in perceived hues, due to the difference in lightness [80]. It defined luminosity contrast as the difference in lightness contrast. Luminosity contrast is independent from hue and saturation.

The Nemcsics color harmony has been used in visualization of volume data by Wang and Kaufman [116]. Their work introduced an automated algorithm to maintain the color harmony for direct volume renderings. Their algorithm also adjusts the saturation and lightness in the rendered image to provide a visually pleasing result [116].

2.3.6 Matsuda's Color Harmony

The Matsuda color harmony is based on the relative locations of colors on the Matsuda hue circle and on distribution of value and chroma. The harmonies are expressed by some of his hue templates. Matsuda named each template according to the shape of its associated gray area, as shown in Figure 2.19. The hue templates are the i-type ("Similar harmony"), V-type ("Adjacent harmony"), L-type ("Intermediate harmony"), I-type ("Complementary contrast"), T-type ("Complementary half circle"), Y-type ("Three point contrast"), X-type ("Multi complementary contrast"), and N-type ("Neutral value contrast"), as shown in Figure 2.19.

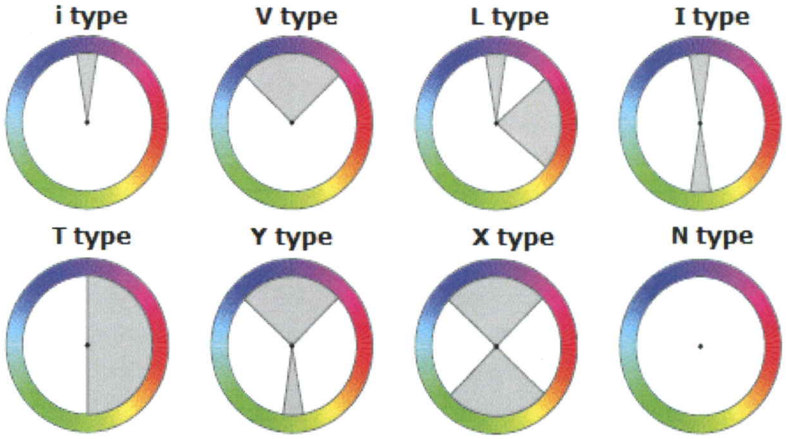


Figure 2.19: Matsuda's eight hue templates, reproduced from Cohen et al. [21]

While some reports have referred to all Matsuda's hue templates as being harmonious, Matsuda explicitly called only three of them as harmonious hue templates. These three hue templates are the i-type ("Similar harmony"), V-type ("Adjacent harmony"), and L-type ("Intermediate harmony").

Some of Matsuda's templates are similar to Itten's complementary contrasts. For example, in the Itten theory, colors that are on opposite side of hue circle form a complementary harmony [49]. Matsuda's I-,T-, and X-types of templates include colors that form complementary harmonies. On the other hand, Matsuda's N-type is similar to the Itten's idea that mixing two or more colors produce neutral gray that form harmonies [49,50]; and Matsuda's Y-type is similar to the simultaneous contrast of Itten [49].

The Matsuda work has been used and described by Tokumaru et al. [107], and his hue template has been used and described by Cohen-Or et al. [21], Wang and Mueller [114], and O'Donovan et al. [83]. In addition, Chamaret and Urban [16] have proposed an approach for assessing quality of a picture using Matsuda harmony templates. Matsuda hue templates also have been used by Chamaret [15] for automatic color harmonization of images (based in part also on Chamaret et al.'s [17] and Chamaret's [15] eye tracking studies).

Figures 2.20 and 2.21 show images, their main colors, and the location of those colors on the Itten hue circle. The image in Figure 2.20 has mostly yellow, yellow-green, and green colors, which are represented on the color bar in the center of Figure 2.20. These colors form a V-shape on Matsuda's hue circle, as illustrated on the right side of Figure 2.20. That shape corresponds to the "V-type" template. The image in Figure 2.21 has mostly greens and purples. These colors are represented on the color bar in the center of Figure 2.21. These colors form an I-shape on Matsuda's hue circle, as shown on the right side of Figure 2.21. That shape corresponds to the "I-type" template.

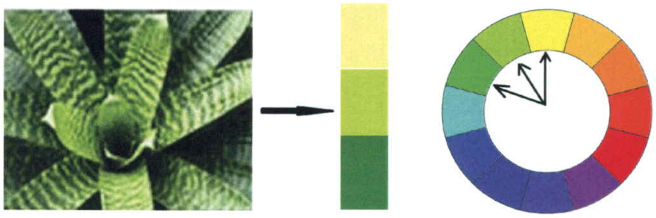


Figure 2.20: Image with color combinations of yellow and green (the "V-type" hue template), duplicated from Tokumaru [72]

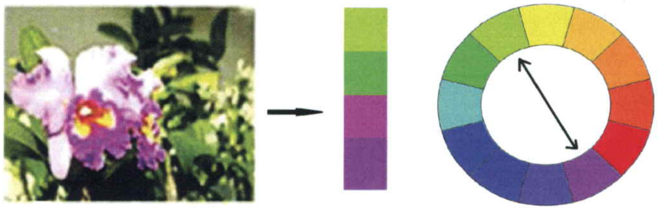


Figure 2.21: Image with color combinations of green and purple (the "I-type" hue template), duplicated from Morton [72]

2.4 Color Opponency

Human color perception was studied in the 1800s by philosophers, physiologists, artists, and psychologists. Schopenhauer, a philosopher, thought human vision used three opponent processes: red versus green, blue versus yellow, and black versus white (dark versus light) [60]. Later, in 1892, the physiologist Hering published his theory about color opponent processes in which he proposed the existence of four perceptual (chromatic) colors arranged as two sets of opposing complementaries on a hue circle, as shown in Figure 2.22, and two opposing achromatic colors. His theory was based on the observation that some color pairs never occur together. For example, Hering observed that we can perceive reddish blue (magenta), bluish green (cyan), greenish yellow, and reddish yellow (orange), but we never perceive reddish green or bluish yellow. Figure 2.22 illustrates the chromatic opponent colors of the hue circle. The center of the circle is neutral gray, which presents the result of mixing lights of complementary colors. The opposing colors of each opponent pair are located on opposite sides of the circle [65]. In fact, the three opponent processes proposed by Hering's theory have been found to actually exist in the human visual system [118].

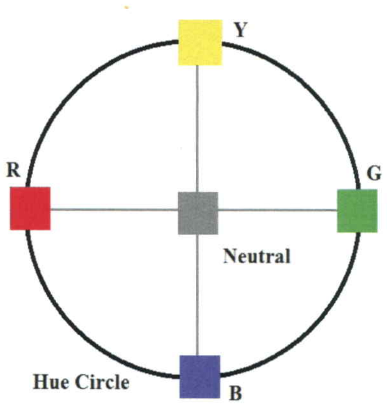


Figure 2.22: Presentation of chromatic opponent colors in hue circle, reproduced from MacEvoy [65]

The main idea behind Hering's opponent process theory was that the chromatic opponents of red with green (and blue with yellow) oppose because they are never simultaneously sensed in human vision. Activation of the sensing for one opponent color prevents activation of sensing for its opponent color (i.e., a single sensor location does not simultaneously sense opposing colors). In other word, responding to one member (color) of an opponent pair is antagonistic to responding to the other member of the pair [47]. Hurvich and Jameson [47] have called this phenomenon "hue cancellation." In the case of red light mixed with green light, the result is a cancellation that produces yellow. In the case of a mixture of yellow light and blue light, the result is a cancellation that produces white. These types of mixtures are said to cancel since each produces a color of another opponency channel.

Each chromatic opponent channel is controlled by opponent neurons. These opponent neurons have an excitatory response to one small range of wavelengths and an inhibitory response to another small range of wavelengths (i.e., the wavelength representing the opponent color). For example, certain neurons in the red-green channel may have a positive (excitatory) response to red colors and a negative (inhibitory) response to green colors; such neurons are sensitive to colors containing wavelengths associated with reds or greens [6, 41, 59, 112].

The opponent color theory also can explain the afterimage effect of still seeing an image (but in an opposing color) after it has vanished [134]. For example, staring at the white dot in the flag in Figure 2.23 for 10 seconds followed by moving eyes away produces an afterimage, like what is shown in Figure 2.24.

Figure 2.23: Initial image for after image effect, duplicated from Delecce [134]

Figure 2.24: The after image effect image, duplicated from Delecce [134]

2.5 Summary

In summary, this chapter has described some of the color models and color theories, with focus on ones related to harmony, disharmony, and opponency, including color harmony ideas and models from Goethe, Ostwald, Munsell, Itten, Nemcsics, and Matsuda.

A subset of the above color harmony rules are considered in this dissertation. The focus here is on studying effective color combinations using color harmony rules (i.e., based on the Itten, Nemcsics, and Matsuda color model), disharmony, and chromatic opponent colors in map-based and isosurface-based volume visualizations.

CHAPTER 3

USE OF COLOR THEORIES IN MAP-BASED VISUALIZATION

This chapter focuses on color theory in map-based visualization. Visual properties of well-designed maps are described first. Then, our studies of several classes of color combinations (i.e., harmonious, disharmonious, opponent, high and low saturated, and high and low lightness colors) in map-based visualization are presented.

3.1 Map-Based Visualization

Millions of maps are designed, produced, and used for scientific, political, environmental, and social needs. Maps are often used to find and identify data attributes that are spatially distributed. Some of the visual properties used by well-designed maps in presenting data attributes were made known by Tyner [109] and Darkes and Spence [22]. According to Tyner, maps are considered to be well designed and thus more usable if they have (or use): 1) clear and legible layouts (i.e., they can be read without confusion and difficulty), 2) an appropriate visual hierarchy expressed using size, color, or other visual attributes (which divides map elements into different levels of emphasis), and 3) colors and patterns that are well-understood (such as by using conventional meanings for colors like blue for water, green for grass, etc.) [109].

Darkes and Spence [22] described another set of visual properties of well-designed maps. Some of these properties are the use of: 1) good visual contrast (which is related to symbol size, color, shape, and orientation), 2) appropriate separation of figure and ground (which determines the important parts and separates them from background), and 3) balance between different parts of maps, including balanced typography (i.e., the typefaces are not too fancy or too big).

One of the focuses in this dissertation is on use of color in overlay-based visualization on a map.

In map-based visualization, the attributes (features) of the data are presented as the visual features of the map, often using symbols. One way to present these data attributes is as overlays on a map. Some overlays use graphical symbols, while others use letters, numbers, or words, and then use location, size, font, color, or direction of the words as the visual features. One of the parts of this dissertation research considers suitability of certain classes of color combinations for word overlays on maps.

Using color as a visual feature in map-based visualization has several advantages, such as (1) allowing more attributes to be displayed than if only grayscale was used, (2) allowing more variation (or distinguishing levels) to be displayed, and (3) possibly allowing easier discovery of the information on the map.

However, color must not be used randomly in maps [9]. Color must also serve a purpose in map-based visualization [108]. For example, in the case of maps, color could be used to enhance noticeability [22]. Color can be used to distinguish symbols that have the same shape [109]. Color can also be used to establish visual hierarchy [22, 109].

Colors are often represented using color models. If maps are designed for screen display, the RGB color model is a good choice because it is an additive model and it is often used by electronic display devices. If maps are designed for printing, the CMYK color model is a good choice. Unlike the RGB model, it is a subtractive color model, which is appropriate for printing. If maps are designed to be used interactively, the HSV color model is a good choice because it is quite similar to the way humans perceive color. HSV is also conceptually simple —each attribute of HSV color model corresponds to a basic color concept (i.e., hue, saturation, and value). It is also easy to convert HSV color to RGB.

Cartographers have certain guidelines for color selection to display information on maps. Some of these guidelines are: 1) a few shades of one color should be used for distinguishing the levels of one attribute, (for example, to represent elevation levels) [9], 2) high chroma should be used for displaying attributes that need to be emphasized [8, 9], 3) different shades of a single hue should be used in shaded areas of the background [9, 22], 4) bright colors should be used for the attributes that are the highest in a hierarchy [9, 22, 109], 5) contrast in color should be used for distinguishing attributes [22], and 6) saturated colors should be used for distinguishing overlays from the surrounding area [9, 22, 109], etc.

Saturated colors also have other values in maps. For example, Brown and Feringa [9] have observed that the use of highly saturated colors for feature overlays in maps often draws viewer attention. In addition, Tyner [109] has observed that using differences in saturation can allow observers to distinguish subcategories within categories, for example, vegetation types. Moreover, Darkes and Spence [22] have observed that distinguishability of features on a map can be improved by rendering the important features using more saturated colors and rendering the background using less saturated colors. Brewer [8] has also suggested that small symbols or features on the map can be distinguished by using a higher saturation for them than is used for the background. She has also pointed out that saturation must be used carefully, especially for large areas; the most saturated colors may appear to dominate the map.

There are also some guidelines (suggested by [8, 9, 22]) cartographers use for text overlays on a map. Some of these are: 1) shadows for text overlays should be used to increase the legibility of text, 2) halos should be used for text overlays to increase legibility, especially when there are lines on the map, 3) uppercase letters should be used to indicate important features or attributes that are the highest in a hierarchy, 4) lowercase letters should be used to indicate attributes that are the lowest in a hierarchy, 5) different hues should be used for different categories, 6) lightness levels should be used for indicating ordering in ordinal data (e.g., using light blue for shallow water and dark blue for deep water), and 7) contrast should be used to enhance differences between adjacent objects.

The focus of this dissertation is to investigate distinguishability of attributes overlaid on maps in map-based information visualization using certain classes of color combinations (i.e., harmonious, disharmonious, opponent, high (and low) saturated, and high (and low) lightness combinations). Most of the investigation is based on user evaluations of these overlays.

3.2 Experimental Design

Here, the detailed design of the studies are presented. Seven classes of experiments were performed. Six classes involved participants.

The study participants all had normal or corrected-to-normal vision and no known visual impairments. We recruited participants who either reported they knew they were not color blind or, if they were uncertain, passed a color test we administered. Thus, all participants were likely not color blind. They were all older than age 18 and either undergraduate or graduate students with some computing knowledge. Each participant took 10 to 15 minutes to complete their part of the study. All experiments involved seated participants. All participants had the possibility to adjust the chair and monitor height, orientation, and distance to their preference for comfort. In addition, room lighting was identical for all participants.

Most experiments involved viewing label overlays on single- or multi-color background maps. One experiment instead involved viewing glyph overlays on a single-color background map. All participants viewed the visualizations on the same 20-inch LCD display with a pixel resolution of $1,680 \times 1,050$. The display was color-calibrated at least once per week or after every fifth participant, whichever came first. This calibration was performed using the Windows 7 display color calibration and the PowerStrip [129] calibration packages.

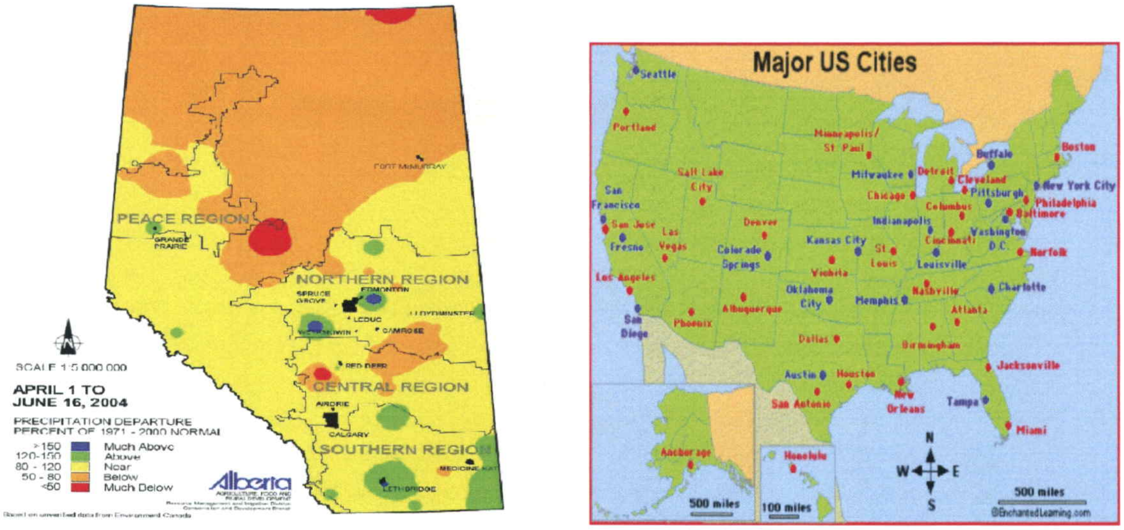
The overlays used certain classes of color combinations whose effectiveness we wanted to examine. These included colors (1) harmonious with the background color(s); (2) disharmonious with the background color(s); or (3) having an opponency relationship with the background color(s). Three types of color harmony models were also examined against each other: Itten, Matsuda, and Nemcsics harmonies.

The raw maps used in the visualizations were JPEG files. The map resolutions were 570 × 770, 960 × 550, 995 × 700, or 1024 × 567. They were first converted to bitmaps. Then, we determined the color of map backgrounds using the color picker tool of the ColorWheel Expert [127] software. The maps were next imported into OpenGL. Then, label overlays were generated using OpenGL with GLUT, drawn atop maps. Each overlay character was a bitmap font of size 8 by 13 pixels (i.e., generated using GLUT_BITMAP_8_BY_13). The overlaid label colors were selected using ColorWheel Expert, to be harmonious, disharmonious, or opponent (as appropriate) to the background. After adding the labels we made sure that labels still maintained a harmonious, disharmonious, or opponent color relationship (as appropriate) with the background color.

In the experiments, participants completed timed tasks and/or answered questions about which color combinations were preferred and which color combinations were distinct. The questions were:

(1) Which color combinations of label overlays on maps were most distinct?

(2) For the label overlays, are there any differences between Itten and Nemcsics harmonies?



(a) Crowded Map A (before additional overlays) (b) Crowded Map B (before additional overlays)

Figure 3.1: Group One maps

(3) Are disharmonious (or opponent) color combinations more distinguishable than harmonious ones? Which color combinations are preferred?

(4) For the label overlays, are opponent color combinations more distinguishable than disharmonious color combinations? Which color combinations are preferred?

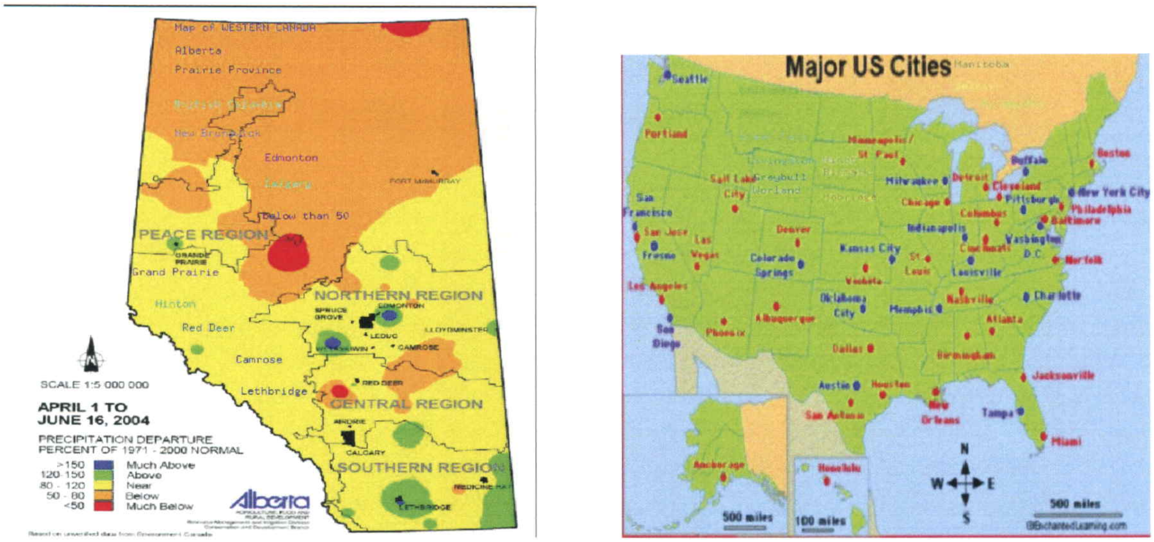
(5) For the label overlays, which color combinations (i.e., disharmonious, high saturated, low saturated, high lightness, low lightness) are most distinct?

All the experiments involving users were IRB-approved. Details of these experiments are discussed in the following sections.

3.2.1 Experiment One: Itten Harmonies vs. Disharmonies For Label Overlays

In Experiment One, participants considered disharmonious colors versus Itten harmonious color combinations for label overlays. This experiment was designed to evaluate the noticeability of Itten color harmonies versus disharmonious color overlays. The participants viewed two maps (a map of the Canadian province of Alberta and a map of the entire United States). These maps are called the Crowded Maps A and B, as shown in Figure 3.1. These maps already contained labels for some well known places. Additional color labels of relatively less well-known place names were added to these maps. Two sets of overlays were generated. Set One used a total of 13 harmoniously colored labels and Set Two used a total of 13 disharmoniously colored labels. The harmoniously colored label overlays were based on the Itten rules of harmony. The disharmoniously colored label overlays were based on colors separated by 80 or 150 degrees on the hue circle from background colors. Since some research has previously suggested that two colors separated by 80 degrees on the Nemcsics hue circle had less harmony than two colors separated by any other degree of separation [80], the labels in colors located 80 degrees from background color on the hue circle were taken to be one of the disharmoniously colored labels.

The maps with added harmoniously colored labels were viewed by participants. The participants were asked to recite the label overlays in perceived noticeability order. Next, the maps with added disharmoniously colored labels were viewed by participants. The participants were asked to recite the label overlays in perceived



(a) Crowded Map A (after added overlays)

(b) Crowded Map B (after added overlays)

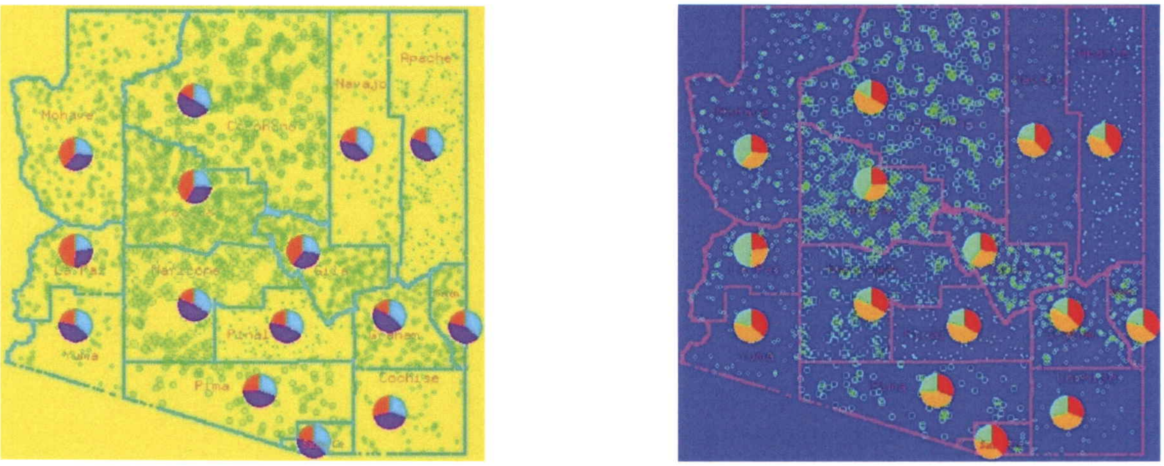
Figure 3.2: Crowded maps with added harmoniously colored overlaid labels

noticeability order. The time to complete the task of reciting these labels was recorded for each participant. These times were taken as the base measure for the degree of noticeability.

Twenty volunteers (10 males and 10 females) took part in Experiment One.

3.2.2 Experiment Two: Itten Harmony vs. Disharmonies for Glyph Overlays

Experiment Two was designed to evaluate the noticeability of Itten harmonious versus disharmonious color combinations (i.e., colors separated by 80 or 150 degree on the Itten hue circle). The participants viewed pairs of map-based visualizations of county-by-county demographic information of the state of Arizona. The demographic data was retrieved from the United States Census website [137]. For each county, the counts of paid employees, employee ratio, and the counts of population based on age



(a) Itten Harmonies

(b) 150 degree Disharmonies

Figure 3.3: Example of map-based visualization using Itten harmonies and disharmonies on Itten hue circle

distribution (i.e., less than 20 years old, between 20 and 50 years old, and over 50 years old) during 2011 were determined. In the visualization, one color was used to represent each dimension of the multivariate data. In these visualizations, a dot glyph was used. The number of dots represented the working age population and the size of the dots represented paid employees. Pie charts represented age (with pie slice sizes used to represent the three classes: less than 20 years old, between 20 and 50 years old, and over 50 years old).

Four instances of harmonious color map-based glyph visualizations were used. For each background color (i.e., red, blue, green, and yellow background color), four Itten harmonious colors with the background were utilized for glyph overlays. The harmonious color combinations were chosen based on Itten's four-color harmonies (i.e., his tetrad harmonies, which form a rectangle on Itten hue circle).

Four instances of disharmonious color map-based glyph visualizations were also used. For each background color (i.e., red, blue, green, and yellow), four colors disharmonious with the background were utilized. The disharmonious color combinations were colors that separated by 150 or 210 degree from the background color on the Itten hue circle.

Figure 3.3 shows two of the visualizations based on Itten tetrad harmonies (left) and disharmonies (right).

Participants compared pairs of visualizations to answer following questions: (1) which visualization of the pair was distinct? and (2) which visualization of the pair was preferred?

Thirty volunteers (15 females and 15 males) took part in Experiment Two.

3.2.3 Experiment Three: Matsuda Harmonies vs. Disharmony

In Experiment Three, participants considered the Matsuda i-type harmonies versus disharmonious color overlays and overlays that were neither harmonious nor disharmonious. The experiment was designed to evaluate noticeability of Matsuda i-type harmonies versus disharmonious color overlays. The participants viewed three color maps of the U.S. state of Alabama, as shown in Figure 3.4.

Twelve labels were overlaid on each map using different colors. The colors were chosen based on their position on the hue circle. Two of the labels had a color that formed a Matsuda i-type harmony with the main background color. They were colors offset by 30 and 330 degrees clockwise from the background color. Three of the labels had a color that formed disharmonies with the background color. They were

(a) (b) (c)

Figure 3.4: Political Information of a U.S state (Alabama)

colors offset by 80, 150, and 210 degrees clockwise from the background color. The other labels were colored with colors positioned on the hue circle offset by 60°, 90°, 120°, 180°, 240°, 270°, and 300° clockwise from the background color.

The participants were asked to recite the overlaid labels in perceived noticeability order, from most to least noticeable. The time for reciting each label was recorded for each participant and taken as the base measure for the degree of noticeability. The participants were limited to 30 seconds to recite the label overlays. For any label not seen by participants a value of 31 seconds was recorded. For each participants 12 measures were recorded. Participants were also asked to report which color overlay on each map was the most pleasant and the most distinct color.

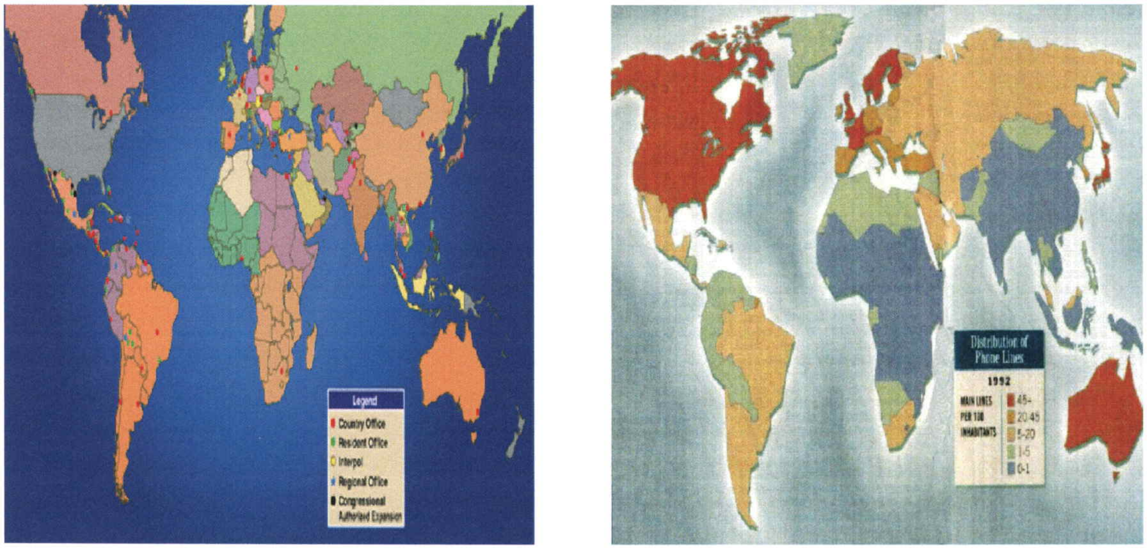
Thirty volunteers (15 males and 15 females) took part in Experiment Three. Ten of these participants noticed all the labels and eight of these participants could not notice three or more of the labels.

3.2.4 Experiment Four: Nemcsics vs. Itten Harmonies

In Experiment Four, participants considered overlays using Nemcsics harmonies versus overlays using Itten harmonies. The experiment was designed to evaluate noticeability of Nemcsics harmonies versus Itten harmonies for label overlays on maps. The participants viewed two groups of visualizations. Group One used two maps that were also used in Experiment One (Crowded Maps A and B), as shown in Figure 3.1. Group Two used three maps (maps of the world), which displayed certain features of political subdivisions using color codings. The Group Two maps had no overlaid labels, as shown in Figure 3.5 (a, b, and c). These maps are termed here "the non-crowded maps." In both groups, two instances of each map were used. One instance used harmoniously colored label overlays according to the Itten harmonies. The other instance used harmoniously colored label overlays according to the Nemcsics harmonies. For eliminating possible biases from personal knowledge, relatively unknown place names were utilized for the added label overlays.

Example of crowded and non-crowded maps with added label overlays using Itten harmonies are shown in Figure 3.6 (a and b).

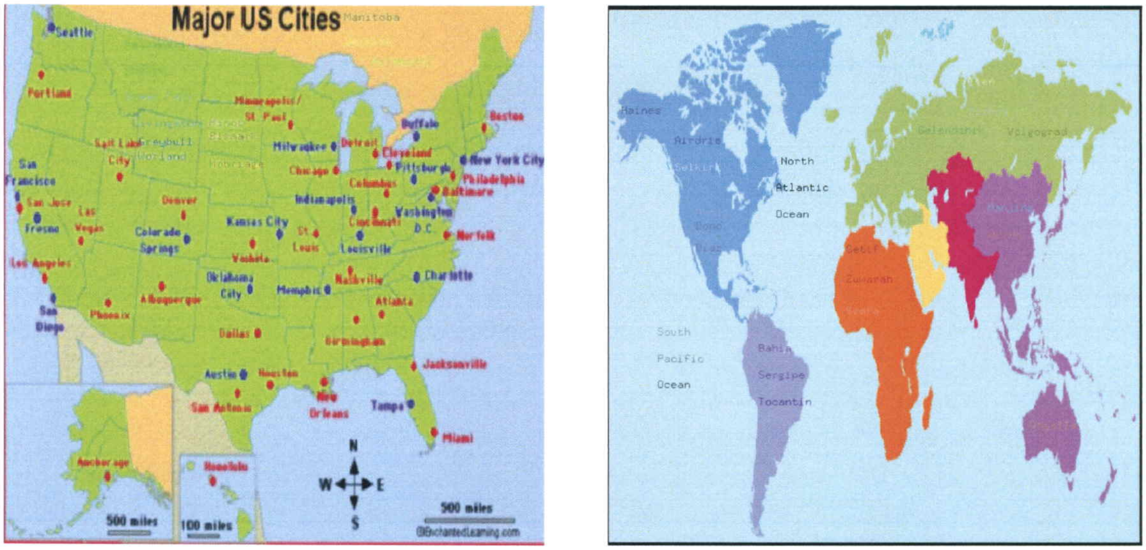
For each group of maps, the participants were given a task to recite the overlaid labels in perceived noticeability order. The maps were presented in a randomized order to limit possible biases based on order. Each participant's total elapsed time to recite the labels was recorded. These times were taken as the base measure for the degree of noticeability. Participants were also asked to report which color overlay on each map was the most noticeable.



(a) (Non-Crowded) Map#1 (b) (Non-Crowded) Map#2

(c) (Non-Crowded) Map#3

Figure 3.5: Group Two maps



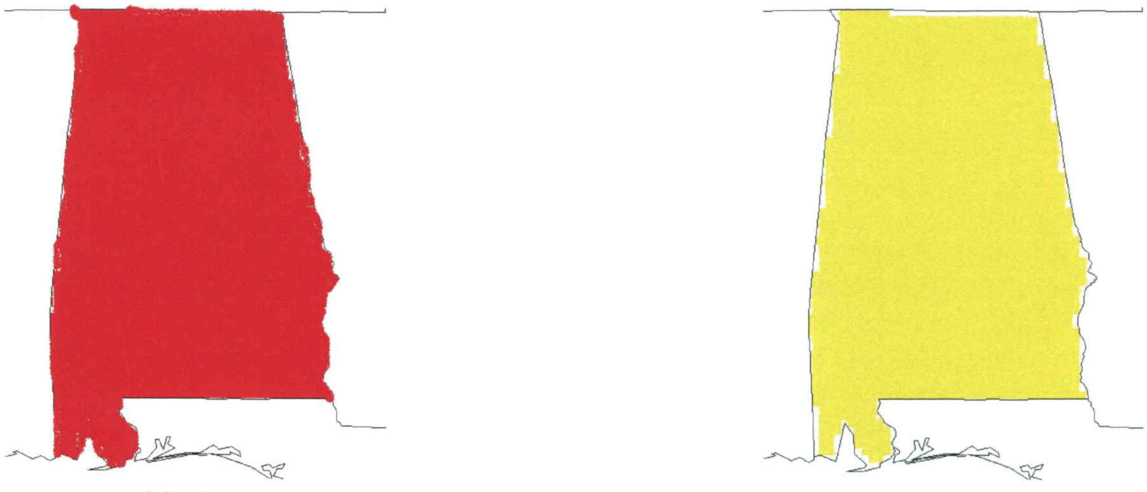
(a) Crowded Map B (b) Non-Crowded Map#3

Figure 3.6: Two maps with added label overlays using Itten harmonies

Forty volunteers (20 males and 20 females) took part in Experiment Four.

3.2.5 Experiment Five: Disharmonious vs. Opponent

In Experiment Five, participants considered disharmonious color overlays versus opponent ones. In it, four colored maps of the U.S. state of Alabama, called Map1, Map2, Map3, and Map4, were viewed by participants. The maps had solid background colors: red for Map1, yellow for Map2, green for Map3, and blue for Map4. Figure 3.7 shows Map1 and Map2 before adding any label overlays. Some of the disharmoniously colored label overlays were in colors separated by 150 degrees on the hue circle from the background color. The others were in colors separated by 80 degrees on the hue circle from the background color. The label overlays forming



(a) Map1

(b) Map2

Figure 3.7: The U.S. state (Alabama) map with two different background colors

opponent color combinations with the background were chosen based on chromatic opponency (i.e., red-green and blue-yellow).

Participants viewed a series of map pairs. In each pair, one map used a disharmoniously colored label and the other used either another disharmoniously colored label or an opponent color label. For each pair, participants reported which label was the most noticeable. The total number of participants choosing each label type as the most noticeable one was then determined. These values were recorded as the base measure for the degree of noticeability.

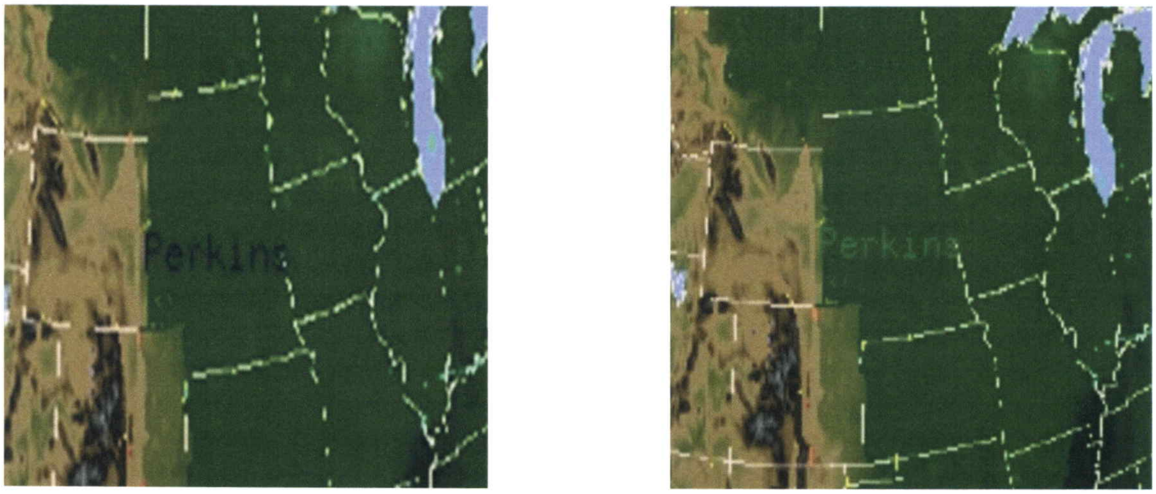
Twenty one volunteers (11 males and 10 females) took part in Experiment Five.

3.2.6 Experiment Six: Disharmonious vs. Saturated vs. Lightness Colors

In Experiment Six, participants considered four alternative color combinations against each other: high saturated, low saturated, high lightness, and low lightness color overlays. These were compared to one another and to labels colored disharmoniously. In it, participants made pairwise comparison.The labels were overlaid on eight colored weather maps of the entire United States. These maps were from the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service. The disharmoniously colored label overlays were positioned at 150 degrees separation on the hue circle from the background color. This choice was based on the result of the experiment described in Section 3.2.1. (Those results are presented in a later section, Section 4.6.) The color of these labels also had 42% level of saturation and 58% level of lightness. The color combinations for both the high and low saturation label overlays had a 58% level of lightness. The color combinations for both the high and low lightness label overlays had a 42% level of saturation. (These saturation and lightness levels are the colors' **S** and **L** values in the HSL color model.)

The same labels were used in all maps in the same locations (although in suitable colors for the trial). Figure 3.8 shows examples of one map with a disharmoniously colored overlay (left) and another map with a low saturated color overlay (right). For presentation purposes, this figure is zoomed-in.

Participants viewed a series of map pairs. In one series, one map used a disharmonious color label and the other map used either a high (or low) saturated color or a high (or low) lightness color label. In another series, one map used a high



(a) Overlay with disharmonious color (b) Overlay with low saturated color

Figure 3.8: Weather forecast map (zoomed-in) with added label overlay (Perkins) using disharmony and low saturated colors

saturated color label and the other map used either a low saturated color label, or a high lightness color label, or a low lightness color label. Finally, in the last series, one map used a high lightness color label and the other used a low lightness color label. For each pair, participants reported which label was the most noticeable. The total number of participants choosing each label type as the most noticeable one was recorded. For each participant, the percentage of times for each color combination type was also determined. These values were recorded as the base measure for the degree of noticeability.

Twenty six volunteers (13 males and 10 females) took part in Experiment Six.

3.2.7 Experiment Seven: Investigation on Existing Maps

In Experiment Seven, an investigation on color combinations used in an existing weather forecast visualization was performed. The investigation used a series of approximately 10 weather forecast visualization maps from the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service [126] that already had color overlays of some weather and geographic features (i.e., fronts, low pressures, and high pressures). Figure 3.9 shows an example of one of the NOAA maps. We found that the color overlays on these maps appeared to follow a variety of color theories or properties. For example, some overlays used Itten harmonies (which were explained in the Section 2.3.3). There are ten harmonious overlays on the map in Figure 3.9. Figure 3.10 (a) shows one of these (i.e., of the label 1020), which is harmonious with the background color. We also found that some overlays used disharmonious colors. There are ten disharmoniously colored overlays on the map in Figure 3.9. Figure 3.10 (b) shows one of these (i.e., of the label **L**), which is disharmonious (i.e., in a color offset by 150°) with the background color. We also found that some overlays used chromatic opponent colors. There are twelve opponent overlays on the map in Figure 3.9. Figure 3.11 (a) shows some of these. (The opponent color overlays are the yellow numbers. They are opponent with the blue background). Lastly, we found that some overlays used saturated colors. There are eight saturated overlays on the map in Figure 3.9. Figure 3.11 (b) shows one of these (i.e., of the label **H**), which has a saturation level of 99% against a background saturation level of 38%.

3.3 Summary

In this chapter we reported seven experiments to investigate distinguishability resulting from certain color combinations in map-based visualization. The ex-

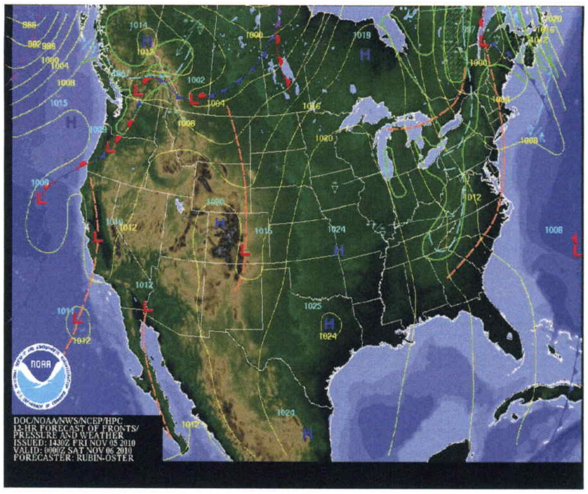
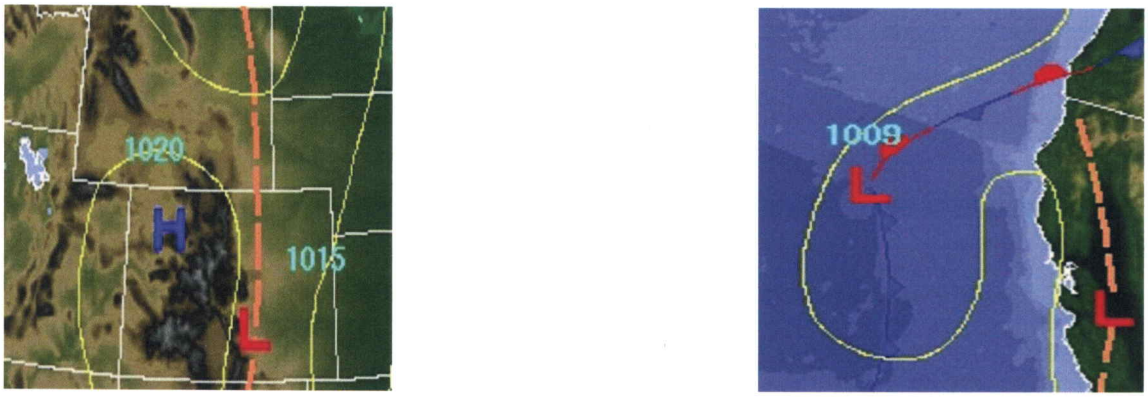


Figure 3.9: Weather forecast map from the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service [126]



(a) Harmonious Overlay (**1020**)

(b) Disharmonious Overlay (**L**)

Figure 3.10: Weather forecast map (zoomed-in) with harmoniously and disharmoniously colored overlays from background colors

periments focused on noticeability of overlays on a map. The color combinations considered were (1) harmonious colors (based on Itten, Nemcsics, and Matsuda harmonies), (2) disharmonious colors, (3) chromatic opponent colors, (4) high and low

(a) Opponent Overlays (yellow numbers)

(b) Saturated Overlay (**H**)

Figure 3.11: Weather forecast map (zoomed-in) with chromatic opponent and saturated overlays from background colors

saturated colors, and (5) high and low lightness colors. One experiment investigated color combinations in some existing weather forecast visualizations.

CHAPTER 4

EXPERIMENTAL RESULTS AND STATISTICAL ANALYSIS OF USING COLOR THEORIES IN MAP-BASED VISUALIZATION

This chapter presents the statistical tests and analysis that were performed for each experiment described in Chapter 3. The statistical testing involves using z-Tests and t-Tests at the 95% confidence level to determine statistical significance.

4.1 Experiment One: Itten Harmonies vs. Disharmony for Label Overlays

As stated in Section 3.2.1, in Experiment One (1) 13 instances of harmoniously colored overlays were considered on each map, and (2) 13 instances of disharmoniously colored overlays were considered on each map.

4.1.1 Raw Results of Experiment One

Table 4.1 shows the average response times (in seconds) for Experiment One's task of finding the label overlays on crowded maps (that were shown in Figure 3.1 (a, b)) colored harmoniously, according to Itten harmonies, and colored disharmoniously. Table 4.2 summarizes the overall average response times (in seconds) for the experiment. In these results, the labels that were colored disharmoniously often were found in under 3 seconds. In addition, the labels that were colored harmoniously often were found in more than 3 seconds.

Table 4.1: Average time (sec) to find the label overlays on the two crowded maps.

	Color Theory	Label #												
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
Map1	Disharmony	3.1	4.2	3.4	3.8	2.1	2.6	2.1	2.8	2.6	1.4	2.3	1.8	2.6
	Harmony	4.4	5.2	4.4	5.0	3.7	2.9	2.8	3.7	4.4	4.1	4.9	3.2	3.3
Map2	Disharmony	1.4	3.0	2.0	2.0	2.3	2.0	2.0	1.7	1.8	2.0	1.4	2.1	1.4
	Harmony	2.4	3.9	2.5	3.4	3.0	3.2	3.0	3.0	2.5	2.1	3.1	3.5	2.7

Table 4.2: Average time (sec) to find the label overlays on the maps.

Color Theory	Label #												
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
Disharmony	2.2	3.6	2.7	2.9	2.2	2.3	2.0	2.3	2.2	1.7	1.9	1.9	2.0
Harmony	3.4	4.6	3.6	4.2	3.4	3.0	2.9	3.4	3.4	3.1	3.7	3.4	3.0

Tables 4.3 and 4.4 show the average response time, in seconds, for finding label overlays colored harmoniously versus colored disharmoniously for the male and female participants, respectively. In both cases the disharmoniously colored label overlays were usually noticed first.

Table 4.3: Average time, (sec), to find the label overlays on the maps for **male** participants.

Color Theory	Label #												
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
Disharmony	2.4	4.3	2.9	3.3	2.4	3.1	2.4	2.6	2.4	1.8	2.6	2.3	2.2
Harmony	4.1	4.5	4.0	4.0	3.2	3.2	3.7	3.0	3.9	3.5	4.4	3.5	3.2

Table 4.4: Average time, (sec), to find the label overlays on the maps for **female** participants.

Color Theory	Label #												
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
Disharmony	2.0	2.9	2.5	2.5	2.1	1.5	1.7	1.9	2.0	1.6	1.2	1.6	1.8
Harmony	2.7	4.6	3.0	4.4	3.6	2.8	2.2	3.8	2.9	2.8	3.1	3.3	2.8

The overall average response times for each of the color theories tested is shown in Table 4.5. The overall average response time for finding labels colored disharmoniously with the background color was 2.28 seconds and average time for finding labels colored harmoniously was 3.44 seconds. Therefore, in these trials labels colored disharmoniously were distinguished 66% faster than labels colored harmoniously with the background color.

Table 4.5: Two sample t-Test for disharmonious vs. Itten harmonious overlays

	Harmonious	Disharmonious
Mean	3.44	2.28
Variance	0.22	0.26
Observations	13	13
t-Stat	6.024	
t-Critical	1.711	⇒ SIGNIFICANT

4.1.2 Analysis of Experiment One

To determine the statistical significance of the difference in response times for label overlays colored harmoniously versus disharmoniously in Experiment One, a two sample t-Test was performed. Table 4.5 includes the t-Test results. The t-Test of the results here show there is strong evidence that label overlays colored disharmoniously are more noticeable than labels colored harmoniously (at least according to Itten's harmony theory).

The overall average response time by male participants for finding labels colored disharmoniously with the background color was 2.64 seconds and average time for finding labels colored harmoniously was 3.68 seconds. Table 4.6 presents the t-Test results for male participants.

Table 4.6: Two sample t-Test for Male participants using disharmonious vs. Itten harmonious overlays

	Harmonious	Disharmonious
Mean	3.68	2.64
Variance	0.24	0.40
Observations	13	13
t-Stat	4.681	
t-Critical	1.711	⇒ SIGNIFICANT

The overall average response time by female participants for finding labels colored disharmoniously with the background color was 1.92 seconds and average time for finding labels colored harmoniously was 3.20 seconds. Table 4.7 presents the t-Test results for female participants. The results in both cases suggest there were statistically significant time differences between finding labels colored disharmoniously and labels colored harmoniously for both males and females.

Table 4.7: Two sample t-Test for Female participants using disharmonious vs. Itten harmonious overlays

	Harmonious	Disharmonious
Mean	3.20	1.92
Variance	0.49	0.22
Observations	13	13
t-Stat	5.423	
t-Critical	1.711	⇒ SIGNIFICANT

4.2 Experiment Two: Itten Harmonies vs. Disharmonies for Glyph Overlays

As stated in Section 3.2.2, in Experiment Two the demographic information of each county in the state of Arizona was visualized using glyph overlays colored with (1) harmonious and (2) disharmonious color combinations.

4.2.1 Raw Results of Experiment Two

Table 4.8 shows counts of participant choices for the experiment's evaluation of distinctness for glyph-based visualizations using harmonious versus disharmonious color combinations. Results are broken out by background color. In this experiment, participants found the overlays colored with the Itten harmonies to be more distinct somewhat more often than those colored disharmoniously.

Table 4.8: Count of participants' responses who noticed glyph overlays using Itten harmonies vs. disharmonies

	Pairwise Distinctness Comparison	
Background Color	Itten Harmony	Disharmony
Red	16	14
Green	17	15
Blue	18	11
Yellow	19	13

Table 4.9 shows counts of participant choices for the experiment's evaluation of preference for glyph-based visualizations using harmonious color combinations versus disharmonious color combinations. Results are broken out by background color. In this experiment, for one background color more participants preferred the overlays colored disharmoniously, but for two other background colors more participants preferred overlays colored harmoniously.

Table 4.9: Count of participants' responses who preferred glyph overlays using harmonious vs. disharmonious color combinations

	Pairwise Preference Comparison	
Background Color	Itten Harmony	Disharmony
Red	16	14
Green	12	18
Blue	16	14
Yellow	15	15

Next we report an overall summary of the distinctness results. Table 4.10 shows the results. Here, the averages are the average selection count (e.g., 2.33 for Itten harmonies means the average person chose the Itten harmonious color overlays as the most distinct one for 2.33 of the 4 trials). In these trials glyph overlays colored harmoniously were the more common choice.

Table 4.10: Two sample t-Test for distinctness of Itten harmonies versus disharmonies for glyphs

Pairwise Distinctness Comparison		
	Itten Harmonies	Disharmonies
Mean	2.33	1.77
Variance	0.85	0.87
Observations	30	30
t-Stat	2.36	
t-Critical	2.002	⇒ SIGNIFICANT

The overall averages of the preference results are shown in Table 4.11. Here, the averages are the average selection count (e.g., 2.03 for disharmonies means the average person chose the disharmonious color glyph overlay as the most preferred one for 2.03 of the 4 trials). In these trials there was no common choice for preference of glyph overlays colored harmoniously versus the ones colored disharmoniously.

Table 4.11: Two sample t-Test for preference of Itten harmonies versus disharmonies

Pairwise Preference Comparison		
	Disharmonies	Itten Harmonies
Mean	2.03	1.97
Variance	0.73	0.73
Observations	30	30
t-Stat	0.30	
t-Critical	2.002	⇒ NOT SIGNIFICANT

4.2.2 Analysis of Experiment Two

To determine the statistical significance of the difference in distinctness of the Itten harmonies versus the disharmonious color glyph overlays, two sample t-Testing was performed. Table 4.10 includes the t-Test results. There was a statistically significant difference in the distinctness of the Itten harmonies and disharmonious color combinations; glyph overlays colored with Itten harmonies are likely more noticeable than disharmonies.

To determine the statistical significance of the difference in preference of the Itten harmonies versus the disharmonies color overlays, two sample t-Testing was performed. Table 4.11 includes the t-Test results. There was no statistically significant difference in the preference of the Itten harmonies and disharmonies for glyph overlays.

4.3 Experiment Three: Matsuda i-type Harmonies vs. Disharmony

Next, the Experiment Three results are presented. As stated earlier, the experiment considered the Matsuda i-type harmonies, disharmonies, and labels that were not definitively harmonious or disharmonious (according to the Matsuda theory).

4.3.1 Raw Results of Experiment Three

Table 4.12 shows the average response times to find each label for the 22 participants who recited all, all but one, or all but two of the labels. The results are broken out by the color's offset (clockwise on the hue circle) from the dominant color of the background. In this experiment, the labels whose colors were 150 degrees from the background color tended to be the first ones noticed, whereas the labels whose colors formed a Matsuda i-type harmony with the background (i.e., especially the labels whose colors were positioned 330° clockwise from the background) tended to be noticed later.

Table 4.12: Average Time (sec) per overlay color to find labels

	Label Color offset											
	30°	60°	80°	90°	120°	150°	180°	210°	240°	270°	300°	330°
Time	13.45	21.64	18.64	22.77	12.36	7.45	10.68	11.23	11.37	11.91	16.86	22.23

The overall average response times are broken out by theory in Table 4.13. The i-type harmony labels were found in an average of 5.4 seconds more time than the disharmoniously colored labels.

Table 4.13: The two sample t-Test for i-type harmonies vs. disharmonies

	i-Type Harmonies	Disharmonies
Mean	17.84	12.44
Variance	23.87	5.62
Observations	22	22
t-Stat	4.665	
t-Critical	1.717	⇒ SIGNIFICANT

We also considered the difference in response times for the Matsuda i-type harmonies versus the non i-type color combinations. The averages for each are shown in Table 4.14.

Table 4.14: The two sample t-Test for i-type harmonies vs. non i-type colors

	i-type Harmonies	Non i-type Colors
Mean	17.84	14.53
Variance	23.87	4.93
Observations	22	22
T-Stat	2.896	
t-Critical	1.717	⇒ SIGNIFICANT

Finally, we considered the difference in response time for the 80 degree disharmonies versus the 150 degree disharmonies. The averages for each one are shown in Table 4.15. The 80 degree disharmony labels were found in about twice the time as the 150 degree ones.

Table 4.15: The two sample t-Test for 80 degrees vs. 150 degrees disharmonies

	150 degree	80 degree
Mean	7.45	18.64
Variance	15.83	35.29
Observations	22	22
t-Stat	6.097	
t-Critical	1.717	⇒ SIGNIFICANT

4.3.2 Analysis of Experiment Three

To determine statistical significance of the difference in response times for label overlays that were i-type Matsuda harmonies (i.e., colors at offsets of 30 and 330 degrees from the background color) versus ones that were disharmonies (i.e., colors at 80, 150 and 210 degrees from the background color), a two sample t-Test was performed. Table 4.13 also shows these results. These statistical test results show there is strong evidence that label overlays using i-type color harmonies are not as noticeable as label overlays using disharmonies; label overlays colored disharmoniously are likely more noticeable.

Statistical significance of the Matsuda i-type harmonies versus the non i-type colors was again tested using a two sample t-Test. Those statistical test results are also shown in Table 4.14. There was a statistically significant difference in the times to notice overlays using i-type color harmonies versus non i-type colors; overlays using i-type color harmonies are likely inherently less noticeable.

Statistical significance of the 80 degree versus 150 degree disharmonies was again tested using a two sample t-Test. (The 150 and 210 degree position results were aggregated to form the 150 degree offset disharmonies.) Table 4.15 shows the results. There was a statistically significant difference in the times between noticeability of label overlays using colors offset on the hue circle from the background color by 150 degrees versus those offset by 80 degrees; the 150 degree disharmonies seem to be more noticeable than the 80 degree ones.

4.4 Experiment Four: Nemcsics vs. Itten Harmonies

The fourth experiment considered the use of label overlays colored with Nemcsics harmonies versus Itten harmonies on 5 maps.

4.4.1 Raw Results of Experiment Four

Table 4.16 shows the average, minimum, and maximum response times (in seconds) for Experiment Four's task. The columns labeled "AN" denote times for completing the task for the Nemcsics color harmonies. The columns labeled "JI" denote times for completing the task for the Itten color harmonies. Results are broken out by map.

Table 4.16: Time (sec) to find label overlays using harmonious color combinations

	Map1		Map2		Map3		Map4		Map5	
	AN	JI	AN	JI	AN	jI	AN	JI	AN	JI
Mean	3.3	3.9	2.9	2.8	5.8	6.1	6.3	4.4	8.7	8.3
Min	1.8	1.9	1.5	1.8	5.0	4.4	4.3	3.6	6.8	5.5
Max	10.0	7.4	6.1	4.8	6.4	7.1	7.1	5.5	9.7	10.3
Std. Dev.	1.97	1.53	1.17	0.89	0.40	0.65	0.64	0.39	0.69	1.36

Table 4.17 summarizes the overall minimum, maximum, standard deviation, and average response times (in seconds) for each harmony theory. The tasks using the Itten harmonies were completed slightly faster (in 5.11 seconds on average) than the ones using the Nemcsics harmonies (in 5.40 seconds on average).

Table 4.17: The overall time (sec) for finding the overlays on the maps using harmonious color combinations.

Color Model	Mean	Min	Max	Std. Dev.
AN	5.40	1.54	10.04	0.63
JI	5.11	1.81	10.28	0.48

We also studied response times for these two color harmony theories for male versus female participants and for those with normal vision versus those with corrected-to-normal vision. Table 4.18 shows the average, minimum, and maximum response time (in seconds) for female (F) and male (M) participants.

Table 4.19 shows the average, minimum, and maximum time (in seconds) for those with normal vision (OK) versus those with corrected-to-normal vision (WG).

Table 4.18: Time (sec) to find the label overlays using harmonies for female (F) and male (M) participants.

	Map1				Map2				Map3				Map4				Map5			
	AN		JI		AN		JI		AN		JI		AN		JI		AN		JI	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Mean	4.2	2.3	4.1	3.8	3.2	2.6	3.1	2.5	5.8	5.9	5.9	6.3	6.3	6.4	4.3	4.5	8.5	8.9	8.2	8.4
Min	1.8	1.0	2.1	1.5	1.5	1.2	1.5	1.2	4.6	4.6	3.5	3.2	4.6	3.9	2.8	3.8	7.3	5.5	5.4	4.1
Max	15.5	5.2	11.2	9.3	6.8	5.4	6.0	5.1	7.5	7.1	7.1	7.1	7.3	7.5	5.0	6.4	10.7	11.0	10.8	10.7
Std. Dev.	3.1	1.2	2.3	2.3	1.4	1.2	1.2	0.9	0.7	0.6	1.0	0.9	0.8	0.8	0.5	0.6	0.9	1.4	1.5	1.9

Table 4.19: Time (sec) to find the label overlays using harmonies by participants with normal vision(OK) and corrected-to-normal vision (WG)

	Map1				Map2				Map3				Map4				Map5			
	AN		JI		AN		JI		AN		JI		AN		JI		AN		JI	
	WG	OK	WG	OK	WG	OK	WG	OK	WG	OK	WG	OK	WG	OK	WG	OK	WG	OK	WG	OK
Mean	3.5	3.1	3.2	4.3	2.5	1.4	2.7	2.9	5.0	5.6	6.2	6.0	6.5	6.3	4.4	4.5	8.9	8.4	8.3	8.1
Min	1.8	1.6	2.4	2.9	1.6	1.4	2.0	1.9	5.0	5.0	4.9	5.2	5.6	4.5	4.1	4.0	8.0	5.5	6.8	4.1
Max	9.1	5.6	4.3	6.5	3.5	4.8	3.8	5.5	6.8	6.3	7.1	7.1	7.0	7.1	5.0	5.1	9.9	10.2	9.9	10.7
Std.Dev.	2.4	1.5	0.6	1.3	0.6	1.3	0.6	1.0	0.5	0.4	0.6	0.6	0.4	0.7	0.3	0.3	0.7	1.3	1.0	1.9

4.4.2 Analysis of Experiment Four

To determine the statistical significance of the difference in response times for the Itten versus Nemcsics harmonies for label overlays, a two sample t-Test was performed. Table 4.20 shows these test results. Although the Itten harmony time was lower, the difference between it and the Nemcsics harmony time was not statistically significant. However, the value was close to the significance cut-off, so additional study may needed.

Table 4.20: The two sample t-Test for Nemcsics vs. Itten harmonies for all five maps

t-Test Result		
	Nemcsics	Itten
Mean	5.40	5.11
Variance	0.57	0.33
Observations	40	40
t-Stat	1.980	
t-Critical	1.991	⇒ NOT SIGNIFICANT

The two-sample t-Test results for male participants versus female participants is shown in Table 4.21. The male participant results are shown on the left and the female participant results are shown on the right. As the tables show, the Nemcsics and Itten harmonies have a statistically significant difference for males but this difference was not significant for females.

Table 4.21: The two sample t-Test for Nemcsics vs. Itten harmonies for Male and Female participants

Male Participants

t-Test Result		
	Nemcsics	Itten
Mean	5.59	5.12
Variance	0.79	0.20
Observations	20	20
t-Stat	2.147	
t-Critical	2.024	⇒ SIGNIFICANT

Female Participants

t-Test Result		
	Nemcsics	Itten
Mean	5.22	5.09
Variance	0.30	0.49
Observations	20	20
t-Stat	0.592	
t-Critical	2.024	⇒ NOT SIGNIFICANT

4.5 Experiment Five: Disharmonious vs. Opponent

The fifth experiment considered use of label overlays colored disharmoniously versus label overlays colored with opponent colors.

4.5.1 Raw Results of Experiment Five

Table 4.22 shows counts of participant choices for Experiment Five's task of noticing and reciting the label overlays colored disharmoniously (i.e., in colors with 80° and 150° separation on Itten's hue circle from the background color) versus each other and versus overlays colored in opponent colors (i.e., chromatic opponents) based on perceived noticeability order. The columns labeled "Opp" denote results for chromatic opponent colors. The columns labeled "80" and "150" denote the results for the 80 degree and 150 degree disharmonies, respectively. In this experiment, more participants noticed the labels colored with the 150 degree disharmonies than the labels colored with the 80 degree disharmonies.

Table 4.22: Number of participants who noticed and recited label overlays using Disharmonious vs. Opponent colors.

	Pairwise Noticeability Comparison					
	Opp	80°	Opp	150°	150°	80°
Map1	10	10	10	12	15	8
Map2	11	11	5	18	20	1
Map3	17	4	10	12	20	1
Map4	15	6	16	5	18	3

The overall averages for the noticeability of the 80 degree disharmonies versus the opponent color overlays are shown in Table 4.23. Here, the averages are the average selection count (e.g., 2.52 for opponent means the average person chose the opponent color label as the most noticeable one for 2.52 of the 4 maps). Opponent colors were the more common choice.

Table 4.23: Two sample t-Test for Opponent Colors versus Disharmonious Colors (80° separation)

Pairwise Noticeability Comparison		
	Opponent	80 degrees
Mean	2.52	1.48
Variance	1.46	1.26
Observations	21	21
t-Stat	2.076	
t-Critical	1.721	⇒ SIGNIFICANT

We also considered the 80 degree disharmonies versus the 150 degree disharmonies. Averages are shown in Table 4.24. The counts here have a similar meaning as in the Table 4.23. The 150 degree disharmonies were the more common choice.

Table 4.24: Two sample t-Test for 150 degree versus 80 degree disharmonies, averaged

Pairwise Noticeability Comparison		
	150 degrees	80 degrees
Mean	3.48	0.62
Variance	0.36	0.45
Observations	21	21
t-Stat	10.954	
t-Critical	1.721	⇒ SIGNIFICANT

The averages for the 150 degree disharmonies versus the opponent colors are shown in Table 4.25.

Table 4.25: Two sample t-Test for 150 degree disharmonies versus Opponent colors , averaged

Pairwise Noticeability Comparison		
	150 degrees	Opponent
Mean	2.24	1.95
Variance	1.19	1.25
Observations	21	21
t-Stat	0.603	
t-Critical	1.721	⇒ NOT SIGNIFICANT

4.5.2 Analysis of Experiment Five

To determine the statistical significance of the difference in noticeability of the 80 degree disharmonies versus the opponent color overlays, a two sample t-Test was performed. Table 4.23 also shows these results. It also includes the overall averages. There was a statistically significant difference in the noticeability of the opponent colors and the 80 degree disharmonious ones; label overlays colored with chromatic opponent colors are likely more noticeable than 80 degree disharmonies.

The two sample t-Testing results for the 80 degree versus 150 degree disharmony noticeabilities are also shown in Table 4.24. There was a statistically significant difference in these noticeabilities; label overlays using 150 degree disharmonies were more noticeable than label overlays using colors with 80 degree disharmonies.

The t-Test results for the 150 degree disharmonies versus opponent colors are also shown in Table 4.25. There was no statistically significant difference between these. Thus, either opponent colors or 150 degree disharmonies may be good choices for overlay colors in visualization.

4.6 Experiment Six: Disharmonious vs. Saturated vs. Lightness Colors

The sixth experiment considered use of label overlays colored disharmoniously versus ones with high or low saturated colors versus ones with high or low lightness.

4.6.1 Raw Results of Experiment Six

Table 4.26 shows the count of participants' responses for the experiment. The columns labeled "Dis" denote counts for 150 degree disharmonies. The columns labeled "HS" denote counts for highly saturated color labels. The columns labeled "HL" denote counts for high lightness color labels. The columns labeled "LS" denote counts for low saturation color labels. The columns labeled "LL" denote counts for low lightness color labels. It appears that participants noticed label overlays colored disharmoniously more readily than the others. It also appears that high saturation color overlays are more noticeable than low saturation, low lightness, and high lightness ones.

Table 4.26: Count of participants' responses who noticed label overlays using disharmonious, high and low saturated, and high and low lightness

	Pairwise Noticeability Comparisons															
	Dis	HS	Dis	LS	Dis	HL	Dis	LL	HS	LS	HS	HL	HS	LL	HL	LL
Participants	17	10	24	2	25	1	14	12	23	3	25	1	19	7	5	21

4.6.2 Analysis of Experiment Six

To determine the statistical significance of the Experiment Six's findings, we determined the percentage of times each color combination was chosen in each pairwise testing type for each user. Since these percentages represent proportion information, which are the only values we have here, z-testing (the Z Proportion test) was used to determined statistical significance. The 95% confidence level was used in these testing.

Table 4.27 shows the results for the (150°) disharmonies versus the highly saturated color overlays. Here, on average, users chose the disharmonious labels 65.3% of the time. For our sample size, this was not statistically significant; there is not strong evidence that label overlays colored disharmoniously are more noticeable than labels with highly saturated colors.

The overall average and statistical test summary for z-testing for disharmonious versus low saturation colors are shown in Table 4.28. Again, the 95% confidence level was used, and that level is also used in all the other tests in this section. The

Table 4.27: z-Test (z Proportions Test) for Disharmonies vs. Highly Saturated overlays

	Disharmony	Highly Saturated
Proportion	0.653	0.346
Observations	26	26
Z-Stat	1.568	
Z-Critical	1.960	⇒ NOT SIGNIFICANT

proportion of participants selecting the disharmonious color (92.3%) is a significant outcome; there is strong evidence that label overlays colored disharmoniously are more noticeable than labels with low saturated colors.

Table 4.28: z-Test (z Proportions Test) for Disharmonies vs. Low Saturated overlays.

	Disharmony	Low Saturated
Proportion	0.923	0.077
Observations	26	26
Z-Stat	4.315	
Z-Critical	1.960	⇒ SIGNIFICANT

The overall average and statistical test summary for disharmonious versus high lightness colors are shown in Table 4.29. The proportion of selecting the disharmonious color (96.1%) is a significant outcome; there is strong evidence that label overlays colored disharmoniously are more noticeable than labels with high lightness colors.

The overall average and statistical test summary for disharmonious versus low lightness colors are shown in Table 4.30. The proportion of selecting the dishar-

Table 4.29: z-Test (z Proportions Test) for Disharmonies vs. High Lightness overlays.

	Disharmony	High Lightness
Proportion	0.961	0.039
Observations	26	26
Z-Stat	4.707	
Z-Critical	1.960	⇒ SIGNIFICANT

monious color (53.8%) is not a significant outcome; there is not enough evidence that label overlays colored disharmoniously are more noticeable than labels with low lightness colors.

Table 4.30: z-Test (z Proportions Test) for Disharmonies vs. Low Lightness overlays.

	Disharmony	Low Lightness
Proportion	0.538	0.462
Observations	26	26
Z-Stat	0.392	
Z-Critical	1.960	⇒ NOT SIGNIFICANT

The overall average and statistical test summary for high saturated versus high lightness colors are shown in Table 4.31. The proportion of selecting the high saturated colors (96.2%) is a significant outcome; there is strong evidence that label overlays with high saturated colored are more noticeable than labels with high lightness colors.

The overall average and statistical test summary for high saturated versus low saturated colors are shown in Table 4.32. The proportion of the high saturated colors

Table 4.31: z-Test (z Proportions Test) for High Saturated vs. High Lightness overlays.

	High Saturated	High Lightness
Proportion	0.962	0.038
Observations	26	26
Z-Stat	4.707	
Z-Critical	1.960	⇒ SIGNIFICANT

(88.4%) is a significant outcome; there is strong evidence that label overlays with high saturated colored are more noticeable than labels with low saturated colors.

Table 4.32: Z-Test (z Proportions Test) for High Saturated vs. Low Saturated overlays.

	High Saturated	Low Saturated
Proportion	0.884	0.115
Observations	26	26
Z-Stat	3.922	
Z-Critical	1.960	⇒ SIGNIFICANT

The overall average and statistical test summary for high saturated versus low lightness colors are shown in Table 4.33. The proportion of the high saturated colors (72.2%) is a significant outcome; there is strong evidence that label overlays with high saturated colored are more noticeable than labels with low lightness colors.

In summary, it appears that disharmonious color combinations are more noticeable than high lightness and low saturation color combinations. High saturated colors are also apparently a better choice than low saturation, high lightness, and low lightness color combinations, as well.

Table 4.33: Z-Test (z Proportions Test) for High Saturated vs. Low Lightness overlays.

	High Saturated	Low Lightness
Proportion	0.722	0.280
Observations	26	26
Z-Stat	2.210	
Z-Critical	1.960	⇒ SIGNIFICANT

4.7 Summary

In summary, this chapter presented the results and statistical evaluation of results for six experiments which were described in the Chapter 3. The experiments focused on the role of certain classes of color combinations for noticeability of overlays on map-based visualizations. These color combinations were chosen based on the subset of harmonious colors (based on Itten, Nemcsics, and Matsuda), disharmonious colors, chromatic opponent colors, different degree of saturated colors, and different degree of lightness with the background color(s). The analysis involved statistical testing of significance using t-Tests at the 95% confidence level and z-testing (the Z Proportion test) at the 95% confidence level for Experiment Six.

The outcomes of these experiments follow.

Label overlays colored disharmoniously are more noticeable than label overlays with harmonious, low saturated, and high lightness colors.

Label overlays colored with 150 degree disharmonies on the Itten hue circle are more noticeable compared to 80 degree disharmonies.

Glyph overlays colored with Itten harmonious color combinations are more noticeable than glyph overlay with disharmonious color combination.

There is insufficient evidence to have a conclusion on noticeability of opponent colors compared to 150 degree disharmonies.

Label overlays whose colors formed a Matsuda i-type are more noticeable than non i-type colors.

There is insufficient evidence if label overlays using Itten harmonies are more noticeable than Nemcsics harmonies.

Categories such as wearing glasses appear to have no effect. Gender seems to have less effect, for example it appears gender has no effect on relative preference and distinctness of the harmonious versus disharmonious color combinations. There was a gender difference for Nemcsics harmonies versus Itten harmonies only for male participants. This differences was statistically significant.

Opponent colors and possibly highly saturated colors may merit more study.

CHAPTER 5

USE OF COLOR THEORIES IN SURFACE-BASED VOLUME VISUALIZATION

This chapter focuses on color selection in surface-based volume visualization. The effects of color theories about harmonious, disharmonious, and opponent color combinations are investigated in surface-based volume visualization.

5.1 Isosurface Visualization

Volumetric data is a set of data values in a three-dimensional space, which is used extensively in medical, scientific, and certain industrial domains. Volume data sets are usually established by simulation, sampling, or modeling techniques. Volume visualization is used to extract and display meaningful information from volume data [18]. One popular form of visualization for volume datasets tends to be isosurfacing, since it can be rendered by a simple polygonal model, which can be drawn on the screen very quickly. Isosurface renderings are used as data visualization methods in computational fluid dynamics (CFD), allowing engineers to study features of a fluid flow (gas or liquid) around objects, such as aircraft wings. In medical imaging of three dimensional CT scans isosurfaces may be used to represent regions

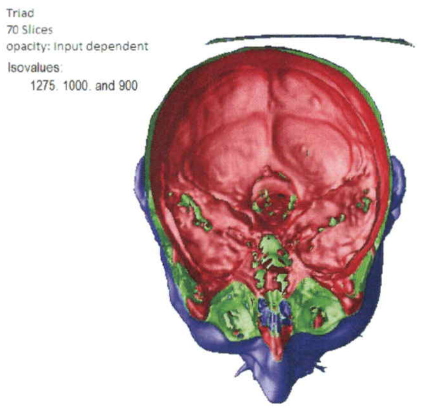


Figure 5.1: Rendering of Human head volumetric dataset [136]

of a particular density, allowing the visualization of internal organs, bones, or other structures. An isosurface is a 3D surface mapping the location of a constant value of single parameter (e.g., pressure, temperature, velocity, or density) within a volume. This constant value is called an *isovalue* and is denoted by α.

In this dissertation research, we are interested in a situation where multiple isosurfaces (each associated with a unique isovalue) need to be visualized simultaneously in a single rendering. For example, in computational fluid dynamics (CFD), an isosurface associated with wings and another associated with gas or liquid might need to be visualized simultaneously; or in medical data, an isosurface associated with bones and another associated with soft tissue such as skin may need to be visualized simultaneously. Figure 5.1 shows a rendering of a human head dataset: three isosurfaces, associated with $\alpha \in \{1275, 1000, 900\}$, are rendered simultaneously. One way to visualize isosurfaces simultaneously in a single rendering is utilizing color.

Color selection is a challenge in these types of simultaneous visualization of multiple isosurfaces, since each needs to be presented in its own color. Various color mapping schemes, including heat maps, color spectrum maps, etc., have been explored in visualization. A number of investigators have studied the usage of different color properties for the effective visualization of isosurfaces. For example, Bischoff and Kobbelt [5] used color darkness to specify distance from an isosurface boundary. Viola et al. [110] have discovered that using highly saturated colors in isosurfacing attracts an observer's attention more than colors close to gray. They also suggested that it is important for occluded surfaces to be presented using both color and opacity that differ from the color and opacity used for non-occluded areas. Ebert [28] has proposed the use of color temperature for shading isosurfaces. Specifically, he proposed the use of warm colors for advancing the perception of depth in volume renderings [28].

In most isosurface rendering processes that follow the Marching Cubes methodology, Gouraud interpolative shading is used to determine pixel colors, usually with a single base material color. Rhodes et al. [90] have described a method for determining color in isosurfacing of multi-resolution data with varying degrees of uncertainty. Their method still uses Gouraud shading, but, depending on the degree of uncertainty of the data, the base color hue is varied. Rhodes et al. [90] used variation in hue rather than saturation or lightness since (1) generally humans are more sensitive to hue changes than to saturation changes [90] and (2) they reserved lightness variation for conveying shape of isosurfaces. In medical imaging data, Preim et al. [88] have considered the use of highlighting in non-photorealistic rendering. They discussed illustrative techniques that are applicable to surgical planning, such as the use of highly saturated colors to allow easy recognition of a region of interest [88]. Krüger et al. [56] have reduced the saturation and lightness of some structures in medical image visualizations to improve visibility of other structures. They also used transparency to expose some key structures for their applications (e.g., lymph nodes). In particular, to enhance the visibility of lymph nodes and tumors, they reduced the saturation and lightness of other structures [56].

Transparency has also been considered in isosurface renderings. For example, Wang et al. [117] have described a transparency-based multivariate visualization method for 3D flow data. Their method uses the transparency of surfaces to represent how vorticity magnitude varies in regions of interest. House et al. [45] have proposed the use of transparency for the top surfaces in simultaneous visualization of multiple isosurfaces to reduce occlusion. Silverstein et al. [102] have implemented a perceptual colorization algorithm using transparency for CT datasets to generate realistic and accurate visualizations for surgical planning. Their colorization algorithm is also applicable to other domains. Their algorithm used tissue density to determine transparency and rendered structures in the body that have low density (such as the lungs) as transparent items and structures that have high density (such as bones) as opaque items. It also maximized luminance contrast to generate colors that produce accurate and realistic visualizations [102]. Use of transparency for volume visualization has also been investigated by Interrante et al. [48]. Their investigations considered layered surface-based visualization for radiation therapy applications. Their results suggested that using transparency may compromise accurately evaluating relative depth of transparent surfaces (versus opaque structures' depths). Therefore, they added opaque texture elements (such as strokes) to a transparent surface to improve perception of surface shape and depth. They also used color for texture elements as a labeling device to indicate distance between the outer surface and inner surface at each point.

This chapter reports user studies that explore certain aspects of color theories about harmony, disharmony, and opponencies in surface-based volume visualization. In this research study, the use of these three color combinations were examined to determine distinguishablity. In particular, we investigated which color combinations for isosurfaces can aid observers to easily *distinguish* multiple isosurfaces in a single rendering. We also investigated which of these three color theories are *preferred* by the viewers to visualize multiple isosurfaces in a single rendering.

In these studies we used three datasets from the Volume Library website [136]; the DTI (a Diffusion Tensor MRI brain scan, size: $128 \times 128 \times 58$); CT scan of the Engine Block (size: $256 \times 256 \times 256$); and the H_2O (a simulation of the electron distribution in a water molecule, size: $128 \times 128 \times 128$) datasets. For the DTI and the Engine Block renderings, two isosurfaces were extracted and overlaid. For the H_2O rendering, three isosurfaces were extracted and overlaid. In summary, the relative distinctiveness and preferences of each disharmonious, opponent, and harmonious color combinations were determined for each isosurface rendering. Figure 5.2 presents the isosurface renderings of these datasets that were used for studying opponent colors.


(a) DTI (b) Engine (c) H_2O

Figure 5.2: Example Rendering of Nested Isosurfaces from the Volume Library website [136]

5.2 Experimental Design

We conducted user studies utilizing participants with normal or corrected-to-normal vision and no known visual impairments. They were all older than age 18 and either undergraduate or graduate students with some computing knowledge. Each participant took 10 to 15 minutes to complete their part of the study. All experiments involved seated participants viewing the isosurface renderings. All participants had the possibility to adjust the chair and monitor height, orientation, and distance to their preference for comfort. The isosurface renderings were generated using the OpenDX open source visualization software package. Each rendering contained at least two isosurfaces. For the Engine Block and DTI datasets, two isosurfaces were rendered (associated with $\alpha \in \{180, 60\}$ for the Engine Block and $\alpha \in \{1200, 200\}$ for the DTI). For the H_2O dataset, three isosurfaces were rendered (associated with $\alpha \in \{100, 75, 50\}$). The isosurface renderings used certain classes of color combinations whose effectiveness were examined. These included (1) harmonious colors; (2) disharmonious colors; and (3) opponent colors.

Three classes of experiments were performed for each dataset in order to explore distinct and preferred color combinations for multiple isosurfaces in a single rendering. Three sets of renderings based on harmonious, disharmonious, and opponent colors were utilized for each dataset. The base colors for each set were red, green, blue, and yellow.

In these experiments, forty participants (i.e., 20 female and 20 male) answered questions about which color combinations were preferred and which color combinations were distinct. The questions were:

(1) Which opponent or disharmonious color combinations of isosurface renderings are the most distinct and preferred ones?

(2) Which harmonious or disharmonious color combinations of isosurface renderings are the most distinct and preferred ones?

(3) Which harmonious or opponent color combinations of isosurface renderings are the most distinct and preferred ones?

5.2.1 Experiment One: Disharmonious vs. Opponent

In Experiment One, participants considered disharmonious colors versus opponent ones. This experiment was designed to evaluate the noticeability of isosurface renderings colored disharmoniously versus isosurface renderings colored using opponent ones. The participants viewed renderings of three datasets (i.e., the DTI, the Engine Block, and the H_2O) using opponent and disharmonious color combinations.

For each dataset, four renderings were utilized based on disharmonious color combinations and two renderings were utilized based on opponent colors. For the disharmonious color combinations, the colors for isosurfaces were selected based on prior work [25], which found colors separated by 150° (or 210°) on the Itten hue circle were the most disharmonious ones. For the renderings with two isosurfaces (i.e., the DTI and the Engine Block datasets), the selected colors were ones separated by 150° from the base colors (i.e., red, green, blue, and yellow) on the Itten hue circle. For the renderings with three isosurfaces (i.e., the H_2O dataset), the selected colors were ones separated by 150° and 210° on the Itten hue circle from the base colors. For renderings using the opponent color combinations for isosurfaces, the chromatic opponents (i.e., red-green and blue-yellow) were considered.

The participants were asked to select the most distinct rendering and the most preferred one among all six renderings. Thus, participants selected one rendering as distinct and selected one rendering as preferred.

5.2.2 Experiment Two: Itten Harmonies vs. Disharmonies

In Experiment Two, the most distinct and preferred color combinations were determined for renderings of three datasets (i.e., the DTI, the Engine Block, and H_2O) using harmonious and disharmonious color combinations. For two datasets, (i.e., the DTI and the Engine Block) eight isosurface renderings based on harmonious color combinations were utilized. For the third dataset (i.e., the H_2O dataset) four isosurface renderings based on harmonious color combinations were utilized. The harmonious colors used formed analogous harmonies (i.e., the colors whose hues are adjacent on Itten's hue circle) or the Matsuda V-type ("Adjacent harmony") harmony.

Pairwise presentation of harmonious and disharmonious color combination renderings were utilized for each dataset. The pairwise presentations were performed in three steps. In the first step, harmonious color combination renderings of each dataset (i.e., eight isosurface rendering for the Engine Block and DTI, and four isosurface renderings for the H_2O dataset) were compared to determine the most distinct and the most preferred harmony for each dataset. In the second step, the most distinct and most preferred disharmonious color(s) were utilized. In the third step, participants compared the result of step one with step two. In their comparison participants determined the most distinct and the most preferred renderings among the harmonious and disharmonious ones. As a result, participants appointed one isosurface rendering as the most distinct and one as most preferred.

5.2.3 Experiment Three: Itten Harmonies vs. Opponent

In Experiment Three, the most distinct and preferred color combinations were determined for renderings of three datasets (i.e., the DTI, the Engine Block, and H_2O). The experiment considered harmonious and opponent color combinations. It used one isosurface rendering with harmonious colors selected from the second experiment renderings and an isosurface rendering with opponent colors selected from the first experiment renderings. Participants were asked to perform pairwise comparisons. For each pair, they determined which one was more distinct and which one they preferred.

5.2.4 Summary

In this chapter we described three experiments to investigate distinguishability resulting from certain color combinations in isosurface-based volume visualization. The experiments focused on noticeability of isosurface rendering based on their color combinations. The color combinations considered were (1) disharmonious colors, (2) harmonious color, and (3) chromatic opponent colors. The experiments results and analysis are reported in Chapter 6.

CHAPTER 6

EXPERIMENTAL RESULTS AND STATISTICAL ANALYSIS OF USING COLOR THEORIES IN SURFACE-BASED VISUALIZATION

This chapter presents the results and statistical analysis for each of the isosurface rendering experiments in the Chapter 5. The focus here is considering harmonious versus disharmonious, disharmonious versus opponent, and harmonious versus opponent color combinations.

The statistical analysis used a statistical sign test. For this test, distinguishability of two sets of visualizations for each dataset was assessed by viewers considering distinctness and preference. We used differences in viewer response raw counts in the statistical tests.

6.1 Results of Experiment One: Disharmonious vs. Opponent

The Experiment One distinctness question results are shown in Table 6.1. It shows counts of participant choices for determining distinctness for isosurface renderings colored disharmoniously versus renderings colored in opponent colors. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown. For all three datasets considered the disharmonious color combinations were picked most often. There are statistically significant differences (at the 95% confidence level) in the distinctness between the disharmonious and opponent color combinations for isosurface renderings of two datasets. For the other dataset, the difference is significant only at the 90% confidence level. In conclusion, surfaces rendered with disharmonious color combinations are likely more distinct than surfaces rendered with opponent colors in surface-based volume visualization.

Table 6.1: Distinctness—Disharmonious vs. Opponent color combinations

	Dataset		
	Engine	DTI	H_2O
Total, excluding Undecideds	40	39	40
# of Disharmony	35	31	25
# of Opponent	5	8	15
# of Undecided	0	1	0
Z Score	4.585	3.523	1.425
Confidence Level	99%	99%	92%

Table 6.2 shows similar summarizing information for the Experiment One preference question results. For all three datasets considered, the disharmonious color combinations were usually preferred. In addition, these differences are statistically significant at the 95% confidence level; participants likely do prefer disharmonious color combinations over opponent colors for surface-based volume visualization.

An overall summary across all the datasets is shown in Table 6.3. Overall, the disharmonious colors were described as distinct and preferred for over two-thirds of the cases. The Z-scores here are also very large, providing evidence that there is a

Table 6.2: Preference—Disharmonious vs. Opponent color combinations

	Dataset		
	Engine	DTI	H_2O
Total, excluding Undecideds	40	40	40
# of Disharmony	33	33	35
# of Opponent	7	7	5
# of Undecided	0	0	0
Z Score	3.953	3.953	4.585
Confidence Level	99%	99%	99%

Table 6.3: Disharmonious vs. Opponent color combinations, Summary

	Distinctness	Preference
	Disharmony vs. Opponent	Disharmony vs. Opponent
Total,excluding Undecideds	119	120
# of Disharmony	91	101
# of Opponent	28	19
# of Undecided	1	0
Z Score	5.881	5.962
Confidence Level	99%	99%

statistically significant difference; disharmonious color combinations are distinct and preferred over opponent colors for isosurface rendering.

6.2 Results of Experiment Two: Disharmonious vs. Harmonious

The Experiment Two distinctness question results are shown in Table 6.4. It shows counts of participant choices for determining distinctness for isosurface renderings colored disharmoniously versus renderings colored harmoniously. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z-score for the sign test, and confidence level are shown. The disharmonious color combinations were selected more often than the harmonious ones. However, only the differences for the Engine Block and H_2O datasets were statistically significant at the 95% confidence level.

Table 6.4: Distinctness—Disharmonious vs. Harmonious color combinations

	Dataset		
	Engine	DTI	H_2O
Total, excluding Undecideds	36	35	30
# of Disharmony	27	19	22
# of Harmony	9	16	8
# of Undecided	4	5	10
Z Score	3.272	.462	2.769
Confidence Level	99%	68%	99%

Table 6.5 shows similar summarizing information for the Experiment Two preference question results. It shows counts of participant choices for determining preference for isosurface renderings colored disharmoniously versus renderings colored harmoniously. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was preferred), the Z-score for the sign test, and confidence level are shown. The disharmonious color combinations were selected more often than the harmonious ones, especially for the Engine and H_2O datasets. Only the difference for the Engine Block and H_2O datasets were statistically significant at the 95% confidence level.

An overall summary across all datasets is shown in Table 6.6. It shows counts of participant choices for determining distinctness and preference for all three isosurface renderings colored disharmoniously versus renderings colored harmoniously. In addition, the number of undecided participants, the Z-score for the sign test, and con-

Table 6.5: Preference—Disharmonious vs. Harmonious color combinations

	Dataset		
	Engine	DTI	H_2O
Total, excluding Undecideds	38	34	33
# of Disharmony	26	18	25
# of Harmony	12	16	8
# of Undecided	2	6	7
Z Score	2.551	0.243	3.210
Confidence Level	99%	60%	99%

Table 6.6: Disharmonious vs. Harmonious color combinations, Summary

	Distinctness	Preference
	Disharmony vs. Harmony	Disharmony vs. Harmony
Total,excluding Undecideds	101	105
# of Disharmony	68	69
# of Harmony	33	36
# of Undecided	19	15
Z Score	4.120	3.850
Confidence Level	99%	99%

fidence level are shown. The disharmonious color combinations were selected much more often than the harmonious ones for both distinctness and preference. In these overall results, the differences were statistically significant at the 95% confidence level.

6.3 Experiment Three Results: Harmonious vs. Opponent

The Experiment Three distinctness question results are shown in Table 6.7. It shows counts of participant choices for determining distinctness for isosurface renderings colored harmoniously versus renderings colored in opponent colors. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown. The harmonious combinations were selected more often than the opponent ones for the Engine Block and the DTI datasets. However, only the difference for the DTI dataset was statistically significant at 95% confidence level. For the Engine Block the difference is significant at the 90% confidence level, though.

Table 6.7: Distinctness—Harmonious vs. Opponent color combinations

	Dataset		
	Engine	DTI	H_2O
Total, excluding Undecideds	13	21	18
# of Harmony	9	16	8
# of Opponent	4	5	10
# of Undecided	27	19	22
Z Score	1.33	2.514	1.06
Confidence Level	91%	99%	85%

Table 6.8 shows similar summarizing information for the Experiment Three preference question results. It shows counts of participant choices for determining preference for isosurface renderings colored harmoniously versus renderings colored in opponent colors. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown at the 95% confidence level. The harmonious combinations were selected much more often than the opponent ones for the Engine Block and DTI datasets. For H_2O, preferences were approximately the same. Only the difference for the Engine Block and the DTI datasets was statistically significant at 95% confidence level.

Table 6.8: Preference—Harmonious vs. Opponent color combinations

	Dataset		
	Engine	DTI	H_2O
Total, excluding Undecideds	38	34	33
# of Harmony	12	16	8
# of Opponent	2	6	7
# of Undecided	26	18	25
Z Score	2.561	2.250	0.001
Confidence Level	99%	98%	51%

An overall summary across all datasets is shown in Table 6.9. It shows counts of participant choices for determining distinctness and preference for all three isosurface renderings colored harmoniously versus renderings colored with opponent colors. In addition, the number of undecided participants, the Z-score for the sign test, and confidence level are shown. The harmonious color combinations were selected about twice as often as the opponent ones for both distinctness and preference. These differences were statistically significant at the 95% confidence level.

Table 6.9: Harmonious vs. Opponent color combinations, Summary

	Distinctness	Preference
	Harmony vs. Opponent	Harmony vs. Opponent
Total,excluding Undecideds	52	51
# of Harmony	33	36
# of Opponent	19	15
# of Undecided	68	69
Z Score	2.263	3.331
Confidence Level	98%	99%

6.4 Summary

In summary, this chapter presented the results and statistical analysis of results for the three experiments which were described in Chapter 5. The analysis involved statistical sign testing. The results based on participant choices for isosurface renderings suggest that disharmonious color combinations are usually both more distinct and preferred over both harmonious and opponent color combinations for such renderings. Also, harmonious color combinations often tend to be more distinct and preferred to opponent ones, however less confidence can be placed in this latter result (i.e., since more individuals were undecided, that is almost 57% of individuals). Thus, we recommend use of disharmonious colors for rendering multiple isosurfaces in the same display.

CHAPTER 7

COLOR SELECTION GUIDELINES IN VOLUME VISUALIZATION

This chapter considers two color selection rules proposed previously for visualization. Our goal is to apply those rules in surface-based volume visualization and consider some inter-relationships with color theories about harmonious, disharmonious, and opponent color combinations.

7.1 Ebert Color Selection Guidelines

Ebert et al. [27, 28] have described a volume visualization technique that uses direct volume rendering and non-photorealistic rendering. This technique aims at improving perception of structure, shape, orientation, and depth relationships. In particular, it uses warm colors (i.e., in color temperature) for surfaces facing a light source and cool colors for other surfaces. Warm colors were also used to increase the sense of depth that something was close by, while cool colors were used to promote sensation that something was far away. We will call these Ebert et al. guidelines the "Ebert et al. color guidelines" and "Ebert-based rules."

Figure 7.1 shows an Engine Block isosurface rendering using Ebert et al. color guidelines. This Engine Block rendering contains two isosurfaces that are associated with isovalues 180 and 60. These isosurfaces have 40% opacity. The Ebert-based rules were applied in generating this rendering. They were applied as follows. The surface associated with the lower isovalue was rendered using a warm color (i.e., reddish-brown). The other surface was rendered using a cool color (i.e., yellowish-green) that is also harmonious with the warm color. This harmonious color is based on Itten's analogous harmonies. The isosurface with warm color encloses the other one, so its "front" is closer to the viewer.

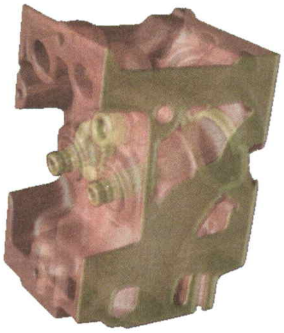


Figure 7.1: Engine Block isosurface rendering using Ebert et al. color guidelines

7.2 House Color Selection Guidelines

House et al. [45] have proposed a framework that considers perceptual issues that affect visualization quality. Their framework uses texture mapping to enhance visualizations of two layered surfaces. They conducted a wide range of tests using this framework and, based on the results of these tests, they developed a set of guidelines for reducing occlusion when rendering layered surfaces. Some parts of these guidelines are related to our work here: (1) saturation should be higher for the bottom surface than for the top surface; (2) color value for the bottom surface should be about either 50% or 80% of full-scale brightness; and (3) the opacity for the top surface should be between 20% and 60% of the opacity of the bottom surface. We will call these three House et al. guidelines the "House et al. color guidelines" and "House-based rules."

Figure 7.2 shows the Engine Block isosurface rendering using House et al. color guidelines. This rendering uses the same isovalues discussed in Section 7.1. These isosurfaces are opaque. House-based rules were applied to this rendering as follows. The saturation of the inner surface (i.e., isosurface associated with isovalue 180) was higher than the saturation of the outer surface (i.e., isosurface associated with isovalue 60). The color value of the bottom surface was selected as 80% of full-scale brightness. The opacity of the top surface was 40% of the opacity of the bottom surface.

Figure 7.2: Engine Block isosurface rendering using House et al. color guidelines

7.3 Overview

In Chapter 5, we considered the effects of color theories about harmonious, disharmonious, and opponent color combinations in surface-based volume visualization. In this chapter, we consider broader issues than were examined in Chapter 5. Specifically, we describe an investigation of the guidelines that were identified by Ebert et al. [27, 28] and House et al. [45] in conjunction with harmonious, disharmonious, or opponent color combinations in formation of isosurface renderings. Our work focuses on the multiple isosurface visualization application domain. We consider those here for the same isosurface renderings (i.e., the DTI; CT scan of the Engine Block; and the H_2O) used in Chapter 5. We also compare the results here against those described in Chapter 5.

7.4 Analogous Harmonies

As mentioned in Chapter 2, Itten described harmonies for two, three, four, or six colors whose hues were equally spaced on his hue wheel. He also described the *analogous colors*, which are another class of harmony. Analogous colors are colors that are adjacent on his hue circle. Figure 7.3 shows an Engine Block rendering with the same isosurfaces described earlier. It uses colorings following Itten's analogous colors. The Itten analogous colors are similar to the V-type ("Adjacent harmony") of the Matsuda hue templates.

In our investigations reported here, all harmonious color combinations were analogous harmonies. For some of our isosurface rendering studies using harmonious color combinations here, we colored isosurfaces using Itten's analogous harmonies that also satisfy the Ebert et al. color guidelines. For our other studies using harmonious color combinations here, we colored isosurfaces using Itten's analogous harmonies that also satisfy the House et al. color guidelines.

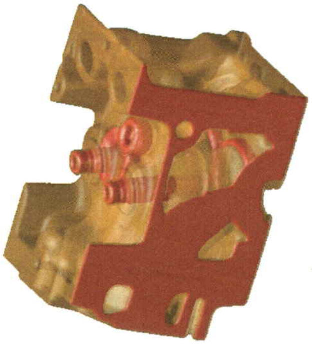


Figure 7.3: Engine Block isosurface rendering using Itten analogous harmony

7.5 Disharmonies

The disharmonious color combinations used for isosurface renderings were selected based on results of our investigation in Chapter 3, which found colors separated by 150° on the Itten hue circle were the most disharmonious ones. For some of our isosurface rendering studies using disharmonious color combinations here, we utilized disharmonies that also satisfy the Ebert et al. color guidelines. For other isosurface rendering studies using disharmonious color combinations here, we colored isosurfaces using disharmonies that also satisfy the House et al. color guidelines on isosurface renderings.

7.6 Opponent Colors

For our studies here of opponent color combinations for isosurfaces, the chromatic opponent colors (i.e., red-green and blue-yellow) were considered. For some of our isosurface rendering studies using opponent color combinations here, we used chromatic opponent colors that also satisfy the Ebert et al. color guidelines on isosurface renderings. For other isosurface rendering studies using opponent color combinations here, we colored isosurfaces using chromatic opponent colors that also satisfy the House et al. color guidelines.

7.7 Experimental Design

The experiments we conducted here involved participants viewing eight, four, or two renderings at a time. We conducted participant perception studies utilizing participants with normal or corrected-to-normal vision and no known visual impairments. They were all older than age 18 and either undergraduate or graduate students with some computing knowledge. Each participant took 10 to 15 minutes to complete their part of the study. All experiments involved seated participants viewing the isosurface renderings. All participants had the possibility to adjust the chair and monitor height, orientation, and distance to their preference for comfort. The isosurface renderings were generated using the OpenDX open source visualization software package. Each rendering contained at least two isosurfaces. For the Engine Block and DTI datasets, two isosurfaces were rendered (associated with $\alpha \in \{180, 60\}$ for the Engine Block and $\alpha \in \{1200, 200\}$ for the DTI). For the H_2O dataset, three isosurfaces were rendered (associated with $\alpha \in \{100, 75, 50\}$). The isosurface renderings used certain classes of color combinations whose effectiveness were examined. These included (1) harmonious colors; (2) disharmonious colors; and (3) opponent colors.

Three classes of experiments were performed for each dataset in order to explore distinct and preferred color combinations for multiple isosurfaces in a single rendering, as was done in Chapter 5. Specifically, three classes of experiments using the Ebert et al. guidelines and three classes of experiments using the House et al. guidelines were performed. One set of renderings based on harmonious color combinations was utilized for each dataset per guideline. In addition, one set of renderings based on disharmonious color combinations was used for each dataset per guideline. Finally, one set of renderings based on opponent colors was used for each dataset per guideline. In each set, multiple instances (i.e., eight instances for harmonious, eight instances for disharmonious color combinations, and four instances for opponent colors for each dataset per guideline) of renderings were generated. Each instance started with a background color. Background colors were red, green, blue, and yellow.

In these experiments, forty participants (i.e., 20 female and 20 male) answered questions about which color combinations were preferred and which color combinations were distinct. The questions were:

(1) For the opponent versus disharmonious color combination tests, which rendering in a pair was the most distinct one? Which one was the preferred one?

(2) For the harmonious versus disharmonious color combination tests, which rendering in a pair was the most distinct one? Which one was the preferred one?

(3) For the harmonious versus opponent color combination tests, which rendering in a pair was the most distinct one? Which one was the preferred one?

7.7.1 Experiment One: Disharmonious vs. Opponent

In Experiment One, the first set of questions was considered. In it, participants considered isosurface renderings using disharmonious colors versus ones in opponent colors. Certain disharmonious and opponent color renderings were based on the Ebert et al. guidelines. Others were based on the House et al. guidelines. The participants viewed such types of isosurface renderings of three datasets (i.e., the DTI, the Engine Block, and the H_2O). For each dataset, there were eight Ebert- and eight House-based renderings using disharmonious color combinations and four Ebert- and four House-based renderings using opponent color combinations.

For the disharmonious color renderings following Ebert-based rules, the base colors for the two isosurfaces in the Engine Block and DTI were ones separated by 150° on the Itten hue circle. In addition, in these two dataset's isosurface renderings, the disharmonious colors also satisfied the Ebert et al. guidelines. For the three isosurfaces in H_2O, the base colors for two isosurfaces were ones positioned at the 150° and 210° clockwise positions (on the hue circle) from the base color of the third isosurface (i.e., the isosurface associated with isovalue 100). In this dataset, the first two isosurface colors are only disharmonious with the third isosurface. In addition, in these H_2O renderings, the disharmonious colors also satisfied the Ebert et al. guidelines.

For the disharmonious color renderings following House-based rules, the base colors for the two isosurfaces in the Engine Block and DTI were ones separated by 150° on the Itten hue circle. In addition, in these two dataset's isosurface renderings, the disharmonious colors also satisfied the House et al. guidelines. For the three isosurfaces in H_2O, the base colors for two isosurfaces were ones positioned at the 150° and 210° clockwise positions (on the hue circle) from the base color of the third isosurface (i.e., the isosurface associated with isovalue 100). In this dataset, the first two isosurface colors are only disharmonious with the third isosurface. In addition, in these H_2O renderings, the disharmonious colors also satisfied the House et al. guidelines.

For the opponent color renderings, the chromatic opponent (i.e., red-green and blue-yellow) colors were used as the base colors of the two isosurfaces rendered for the Engine Block and DTI datasets. For the three isosurfaces in H_2O, the base colors for two isosurfaces were opponent colors from the base color of the third isosurface (i.e., the isosurface associated with isovalue 100). In this dataset, the first two isosurface colors are the same type of color but different shades of that color. Those colors are only opponent with the third isosurface color; some areas in one isosurface may have the same color as an area in the other isosurface. Differing opacities (i.e., 50% for one isosurface and 60% for other) were used in the H_2O renderings to increase the difference in appearance of these two isosurfaces. In addition, for the renderings following the Ebert-based rules the chromatic opponent colors that were used were ones that also satisfied the Ebert et al. guidelines. For the renderings following the House-based rules, the chromatic opponent color combinations that were used were ones that also satisfied the House et al. guidelines.

Two sets of presentations were utilized for each dataset per guideline. One set was based on eight instances of disharmonious color combination renderings and another set was based on four instances of opponent color combination renderings. The presentations were made in three steps. In the first step, for each dataset (i.e., the Engine Block, the DTI, and the H_2O) eight disharmonious color combination renderings per guideline were compared at once. From these, each participant selected one rendering as the most distinct. Each participant also selected one of these renderings as the most preferred. In the second step, for the same datasets, four opponent color combination renderings per guideline were compared at once. From these, each participant selected one rendering as the most distinct. Each participant also selected one of these renderings as the most preferred. In the third step, for distinctness, for each dataset (per guideline) participants compared the result of the first step (i.e., their most distinct disharmonious rendering) with the result of the second step (i.e., their most distinct opponent rendering). Participants selected the most distinct one of these two. This process was followed for each guideline separately. For preference, participants also compared the result of the first step (i.e., their most preferred disharmonious rendering) with the result of the second step (i.e., their most preferred opponent rendering). Participants selected the most preferred one of these two. As a result, for each dataset per guideline participants appointed one isosurface rendering as the most distinct and one as most preferred.

7.7.2 Experiment Two: Harmonies vs. Disharmonies

In Experiment Two, the second set of questions was considered. In it, participants considered isosurface renderings using harmonious colors versus ones in disharmonious colors. Certain harmonious and disharmonious color renderings were based on the Ebert et al. guidelines. Others were based on the House et al. guidelines. The participants viewed such types of isosurface renderings of three datasets (i.e., the DTI, the Engine Block, and H_2O). For each dataset, there were eight Ebert- and eight House-based renderings using harmonious color combinations as well as eight Ebert- and eight House-based renderings using disharmonious color combinations.

For the harmonious color renderings following Ebert-based rules, the base colors for the two isosurfaces in the Engine Block and DTI were ones forming analogous harmonies (i.e., the colors whose hues are adjacent on Itten's hue circle). In addition, in these two dataset's isosurface renderings, the harmonious colors also satisfied the Ebert et al. guidelines. For the three isosurfaces in H_2O, the base colors for the isosurfaces in the rendering were ones forming harmonies according to the Matsuda V-type template ("Adjacent harmony"). In addition, in those H_2O renderings, the harmonious colors also satisfied the Ebert et al. guidelines.

For the harmonious color renderings following House-based rules, the base colors for the Engine Block and DTI isosurfaces were ones forming analogous harmonies. In addition, in these two dataset's renderings, the harmonious colors also satisfied the House et al. guidelines. For the three isosurfaces in H_2O, the base colors for the isosurfaces in the rendering were ones forming harmonies according to the Matsuda V-type template ("Adjacent harmony"). In addition, in those H_2O renderings, the harmonious colors also satisfied the House et al. guidelines.

For the disharmonious color renderings following Ebert-based rules, the base colors for the Engine Block and DTI isosurfaces were ones separated by 150° on the Itten hue circle. In addition, in these two dataset's renderings, the disharmonious colors also satisfied the Ebert et al. guidelines. For the three isosurfaces in H_2O, the base colors used for two isosurfaces in the rendering were ones positioned at the 150° and 210° clockwise positions (on the hue circle) from the base color of the third isosurface (i.e., the isosurface associated with isovalue 100). In this dataset, the first two isosurface colors are only disharmonious with the third isosurface. In addition, in these H_2O renderings, the disharmonious colors also satisfied the Ebert et al. guidelines.

For the disharmonious color renderings following House-based rules, the base colors for the Engine Block and DTI isosurfaces were ones separated by 150° on the Itten hue circle. In addition, in these two dataset's renderings, the disharmonious colors also satisfied the House et al. guidelines. For the three isosurfaces in H_2O, the base colors used for two isosurfaces in the rendering were ones positioned at the 150° and 210° clockwise positions (on the hue circle) from the base color of the third isosurface (i.e., the isosurface associated with isovalue 100). In this dataset, the first two isosurface colors are only disharmonious with the third isosurface. In addition, in these H_2O renderings, the disharmonious colors also satisfied the House et al. guidelines.

Two set of presentations were utilized for each dataset per guideline. One set was based on eight instances of harmonious color combination renderings and another set was based on eight instances of disharmonious color combination renderings. The presentations were made in three steps. In the first step, for each dataset (i.e., the Engine Block, the DTI, and the H_2O) eight harmonious color combination renderings per guideline were compared at once. From these, each participant selected one rendering as the most distinct. Each participant also selected one of these renderings as the most preferred. In the second step, for the same datasets, eight disharmonious color combination renderings per guideline were compared at once. Each participant selected one of these renderings as the most distinct. Each participant also selected one of these renderings as the most preferred. In the third step, for distinctness, for each dataset (per guideline) participants compared the result of the first step (i.e., their most distinct harmonious rendering) with the result of the second step (i.e., their most distinct disharmonious rendering). Participants selected the most distinct one of these two. This process was followed for each guideline separately. For preference, participants also compared the result of the first step (i.e., their most preferred harmonious rendering) with the result of the second step (i.e., their most preferred disharmonious rendering). Participants selected the most preferred one of these two. As a result, for each dataset per guideline participants appointed one isosurface rendering as the most distinct and one as most preferred.

7.7.3 Experiment Three: Harmonies vs. Opponent

In Experiment Three, the third set of questions was considered. In it, participants considered isosurface renderings using harmonious colors versus ones in opponent colors. Certain harmonious and opponent color renderings were based on Ebert et al. guidelines. Others were based on the House et al. guidelines. The participants viewed isosurface renderings of three datasets (i.e., the DTI, the Engine Block, and the H_2O) using such color combinations. For each dataset, there were eight Ebert- and eight House-based renderings using harmonious color combinations as well as four Ebert- and four House-based renderings using opponent color combinations.

For the harmonious color renderings following Ebert-based rules, the base colors for the two isosurfaces in the Engine Block and DTI were ones forming analogous harmonies (i.e., the colors whose hues are adjacent on Itten's hue circle). In addition, in these two dataset's isosurface renderings, these base colors also satisfied the Ebert et al. guidelines. For the three isosurfaces in H_2O, the base colors used for the isosurfaces in the rendering were ones forming harmonies according to the Matsuda V-type template ("Adjacent harmony"). In addition, in these H_2O renderings, these base colors also satisfied the Ebert et al. guidelines.

For the harmonious color renderings following House-based rules, the base colors for the Engine Block and DTI isosurfaces were ones forming analogous harmonies. In addition, in these two dataset's isosurface renderings, these base colors also satisfied the House et al. guidelines. For the three isosurfaces in H_2O, the base colors used for isosurfaces in the rendering were ones forming harmonies according to the Matsuda V-type template ("Adjacent harmony"). In addition, in those H_2O renderings, these base colors also satisfied the House et al. guidelines.

For the opponent color renderings, the chromatic opponent (i.e., red-green and blue-yellow) colors were used as the base colors of the two isosurfaces rendered for the Engine Block and DTI datasets. For the three isosurfaces in H_2O, the base colors for two isosurfaces were opponent colors from the base color of the third isosurface (i.e., the isosurface associated with isovalue 100). In this dataset, the first two isosurface colors are the same type of color but different shades of that color. Those colors are only opponent with the third isosurface color; some areas in one isosurface may have the same color as an area in the other isosurface. Differing opacities (i.e., 50% for one isosurface and 60% for other) were used in the H_2O renderings to increase the difference in appearance of these two isosurfaces. In addition, for the renderings following the Ebert-based rules the chromatic opponent colors that were used were ones that also satisfied the Ebert et al. guidelines. For the renderings following the House-based rules, the chromatic opponent color combinations that were used were ones that also satisfied the House et al. guidelines.

Two set of presentations were utilized for each dataset per guideline. One set was based on eight instances of harmonious color combination renderings and another set was based on four instances of opponent color combination renderings. The presentations were made in three steps. In the first step, for each dataset (i.e., the Engine Block, the DTI, and the H_2O) eight harmonious color combination renderings per guideline were compared at once. From these, each participant selected one rendering as the most distinct. Each participant also selected one of these renderings as the most preferred. In the second step, for the same datasets, four opponent color combination renderings per guideline were compared at once. Each participant selected one rendering as the most distinct. Each participant also selected one of these renderings as the most preferred. In the third step, for distinctness, for each dataset (per guideline) participants compared the result of the first step (i.e., their most distinct harmonious rendering) with the result of the second step (i.e., their most distinct opponent rendering). Participants selected the most distinct one of these two. This process was followed for each guideline separately. For preference, participants compared the result of the first step (i.e., their most preferred harmonious rendering) with the result of the second step (i.e., their most preferred opponent rendering). Participants selected the most preferred one of these two. As a result, for each dataset per guideline participants appointed one isosurface rendering as the most distinct and one as most preferred.

7.8 Summary

In this chapter, we described three experiments to investigate the distinctness and preference of isosurface rendering using House et al. and Ebert et al. color guidelines. The color combinations considered were (1) harmonious colors, (2) disharmonious colors, and (3) opponent colors. The experiment results and analyses are reported in Chapter 8.

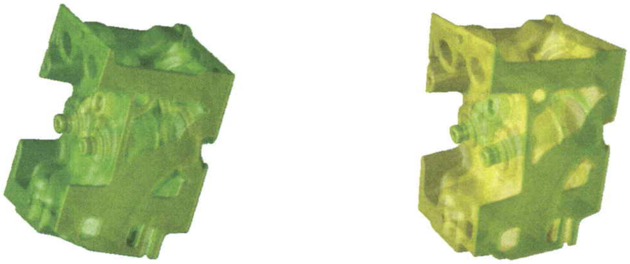
CHAPTER 8

EXPERIMENTAL RESULTS AND STATISTICAL ANALYSIS OF TWO RECENT COLOR SELECTION GUIDELINES

This chapter presents the summarized user responses, statistical tests, and analyses that were performed for each experiment on isosurface renderings described in the Chapter 7. The statistical testing involves using sign test at the 95% confidence level. These tests considered the differences of raw counts which summarized user responses related to the Ebert et al. and House et al. guidelines. We will call the Ebert et al. and House et al. guidelines the Ebert-based and House-based guidelines, respectively. For each guideline, we considered harmonious versus disharmonious colors, disharmonious versus opponent colors, and harmonious versus opponent colors.

8.1 Comparison Results

The testing of the Ebert- and House-based color guidelines used the same three datasets used in our other experiments (i.e., the Engine Block, the DTI, and the H_2O). The isosurface renderings were generated using the OpenDX open source visualization software package. Each rendering contained at least two isosurfaces. For the Engine Block and DTI datasets, two isosurfaces were rendered (associated with



(a) House version (b) Ebert version

Figure 8.1: Example rendering of nested isosurfaces using harmonious color combinations based on the color selection guidelines

$\alpha \in \{180, 60\}$ for the Engine Block and $\alpha \in \{1200, 200\}$ for the DTI). For the H_2O dataset, three isosurfaces were rendered (associated with $\alpha \in \{100, 75, 50\}$). For each dataset, three sets of renderings were utilized. One set contained multiple renderings using harmonious color combinations. Another set contained multiple renderings using disharmonious color combinations. The third set contained multiple renderings using opponent color combinations. Figure 8.1 (a) shows the Engine Block isosurface rendering using Itten analogous harmonies that also satisfies House et al. color guidelines. Figure 8.1 (b) shows another rendering using analogous harmonies that also satisfies the Ebert et al. color guidelines. In each experiment, the participants assessed distinctness and preference by considering two sets of visualizations for each dataset.

8.2 Results and Analysis of Experiment One: Disharmonies vs. Opponent

This section presents the results of Experiment One on the House- and Ebert-based guidelines. The experiment considered isosurface renderings colored with disharmonious and opponent colors based on Ebert- and House-based color guidelines. We report raw counts summarizing user responses and a statistical analysis of significance of those counts for each pairwise presentation. As per standard practice, if a participant could not decide between renderings in a pair, such outcomes were not considered in analyzing statistical significance. The statistical analysis used a statistical sign test on raw counts.

8.2.1 Results of Disharmonies vs. Opponent using Ebert et al. Guidelines

Here, the tests of Ebert-based disharmonies versus Ebert-based opponencies are reported. Table 8.1 summarizes, by dataset, the evaluation of distinctness and preferences for such renderings. It shows counts of participant choices for determining distinctness and preference for isosurface renderings colored disharmoniously versus renderings colored in opponent colors. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown.

For all datasets, most viewers found the Ebert-based opponent color combinations to be more distinct than the disharmonious ones. This distinctness difference is highly significant, exceeding the 95% confidence level's critical value; the participants viewed the isosurface renderings using opponent colors as being more distinct than the ones using disharmonious colors.

For all three datasets the Ebert-based disharmonious color combinations were preferred more often than the opponent color ones. However, this result is not statistically significant at the 95% confidence level. If a 92% confidence level was used, then the result only for the H_2O dataset is significant.

Table 8.1: Disharmonious vs. Opponent color combinations (Ebert et al. Guidelines)

	Distinctness			Preference		
	Engine	DTI	H_2O	Engine	DTI	H_2O
Total, excluding Undecideds	38	38	40	39	40	40
# of Disharmony	7	7	7	21	23	25
# of Opponent	31	31	33	18	17	15
# of Undecided	2	2	0	1	0	0
Z Score	4.056	4.056	4.269	0.320	0.791	1.423
Confidence Level	99%	99%	99%	64%	80%	92%

8.2.2 Results of Disharmonies vs. Opponent using House et al. Guidelines

Here, the tests of House-based disharmonies versus House-based opponencies are reported. Table 8.2 summarizes, by dataset, the evaluation of distinctness and preferences for such renderings. It shows counts of participant choices for determining distinctness and preference for isosurface renderings colored disharmoniously versus renderings colored in opponent colors. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown.

For two of the datasets (i.e., the DTI and H_2O) most viewers found the House-based disharmonious color combinations to be more distinct than the opponent color ones. For the H_2O, the result is statistically significant at the 95% confidence level. For the DTI dataset, the difference is not statistically significant, though.

In addition, for two datasets (i.e., the DTI and H_2O) the House-based disharmonious color combinations were preferred more often. For the H_2O dataset, this result is statistically significant at the 95% confidence level. If a 93% confidence level was used, then this result for the DTI dataset would also be significant. For the other dataset, the difference is not significant.

Table 8.2: Disharmonious vs. Opponent (House et al. Guidelines)

	Distinctness			Preference		
	Engine	DTI	H_2O	Engine	DTI	H_2O
Total, excluding Undecideds	40	40	40	40	40	40
# of Disharmony	12	23	28	17	25	29
# of Opponent	28	17	12	23	15	11
# of Undecided	0	0	0	0	0	0
Z Score	2.688	0.791	2.372	1.107	1.423	2.688
Confidence Level	99%	80%	98%	88%	93%	99%

8.2.3 Overall Results of Disharmonies vs. Opponent

Here, we report an overall summary of the Ebert- and House-based disharmonies versus Ebert- and House-based opponencies. The summary does not distinguish by dataset. Table 8.3 presents this summary. It includes the totals for each and the number of undecided participants (i.e., participants who could not decide which rendering was most distinct and which renderings was most preferred). The Z score for the sign test on the summary counts and confidence level are also shown.

For Ebert-based guidelines most viewers found the opponent color combinations to be more distinct than the disharmonious color ones. This result is statistically significant at the 95% confidence level for the isosurface renderings.

For House-based guidelines the majority of the viewers found the disharmonious color combinations to be more distinct than the opponent color ones, but this difference is not statistically significant.

In addition, for both guidelines the isosurface renderings using disharmonious color combinations were preferred more often than the opponent color ones. These results are statistically significant at the 95% confidence level.

Table 8.3: Disharmonious vs. Opponent color combinations

	Distinctness		Preference	
	House et al.	Ebert et al.	House et al.	Ebert et al.
Total, excluding Undecideds	120	116	120	119
Disharmony	63	21	71	69
Opponent	57	95	49	50
Undecided	0	4	0	1
Z Score	0.456	6.964	1.917	1.650
Confidence Level	70%	99%	97%	95%

8.3 Results and Analysis of Experiment Two: Disharmonies vs. Harmonies

This section presents the results of Experiment Two on the House- and Ebert-based guidelines. The experiment considered isosurface renderings colored with disharmonious and harmonious color combinations based on these guidelines. We report raw counts summarizing user responses and a statistical analysis of those counts for each pairwise presentation. The statistical analysis used a statistical sign test on raw counts.

8.3.1 Results of Disharmonies vs. Harmonies using Ebert et al. Guidelines

Here, the test of Ebert-based disharmonies versus Ebert-based harmonies are reported. Table 8.4 summarizes, by dataset, the evaluation of distinctness and preferences for such renderings. It shows counts of participant choices for determining distinctness and preference for isosurface renderings colored disharmoniously versus renderings colored harmoniously. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown.

For the DTI and H_2O datasets, the harmonious color combinations were usually found to be more distinct. Only the DTI result is statistically significant at the 95% confidence level. If a 92% confidence level was used, then the result for the H_2O would also be significant. For the other dataset, the disharmonious color combinations were usually found to be more distinct. This result is not statistically significant, though.

In addition, for the DTI dataset the Ebert-based disharmonious color combinations were preferred more often. This result is statistically significant at the 95% confidence level. For the other datasets (i.e., the Engine Block and H_2O), the difference is not significant.

Table 8.4: Disharmonious vs. Harmonious color combinations (Ebert et al. Guidelines)

	Distinctness			Preference		
	Engine	DTI	H_2O	Engine	DTI	H_2O
Total, excluding Undecideds	39	40	40	38	40	40
# of Disharmony	21	15	16	19	26	18
# of Harmonious	18	25	24	19	14	22
# of Undecided	1	0	0	2	0	0
Z Score	0.320	1.739	1.423	0.162	1.739	0.791
Confidence Level	64%	95%	92%	58%	95%	80%

8.3.2 Results of Disharmonies vs. Harmonies using House et al. Guidelines

Here, the test of House-based disharmonies versus House-based harmonies are reported. Table 8.5 summarizes, by dataset, the evaluation of distinctness and preferences for such renderings. It shows counts of participant choices for determining distinctness and preference for isosurface renderings colored disharmoniously versus renderings colored harmoniously. In addition, the number of undecided participants

Table 8.5: Disharmonious vs. Harmonious color combinations (House et al. Guidelines)

	Distinctness			Preference		
	Engine	DTI	H_2O	Engine	DTI	H_2O
Total, excluding Undecideds	40	40	40	40	40	40
# of Disharmony	32	31	29	19	23	22
# of Harmonious	8	9	11	21	17	18
# of Undecided	0	0	0	0	0	0
Z Score	3.637	3.320	2.688	0.474	0.791	0.479
Confidence Level	99%	99%	99%	70%	80%	70%

(i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown.

For all datasets, most viewers found the House-based disharmonious color combinations to be more distinct than harmonious ones. For them, the result is statistically significant at the 95% confidence level.

In addition, for two datasets (i.e., the DTI and H_2O) the House-based disharmonious color combinations were preferred more often. For all three datasets, these preference results are not statistically significant, though.

8.3.3 Overall Results of Disharmonies vs. Harmonies

Here, we report an overall summary of the tests of Ebert-based and House-based disharmonies versus Ebert-based and House-based harmonies. Table 8.6 summarizes the evaluation of distinctness and preferences for such renderings. It shows counts of participant choices for determining distinctness and preference for isosurface renderings colored disharmoniously versus renderings colored harmoniously. It

Table 8.6: Disharmonious vs. Harmonious color combinations

	Distinctness		Preference	
	House et al.	Ebert et al.	House et al.	Ebert et al.
Total, excluding Undecideds	120	119	120	118
Disharmony	92	52	64	63
Harmony	28	67	56	55
Undecided	0	1	0	2
Z Score	5.751	1.467	0.639	0.644
Confidence Level	99%	92%	75%	75%

includes the number of undecided participants (i.e., participants who could not decide which rendering was most distinct). The Z score for the sign test on the summary counts and confidence level are also shown.

For House-based guidelines most viewers found the disharmonious color combinations to be more distinct than harmonious color ones. For them, the result is statistically significant at the 95% confidence level for the isosurface renderings. For Ebert-based guidelines most viewers found the harmonious color combinations to be more distinct. If a 92% confidence level was used, then this result would also be significant.

In addition, for House-based guidelines most viewers found the disharmonious color combinations to be preferred over the harmonious color ones. For them, the result is not statistically significant. For Ebert-based guidelines most viewers found the disharmonious color combinations to be more preferred than harmonious color ones. That result is also not statistically significant, though.

8.4 Results and Analysis of Experiment Three: Harmonies vs. Opponent

This section presents the results of Experiment Three on the House- and Ebert-based guidelines. The experiment considered isosurface renderings colored with harmonious and opponent color combinations based on Ebert- and House-based color guidelines. We report raw counts summarizing user responses and a statistical analysis of significance of those counts for each pairwise presentation. The statistical analysis used a statistical sign test. We used differences in user response raw counts in the statistical test.

8.4.1 Results of Harmonies vs. Opponent using Ebert et al. Guidelines

Here, the tests of Ebert-based harmonies versus Ebert-based opponencies are reported. Table 8.7 summarizes, by dataset, the evaluation of distinctness and preferences for such renderings. It shows counts of participant choices for determining distinctness and preference for isosurface renderings colored harmoniously versus renderings colored in opponent colors. In addition, the number of undecided participants (i.e., participants who could not decide which rendering was most distinct), the Z score for the sign test, and confidence level are shown.

For two of the datasets (i.e., the Engine Block and DTI), most viewers found the Ebert-based opponent color combinations to be more distinct than the harmonious color ones. For the H_2O dataset, most viewers found the Ebert-based harmonious color combinations to be more distinct than the opponent color ones. However, none of these results are statistically significant. So, we cannot state which of Ebert-

Table 8.7: Harmonious vs. Opponent color combinations (Ebert et al. Guidelines)

	Distinctness			Preference		
	Engine	DTI	H_2O	Engine	DTI	H_2O
Total, excluding Undecideds	35	38	40	40	37	40
# of Harmonious	15	16	22	21	25	27
# of Opponent	20	22	18	19	12	13
# of Undecided	5	2	0	0	3	0
Z Score	1.014	1.136	0.474	0.158	1.973	2.055
Confidence Level	85%	87%	70%	57%	97%	97%

based harmonious or opponent color combinations produce more distinct isosurface renderings.

For all three datasets the Ebert-based harmonious color combinations were preferred more often. For them, the results are statistically significant for the DTI and H_2O datasets at the 95% confidence level. For the Engine Block dataset, the result is not statistically significant, though.

8.4.2 Results of Harmonies vs. Opponent using House et al. Guidelines

Here, the tests of House-based harmonies versus House-based opponencies are reported. Table 8.8 summarizes, by dataset, the evaluation of distinctness and preferences for such renderings. It shows counts of participant choices for determining distinctness and preference for isosurface renderings colored harmoniously versus renderings colored in opponent colors. There were no undecided participants in this experiment. The Z score for the sign test and confidence level are also shown.

For the Engine Block and H_2O datasets, most viewers found the House-based opponent color combinations to be more distinct than the harmonious color ones.

Table 8.8: Harmonious vs. Opponent color combinations (House et al. Guidelines)

	Distinctness			Preference		
	Engine	DTI	H_2O	Engine	DTI	H_2O
Total, excluding Undecideds	40	40	40	40	40	40
# of Harmonious	9	17	19	23	28	26
# of Opponent	31	3	21	17	12	14
Z Score	3.637	1.107	0.478	0.791	2.372	1.739
Confidence Level	99%	89%	70%	80%	99%	95%

The result is only statistically significant for the Engine Block at the 95% confidence level. The H_2O results here may be affected by two isosurface colorings not being opponent. For the DTI dataset, most viewers found the House-based harmonious color combinations to be more distinct than opponent color ones. This result is not statistically significant.

In addition, for all three datasets most viewers found the House-based harmonious color combinations to be more preferred than opponent color ones. The results are statistically significant for the DTI and H_2O datasets at the 95% confidence level, though. For the Engine Block the result is not statistically significant, though.

8.4.3 Overall Results of Harmonies vs. Opponent

Here, an overall summary of the tests of Ebert-based and House-based harmonies versus Ebert-based and House-based opponencies, respectively, are reported. Table 8.9 summarizes, by guideline, the evaluation of distinctness and preferences for the renderings. It includes the number of undecided participants (i.e., participants who could not decide which rendering was most distinct and which renderings was

Table 8.9: Harmonious vs. Opponent color combinations

	Distinctness		Preference	
	House et al.	Ebert et al.	House et al.	Ebert et al.
Total, excluding Undecideds	120	113	120	117
Harmony	45	53	77	73
Opponent	75	60	43	44
Undecided	0	7	0	3
Z Score	2.830	0.753	3.012	2.589
Confidence Level	99%	78%	99%	99%

most preferred). The Z score for the sign test on the summary counts and confidence level are also shown.

For House- and Ebert-based guidelines most viewers found the opponent color combinations to be more distinct than harmonious color ones. For them, the result is only statistically significant for House-based guidelines at the 95% confidence level. For the Ebert-based guidelines this result is not statistically significant.

In addition, for both guidelines the isosurface renderings using harmonious color combinations were preferred much more than the opponent color ones. These results are statistically significant at the 95% confidence level.

8.5 Summary

This chapter has presented the statistical results of comparisons between two color selections guidelines for surface-based volume visualization. The color selection guidelines we considered were House et al. and Ebert et al. guidelines. Color renderings using harmonious (i.e., Itten analogous harmonies that also satisfy House et al. guidelines and Itten analogous harmonies that also satisfy Ebert et al. guidelines), disharmonious (i.e., color separated by 150 degree on Itten hue circle that also satisfy the House et al. or Ebert et al. guidelines), and opponent colors (i.e., chromatic opponent colors that also satisfy the House et al. or Ebert et al. guidelines) based on these guidelines were considered on the DTI, the Engine Block, and the H_2O datasets. The analysis involved statistical testing of significance using the sign test at the 95% confidence level.

The results of the studies suggest that in layered surface visualization, renderings using disharmonious colors that also follow House-based guidelines are more distinct than ones using harmonious colors. Also, renderings using harmonious colors are often preferred over opponent color combinations for both guidelines. The Engine Block dataset renderings are an exception, though. Opponent colors were sometimes more distinct than harmonious color combinations for the House et al. guidelines, but we do not have enough evidence to make a conclusion for the Ebert-based guidelines. Renderings using disharmonious colors are often more preferred than the opponent colors for both guidelines, but not in all cases. Finally, renderings using opponent colors are more distinct than disharmonious colors for Ebert-based guidelines, but not for House-based guidelines. The results of the studies suggest that the House-based guidelines appear more promising for layered surface visualization compare to the Ebert-based guidelines. However, these studies were performed on only three datasets and were tested using just a subset of the total possible harmonious and disharmonious color combinations. Another limitation in these studies was related to the H_2O dataset using opponent colors, which had three isosurfaces rendered but two of the isosurfaces had colors that were not opponent with each other. (Two of its isosurfaces colors were the same type of color but different shades of that color and had differing opacities.) As a result, some areas may have the same color in two isosurfaces. This may have influenced the results of the experiments involving opponent colors for H_2O dataset.

CHAPTER 9

FASHION COLOR HARMONIES IN VISUALIZATION

Just as color plays an important role in visualization, color also plays an important role in the fashion industry. Fashion designers often use color to obtain harmony, balance, and rhythm in clothing and accessories, since clothes colors have an influence on the appearance of one's eyes, hair, and complexion [69]. Accordingly, clothing and accessory colors which agree with the complexion are often used to improve the appearance of that feature [69]. On the other hand, often colors that disagree with skin tone, color of eyes, and hair can cause unpleasant effects for one's appearance.

Melrose [69] has introduced two main steps for color selection in clothing design. The first step is to select a foundation color. The second step is to select a set of colors that harmonize with that foundation color. The goal of the work reported in this chapter is to evaluate the suitability of these steps for clothing color selections in map-based visualization, using glyphs. We also reported the use of fabrics in visualization.

Color Harmonies

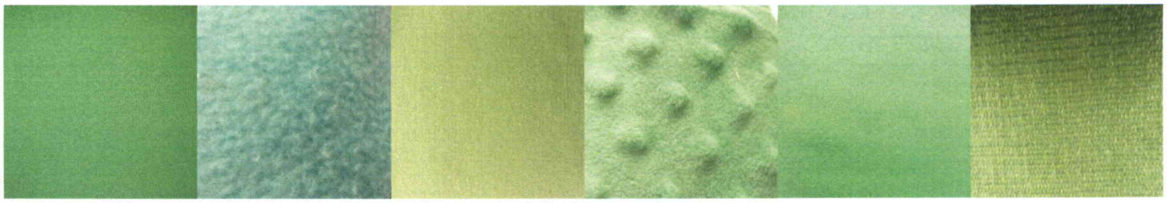
One way to classify costume color combinations is by the harmony of the colors. Melrose [69] has made a list of categories of costume colors according to degree of harmony. She named these categories: (1) harmonize, (2) perfect harmony, (3) rich harmony, (4) deep harmony, (5) subdued harmony, (4) heavy harmony, (5) agreeable harmony, (6) dull harmony, (7) chill or light harmony, (8) cold harmony, (9) quiet harmony, and (10) weak or poor harmony.

In this chapter we report three experiments. In the Experiment One, we investigate the compatibility of Melrose [69] costume / fashion harmonies with Itten and Munsell harmonies. Our goal was to examine if these fashion harmonies are consistent with Itten and Munsell harmonies. The other two experiments focus on the applicability of fashion industry color harmonies in visualization. We also explore the use of color combinations that violate the fashion industry harmony rules. Experiments Two and Three are based on user evaluations.

9.1 Experiment One: Experiment on Different Fabrics

The first experiment investigated the use of fabrics which follow two of the fashion industry harmonious color combinations (i.e., “fashion harmonies”) suggested by Melrose. The two categories were the “harmonize” and “perfect harmony” categories. Samples of these fabrics were used to build a simple visualization. The experiment determined if this simple visualization using fashion harmonies was consistent with two of the classic color theory harmonies. In it, we first compared fashion harmonious color combinations with Itten’s rules of color harmony to determine if these fashion harmonies were also consistent with the Itten harmony [49, 50]. We then compared fashion harmony with Munsell's rules of balance (discussed in Section 2.3.1) to determine if these fashion harmonies were also consistent with the Munsell harmony [37,73].

The visualization was a stacked bar chart of county-by-county demographic information of the state of Arizona. The demographic data was retrieved from the United States Census website [137]. For each county, ratio of paid employees, employment ratio (i.e., ratio of working age population to the total population), and ratio of population in three age brackets (i.e., less than 20 years old, between 20 and 50 years old, and over 50 years old) during 2011 were visualized. Before the visualization of this data was made, we gathered six types of fabric (i.e., denim, fleece, snuggle bubble, magnolia solids, casa, and terry) in colors that could form harmonious color combinations based on the Melrose [69] categories of fashion harmony. Sample of these fabrics with color green are shown in Figure 9.1. For each fabric type we gathered nine samples. These samples were ones that could form fashion harmonies based on the harmonize and perfect harmony categories of the Melrose color combinations as well as ones that could form fashion disharmonies (i.e., based on week or poor harmony category of Melrose). The samples were in the colors of red, blue, green, and yellow. Each fabric sample was photographed indoors under fluorescent light that was similar for all samples. The camera was set to automatic white balancing for these photographs. The results were bitmap files of the samples with a resolution 200 × 300. The visualization used the fabric pictures to form color visualizations of the demographic data. The visualizations were bar charts. Each bar represents one county from the state of Arizona. Examples are shown in Figure 9.2 for the Fleece



(a) Denim (b) Fleece (c) Magnolia (d) Bubble (e) Terry (f) Casa

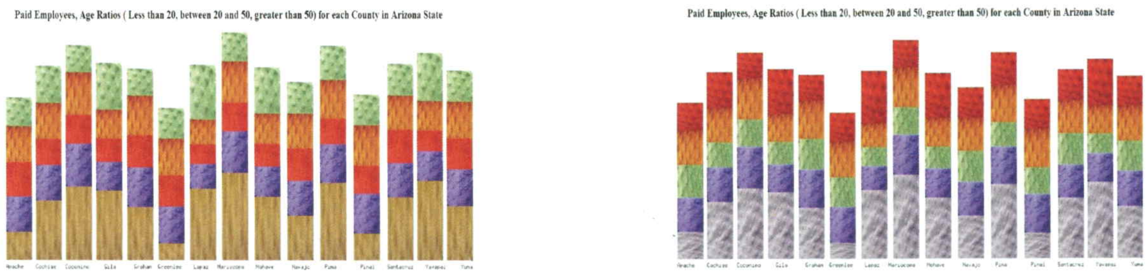
Figure 9.1: Sample of Fabrics

(a) Harmonious color combinations (b) Disharmonious color combinations

Figure 9.2: Example of visualization based on Fleece fabric using harmonious and disharmonious fashion colors

and in Figure 9.3 for the Snuggle Bubble fabrics. For each county five stacked bars were shown. The lowest bar region shows the paid employee ratio. The next region shows employment ratio. The highest three bar regions show population in each age bracket (i.e., less than 20 years old, between 20 and 50 years old, and over 50 years old).

We compared the color combinations of each fashion harmonious visualization with the Itten [49, 50] and Munsell [37, 73] harmonies which were described in Chapter 2.



(a) Harmonious color combinations

(b) Disharmonious color combinations

Figure 9.3: Example of visualization based on Snuggle Bubble fabric using harmonious and disharmonious fashion colors

To investigate if these fashion harmonies follow Itten's rules of harmony, we determined the location of each fabric's color (i.e., based on fashion industry harmonies) on the Itten hue circle, and then checked to see if these colors followed any of Itten's rules of harmony. We did this check for each visualization we built. We found that the fashion harmonies we built followed Itten rules of analogous harmonies, triad harmonies, or tetrad harmonies.

To investigate if these fashion harmonies follow the Munsell balance (or harmony) rules, we determined the value and chroma attributes of each color in the visualizations and the area each color occupied. These computations were done for each county in each visualization. Then, we determined if the colors in each stacked bar balanced each other. We found that these colors are harmonious (based on Munsell's definition of balance). More detailed results of the experiment are presented in the Chapter 10.

9.2 Experimental Design for Experiments Two and Three

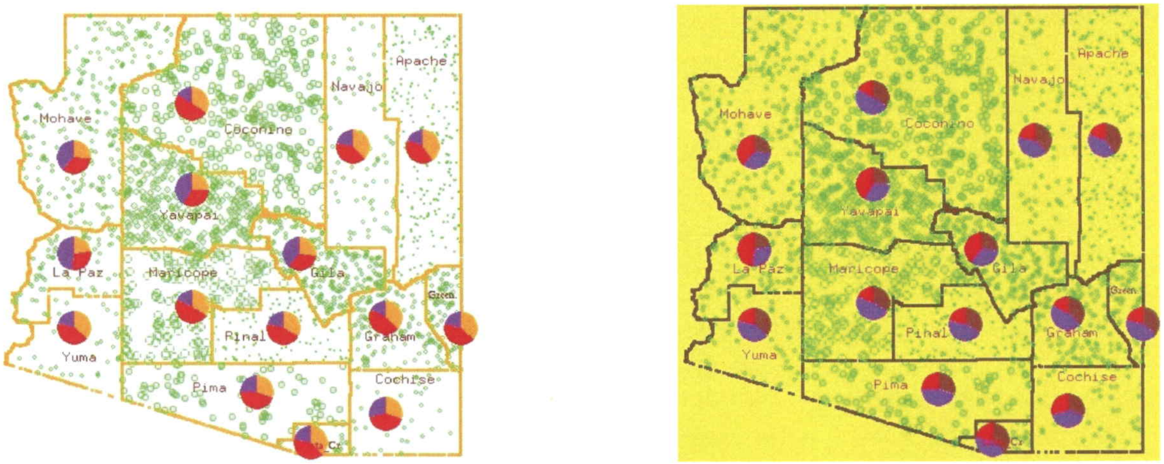
The other experiments were based on user evaluations. Those two experiments are this chapter's Experiments Two and Three. Participants in these experiments all had normal or corrected-to-normal vision and no known visual impairments. They were all older than age 18 and either undergraduate or graduate students with some computing knowledge. Each participant took 10 to 15 minutes to complete their part of the study. The experiments involved seated participants viewing a map of Arizona with a single background color and glyph overlays using multiple colors. All participants had the possibility to adjust the chair and monitor height, orientation, and distance to their preference for comfort.

The overlays used certain classes of color combinations whose effectiveness we wanted to examine. These included combinations that were (1) fashion harmonies (i.e., harmonize category of the Melrose color combinations), (2) fashion disharmonies, and (3) Itten harmonies.

9.3 Experiment Two: Fashion Harmony vs. Fashion Disharmonies

Experiment Two was designed to evaluate the noticeability of fashion harmony versus color combinations that violate fashion harmony. The experiment used a study of user perceptions to compare the use of fashion industry harmonious colors to color combinations that violate the fashion industry harmonies. We call such combinations *fashion disharmonies.* The experiment used a map-based visualization of county-by-county demographic information of the state of Arizona. The demographic data was retrieved from the United States Census website [137]. For each county, five attributes: the number of paid employees, employment ratio (i.e., ratio of working age population to the total population), the counts of population less than 20 years old, the counts of population between 20 and 50 years old, and the counts of population over 50 years old during 2011 were visualized. In the visualization, a unique color was used to represent each attribute of the multivariate data. In these visualizations, a dot glyph was used. The number of dots represented the employment ratio and the size of the dots represented number of paid employees. Pie charts represented the age categories (with pie slice sizes used to represent the three classes: less than 20 years old, between 20 and 50 years old, and over 50 years old).

Several visualizations were made. An equal number were made with each background color: red, blue, green, and yellow. In the harmonize fashion harmony, the harmonious colors with red are yellow, black, gray, and white. (The harmonious colors with blue are brown, orange, green, and yellow. The harmonious colors with green are scarlet, blue, orange, and white. The harmonious colors with yellow are blue, chocolate, black, and scarlet.) In the perfect harmony category of fashion harmony, the harmonious colors with red are orange, green, purple, and gray. (The harmonious colors with blue are scarlet, orange, green, and red. The harmonious colors with green are purple, orange, green citrine, and cyan. The harmonious colors with yellow are crimson, gray, golden brown, and scarlet.) Twelve visualizations (i.e., three different ones with each background color) used harmonize fashion harmony and eight visualizations (i.e., two different ones with each background color) used perfect harmony category of fashion harmony. For each background color, another visualiza-



(a) Fashion Harmonies

(b) Fashion Disharmonies

Figure 9.4: Example of map-based visualization using fashion harmonies and fashion disharmonies

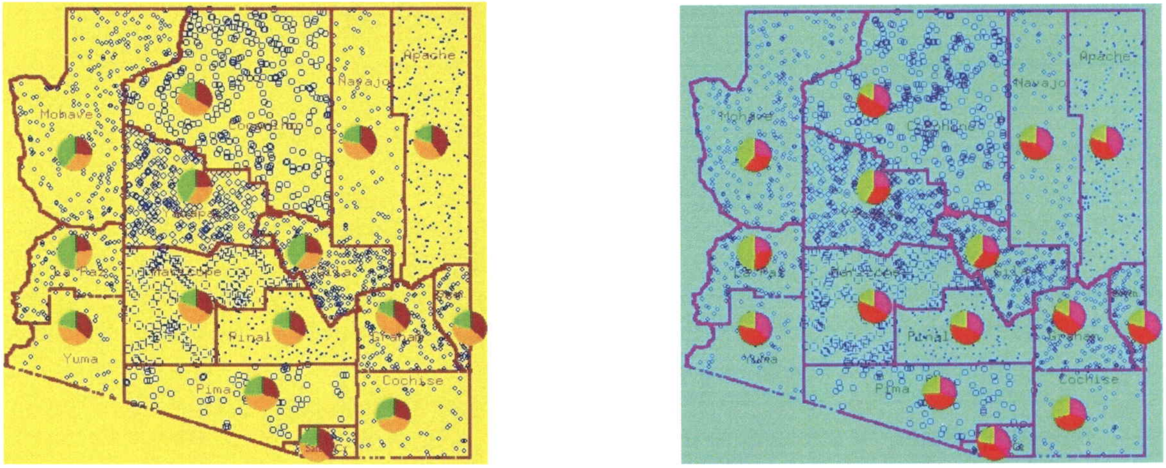
tion with colors forming fashion disharmonious combinations with background was also generated. Figure 9.4 shows two example visualizations of the demographic information of the state of Arizona, one using fashion harmonies (left) and one using fashion disharmonies (right).

In this study participants compared pairs of harmonious and disharmonious visualizations to answer following questions: (1) which visualization of the pair was distinct? and (2) which visualization of the pair was preferred?

Thirty volunteers (15 females and 15 males) took part in Experiment Two.

9.4 Experiment Three: Fashion Harmonies vs. Itten Harmonies

Experiment Three was designed to evaluate the noticeability of fashion harmony versus Itten harmony. The experiment used a user perception study to compare the use of fashion industry harmonious colors to Itten harmonious color combinations



(a) Fashion Harmonies (b) Itten Harmonies

Figure 9.5: Example of map-based visualization using fashion harmonies and Itten harmonies using blue as a base color

in visualization. The experiment used the same fashion harmonious visualizations of county-by-county demographic information of the state of Arizona that were used in Experiment Two in Section 9.3. In the visualization, each attribute was in its own color in the visualization. The experiment also used four visualizations of the same data and visualization type, but using colors consistent with the Itten harmonies. Of these, one had a background that was red. Another rendering used a blue background. Another background for a rendering was green. The last one had a yellow background. The Itten harmonious color combination used here were based on four-color harmonies (i.e., tetrad harmonies) with the background color. Figure 9.5 shows examples of our visualizations of the demographic information of the state of Arizona using fashion harmonies (left) and Itten harmonies (right).

Participants compared pairs of visualizations to answer following questions: (1) which visualization of the pair was distinct? and (2) which visualization of the pair was preferred?

Thirty volunteers (15 females and 15 males) took part in Experiment Three.

9.5 Summary

In this chapter, we described experiments to investigate use in information visualization of color combinations that have been considered to be harmonious in the fashion industry. One experiment used photographed samples of fabrics to compare the fashion harmonious color combinations with Munsell's and Itten's harmonies to determine if these fashion color harmonies follow the rules of Itten harmonies or Munsell harmonies. However, it is possible that this experiment was affected by the fluorescent lighting used (although the auto white balancing of the camera may limit the impact of the lighting). In another experiment, we used a user perception study to investigate noticeability and preference of the fashion color harmonies versus disharmonies. In the last experiment, we also used a user perception study, this time to investigate noticeability and preference of fashion color harmonies versus Itten color harmonies. The experiment results are reported in Chapter 10.

CHAPTER 10

EXPERIMENTAL RESULTS AND STATISTICAL ANALYSIS OF USING FASHION COLOR HARMONIES IN VISUALIZATION

This chapter presents results for the experiments on color combinations used in the fashion industry which were described in the Chapter 9. For the two experiments using participant evaluations (i.e., fashion industry harmonies versus fashion industry disharmonies and versus Itten harmonies), the user response summaries, statistical tests, and analysis that were performed are described. The statistical testing involved using t-Tests at the 95% confidence level. These statistical tests were based on raw count summaries of the user responses.

10.1 Results of Experiment One: Experiment on Different Fabrics

As stated in Section 9.1, in Experiment One visualizations of demographic information of each county in the state of Arizona using color pictures of fabrics were used to investigate if fashion harmonies were consistent with (1) Itten harmonies or with (2) Munsell harmonies. Figure 10.1 shows the counts of our visualizations using fashion color harmonies that are consistent with the Munsell harmonies and Itten harmonies. The heights of the blue bars represent the number consistent with the

Munsell harmonies. The heights of the red bars represent the number consistent with the Itten harmonies. Each bar is labeled by the fabric type it represents. Of the 120 samples tested here for harmonies (i.e., 20 colors for each of the six fabrics tested), 104 of the samples are consistent with the Munsell harmonies, that is about 87% of the time. 78 of the samples are consistent with the Itten harmonies, which is nearly 65% of the time. The type of fabrics may be a factor in these results. For example, for the combinations involving three, four, or five colors of Bubble fabrics 19 of these 20 color combinations are consistent with the Munsell harmonies, that is about 95% of the time, but with the denim fabrics only 13 of the 20 combinations are consistent with the Munsell harmonies, that is about 65% of the time. For the combinations involving three, four, or five fashion colors of Bubble fabrics 13 of these 20 color combinations are consistent with the Itten harmonies, that is about 65% of the time, but with the denim fabrics only 11 of the 20 combinations are consistent with the Itten harmonies, that is about 55% of the time.

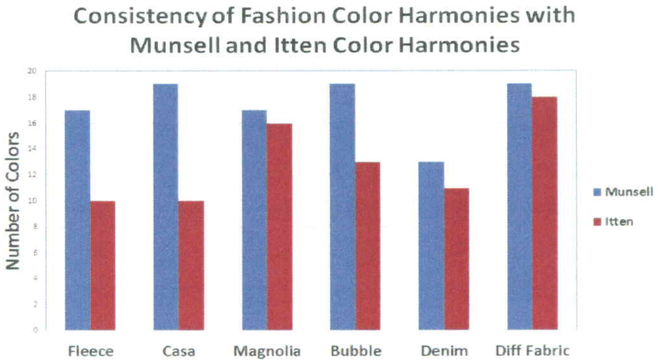


Figure 10.1: Comparison of fashion harmonies to Munsell and Itten rules of harmony using different fabrics

10.2 Results and Analysis of Experiment Two: Fashion Harmony vs. Fashion Disharmonies

This section presents the results of Experiment Two on the fashion industry color harmonies and color disharmonies. As stated in Section 9.3, this experiment considered visualizations of the demographic information of each county in the state of Arizona, which was visualized using glyph overlays on an Arizona map, with one set of visualizations using glyphs colored with fashion harmonies and another set of visualizations using glyphs with fashion disharmonies. We report raw counts summarizing user responses and a statistical analysis of significance of those counts for harmonious and disharmonious color combinations. The statistical analysis used statistical t-Testing.

10.2.1 Raw Results of Fashion Harmony vs. Fashion Disharmonies

Here, the results of the experiment are reported. Table 10.1 summarizes the evaluation of distinctness. It shows the counts of participant choices for glyph overlays colored with the fashion harmonies versus glyph overlays colored with the fashion disharmonies. In this experiment, in 72% of the trials, the participants stated that the overlays colored with the fashion harmonies were more distinct.

Table 10.2 summarizes the evaluation of preference. It shows the counts of participant choices for glyph overlays colored with the fashion harmonies versus glyph overlays colored with the fashion disharmonies. In this experiment, in 67% of the trials, the participants stated that the overlays colored with the fashion harmonies

Table 10.1: Count of participants' responses for pairwise tests of distinctness for fashion harmonies vs. fashion disharmonies for glyph overlays

	Pairwise Distinctness Comparison	
Background Color	Fashion Harmony	Fashion Disharmony
Red	27	4
Green	23	7
Blue	20	11
Yellow	16	13

were preferred, although results varied by background color. For example, for yellow background participants preferred overlays colored with the fashion disharmonies.

Table 10.2: Count of participants' responses for pairwise tests of preference using fashion harmonies vs. fashion disharmonies for glyph overlays

	Pairwise Preference Comparison	
Background Color	Fashion Harmony	Fashion Disharmony
Red	24	6
Green	25	5
Blue	20	10
Yellow	11	19

We also studied the responses for female versus male participants. Table 10.3 shows the counts of male and female participant choices for distinctness and preference in the experiment. Both female and male participants usually stated that the fashion harmonies were more distinct than and preferred to the fashion disharmonies.

Table 10.3: Count of Males and Females responses for pairwise tests of distinctness using fashion harmonies vs. fashion disharmonies for glyph overlays

	Distinctness		Preference	
	Fashion Harmony	Fashion Disharmony	Fashion Harmony	Fashion Disharmony
Female	44	17	37	23
Male	42	18	43	17

10.2.2 Analysis of Experiment Two: Two Sample t-Test

The overall averages for the distinctness question for fashion harmonies versus disharmonies are shown in Table 10.4. Here, the averages are the average selection count (e.g., 2.87 for fashion harmonies means the average person chose the fashion harmonies color overlay as the most distinct one for 2.87 of the 4 trials). Fashion color harmonies were the more common choice.

To determine the statistical significance of the difference in responses, two sample t-Testing was performed. Table 10.4 also shows these results. There was a statistically significant difference in the noticeability of the fashion harmonies and fashion disharmonies; overlays colored with fashion harmonies are likely more distinct than fashion disharmonies.

The overall averages for preference of the fashion harmonies versus the fashion disharmonies are shown in Table 10.5. Here, the averages are the average selection count. The 2.67 value for fashion harmonies means the fashion harmonies were the most preferred one for 2.67 of the 4 trials, which is about 65% of the time. Fashion color harmonies were the more common choice.

Table 10.4: Two sample t-Test on distinctness of fashion harmonies vs. fashion disharmonies for glyph overlays

Pairwise Distinctness Comparison		
	Fashion Harmonies	Fashion Disharmonies
Mean	2.87	1.17
Variance	0.88	0.83
Observations	30	30
t-Stat	7.117	
t-Critical	2.002	⇒ SIGNIFICANT

To determine the statistical significance of the difference in responses, two sample t-Testing was performed. Table 10.5 also shows these results. There was a statistically significant difference in the preference of the fashion harmonies and fashion disharmonies; overlays colored with fashion harmonies are likely more preferred than fashion disharmonies.

Table 10.5: Two sample t-Test on preference of fashion harmonies versus fashion disharmonies for glyph overlays

Pairwise Preference Comparison		
	Fashion Harmonies	Fashion Disharmonies
Mean	2.67	1.33
Variance	0.85	0.85
Observations	30	30
t-Stat	5.599	
t-Critical	2.002	⇒ SIGNIFICANT

The overall averages for distinctness of the fashion harmonies versus the fashion disharmonies for males (left) and females (right) are shown in Table 10.6. Here, the averages are the average selection count (e.g., 2.8 for fashion harmonies means the average male chose the fashion harmonies for overlay as the most distinct one for 2.8 of the 4 trials; 2.93 for fashion harmonies means the average female chose the fashion harmonies for overlay as the most distinct one for 2.93 of the 4 trials). Fashion color harmonies were the more common choice for both females and males.

To determine the statistical significance of the difference in responses for male and female participants, two sample t-Testing was performed for each population separately. Table 10.6 also shows these results for distinctness of the fashion harmonies versus fashion disharmonies. There was a statistically significant difference in the distinctness of the fashion harmonies versus fashion disharmonies for male participants; overlays colored with fashion harmonies are likely more distinct than fashion disharmonies. There also was statistically significant difference in the distinctness of the fashion harmonies versus fashion disharmonies for female participants, overlays colored with fashion harmonies are likely more distinct than fashion disharmonies.

Table 10.6: The two sample t-Test for distinctness of fashion harmonies vs. fashion disharmonies for Male and Female participants for glyph overlays

Male Participants

t-Test Result		
	Harmonies	Disharmonies
Mean	2.8	1.2
Variance	0.89	0.89
Observations	15	15
t-Stat	4.656	
t-Critical	2.048	⇒ SIGNIFICANT

Female Participants

t-Test Result		
	Harmonies	Disharmonies
Mean	2.93	1.13
Variance	0.92	0.84
Observations	15	15
t-Stat	5.252	
t-Critical	2.048	⇒ SIGNIFICANT

10.3 Results and Analysis of Experiment Three: Fashion Harmony vs. Itten Harmonies

This section presents the results of Experiment Three on the fashion industry color harmonies versus Itten color harmonies (i.e., four-color harmonies or tetrad harmonies). As stated in Section 9.4, this experiment considered the demographic information of each Arizona county, with one set of visualizations using glyph overlays colored with fashion harmonies and the other set using glyph overlays colored with Itten harmonies. We report raw counts summarizing user responses and a statistical analysis of significance of those counts for fashion harmonies and Itten harmonious color combinations. The statistical analysis used statistical t-Testing.

10.3.1 Raw Results of Fashion Harmonies vs. Itten Harmonies

Here, the results of the experiment are reported. Table 10.7 summarizes the evaluation of distinctness. It shows the counts of participants choice for glyph overlays colored with the fashion harmonies versus glyph overlays colored with the Itten harmonies. In this experiment, 74% participants stated that the overlays colored with the fashion harmonies were more distinct.

Table 10.8 summarizes the evaluation of preference. It shows the counts of participant choices for determining preference of glyph overlays colored with the fashion harmonies versus glyph overlays colored with the Itten harmonies. In this experiment, 71% of participants preferred the overlays colored with the fashion harmonies.

Table 10.7: Count of participants' responses on distinctness of fashion harmonious vs. Itten harmonious color combinations for glyph overlays

	Pairwise Distinctness Comparison	
Background Color	Fashion Harmony	Itten Harmony
Red	25	5
Green	28	2
Blue	18	12
Yellow	18	12

Table 10.8: Count of participants' responses on preference of fashion harmonious vs. Itten harmonious color combinations for glyph overlays

	Pairwise Preference Comparison	
Background Color	Fashion Harmonies	Itten Harmonies
Red	25	7
Green	26	4
Blue	22	8
Yellow	14	16

10.4 Analysis of Experiment Three: Two Sample t-Test

The overall averages for the distinctness question for the fashion harmonies versus the Itten harmonies are shown in Table 10.9. Here, the averages are the average selection count. The 2.97 for fashion harmonies means the average person chose the fashion harmonies color overlays as the most distinct one for 2.97 of the 4 trials, which is nearly 75% of the time. Fashion harmonies were the more common choice.

To determine the statistical significance of the difference in responses, two sample t-Testing was performed. Table 10.9 also shows these results. There was a statistically significant difference in the noticeability of the fashion harmonies and Itten harmonies; overlays colored with fashion harmonies are likely more distinct than the Itten harmonies.

Table 10.9: Two sample t-Test on distinctness of fashion harmonies vs. Itten harmonies for glyph overlays

Pairwise Distinctness Comparison		
	Fashion Harmonies	Itten Harmonies
Mean	2.97	1.03
Variance	0.79	0.79
Observations	30	30
t-Stat	8.41	
t-Critical	2.002	⇒ SIGNIFICANT

The overall averages for preference of the fashion harmonies versus Itten harmonies are shown in Table 10.10. Here, the averages are the average selection count. The 2.83 for fashion harmonies means the average person chose the fashion harmonious color overlay as the most preferred one for 2.83 of the 4 trials, which is about 70% of the time.

To determine the statistical significance of the difference in responses, two sample t-Testing was performed. Table 10.10 also shows these results. There was a statistically significant difference in the preference of the fashion harmonies and Itten harmonies; overlays colored with fashion harmonies are likely more preferred than Itten harmonies.

An overall summary of the distinctness and preference of fashion harmonies and Itten harmonies for the glyph overlay visualizations is shown in Table 10.11. It

Table 10.10: Two sample t-Test on preference of fashion harmonies vs. Itten harmonies for glyph overlays

Pairwise Preference Comparison		
	Fashion Harmonies	Itten Harmonies
Mean	2.83	1.17
Variance	0.97	0.97
Observations	30	30
t-Stat	6.55	
t-Critical	2.002	⇒ SIGNIFICANT

shows counts of participant choices, the Z-score, and the confidence level. The fashion harmonies were selected more often than the Itten harmonies. The difference for both distinctness and preference was statistically significant at the 95% confidence level.

Table 10.11: Z-Test for fashion harmonious vs. Itten's harmonious color combinations for glyph overlays

	Distinctness	Preference
Total, excluding Undecideds	120	120
# of Fashion Harmony	89	85
# of Itten Harmony	31	35
Z Score	5.203	4.473
Confidence Level	99%	99%

10.5 Summary

In this chapter, we investigated the use in information visualization of color combinations regarded as harmonious and disharmonious by the fashion industry.

We first reported on the consistency of harmonious colors in fashion industry with Munsell's and Itten's rules of harmony using photographs of six different fabrics. Based on the fashion harmonious colors we tested, nearly 87% of time fashion harmonies were found to be consistent with the Munsell harmonies and nearly 65% of the time fashion harmonies were found to be consistent with the Itten harmonies.

Next, we reported on distinctness and preference of visualizations using glyph overlays colored with fashion harmonies versus visualizations using glyph overlays colored with fashion disharmonies. The harmonious colors of the fashion industry were found to be more distinct than and preferred over disharmonious colors of the fashion industry for these visualizations.

In the last experiment, we reported on distinctness and preference of visualizations using glyph overlays colored with fashion harmony colors versus ones colored with Itten harmonious color combinations. The results provide evidence that harmonious colors in fashion industry are more distinct and preferred over Itten harmonious color combinations for glyph overlay visualizations.

The results of the studies suggest that the fashion industry harmonies appear to be good candidates for glyph overlay visualizations. It appears that fashion harmonies are better choices than fashion disharmonies for at least some classes of information visualizations. The results were unexpected given the results we found for surface-based visualization and color label overlay for map-based visualization of related disharmonies.

The results also suggest that if for any reason we need to use color combinations of fashion harmonies that are consistent with the Munsell harmonies, the casa, bubble, and combination of different fabrics we used will be the best choices. (They are consistent with the Munsell harmonies 95% of the time.) If the fashion harmonies need to be consistent with the Itten harmonies, the combination of different fabrics will be the best choice. (They are consistent with the Itten harmonies 90% of the time.) If just one type of fabric need to be used in a visualization based on harmonious colors, the casa and bubble fabrics we used have high consistency with Munsell harmonies and the magnolia fabric we used has high consistency with Itten harmonies.

There was no comparison on distinctness of fashion harmonies versus standard disharmonies for glyph overlays, which we will investigate in future studies.

We should include that the studies we did were performed only on a subset of fashion industry harmonies and a subset of fabrics, though.

CHAPTER 11

CONCLUSION AND FUTURE WORKS

This dissertation research focused on investigating the use of certain classes of color theories for color selection in visualization. These are theories about harmonious colors, disharmonious colors, and opponent color combinations. Our investigations targeted two classes of visualizations: label and glyph overlays on map-based visualizations and on surface-based volume visualization. For map-based visualization, we also investigated using high (or low) saturated colors and high (or low) lightness colors for label overlays. In addition, we examined applicability of harmonious color combinations introduced by fashion industry for visualization. We utilized studies of participants perceptions for our investigations.

11.1 Map-Based Visualization

For map-based visualization, we examined the distinctness of label overlays using three theories about harmonious colors (based on Itten, Nemcsics, and Matsuda rules), disharmonious colors, opponent colors, high and low saturated colors, and high and low lightness colors. The results of the participants studies, based upon their' responses, suggested that label overlays colored disharmoniously are more noticeable than label overlays colored with harmonious, opponent, low saturated, or high lightness colors on map-based visualizations.

We also observed that label overlays colored with 150 degree disharmonies (i.e., colors separated by 150 degrees on the Itten hue circle from a base color) form the most distinct color combinations and are more distinct compared to 80 degree disharmonies. Since some research has previously suggested that two colors separated by 80 degrees from the background color on the Itten hue circle had less harmony than two colors separated by any other degree of separation [80], colors separated by 80 degrees were a good candidate for disharmonious color combinations. However, based on our investigations we found out that colors separated by 150 degree on the hue circle are also disharmonious ones and usually better choices for overlay in information visualization..

In addition, label overlays whose colors formed a Matsuda i-type harmony with the background tended to be noticed later than overlays with non i-type colors. Therefore, label overlays with non i-type color combinations are more noticeable than i-type harmony ones.

We compared Itten harmonies with Nemcsics harmonies and the results showed, there is insufficient evidence if label overlays using Itten harmonies are more noticeable than Nemcsics harmonies.

Gender or the wearing of glasses do not appear to have affect on noticeability of harmoniously colored label overlays on map-based visualizations using Nemcsics harmonies versus Itten harmonies.

11.2 Surface-Based Visualization

For surface-based volume visualization, we explored the distinctness and preference of color theories about harmonious, disharmonious, and opponent color combinations for multiple isosurfaces in a single rendering. The results based on participant choices for isosurface renderings suggest that disharmonious color combinations are more distinct (just about 67% of time) and preferred (just about 66% of time) over harmonious color combinations. The results based on participant choices for isosurface renderings also suggest that disharmonious color combinations are more distinct (just about 76% of time) and preferred (just about 84% of time) over opponent color combinations. Also, harmonious color combinations are more distinct (just about 63% of time) and preferred (just about 71% of time) to opponent ones. In fact, the harmonious color combinations were selected about twice as often as the opponent ones for both distinctness and preference.

In addition, for surface-based volume visualization, we compared three color selection guidelines. The color selection guidelines we considered were Itten [21, 49] and House et al. [45] and Ebert et al. [27, 28] guidelines. The color combinations considered were (1) Itten analogous harmonious colors, (2) Itten analogous harmonious colors that also satisfied the Ebert-based guidelines, (3) Itten analogous harmonious colors that also satisfied the House-based guidelines, (4) 150° disharmonies on the Itten hue circle, (5) 150° disharmonies (on the Itten hue circle) that also satisfied the Ebert-based guidelines, (6) 150° disharmonies (on the Itten hue circle) that also satisfied the House-based guidelines, (7) chromatic opponent colors on Itten hue circle,

(8) chromatic opponent colors (on Itten hue circle) that also satisfied the Ebert-based guidelines, and (9) chromatic opponent colors (on Itten hue circle) that also satisfied the House-based guidelines. The results of participants perceptions studies, based on their responses, suggest that renderings using disharmonies that also follow House-based guidelines are more distinct than renderings using harmonies that also follow House-based guidelines. However, the House-based disharmonies are not as uniformly valuable as Itten-based ones. And for one dataset's renderings, the participants preferred House-based harmonies over House-based disharmonies. The results also suggest that renderings using harmonious color combinations are preferred over ones using opponent color combinations for all three guidelines, and renderings using disharmonies are preferred over ones using harmonies for Itten-based guidelines.

Lastly, we investigated color harmonies of the fashion industry for visualizations. We compared the compatibility of fashion harmony with Munsell's and Itten's rules of harmony using six different fabrics. The results show 87% of the visualizations we built using harmonious colors of the fashion industry are compatible with Munsell's rules for harmony. 65% of them are compatible with Itten's rules of harmony. We also studied fashion harmony and Itten's rules of harmony in map-based visualization using glyph with participants studies. Based on their responses, glyph-based visualizations using fashion harmony colors has more distinct and preferred presentations compared to when Itten's rules of harmony are used.

Based on our investigation results, our recommendations are as follows:

(1) In map-based visualizations, for label overlays to be distinct from other features on a map, the disharmonious color combinations are the best choice.

(2) In map-based visualizations, for glyph overlays on a map, fashion harmonies are also a suitable choice.

(3) In surface-based volume visualizations, for rendering multiple isosurfaces in the same display, disharmonious color combinations are good choices.

(4) In surface-based volume visualizations, for rendering multiple isosurfaces in the same display, using disharmonious color combinations that also satisfy House-based guidelines are good choices.

11.3 Future Works

In the future, we plan to investigate the effect of the color theories with different demographic groups. For example, it would be interesting to explore if age or known eye disorders, such as glaucoma, cataracts etc., affect the relationship between perceived readability and color separations. We also plan to study the cultural effect of color theories in visualization. The results of these findings could benefit geographers, social scientists, urban researchers, and more.

In addition, we plan to study other datasets for surface-based volume visualization and to try to discover if the shape and structures of a volumetric datasets affect the perception of which color combination is the most suitable for nested isosurfaces in a single rendering. Also, we want to investigate the effect of the above color selection guidelines in other visualizations.

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