

Color Illusions on Liquid Crystal Displays and Design Guidelines for Information Visualization

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(ABSTRACT)

The influence of color on size and depth perception has been explored for a century, but there is very limited research on interventions that can reduce the color illusions. This study was motivated to identify interventions and propose design guidelines for information visualization, especially where size judgment is critical.

This study replicated the color size illusion and color depth illusion on an LCD monitor and it was found that yellow is the smallest and farthest color among red, yellow, green, and blue on a white background. Three types of interventions (background brightness, border color, and background grid brightness) were tested to identify the conditions that reduce the color illusions, but all of them were not statistically significant.

Based on the experiment results and literature survey, design guidelines were proposed. To extend the guidelines to the bioinformatics field, design recommendations were proposed and implementation examples were illustrated. Evaluations on design implementations were evaluated by interviewing domain experts.

Additionally, the relationship between the color size illusion and the color depth illusion was explored.

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Chapter 1

Introduction

1.1 Background

Color is widely used in information visualization to deliver different types of information such as extreme values, patterns, and attribute values. Color coding is the most effective way to represent extreme values because of pre-attentive vision, the human ability to perceive visual stimuli instantaneously and effortlessly without focusing attention on local detail (Julész, 1981). Successive research demonstrated that color would take priority over other visual properties for nominal data mapping (Christ, 1975; Cleveland & McGill, 1984; Mackinlay, 1986; Nowell, Schulman, & Hix, 2002). In the case of quantitative data, some researchers have demonstrated that color conveys quantitative data more accurately than either shape or size (Christ, 1975; Nowell et al., 2002), although Cleveland and McGill (1984) and Mackinlay (1986) have both argued that color is more accurate than shape, but not more than size (volume). Additionally, many display design guidelines suggest redundant color coding, since it enhances visual searching performance (Bundesen & Pedersen, 1983; Cahill & Carter, 1976; Carter, 1982; Christ, 1975; Hughes & Creed, 1994; Treisman & Gormican, 1988).

Nevertheless, color should be carefully used because of the characteristics of human

visual perception. Cleveland and McGill (1983) reported that participants erred in judging the size of colored area in statistical maps. Claessen and his colleagues (1995) also reported that participants consistently selected larger or smaller pegs to fit a hole when the peg was colored. These empirical studies imply that color has an influence on size perception and can result in human errors.

The influence of color on size perception has been explored for a long time. A series of research studies has shown that the color of an object influences its perceived size (Cleveland & McGill, 1983; Gentilucci, Benuzzi, Bertolani, & Gangitano, 2001; Gundlach & Macoubrey, 1931; Tedford, Bergquist, & Flynn, 1977; Wallis, 1935). The researchers in these studies used slide projectors, colored boards, colored cubes, or Cathode Ray Tube (CRT) monitors to replicate the color size illusion, but no study has replicated the color size illusion on Liquid Crystal Display (LCD) monitors.

This study focused on the color size illusion on LCD monitors. LCD monitors are quickly replacing CRT monitors. There are several reasons for this; for example, one study shows that visual display terminal (VDT) workers prefer TFT-LCD to CRT monitors (Chen & Lin, 2004). Furthermore, LCD monitors use less space and energy than CRT monitors do, and they are now affordable. Accordingly, it is likely that there will continue to be greater use of LCD monitors. Therefore, it would be meaningful to confirm that the color size illusion occurs on LCD monitors, so that further research studies can be based on the findings of the current study.

The current study tested three interventions, which were designed to reduce the influence of color and to enhance decision-making performance. Based on the results, some design guidelines were proposed in situations where the visual perception of size is critical.

In addition to the research on the color size illusion, this research also investigated the influence of color on depth perception, the color depth illusion, since chromo-stereopsis has been considered as the cause of the color size illusion (Gentilucci et al., 2001; Tedford

et al., 1977). However, the correlation between the color size illusion and the color depth illusion has not been explored through simultaneous observation. This research observed the color size illusion and the color depth illusion at the same time.

1.2 Research Questions and Hypotheses

This study was designed to explore the influence of color on size and depth perception. Research questions and corresponding hypotheses are listed as follows:

1. Research Question: To what extent is the color size illusion replicated on an LCD monitor?

Hypothesis: The color size illusion will be replicated on an LCD monitor.

2. Research Question: To what extent is the color depth illusion replicated on an LCD monitor?

Hypothesis: The color depth illusion will be replicated on an LCD monitor.

3. Research Question: To what extent does background brightness influence the degree of the color size illusion?

Hypothesis: Background brightness will influence the degree of the color size illusion.

4. Research Question: To what extent does background brightness influence the degree of the color depth illusion?

Hypothesis: Background brightness will influence the degree of the color depth illusion.

5. Research Question: To what extent does border color of the comparison object influence the degree of the color size illusion?

Hypothesis: Border color of the comparison object will influence the degree of the color size illusion.

6. Research Question: To what extent does border color of the comparison object influence the degree of the color depth illusion?

Hypothesis: Border color of the comparison object will influence the degree of the color depth illusion.

7. Research Question: To what extent does background grid brightness influence the degree of the color size illusion?

Hypothesis: Background grid brightness will influence the degree of the color size illusion.

8. Research Question: To what extent does background grid brightness influence the degree of the color depth illusion?

Hypothesis: Background grid brightness will influence the degree of the color depth illusion.

1.3 Research Significance

Understanding the color size illusion is important, since color is widely used in information visualization. According to empirical studies (Claessen et al., 1995; Cleveland & McGill, 1983), the color size illusion has caused human errors. Errors in certain domains, such as an air traffic control systems are critical, since a mistake in controlling a passenger aircraft can cause a disaster. It is vital to overcome the size judgment error of colored objects when users make critical decision under limited time constraints or when decision errors can be disastrous.

Even when errors are not critical and decisions are not made under urgent situations, there are several domains in which size judgment is still important, since errors can decrease the effectiveness and efficiency of visualizations. Figure 1 illustrates a general visualization, in which color mapping can cause an error in data reading, which was

mapped on the size. A scatter-plot designed to display film information has multidimensional data such as year filmed, running time, subject (genre), popularity, awards, and so on. A designer can map each attribute using visual mapping properties: for example, year filmed can be placed on an x-axis, running time can be placed on a y-axis, subject can be placed on the color of the marks, and popularity can be placed on the size of marks. This mapping may cloud the understanding of the data, since a bright colored mark can be overestimated in its size due to the color size illusion. As a result, one may conclude that dramas were more popular than comedies in the 1950s because of the illusionary perception caused by the yellow and blue colors.

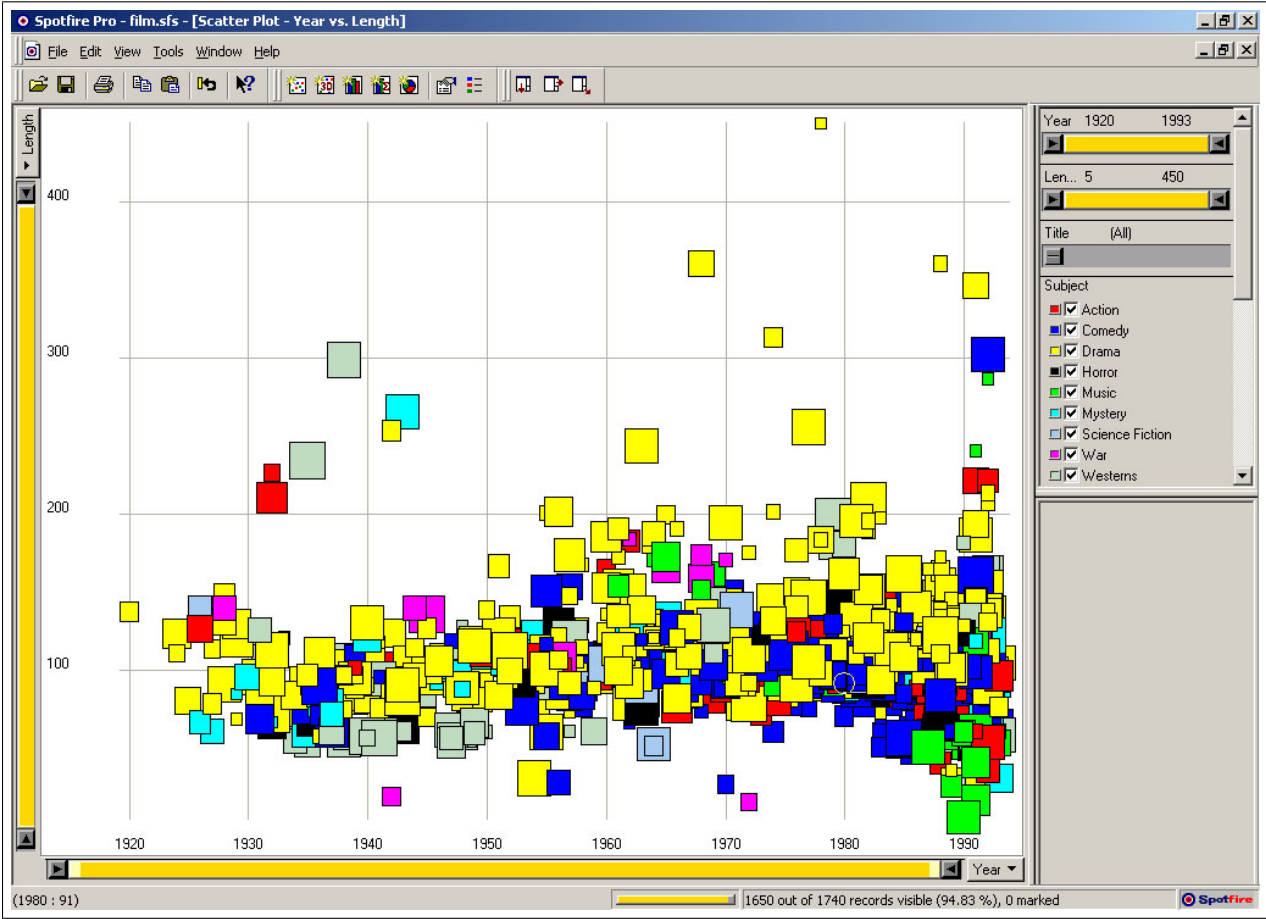


Figure 1: Scatter-plot visualization of film information

A statistical plot would be another example. Figure 2 is a bubble plot visualizing a crime report. The x-axis values represent population sizes, y-axis values represent unemployment rates, the bubble sizes represent crime rates, and the colors represent reported fatal crimes. In this example, users can underestimate or overestimate the crime rate due to the coding colors. In other cases, the color size illusion can force the user revisit the raw data to double-check judgments.

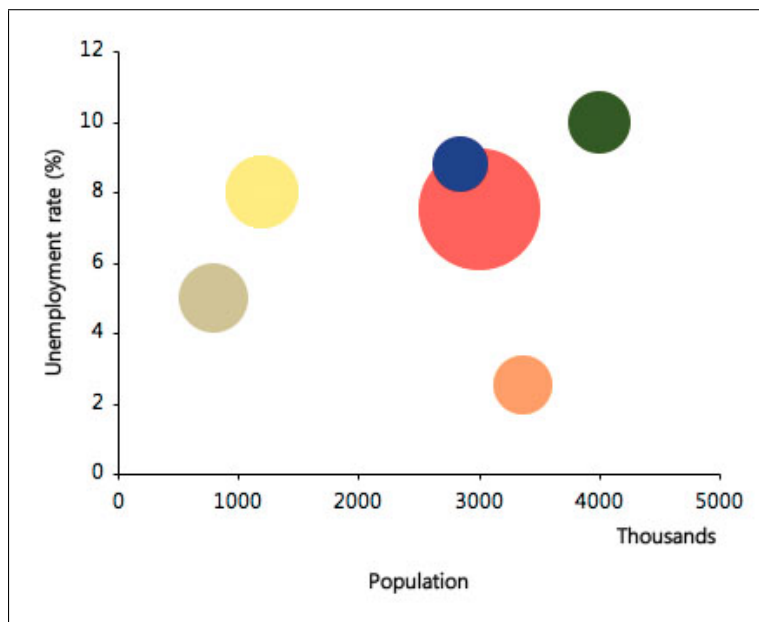


Figure 2: Statistical plot of crime report

This study is focused on bioinformatics because this discipline relies upon scientific tools in which human judgment is indispensable. Bioinformatics is an interdisciplinary research field that involves the use of techniques and tools from a variety of areas, including applied mathematics, statistics, computer science, chemistry, and biochemistry to solve biological problems usually on the molecular level. Even though bioinformatics research relies heavily on computational automation, human judgment is indispensable when the computational results are inconsistent or when the human reviews on the final results are necessary.

Comparative genome analysis is one area among the major research areas of bioinformatics. Comparative genome analysis enables biologists to understand the functions of genomic sequences in organisms (Hardison, 2003). It is especially important in analyzing and understanding how the functions of genomic sequences are related in health and disease at an “unprecedented level of molecular detail” (Collins, Green, Guttmacher, & Guyer, 2003) (p. 835). Curation is a process of comparative genomic analysis that defines the function of a genomic sequence based on homology; similarities of genomic sequences in different species or strains. An effective and efficient curation requires not only computational tools but also visualization tools. Computational automation covers almost all cases, since the majority of the cases are straight forward and do not require any further manual modifications. However, curators must make a judgment when the curation evidence conflicts (Snyder, 2006). Visualization will be useful in this case (Wang, Su, Mackey, Kraemer, & Kissinger, 2006).

To support the comparative analysis of genomic sequences, several visualization tools, such as the Generic Genome Browser (GBrowse) (Stein et al., 2002), the genome browser from The University of California at Santa Cruz (UCSC) (Kent et al., 2002), and Ensembl (Hubbard et al., 2002) have been implemented. Figure 3 is a screen-shot of GBrowse, which is a web-based application for visualizing genomic annotation and features. GBrowse has been widely adopted (Wang et al., 2006). Similar to GBrowse, the Genomic Sequence Viewer is implemented (Figure 4), which makes it possible to view multiple curation evidence in a display so that curators can simultaneously compare locations and sizes of evidence features. In the examples of several genome browsers and the Genomic Sequence Viewer, each feature has color coding to distinguish one from another and to link to detailed information listed below the visualization. However, it is possible that the color coding may mislead researchers to perceive some features as larger or smaller than the actual size because of the color effect.

This study was also motivated by a desire to bridge the efforts of understanding color illusions and display technology. Physiological psychologists have tried to explain color illusions. For example, researchers tried to explain the color depth illusion as an effect of ocular chromatic aberration (Verhoeff, 1928; Winn, Bradley, Strang, McGraw, & Thibos, 1995). However, no study have tried to explain the color illusion in terms of display device mechanisms. This study has investigated two color illusions on an LCD monitor and tried to explain the result integrating the characteristics of display mechanism and psychological theories.

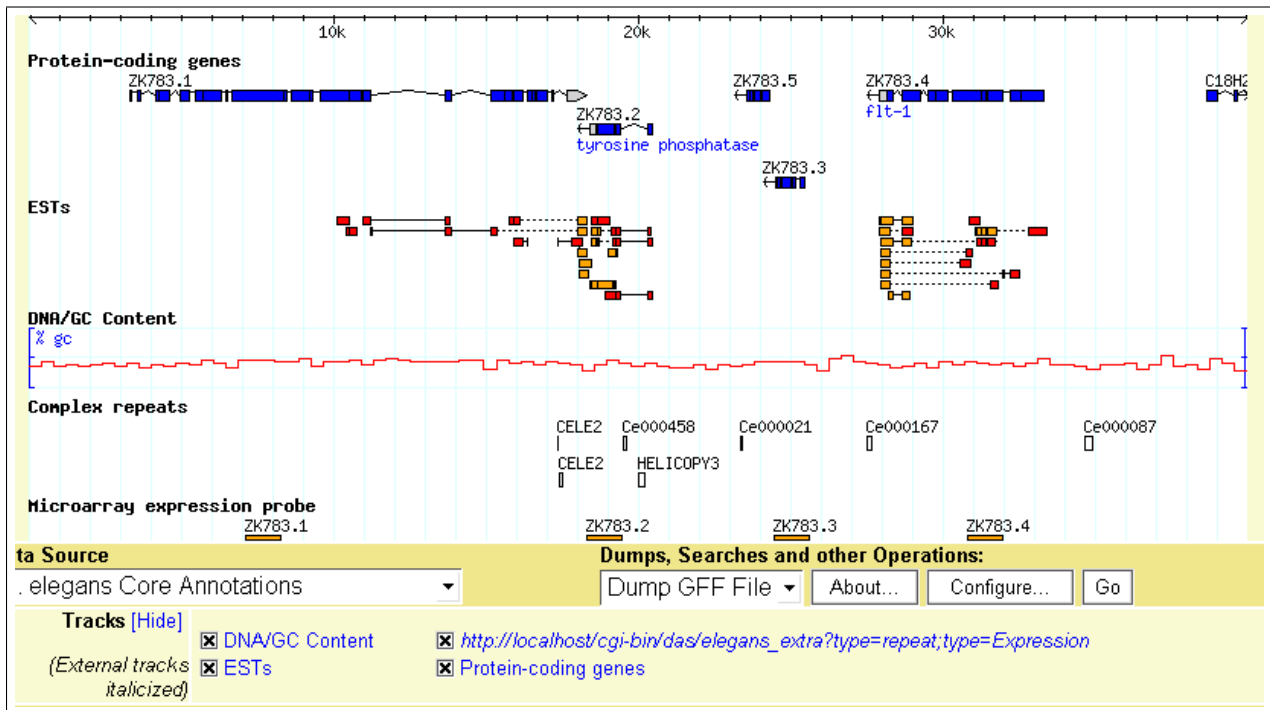


Figure 3: Screen shot of GBrowse

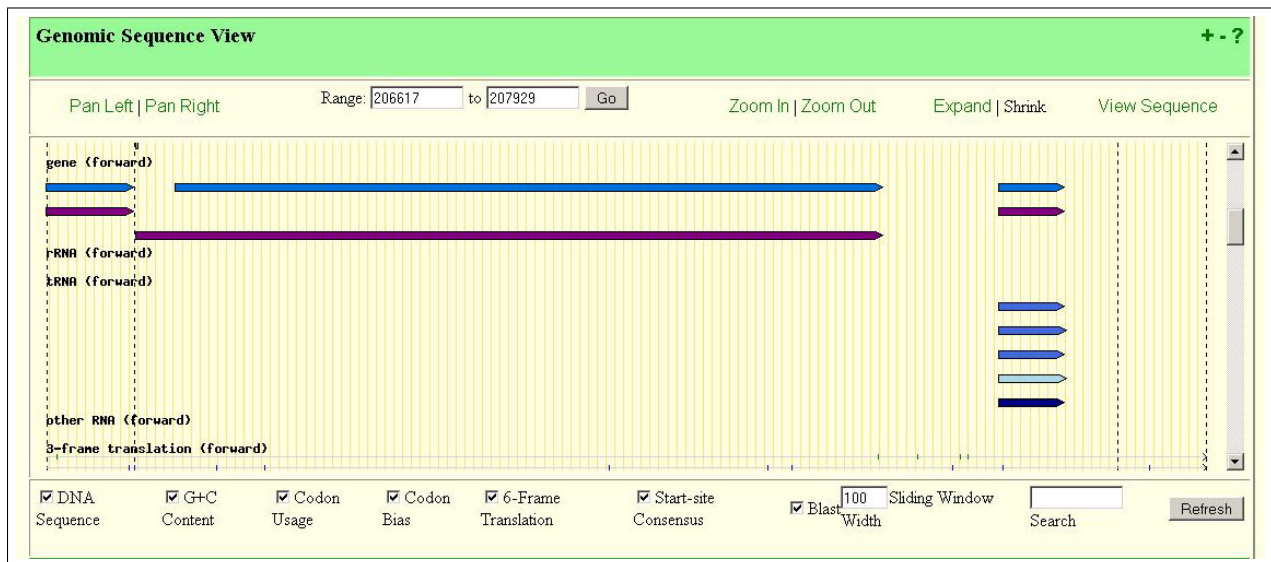


Figure 4: Screen shot of Genomic Sequence Viewer

Chapter 2

Literature Review

2.1 The Influence of Color on Size Perception

2.1.1 The Effect of Brightness (luminance)

Brightness was the first component of color that was identified for its influence on size perception. Payne (1964) reviewed previous research studies and concluded that luminance appears to be the major cue to apparent size. He pointed out that at that time, there was no research on the effect of hue on apparent size under the condition of constant luminance.

2.1.2 The Effect of Hue and Saturation

In the early 20th century, the effect of color on apparent size was controversial. Warden and Flynn (1926) argued that there was no effect on apparent size due to color, while Gundlach and Macoubrey (1931), using an experiment setting similar to Warden, found that there was an effect. They subsequently confirmed with a different method. As Payne (1964) pointed out, the confusion was due to the fact that no one had separated the color dimensions (hue, luminance, and saturation) accordingly and controlled other dimensions when one of them was manipulated.

Tedford, Gerguist and Flynn (1977) conducted research that precisely controlled hue, brightness, and saturation. They found an effect of hue with a constant saturation and brightness; the red-purple rectangle was observed as larger than the yellow-red one, and the yellow-red or purple-blue rectangle was observed to be larger than the green one. They also found an effect of saturation with a constant hue and brightness; low saturation colors were perceived to be larger than high saturation colors when both were placed over a gray background. They used eight colors by combining four hues, two saturations, and one intensity from the Munsell Color Book (Munsell, 1950): RP 5/4, RP 5/8, YR 5/4, YR 5/8, G 5/4, G5/8, PB 5/4, PB 5/8. They compared every pair of colored cards. When the high saturation colors were compared ($/8$), the color-size illusion was more significant than when low saturation colors ($/4$) were compared. Additionally, they found that the effects of hue and saturation were additive.

The findings of Tedford and his colleagues (1977) were consistent with previous research (Gundlach & Macoubrey, 1931; Wallis, 1935). The difference from previous studies was that Tedford (1977) used reflected color from a slide projector while previous studies used colored cardboard. In this study, the effect of hue and saturation on size perception will be extended to self-luminous colors on a LCD monitor.

Recently, Gentilucci, Benuzzi, Bertolani, and Gangitano (2001) confirmed the influence of color on size perception with a grasping task. Participants were asked to open their right thumb and index finger to match the size of colored target objects, which were placed at a distance from the participants. Perceived size was measured by the distance of two fingers using the markers placed on the nails of the thumb and the index finger. The result was consistent with results of previous psychophysical studies (Gundlach & Macoubrey, 1931; Tedford et al., 1977; Wallis, 1935).

The Gentilucci study is meaningful in that the paired-comparison method was justified with another method. According to Gundlach (1931), researchers have used

paired-comparison to compare the size of various objects. Gentilucci et al. (2001) calculated the absolute distance between fingers to estimate the perceived size and confirmed the result of the paired-comparison method. This study also used the paired-comparison method to compare the apparent size of objects.

2.2 Empirical Cases of the Color Size Illusion

Cleveland and McGill (1983) provided considerable empirical evidence of the color size illusion with a statistical map. They displayed a map of Nevada in which some of the counties were colored red (Munsell color: 7.5 Red 4/14) and others were colored green (2.5 Green 5/12). Participants were asked to identify whether the colored areas looked different. The researchers varied the colored areas keeping the ratio equal. Almost half of the participants responded that red was bigger, while 22% of participants judged green as bigger. When they used low saturation colors, no illusion was observed between green-yellow (7.5 Green-Yellow 8/2) and yellow (2.5 Yellow 8.5/4). They concluded that statistical graphs should be careful with color, since it may affect the perceived data on the graphs. The result implies that color can cause a human error; this type of human error would presumably occur on a bioinformatics visualization, such as a genome browsing application, in which the interface was designed to read the size of colored objects.

Another empirical study was conducted using puzzle pegs (Claessen et al., 1995). Participants were given different sized pegs and asked to select one peg to fit a hole. The experiments were varied using two different types of puzzle (real puzzles and computer simulation), two different colors (red and blue), and two different brightness levels (light and dark). It was assumed that participants would pick red pegs that were smaller than the hole, as the red color would presumably make the peg seem bigger. It was also assumed that participants would pick lighter pegs that were smaller than the hole, as the bright colors would make the pegs seem bigger. With real puzzles, the researchers confirmed the

pattern with light colors, and with self-luminous colors on a computer screen (CRT), the hypotheses on the effect of hue and brightness were both confirmed. This study showed that the color size illusion influenced the user's task and directly caused human error.

2.3 The Influence of Color on Depth Perception.

Color influence on depth perception is known as chromostereopsis, which is a phenomenon of human visual perception that equidistant objects of different colors were perceived at different depths. This phenomenon was observed in the 19th century by Brewster (1851) and explained by chromatic aberration (Benzschawel, 1985). Most observers saw red as closer than blue (Kishto, 1965; Sundet, 1976), but the order of color depth was reversed when the background color was changed (Dengler & Nitschke, 1993; Thompson & Stone, 1993; Winn et al., 1995).

Dengler and Nitschke (1993) used four colored threads: red, yellow, green, and blue. When the colored threads were displayed on a black background, participants experienced positive color stereopsis, in which long-wavelength colors seemed closer than short-wavelength colors. However, when the threads were displayed on a white background, the same participants reported a reversed order of color depth with some exceptions. For example, green was seen to be nearest the observer, followed by blue, red, and yellow. This observation was consistent with previous studies (Hartridge, 1947; Verhoeff, 1928).

2.4 Color Vision Theories

2.4.1 Three Theories of Color Vision

Several theories have been proposed to explain color vision; in particular, researchers have sought to understand how the visual system converts wavelengths into color perception.

Three main theories have been developed and accepted. After the trichromatic theory had been accepted, the color opponent-process theory and the retinex theory proposed to explain the phenomena, which had not been resolved by previous theories.

The trichromatic theory assumed that visual receptors respond to three primary colors. The assumption was confirmed with the existence of three cone types (Wald, 1968); the visual system has long-wavelength cones, medium-wavelength cones, and short-wavelength cones. The trichromatic theory states that the visual system perceives color based on the difference of activation levels among the three cone types.

The opponent-process theory of color vision, proposed by Ewald Hering (1920), describes the process of visual information after it leaves the cones in the retina (Bornstein, Kessen, & Weiskopf, 1976; Gordon, Abramov, & Chan, 1994; Hering, 1920). According to this theory, the visual system perceives color in terms of three opponent pairs, red-green, yellow-blue, and white-black. Within pairs, neural signals affect each other. Following studies confirmed the theory with findings that the responses of three kinds of cones excite or inhibit bipolar cells, which transfer their responses to later cells in the visual system (DeValois, 1965; Michael, 1978). Bipolar cell 1 receives an excitatory signal from long-wavelength cones and an inhibitory signal from medium-wavelength cones. Bipolar cell 2 receives an excitatory signal from the short-wavelength cones and an inhibitory signal from either the long-wavelength cones or the medium-wavelength cones.

The retinex theory, proposed by Edwin Land, enables us to understand the phenomena that humans can perceive color under a certain colored illumination. According to this theory, humans perceive color through the cerebral cortex's comparison of various retinal patterns. The cerebral cortex compares the patterns of light coming from different areas of the retina and synthesizes a color perception for each area (Land, Hubel, Livingstone, Perry, & Burns, 1983; Land & McCann, 1971).

From the color vision theories, we can infer that color vision is not a simple reaction of color receptors; it is a complex system, which has sensors (the trichromatic theory), a gain control system (the opponent-process theory of color vision), and an error recovery system (the retinex theory). Even for a simple visual task, the result can be interpreted in several ways. For example, in comparing red and green bars, color perception can be influenced by several factors. According to the opponent-process theory, if two bars fall in the retina area, one color will affect the perception of the other color. Background color will influence the color perception as well due to the interference of opponent-process pairs. According to the retinex theory, it is possible that the visual system overcomes the effect of surrounding color stimuli, since the cerebral cortex integrates various retinal stimuli. However, it is unknown to what extent the cerebral cortex reorganizes color stimuli and perceives color. Chapter 2.4.2 illustrates a specific example of complexity of color vision.

2.4.2 The Influence of Surrounding Stimuli on Color Perception

Even though the same stimulus was given, the effect can be the opposite, depending on the frequency. Simultaneous brightness contrast and brightness assimilation (Shapley & Reid, 1985) are good examples. Simultaneous brightness contrast describes a phenomenon in which background brightness affects the brightness perception, opposing it to the brightness of the background. Center squares of both part a and b in Figure 5 have equal brightness, but the one with a black background (part b) seems brighter than the one with a gray background (part a). This phenomenon is explained by the lateral inhibition theory (Arend, 1993; Hartline & Ratliff, 1957). A dark background inhibits the brightness reception of the center square, which makes it seem brighter than original brightness.

Brightness assimilation is an opposite case. Brightness assimilation describes a phenomenon in which background brightness affects the brightness perception, making it seem similar to the background brightness. The gray stripes of both part a and b in Figure

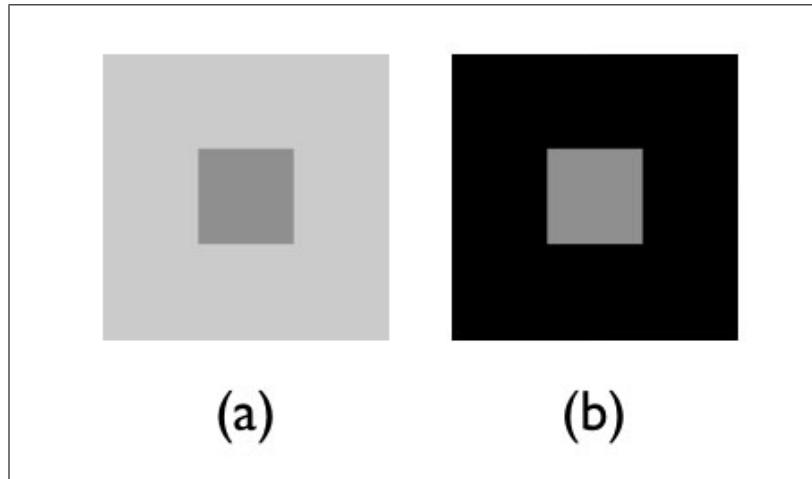


Figure 5: Example of simultaneous brightness contrast.

6 have equal brightness, but the one on a white background (part a) seems brighter than the other one (part b). Hue also has similar phenomena, which are called, respectively, simultaneous color contrast and color assimilation.

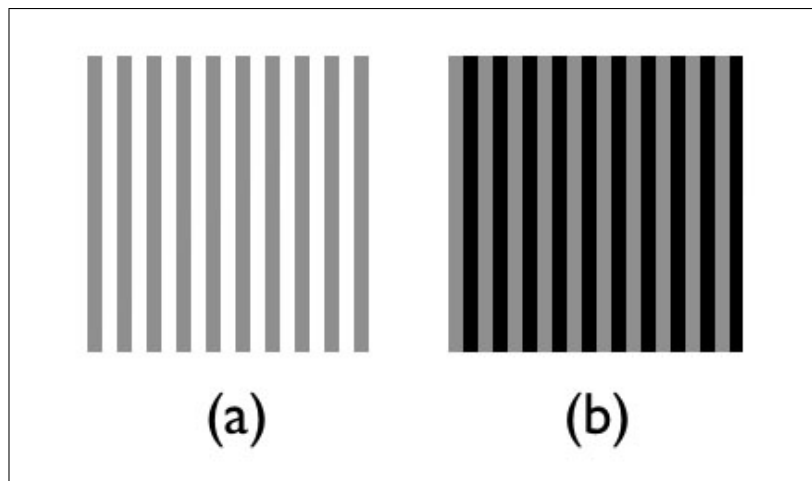


Figure 6: Example of brightness assimilation.

2.5 Interventions

Considering that brightness is a component of color that influences size perception (Payne, 1964), it has been reasoned that the color size illusion can be reduced by altering the brightness of an object. According to simultaneous brightness contrast and brightness assimilation, background brightness can change the brightness perception of centered object that is either to similar or different from the background brightness (Shapley & Reid, 1985). Five different levels of background brightness were designed to test as an intervention that reduces the color size illusion.

In addition to background brightness, it was assumed that additional visual cues such as border or background grids would help people judge size correctly. Border was expected to help people distinguish target objects from background and see both ends clearly. In the case of border, however, there were many design factors that had to be tested, including border width, border color (hue, brightness, saturation), border style (solid line, dashed line) and so on. Since there have not been any studies about the influence of border design factors on the color size illusion, this study started with very simple factors: three brightness levels and one saturation level. The border width was fixed at two pixels, based upon a study that argued a two pixel border was wide enough to distinguish an icon on an LCD monitor (Huang & Chiu, 2007).

In case of the background grid, more design factors were possible; the background grid color (hue, brightness, saturation), grid line style (solid, dashed), grid pattern (vertical line, horizontal line, or both), grid line width, grid frequency and so on were all adjustable. As in the case of border design factors, this study started from the simplest factor, background grid brightness. Five levels of background grid brightness were designed to test as an intervention.

2.6 The Importance of the Color Illusion Study on LCD Monitors

LCD monitors are rapidly replacing CRT monitors. Even though there is no significant evidence that LCD monitors enhanced user performance, Chen and Lin (2004) demonstrated that user satisfaction on LCD monitors is better than on CRT monitors. They measured the minimum recognized size of Landolt-C rings to compare visual performance, but the difference was not significant. However, when they measured user satisfaction, the difference was significant. Participants were asked to evaluate the display devices in 100 scale value considering clearness, aesthetic appearance, and visual comfort.

Although the Chen & Lin (2004) study had some limitations on measurement, it provides a good reason for the continued adaptation of LCD monitors and emphasizes the importance of increased investigation of visual illusions into LCD monitors. To strengthen the significance of the result, it would be better to measure user performance with more realistic tasks rather than measuring visual acuity and it would be better to address performance times as well. In terms of user satisfaction measurement, it might be better to capture the user values more precisely rather than asking for subjective ratings in total.

2.7 Summary

In summary, both the color size illusion and the color depth illusion have been observed and the color size illusion caused human errors (Claessen et al., 1995; Cleveland & McGill, 1983). Although the color perception process is complex and difficult to understand in detail as we can see in chapter 2.4, we still need to know more about and have design guidelines to reduce human errors and prevent the errors ultimately. For this reason, this study is motivated to identify visual interventions not only to reduce human errors but also to understand the color perception process better.

Chapter 3

Method

The literature review identified the significance of studying color illusions on LCD monitors, as well as the needs for design guidelines. The first objective of this study is to replicate the color size illusion and the color depth illusion on an LCD monitor (experiment 1). The second objective is to identify interventions that minimize the color illusions; this, in turn, will enable the construction of design guidelines. Background brightness (experiment 2), border color (experiment 3), and grid brightness (experiment 4) were considered as possible interventions.

3.1 Experimental Design

The research questions, hypotheses, independent variables, dependent variables, and the purpose of each experiment are summarized in Table 1.

Experiment 1 was designed to replicate the color size illusion (Tedford et al., 1977) and the color depth illusion (Thompson & Stone, 1993) of computer generated images on an LCD monitor. Replicating the illusions on LCD monitors is meaningful because previous research showed that color size illusion replicated on a CRT monitor (Claessen et al., 1995), but few studies have been conducted on an LCD monitor. Additionally, replication is

needed to provide evidence that reduced illusions are not caused by LCD monitors, but by the visual properties of interventions, which were manipulated in experiment 2, 3, and 4.

Experiment 2, 3, and 4 were designed to find appropriate interventions. Experiment 2 tested the effect of background brightness, experiment 3 tested the effect of borders, and experiment 4 tested the effect of background grid brightness.

Table 1: Summary of Experimental Designs

Experiment 1	Research Questions	To what extent is the color size illusion replicated on an LCD monitor? To what extent is the color depth illusion replicated on an LCD monitor?
	Hypotheses	The color size illusion will occur on an LCD monitor. The color depth illusion will occur on an LCD monitor.
	Independent Variables	Hue comparison pair(H), Saturation(S), Position(P)
	Dependent Variables	Size Discrimination, Depth Discrimination, Discrimination Difficulty
	Purpose	Replicate color size illusion and color depth illusion on an LCD monitor.
	Experiment 2	Research Questions
Hypotheses		Background brightness will influence the degree of the color size illusion. Background brightness will influence the degree of the color depth illusion.

	Independent Variables	Position(P), Background Brightness(B)
	Dependent Variables	Size Discrimination, Depth Discrimination, Discrimination Difficulty
	Purpose	To understand how the background brightness affects the color influence on illusions.
Experiment 3	Research Questions	To what extent does border color of the comparison object influence the degree of the color size illusion? To what extent does border color of the comparison object influence the degree of the color depth illusion?
	Hypotheses	Border color of the comparison object will influence the degree of the color size illusion. Border color of the comparison object will influence the degree of the color depth illusion.
	Independent Variables	Position(P), Border Color(R)
	Dependent Variables	Size Discrimination, Depth Discrimination, Discrimination Difficulty
	Purpose	To understand how the border color of the comparison object affects the color influence on illusions.
	Experiment 4	Research Questions
Hypotheses		Background grid brightness will influence the degree of the color size illusion.

		Background grid brightness will influence the degree of the color depth illusion.
	Independent Variables	Position(P), Background Grid Brightness(G)
	Dependent Variables	Size Discrimination, Depth Discrimination, Discrimination Difficulty
	Purpose	To understand how the background grid affects the color influence on illusions.

The order of experiments were counterbalanced across all participants. Within each experiment, the order of tests were counterbalanced.

All experiments were within-subjects designs. According to Claessen(1995), experimental design on color perception should be a within-subjects design, since people differed from the perceived depth systematically in previous chromo-stereopsis research (Thompson & Stone, 1993). In the research, most participants perceived a red square to be closer and a blue square to be farther away, while a few participants perceived exactly the opposite (Thompson & Stone, 1993).

3.1.1 Rationale

Previous research (Cleveland & McGill, 1983; Gundlach & Macoubrey, 1931; Tedford et al., 1977) used paired-comparisons of different colored objects and those studies asked participants to judge which one was larger than the other. This study used paired-comparisons as well. For example, participant were given red and blue bars at the same time. They were asked which was longer than the other to measure the apparent size. They also were asked which was closer, in order to measure the apparent depth (distance).

It was assumed that if the LCD monitor did not interfere with the mechanism, then the color influences on the apparent size and the color size illusion will be reproduced

similar to the CRT monitor study conducted by Claessen et al.(1995). It was assumed that the color size illusion would not be observed or will be observed less, if a certain level of background brightness reduced the influence of color on apparent size. Same assumptions on both border color of comparison object and background grid brightness were conjectured.

3.1.2 Dependent Variables

Size perception and depth perception were dependent variables in experiments 1 through 4. To measure the apparent size and apparent depth, the following questions were asked in each trial (see Figure 8, Figure 9, Figure 10, Figure 11).

1. Which bar is longer than the other?
 - (a) No Difference
 - (b) Upper bar is longer
 - (c) Lower bar is longer

2. Which bar is closer to you than the other?
 - (a) No Difference
 - (b) Upper bar is closer
 - (c) Lower bar is closer

In addition to the perceived size, this study measured the effect of color on the performance of decision making. A seven point Likert-type scale question was asked. Besides subjective ratings, time spending to answer both size and depth judgment was measured. User performance time was expected to reveal the user difficulty of decision making. This study used user performance time as a supplemental measure of subjective ratings (Figure 7).

Rate the difficulty of making your decision
Very Easy ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 Very Difficult

Figure 7: Question for difficulty level

3.1.3 Experiment 1 - Replication of Color Size Illusion and Color Depth Illusion

A 6 x 2 x 2 factorial design was used in experiment 1 to answer the research question about the extent of color size and color depth illusion on an LCD monitor. It was hypothesized that color would cause both a size illusion and a depth illusion on an LCD monitor. The main factors were pairs of different hue, position, and saturation and all were within-subject factors. All the conditions are illustrated in appendix E.1. Further information about the levels and types of these factors is provided in Table 2. The data matrix illustrating the design is given in Table 3. Pairs consisted of four different hues: red, yellow, green, and blue. Those colors were adopted from previous research (Tedford et al., 1977). The Commission Internationale de l'Eclairage (CIE) values used in this experiment are listed in Table 4. A DigitalColor Meter was used to measure CIE L*a*b values. White was used for the background as a control.

Table 2: Factor Levels and Types of Experiment 1

Factor Name	Levels	Type
Hue comparison pair (H)	Red-Yellow, Red-Green, Red-Blue, Yellow-Green, Yellow-Blue, Green-Blue	Within-Subjects, Fixed Effects
Saturation (SA)	100%, 75%	Within-Subjects, Fixed Effects
Position (P)	Straight, Inverted	Within-Subjects, Fixed Effects
Subjects (S)	$S_1 \dots S_{24}$	Between-Subject, Random Effects

Table 3: Data Matrix of Experiment 1

		Saturation (S)			
		High Saturation		Low Saturation	
		Position (P)		Position (P)	
		Straight	Inverted	Straight	Inverted
Hue Comparison Pair (H)	Red-Yellow	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Red-Blue	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Red-Green	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Yellow-Blue	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Yellow-Green	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Blue-Green	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$

Table 4: Chromaticity coordinates (CIE L*a*b) of colors used in Experiment 1

Hue	Saturation	CIE L	CIE a	CIE b
Red	High	56.925	79.465	79.215
Yellow	High	96.863	-13.754	96.922
Green	High	85.634	-83.219	81.219
Blue	High	33.783	53.875	-105.785
Red	Low	62.586	66.180	44.219
Yellow	Low	97.130	-12.520	80.016
Green	Low	86.987	-72.637	64.918
Blue	Low	46.384	35.207	-84.828

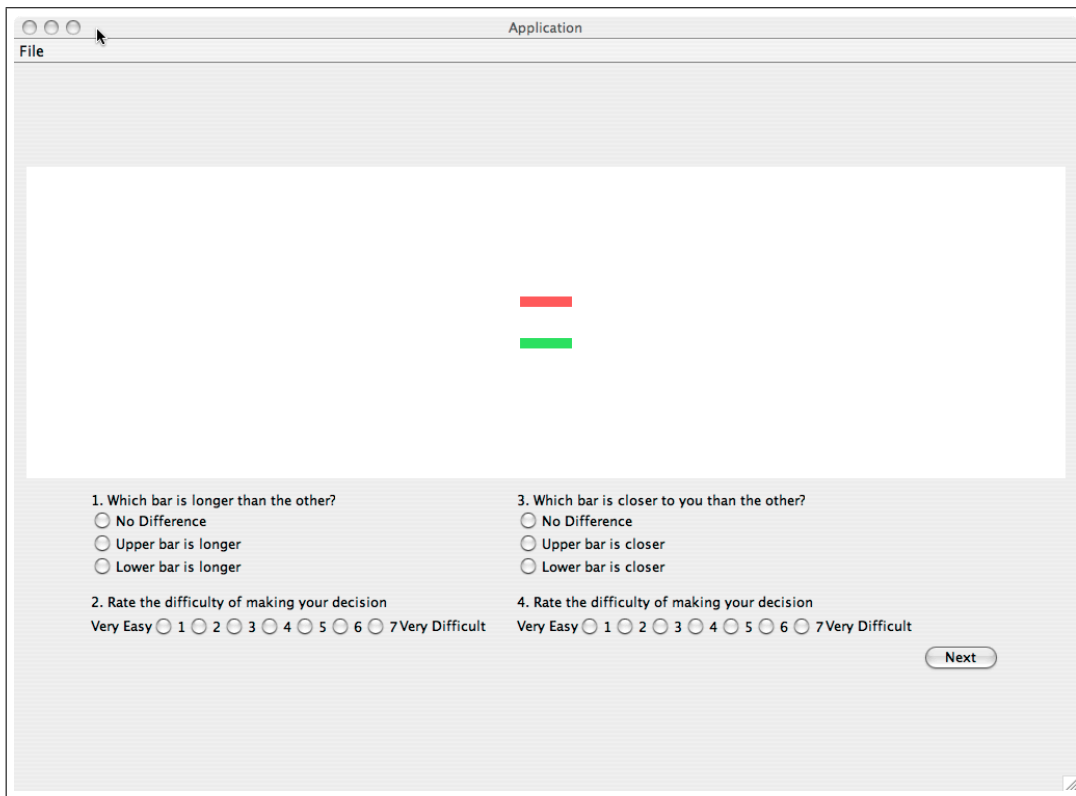


Figure 8: Screen shot of Experiment 1

3.1.4 Experiment 2 - Influence of Background Brightness

A 2 x 5 factorial design was used in experiment 2 to answer the research question about the extent of background brightness, which may influence the degree of color size and color depth illusion. It was hypothesized that background brightness would influence both size and depth illusion on an LCD monitor. The main factors, position and background brightness, were within-subject factors. All the conditions are illustrated in appendix E.2. Further information about the levels and types of these factors is provided in Table 5. The data matrix illustrating the design is given in Table 6. Red and green, which were used in experiment 1, were compared in experiment 2 through 4, since those were extreme cases in previous research (Tedford et al., 1977). Background brightness was varied by five brightness levels: 0% (black), 25% (dark gray), 50% (gray), 75% (light gray), 100% (white).

Table 5: Factor Levels and Types of Experiment 2

Factor Name	Levels	Type
Position (P)	Straight, Inverted	Within-Subjects, Fixed Effects
Background brightness (B)	0% (black), 25%, 50%, 75%, 100% (white)	Within-Subjects, Fixed Effects
Subjects (S)	$S_1 \dots S_{24}$	Between-Subject, Random Effects

Table 6: Data Matrix of Experiment 2

		Background Brightness (B)				
		0% (black)	25%	50%	75%	100%(white)
Position (P)	Straight	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Inverted	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$

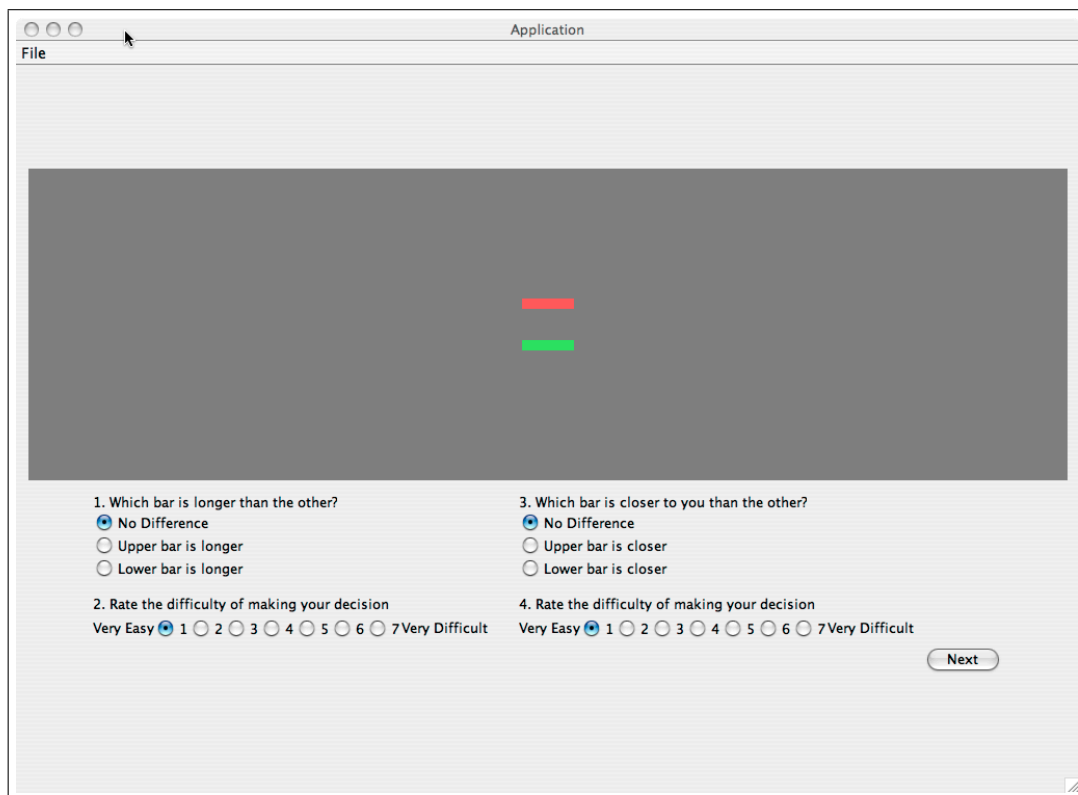


Figure 9: Screen shot of Experiment 2

3.1.5 Experiment 3 - Influence of Border Color

A 2 x 4 factorial design was used in experiment 3 to answer the research question about the extent of boundary borders, which may influence the degree of color-size and color-depth illusion. It was hypothesized that the border of the comparison object would influence both size and depth illusion on an LCD monitor. The main factors, position and border colors, were within-subject factors. All the conditions are illustrated in appendix E.3. All the factors were within subject factors. Border colors were manipulated to include four different levels: pure black (brightness 0%), gray (brightness 50%), less saturation of the color of object, and no border (same hue and saturation with the object). The width of the border was set to 2 pixels (Huang & Chiu, 2007), and white was used for the background as a control. Further information about the levels and types of these factors is provided in Table 7. The data matrix illustrating the design is given in Table 8.

Table 7: Factor Levels and Types of Experiment 3

Factor Name	Levels	Type
Position (P)	Straight, Inverted	Within-Subjects, Fixed Effects
Border color (R)	black(0%), gray(25%), less saturated, without border	Within-Subjects, Fixed Effects
Subjects (S)	$S_1 \dots S_{24}$	Between-Subject, Random Effects

Table 8: Data Matrix of Experiment 3

		Border color(R)			
		black(0%)	gray(50%)	saturated	without border
Position(P)	Straight	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Inverted	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$

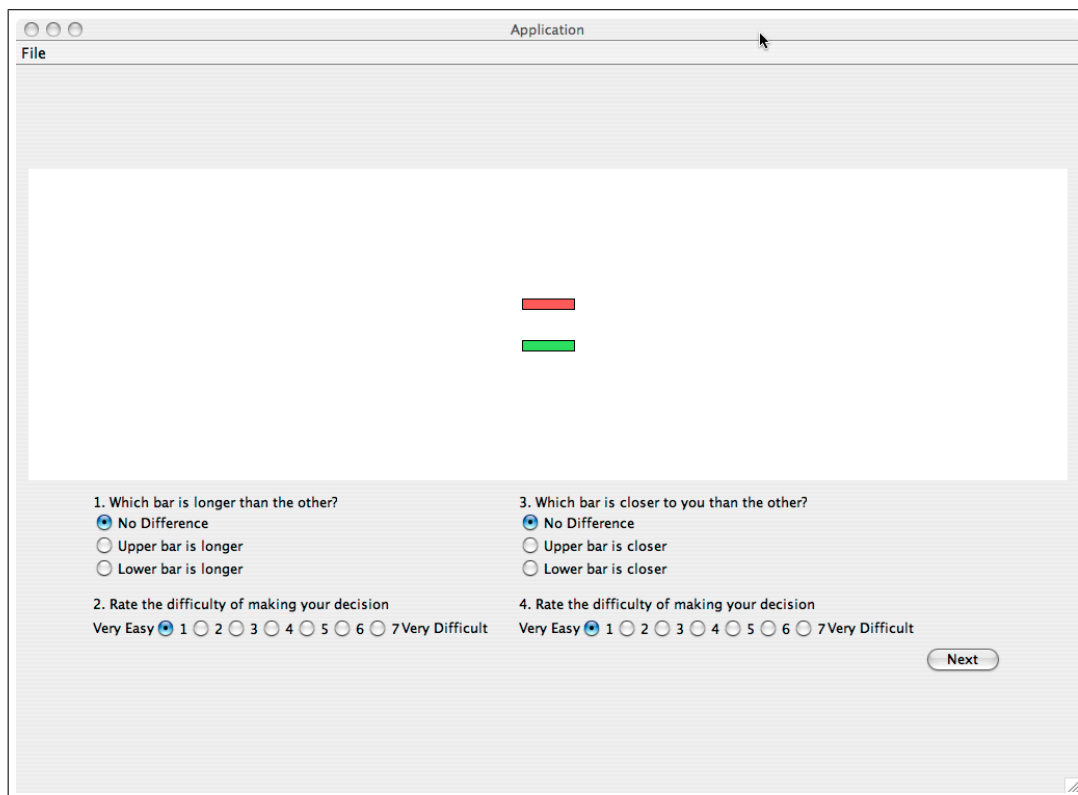


Figure 10: Screen shot of Experiment 3

3.1.6 Experiment 4 - Influence of Background Grid Brightness

A 2 x 5 factorial design was used in experiment 4 to answer the research question about the extent of background grid brightness, which may influence the degree of color size and color depth illusion. It was hypothesized that the background grid would influence both size and depth illusion on an LCD monitor. The main factors were position and background grid brightness. All the conditions are illustrated in appendix E.4. All the factors were within subject factors. Further information about the levels and types of these factors is provided in Table 9. The data matrix illustrating the design is given in Table 10. The width of grid was set to 2 pixels (Huang & Chiu, 2007) and frequency of grid line was set to 20 pixels to simulate the Genomic Sequence Viewer (see Figure 4). White was used for the background as a control.

Table 9: Factor Levels and Types of Experiment 4

Factor Name	Levels	Type
Position (P)	Straight, Inverted	Within-Subjects, Fixed Effects
Background Grid Brightness (G)	black(0%), 25%, 50%, 75%, without grid	Within-Subjects, Fixed Effects
Subjects (S)	$S_1 \dots S_{24}$	Between-Subject, Random Effects

Table 10: Data Matrix of Experiment 4

		Background Grid Brightness (G)				
		0% (black)	25%	50%	75%	without grid
Position (P)	Straight	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$
	Inverted	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$	$S_1 \dots S_{24}$

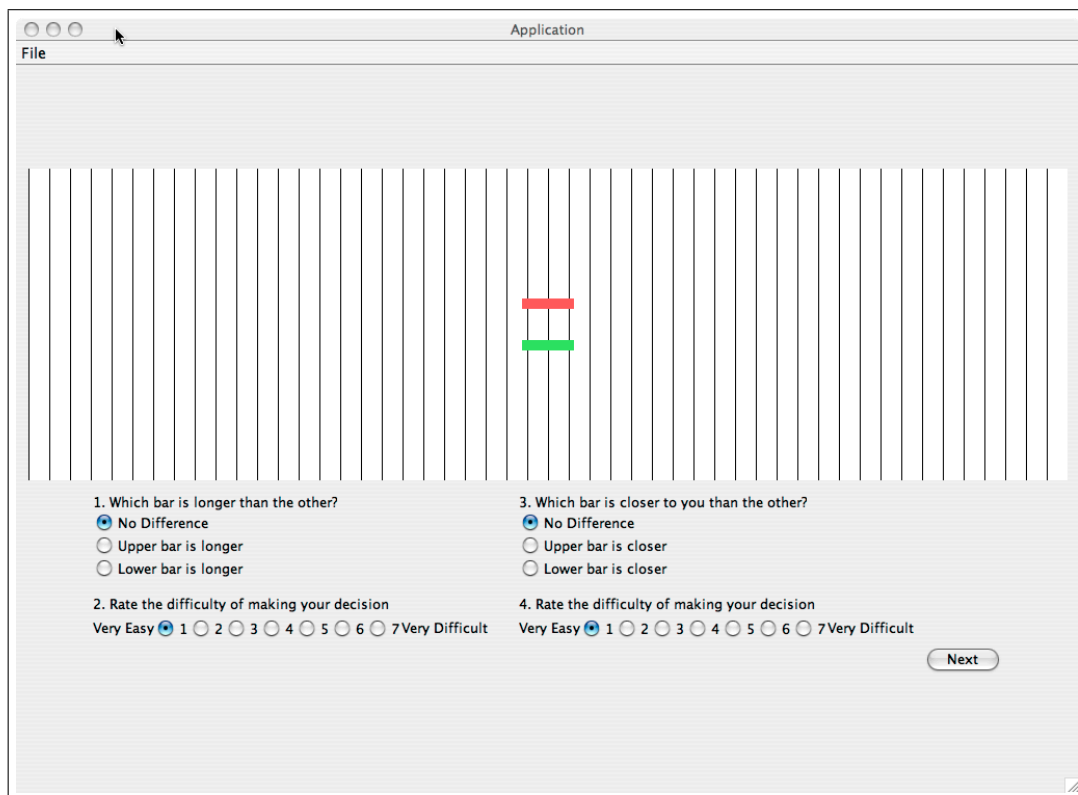


Figure 11: Screen shot of Experiment 4

3.2 Participants

Twenty four university students (14 males, 10 females) participated in the study, and the mean age was 26.9 ($SD = 5.92$) years. They were asked to disqualify themselves if (a) they were younger than 18 years or older than 40 years, or (b) did not have normal or corrected vision, or (c) did not have normal color vision. The participants were recruited through email advertisements, posters, and the Virginia Tech SONA Experiment Management System in the Department of Psychology. Since there was no difference between male and female viewers in previous color size illusion studies (Tedford et al., 1977), the gender ratio was not controlled.

3.3 Procedure

Prior to participation, participants completed an informed consent form (Appendix A) approved by the Virginia Tech Institutional Review Board (IRB#07-322) and a demographic questionnaire (Appendix B). After that, two screening tests for visual acuity and color blindness were administered. Before the experiment, luminance on the LCD screen was measured.

3.3.1 Pre-Screening

Participants completed the Acuity Screening Inventory (Appendix C) (Coren & Hakstian, 1989) and were asked to report whether they wore contact lenses. Participants had normal vision (20/20 or better Snellen score) or corrected vision (wore glasses or contact lenses) except for one participant whose Snellen score was 20/40 (near normal vision). Since a 20/40 Snellen score vision is comparable to normal vision for near vision tasks, the participant was included. After the Acuity Screening Inventory, a computer based color blind test was conducted; participants were given 10 Ishihara color plates on an LCD

monitor and asked to read the numbers. All participants completed the tasks with 100% accuracy. Eventually, all the participants were included.

3.3.2 Prevention of Afterimage Effects

Since all color bars were displayed at the same position on the screen throughout the sessions (a session means a set of questions and a pair of color bars), color perception could be influenced due to the color afterimage effect (Wede & Francis, 2006). To avoid afterimage effects, a blank page with instructions (see Appendix D) was displayed for at least 6 seconds between the sessions, because chromatic afterimages often last for around 6 seconds (Kelly & Martinez-Uriegas, 1993; Suzuki & Grabowecky, 2003).

3.4 Equipment and Apparatus

3.4.1 Laboratory Setup

The experiment was conducted in the Laboratory for User-Centric Innovations in Design (LUCID) in the Human Factors Engineering and Ergonomics Center at Virginia Tech. The interior walls were painted gray and illuminance was controlled. Two black display boards were placed around the display and the participants to control visual stimuli on peripheral vision. An LCD monitor was calibrated using a monitor calibration system (Spyder2PRO). A chin-mount was set to fix the distance between participants and the display. The distance was 57.5cm. Luminance measured on the display was 220 cd/m^2 on average (deviation within $\pm 5 \text{ cd/m}^2$).

3.4.2 Hardware and Software

An Apple Cinema display and a PowerMac G5, which has four 2.5GHz PowerPC G5, 4GB Ram, and an NVIDIA Quadro FX4500 512MB graphics card, were used to run the



Figure 12: Laboratory setup

experiment. A monitor calibration system (Spyder2PRO) was used to set the correct color profile. A luminance meter (Minolta nt-1°) was used to measure the luminance on the LCD screen. To get the chromaticity coordinates (Table 4), a DigitalColor Meter was used, which calculates the color value from the color profile and the displayed color value.

3.5 Pilot Study

Three participants were recruited for a pilot study, which was conducted to smooth out the operating procedures. Based on the observations of the pilot study, questions were reworded to be delivered clearly (compare the italics in Table 11). It was decided to add a seven point Likert-type scale question (Figure 7) and a response time measure to reveal the perceived difficulty of making size and depth judgment. Moreover, the size of colored stimuli was reduced to simulate more realistic example (Figure 4). Finally, instructions (see Appendix D) were adopted

1. To explain the questions with an example that participants would be asked

2. To provide a chance for participants to ask the experimenter any questions, if they have any
3. To ensure that participants followed the given sequence of questions
4. To ensure that participants balanced response speed and accuracy
5. To inform the participants about the appropriate time to rest during the experiment

Original Question	Revised Question
Which bar <i>looks larger</i> than the other?	Which bar <i>is longer</i> than the other?
Which bar <i>looks closer</i> than the other?	Which bar <i>is closer to you</i> than the other?

Table 11: Revised questions based on pilot study

Chapter 4

Results

4.1 Color Illusion on Apparent Size and Depth

4.1.1 Color Size Illusion on an LCD Monitor

The hypothesis of the first research question is that the color size illusion would be replicated on an LCD monitor.

Color size illusion was observed and varied in degree from 17% to 52% depending on the comparison pairs, which had different hue and saturation levels (see Table 14 in Appendix F, or Figure 13). Apparent size was measured by selecting one of three options; “there is no difference between two bars,” “the upper bar is longer than the other,” or “the lower bar is longer than the other.” Answers in which either of the hue pairs was longer than the other were counted as an error. When the red and yellow were compared, 52% of responses were wrong in both high and low saturation. In case of highly saturated colors, 24 responses stated that the red was longer, one response selected yellow as longer, and 23 responses were that there was no difference between two bars. In the case of low saturation colors, 22 responses stated that the red bar was longer, three responses selected yellow as longer, and 23 responses were that there was no difference. In all cases, however, both bars

were identical in size.

Moreover, the result implies that the color size illusion is influenced by compared hues. Apparent size was compared across the twelve hue and saturation pairs (six pairs from four different colors and two different saturations) and there was a significant difference [$\chi^2(11) = 46.98, N = 576, p < .0001$]. As a result, we can conclude that color (hue) influenced apparent size on LCD monitors.

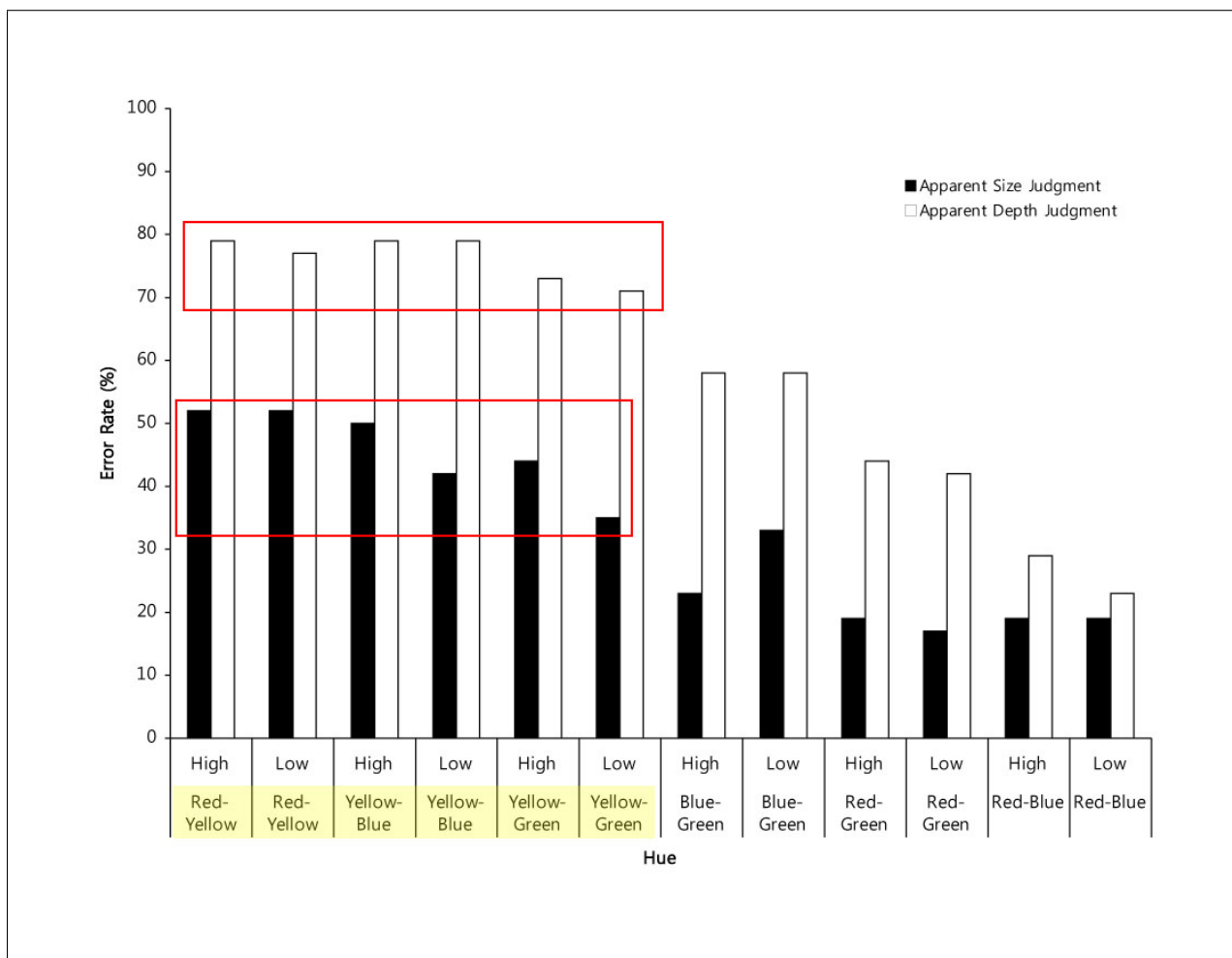


Figure 13: Error rates in apparent size and depth judgment

4.1.2 Color Depth Illusion on an LCD Monitor

The hypothesis of the second research question is that the color depth illusion would be replicated on an LCD monitor.

The color depth illusion was observed and varied from 23% to 79%, depending on comparison pairs, which have different hue and saturation (see Table 15 in Appendix F, or Figure 13). Apparent depth was measured by selecting one of three options as described previously. Answers in which either of the hue pairs was closer than the other were counted as errors. When the red and yellow were compared, almost 80% of responses were wrong in both high and low saturation. In case of highly saturated colors, 37 responses stated that the red was closer, whereas one response selected yellow as closer, and ten responses were that there was no difference. In case of low saturation colors, 37 responses stated that the red was closer, while eleven responses were that there was no difference. However, both bars were equidistant all the time.

Moreover, the result imply that the color depth illusion is influenced by compared hues. Apparent depth was compared across the twelve hue and saturation pairs and there was a significant difference [$\chi^2(11) = 91.64, N = 576, p < .0001$]. As a result, we can conclude that color (hue) had an influence on apparent depth on LCD monitors.

4.2 Identifying Interventions Minimizing Color Illusions

In this study, several levels of three interventions were tested to minimize color size illusion and color depth illusion. No conditions were found that reduced either color size illusion or color depth illusion significantly at alpha level .05.

4.2.1 Background Brightness

The null hypothesis of the third research question was that the color size illusion would not vary throughout different levels of background brightness. Highly saturated red and green were compared in five different levels of background brightness. The color size illusion was observed in 15% to 25% of the responses. The color size illusion was compared across all levels using a chi-square test, but there was no significant difference [$\chi^2(4) = 4.08$, $N = 240$, $p = .3959$].

The null hypothesis of the fourth research question was that the color depth illusion would not vary throughout different levels of background brightness. Highly saturated red and green were compared in five different levels of background brightness. The color depth illusion was observed in 35% to 60% of the responses. The color depth illusion was compared across all levels using a chi-square test, but there was no significant difference [$\chi^2(4) = 8.47$, $N = 240$, $p = .0758$].

In summary, experiment 2 failed to identify any statistically significant background brightness level that reduced the color size illusion and color depth illusion.

4.2.2 Border Color

The null hypothesis of the fifth research question was that the color size illusion would not vary throughout different levels of border color. The color size illusion was observed in 15% to 23% of the responses. The color size illusion was compared across all levels using a chi-square test, but there was no significant difference [$\chi^2(3) = 1.29$, $N = 192$, $p = 0.7324$].

The null hypothesis of the sixth research question was that the color depth illusion would not vary throughout different levels of border color. The color depth illusion was observed in 29% to 48% of the responses. The color depth illusion was compared across all levels using a chi-square test, but there was no significant difference [$\chi^2(3) = 4.232$, $N = 192$, $p = 0.2375$].

In summary, border color of the target object was expected to give boundary information more clearly, so that the user could better judge the size and depth of the object. However, experiment 3 failed to identify any statistically significant border color level that reduced the color size illusion and color depth illusion.

4.2.3 Background Grid Brightness

The null hypothesis of the seventh research question was that the color size illusion would not vary throughout different levels of the background grid. The color size illusion was observed in 19% to 25% of the responses. The color size illusion was compared across all levels using a chi-square test, but there was no significant difference [$\chi^2(4) = 0.79$, $N = 240$, $p = 0.9395$].

The null hypothesis of the eighth research question was that the color depth illusion would not vary throughout different levels of the background grid. The color depth illusion was observed in 35% to 48% of the responses. The color depth illusion was compared across all levels using a chi-square test, but there was no significant difference [$\chi^2(4) = 1.66$, $N = 240$, $p = 0.7988$].

In summary, the background grid brightness was expected to reduce the color size illusion since it can provide an additional cue to estimate the size of the targets. However, experiment 4 failed to identify any statistically significant level of background grid brightness that reduced the color size illusion and color depth illusion.

4.3 Further Analysis on Color Illusions

To enable further analysis especially in terms of individual differences, experiment data was visualized in Figure 14. In the visualization, participant number was displayed on the left hand side, and the number of errors in each participant was displayed on the right hand

side of each visualization. One color block means a trial in experiments. Black represents a correct answer (no error) and each color of the size illusion represents a color that participants selected as longer. Each color of depth illusion represents a color that participants selected as closer. For example, the first participant made no error in size judgment, but made 21 errors out of 24 trials in depth judgment. The first four blocks of the participant placed fifth in size illusion indicate that the participant answered three times that red was longer than yellow and once that that yellow was longer than red. Similarly, from the fifth to eighth blocks of participant five in depth illusion visualization indicate that the participant answered twice that red was closer than blue and reversed the closer color (blue was closer than red) in two instances.

From the size illusion visualization, it was observed that there is an individual difference in size illusion. Six participants made no error and 37.5% of participants made less than 10% size judgment errors (nine participants made errors less than three times). In the meantime, almost 30% of the participants made errors in more than 50% of the trials (seven participants made errors more than twelve times). Although the observation of individual difference is weakened in depth illusion, the individual difference is still obvious. Three participants made no error and 10% of participants made less than 10% depth judgment errors (four participants made errors less than three times), whereas 70.8% of participants made error in more than 50% of the trials (17 participants made errors more than 12 times). A pattern was observed that participant five, nine, and thirteen reversed the selections within the same color comparisons and three participants showed no depth judgment error at all.

In addition to the individual differences, a pattern was observed when yellow was compared. When focusing on the blocks where yellows are, it is clearly observable that the other colors are more prevalent than yellow. Depth illusion shows the pattern more saliently; less than three answers stated that yellow was closer and all others reported that

the other colors (red, green, blue) were closer than yellow. This pattern reveals a color-size order and a color-depth order that yellow seems smaller and farther away than the other colors.

Furthermore, it was observed that more colors are presented in the blocks in which were described above. This means that more errors were made when yellow was compared. This observation is consistent with the results in Chapter 4.1.1 and Chapter 4.1.2.

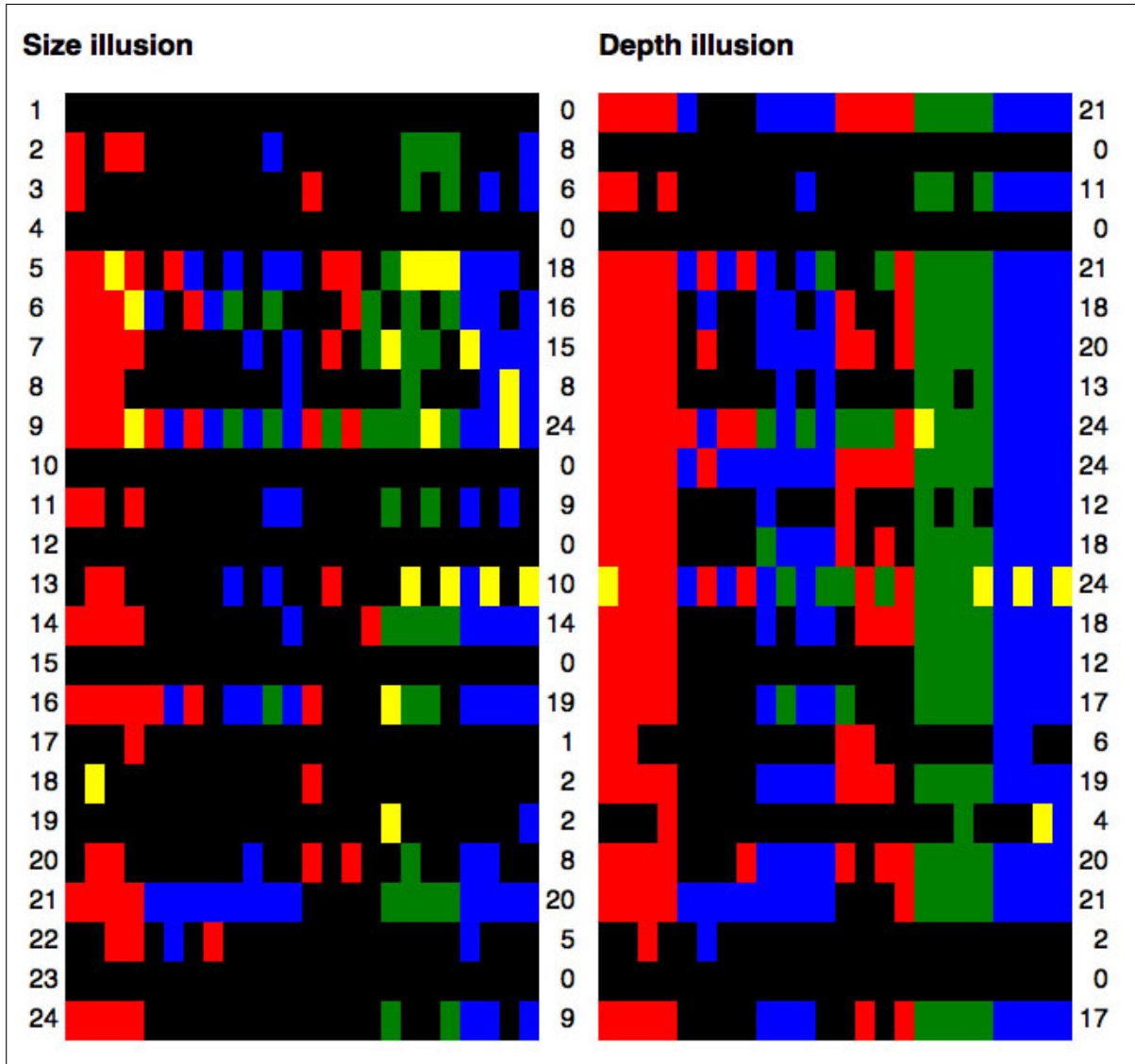


Figure 14: Visualization of size judgment errors and depth judgment errors

4.4 Decision Making Difficulty

Participants were asked to rate the difficulty of making a judgment on each size and depth judgment in order to reveal the influence of color and interventions on user performance. It was expected that the performance measure would explain how people have difficulty with size and depth judgment when color is involved, and how interventions can help people to judge the size and depth correctly and immediately. Further, it was expected that the interventions would not only reduce the illusion, but also would enhance performance on decision making by reducing the effect of factors that caused confusion.

A one-way ANOVA revealed that hue influenced size judgment difficulty, $F(5, 570) = 2.63, p < .05$. Post hoc analysis using Student's t-test on each pair comparison revealed that Yellow-Green ($M = 3.06, SD = 1.92$), Yellow-Red ($M = 3.0, SD = 1.92$), Yellow-Blue ($M = 2.97, SD = 1.83$) comparison were more difficult than Red-Blue ($M = 2.26, SD = 1.62$) comparison (see Figure 15). In other words, participants perceived size judgment to be more difficult when yellow was involved. The influence of hue on depth judgment and the influences of all interventions were not statistically significant at alpha level .05.

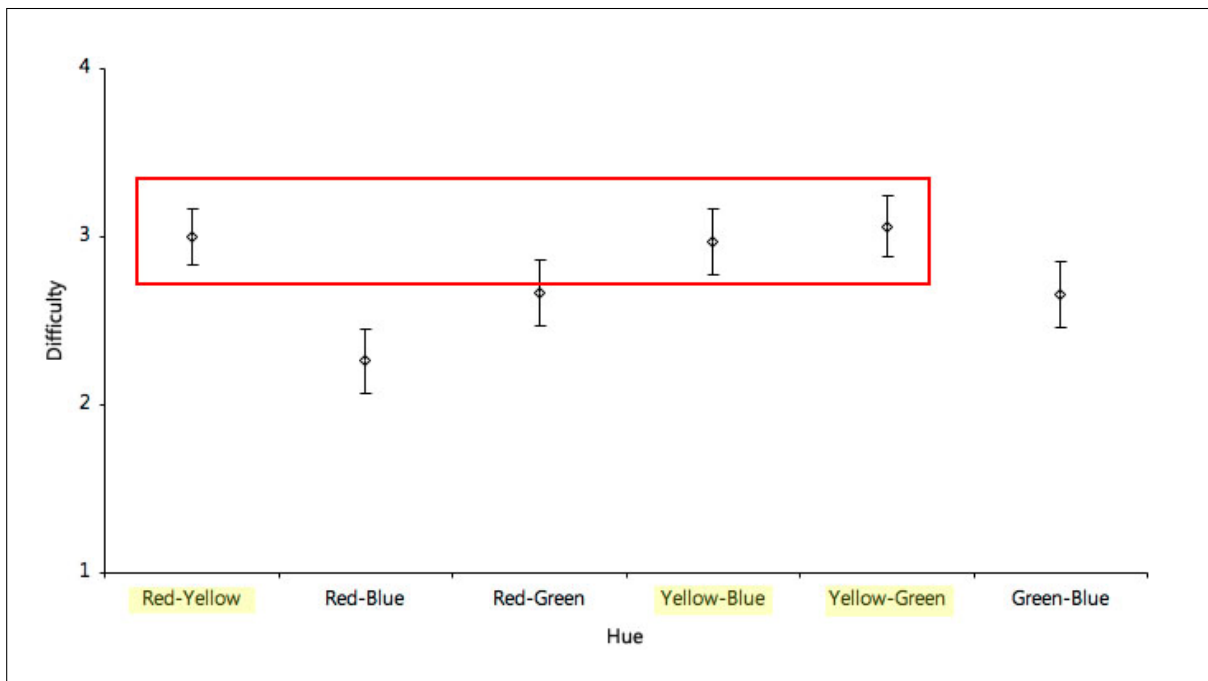


Figure 15: Subjective difficulty of size judgment

Chapter 5

Discussion

This study was designed to replicate the color illusions on LCD monitors and to identify interventions that would minimize color illusions. It was hypothesized that the color size and depth illusion would be replicated on an LCD monitor; these hypotheses were confirmed. In the process of hypotheses testing, an interesting result emerged: participants felt that size judgment was difficult and made more errors when a yellow color was present. More details are discussed in chapter 5.1.

It was also hypothesized that three interventions would influence both apparent size and depth, but the interventions were not statistically significant. Moreover, a literature survey was not able to find any design guidelines for undermining the color size illusion. As a result, designers should be careful when they are mapping color and size together. It would be better that visualization provide additional size information apparently. For example, additional size information can be delivered by presenting extra visual cue. More details are discussed in Chapter 5.2.

Design recommendations were proposed and applied to a specific bioinformatics visualization example. To understand the applicability of design recommendations to the bioinformatics field, domain experts were interviewed. A content analysis revealed evaluations of each design implementation in the context of bioinformatics. More details

are discussed in Chapter 5.3.

In addition to the design recommendations, the relationship between the color size illusion and the color depth illusion was explored. It has been assumed that the color depth illusion caused the color size illusion; bright color is perceived to be larger because it is perceived to be closer. This study found two contradictory pieces of evidence; one is consistent with the previous assumption and the other is opposing. More details are discussed in Chapter 5.4.

5.1 Yellow and Color Illusions

When the color yellow was involved, more illusions were observed. Furthermore, participants rated that size judgments were more difficult than other judgments (see chapter 4.4). When yellow was compared to other colors, such as red, blue, and green, very few participants answered that yellow was longer than other colors. This result is inconsistent with a previous study (Tedford et al., 1977), in which yellow was the second largest color. Background color is a difference that might explain this inconsistency. Tedford used a gray background, but this study used a white background. Since yellow is not a primary color in terms of display mechanism of TFT-LCD, it should be made by combining red and green, which may make it seem brighter than the other primary colors.

Regarding this point two explanations are proposed. One possible explanation is that user confused the boundary line. Since the saturated and bright yellow was similar to the white background, participants may not have been able to distinguish the objects from the background. However, this explanation cannot elucidate why yellow seemed shorter rather than longer. More tests, such as comparing yellow with a border, are required to extend this explanation.

An alternative explanation is offered by the lateral inhibition theory (Arend, 1993; Hartline & Ratliff, 1957). Due to the bright background (white), lateral inhibition reduces

the perceived brightness of yellow that is displayed, which may make the apparent size smaller than the actual size. Through the opponent process theory, this explanation also explains why blue is estimated to be larger (see more detail in Chapter 2.4). According to the color opponent-process theory, a yellow signal from Long and Medium cones can inhibit or excite the neural response of Short cones, which results in underestimation or overestimation of blue. However, this explanation requires additional evidence that lateral inhibition occurs before the opponent-processes affect color perception. Further, this conjecture cannot explain why the judgments involving yellow were difficult until we have evidence that the color opponent process increases the human visual workload.

As discussed in chapter 2.4, color vision is a complex system. More experiment data should be provided to explain this phenomenon. For example, the results of experiments with several background colors and background images (with known-colored objects in) will help us explain this phenomenon with the retinex theory (Land et al., 1983).

In terms of the color depth illusion, the result of this study is consistent with previous studies. In this study, most participants reported that yellow is the distant color comparing to red, blue, and green. Previous studies show that the order of color depth was reversed when the background color was changed from black to white (Dengler & Nitschke, 1993; Hartridge, 1947; Thompson & Stone, 1993; Verhoeff, 1928; Winn et al., 1995).

5.2 Design Guidelines

In this study, tested interventions were not statistically significant to reduce the color size illusion. Other implementations of those interventions might reduce the illusion, but those are not feasible as of now. Moreover, no other design factor has been found to reduce the color size illusion from the literature survey. As a result, the first guideline would be:

Consider the color size illusion when using size and color mapping together.

This is particularly relevant when size judgment is important. Color coding for grouping or redundant coding would be effective, but designers should be careful about a situation in which users have to compare the size of different colored objects. Especially on LCD monitors, designers should be careful using yellow for mapping on a white background, since yellow caused the most significant errors (see Chapter 5.1).

However, in many domains, the reading size of visualized objects would be indispensable. When size judgment is critical, visualization should not solely depend on human judgment and should provide additional information about size or size difference clearly. As a result, the second guidelines would be:

Provide additional information with redundant codings.

For example, visualization can group identically sized objects with a same color, since color is good for categorization (Mackinlay, 1986). Figure 16 (part a) illustrates this approach. Another technique would be to present size differences explicitly with a reference line (Figure 16, part b). Visualization can utilize interaction techniques as well. For instance, when the user clicks on an object, a visualization tool can highlight same size objects, or when the user selects multiple objects, then a visualization tool can display information about size differences or size distribution. This additional information will help visualization users to judge size accurately.

The color coded information can be converted into other visual cues. In the case of nominal data, the information can be delivered by position, shape, length, angle, or text (Mackinlay, 1986). In the case of continuous data, visualizations have used saturation variation, brightness variation, or hue variation (for example, from blue to red). Since the previous study shows that hue, saturation, and brightness influence the size perception (Tedford et al., 1977), these mappings can be problematic. Furthermore, the literature suggests that coding on position, length, angle, or volume is better than color coding for quantitative data (Christ, 1975; Cleveland & McGill, 1984; Mackinlay, 1986; Nowell et al.,

2002).

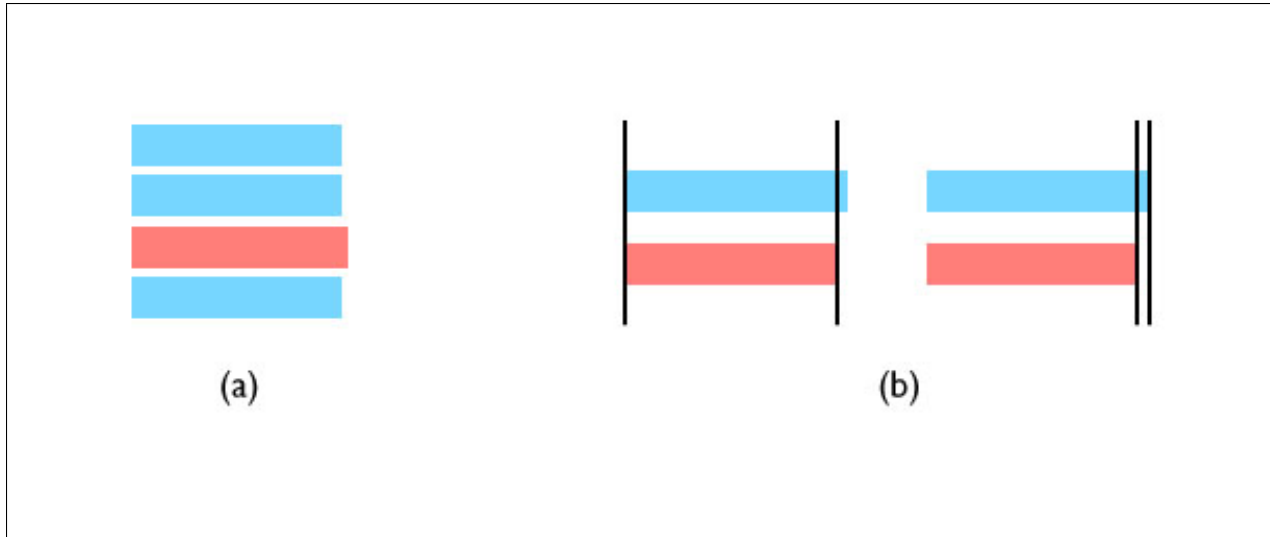


Figure 16: Examples of additional size information

In terms of the color depth illusion, there are some design guidelines. Benzschawel (1985) recommended using less saturated colors and brighter backgrounds to minimize chromostereopsis. However, this guideline should be revised. This study showed that there was no difference of error rates between saturations; participants made errors in both high and low saturated colors. Since the guideline did not specify the definition of the lower saturation clearly, it is possible that the level of low saturation advised by Benzchawel is different from the level used in this study. In spite of the difference, this study implies that designers should consider chromostereopsis regardless of the color (saturation) that they use. In addition to the saturation, this study also replicated the reversed color depth order on a white background (Winn et al., 1995). As a result, using brighter background will not minimize chromostereopsis in every condition.

On the other hand, designers can utilize the color depth illusion to emphasize a target object. For example, a design guideline proposed by Federal Highway Administration, In-Vehicle Display Icons and Other Information Elements

(FHWA-RD-03-065), recommends that designers “Use unsaturated, cool colors for the background, and saturated, warm colors for the foreground image to increase the likelihood that users understand the icon.” (Campbell, Richman, Carney, & Lee, 2004) (p. 2-10). A saturated warm color will make a target object seems closer than the background so that users feel that the target is popping up.

5.3 Design Recommendations for Bioinformatics

Visualization Tools

To extend the design guidelines to the bioinformatics field, design recommendations are proposed. To verify the applicability of those recommendations, six implementation examples were proposed and verified by interviewing domain experts. Evaluations of those examples and insights gained from the expert review are summarized.

5.3.1 Design Recommendations

The following are summaries of design recommendations for visualization design. These recommendations address the color size illusion and the color depth illusion:

1. Consider the color size illusion when you are using size and color mapping together and size judgment is important.
 - (a) Try to avoid mapping on color and size together, if possible.
 - (b) Convert the color coded information to other visual properties. Refer to Makinlay (1986) for the priority of visual properties.
 - (c) Avoid using highly saturated yellow on a white background when either size or depth is compared.

2. Provide additional information with redundant codings. Redundant display coding is a design principle that is recommended to avoid information loss (Wickens & Hollands, 1999) (p. 61).
 - (a) Provide additional size information with other visual cues such as text or reference line.
 - (b) Consider providing size information via interaction techniques or other alternatives. Interactivity can provide much detail information only when it is needed. This approach is supported by a design principle, progressive disclosure (Tufte, 1990).
3. To emphasize a target object, utilize the color illusions. Use a saturated warm color for the target image, and an unsaturated cool color for the background. This recommendation was adopted from Campbell et al (2004) and is supported by the experiment result of this study.
4. Test the colored visualization, since the color perception can be influenced by many factors.

5.3.2 The Genomic Sequence Viewer

The Genomic Sequence Viewer is a bioinformatics tool to decide a feature type and location based on the computed evidence of a given genomic sequence (see Figure 4). Each color bar represent a predicted feature and each feature has a mouse-over interaction, which shows detailed information such as predicted feature type, algorithm name, start position, and end position. Figure 17 illustrates an example; the tFind algorithm identified a tRNA, which starts from 207695 base-pair (bp) to 207768 bp. Researchers compare predicted evidences by moving the mouse pointer over those features or referring the raw data table. If conflicting evidence is present and human judgment is required (as in the

case of Figure 17), researchers follow an analysis process, the Standard Operating Procedures for Manual Nucleic Acid-Level Curation (Snyder, 2006), to make a decision.

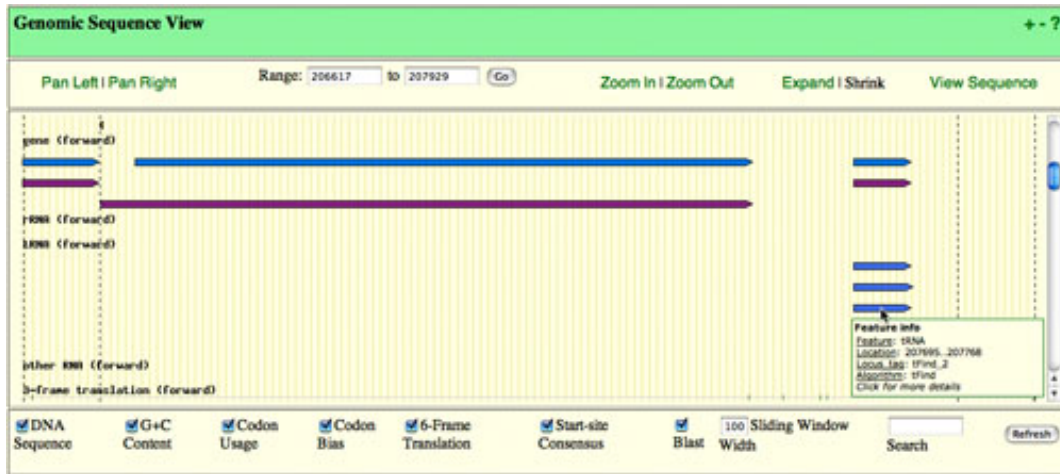


Figure 17: Mouse-over interaction

5.3.3 Implementations of Design Recommendations

The proposed design recommendation can be implemented in various way, six implementation examples are presented in this study.

1. No color coding. A target comparison group was painted with the same color to avoid color influence (see Figure 18). In this example, colors were coded to show each algorithm name which predicted the features. However, the tool also had a mouse-over interaction, which showed same information in a popup window. Thus, users still can retrieve algorithm information with a mouse-over interaction. This approach controls out the influence of color on size perception, but it loses a redundant color coding. The disadvantage of the approach is that it will make users remain in normal human error rate; this is not a way to enhance performance. Moreover, this approach cannot be used in a situation that color coding is a

convention, domain specific population stereotype, in the visualization. Thus, when a specific color coding is widely used in the domain, this approach can cause further confusion to users. This is an implementation example of how one can “Try to avoid mapping on color and size together.”

2. Color coding for size. Colors were used to distinguish size groups (Figure 19).

Considering that the task is deciding a feature type based on several predictions’ results, coloring on the most frequent size features will help users identify the most common evidence. This approach will be limited to a specific test, finding the most common pattern. The advantage of this approach is that it can utilize pre-attentive vision (Julész, 1981). For example, in a case in which 8 out of 10 features have a same size, it will immediately reveal the most salient evidence. However, this approach still requires that the viewer compare the sizes between the size groups. This is an implementation of how to “Provide additional size information with other visual cues.”

3. Reference line. A reference line was given on both ends of features that have the most common size (Figure 20). This approach is also limited to a specific task as described above. If the approach is applied to every comparison of features, users will be confused by many lines. Another disadvantage is that, in cases with very subtle differences, users may not distinguish them, since the differences can be occluded by the width of the line. The advantage of reference lines is that distant features can be compared. In Figure 18, direct comparison of the first and fifth bars is difficult, since they are in relatively distant from each other. However, in Figure 20, comparing them becomes easier because of the reference line. This is an implementation of how to “Provide additional size information with other visual cues.”

4. Interaction example 1. Color coding for size was given when a group of features were

selected (Figure 21). Interactivity is beneficial, since it can provide additional information on demand. However, visualization may have to inform the interactivity, determining what kinds of functions are available so that users understand and utilize the functionality. Sometimes, visualization may have to train users in order for them to utilize the interactivities. Interactivity also can be limited due to the technical feasibility. This is an implementation of how to “Consider providing size information via interaction techniques or other alternatives.”

5. Interaction example 2. Detailed information of size comparisons was given when a group of features were selected (Figure 22). In this example, feature type, location, and size of predicted feature were displayed. In addition to the advantage of interactivity, this approach enables users to compare very subtle difference, since it provides exact numbers. Scalability will be limited to the amount of information that can be displayed in the popup window.
6. Interaction example 3. Instead of selecting a grouping by dragging a mouse, a mouse-over interaction was used to display detail information (Figure 23). When users moved a mouse pointer on one of comparison group features, summary information showed up. This approach will show quick result, since it does not require a dragging action.

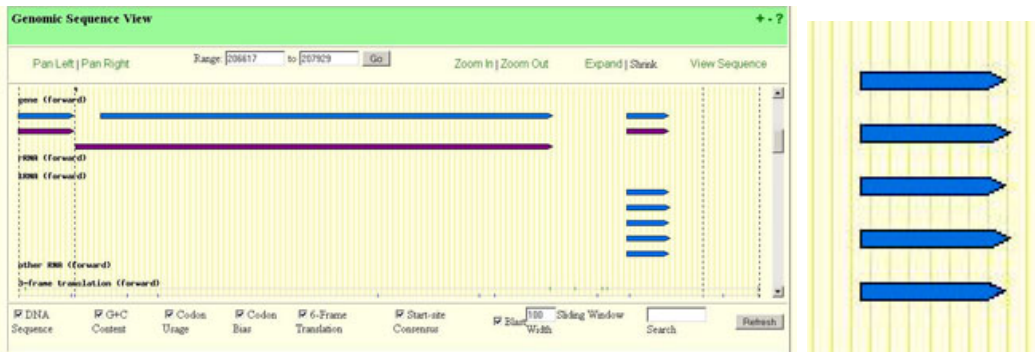


Figure 18: Implementation example: No color coding

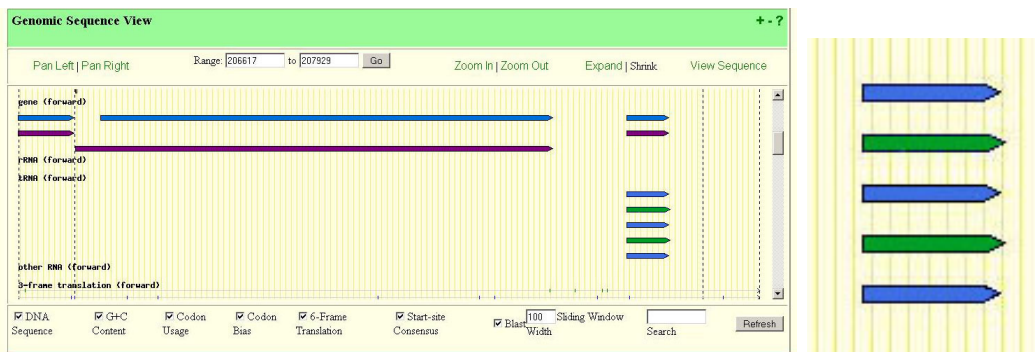


Figure 19: Implementation example: Color grouping

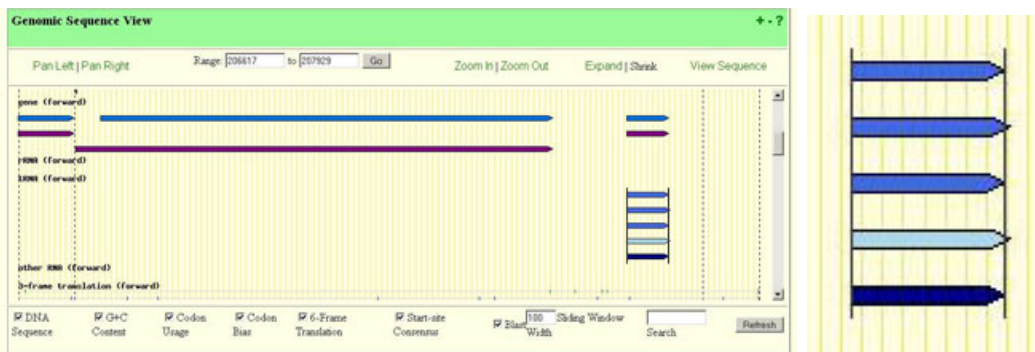


Figure 20: Implementation example: Reference line



Figure 21: Implementation example: Interaction example 1



Figure 22: Implementation example: Interaction example 2



Figure 23: Implementation example: Interaction example 3

5.3.4 Evaluation Method

Proposed implementation examples were evaluated by domain experts who use the Genomic Sequence Viewer in their scientific research. Three domain experts were recruited and interviewed with a semi-structured questionnaire (Appendix G). The questions were mainly designed to reveal the applicability of design recommendations to the bioinformatics field. A content analysis adopted from affinity diagramming was performed. Each open-ended evaluation, concern, and suggestion was recorded in a sticky note; these notes were reorganized and prioritized with two peer researchers. This process was iterated through six implementation examples.

5.3.5 Evaluation of Implementations

To begin with, all participants experienced situations in which they compared features that had small differences in size (very similarly to the case of this example), but these situations were not frequent (from 5% to 10% cases of their experience). Participants responded that these situations made work painful, since they had to roll a mouse-pointer over each feature to see the detail information (start position and end position) and they moved around those features. They usually went back to previous features to remind the numbers, since the mouse-over interaction showed the location information of one feature at a time.

Evaluations on implementation examples from the content analysis were summarized as below,

1. No color coding: Participants responded “it is a little bit different”, but overall evaluations were that the example was not helpful. All of them were worried about losing a visual cue for algorithm information.
2. Color coding for size: Participants responded that they could distinguish size difference, but were concerned about losing algorithm information. Participants

agreed that algorithm information does not have to be displayed by color coding, but they needed to see the information clearly. One solution, for example, would be writing the algorithm name next to the feature.

3. Reference line: Participants responded that they were able to see size differences very clearly and immediately. One participant had a concern that the reference line may occlude the difference when size differences are subtle (for example, different by a codon).
4. Interaction example 1: One participant preferred the reference line, since it showed the difference immediately, whereas this example still requires users to compare size between groups. Participants suggested explaining the expected results of interaction more clearly so that users could understand and utilize the functionality.
5. Interaction example 2: Participants were satisfied with this example, not only because they no longer needed to memorize the numbers, but also because users could discriminate very small differences with exact numbers. Moreover, they could see the detailed information only when it was necessary.
6. Interaction example 3: This example was controversial. One participant liked the example, since it was not necessary to explain the interaction, how to operate it, and the expected result. One participant did not like it; “because it conflicts to the convention. When you roll over a pointer on a feature, this mean you are interested in only that feature.” The participant suggested that this approach would fit better where a group has a natural meaning. For example, in a structural representation of a genomic sequence, it would be useful for displaying detailed information about amino acids rather than atom level information when users move a mouse pointer over an atom.

5.3.6 Insights for Design Recommendations

The domain experts review provided some insights into design recommendations for future bioinformatics visualization tools. In this verification study, mainly three recommendations were evaluated.

The first tested design recommendation was that one should “Try to avoid mapping on color and size together.” Colors are widely used in the bioinformatics field. In a certain application, color coding is a domain specific population stereotype. For example, the Basic Local Alignment Search Tool (BLAST) uses color coding to display E-values, which represent the significance of a result. However, participants suggested that algorithmic information could be displayed by another visual cue, which means that color coding could be avoided depending on the situation.

The second recommendation was that designers should “Provide additional size information with other visual cues.” Participants unanimously agreed that displaying numbers was the most favorable approach. The reference line example got a positive evaluation, since it shows a difference, whereas “color coding for size” let users compare them. Redundant coding of size and size difference would be better. For example, reference lines make it possible for users to identify a difference, and exact numbers enable users to compare them precisely.

The last tested recommendation was that one should “Consider providing size information via interaction techniques.” Interaction techniques got positive evaluations, since users can get detail information when it is necessary. Participants stated that “Being able to drag and see information about them is much more powerful, since it allows you direct your interaction with it. On the other hand, you have more control over seeing the information,” and “I like the interactivity. Since you are specifically selecting these to look at. You are restricting yourself just this block or just this small portion of interface, then I think, you can add a lot of information.”

In summary, avoiding color coding is limited but possible. Additional size information can be delivered by reference line or exact numbers, but there are some trade offs. Selected information according to the task should be presented in the form of reference lines or exact numbers in order not to occlude other information. Redundant coding, having both size and size difference, would be helpful. Interaction technique will be useful, since it does not occlude other information, and it can provide very detail information according as context.

5.4 Relationship Between the Color Size Illusion and the Color Depth Illusion

Previous studies explained the color size illusion with the color depth illusion (Gentilucci et al., 2001; Tedford et al., 1977), but they did not test the relationship between them. It is known that humans can make errors in size perception due to distance information, as in the case of the Ponzo illusion. However, a recent study revealed that the Ponzo illusion is not due to distance illusion, but due to orientation perception; this is called the tilt constancy theory (Prinzmetal, Shimamura, & Mikolinski, 2001). In this study, all the experiments measured the color size illusion and the color depth illusion together. Similar illusion patterns were observed (see Figure 13, Table 12), but only 21.8% showed that both color illusions occurred at the same time. The results revealed that the color depth illusion might not be the direct cause of the color size illusion.

In terms of the color size illusion, the most significant error rate was observed when yellow and red were compared. Error rates were observed in yellow-blue, yellow-green, green-blue, red-blue, and red-green combinations, in decreasing order. In terms of the color depth illusion, a very similar pattern was observed: red-yellow, yellow-blue, yellow-green, green-blue, red-green, and red-blue in decreasing order (see Figure 13, Table 12). The only

difference is that red-blue and red-green pairs were switched in the order. This suggests that there might be a cause and effect relationship between the color size illusion and the color depth illusion or there might be a common cause between them.

Table 12: Error rates in size and depth judgment

Illusion	Saturation	Red- Yellow	Yellow- Blue	Yellow- Green	Green- Blue	Red- Blue	Red- Green
Size	High	52%	50%	44%	23%	19%	19%
Size	Low	52%	42%	35%	33%	19%	17%
Depth	High	79%	79%	73%	58%	29%	44%
Depth	Low	77%	79%	71%	58%	23%	42%

However, both illusions were observed simultaneously in only 21.8% of cases (Figure 24). The responses that size was equal but distance was different were 28.5%, and the reverse case was 5.1%. Within color illusion cases, the assumption that color depth illusion caused color size illusion can only explain 40% of the reported illusions. In other words, 60% of illusions were either a color size illusion or a color depth illusion; 51% reported that size is equal but depth is different, and 10% reported that size is different but depth is equal. This implies that the color depth illusion might not be the direct cause of the color size illusion.

Moreover, a weak relationship was shown between the color size illusion and the color depth illusion. The number of size and depth judgment errors per participant in the first experiment were compared and less than 20% errors of size judgment were explained by depth judgment errors, $r(22) = 0.19$, $p = .02$.

For the further analysis of co-occurrence of color illusions, experiment data were visualized in Figure 25. Brightness illustrates a degree of illusions; white means that no

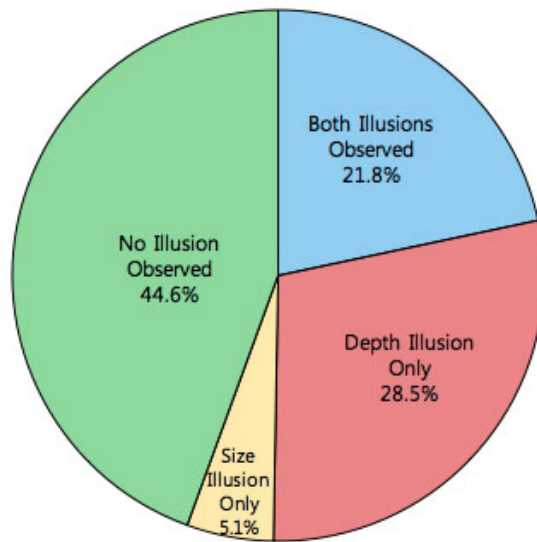


Figure 24: Co-occurrence of the color size illusion and the color depth illusion

illusion was observed, gray means that either the color size illusion or the color depth illusion was observed, and black means that both illusions were observed. Y-axis represents participants and X-axis represents conditions of trials. This visualization was aimed to identify any conditions that produce both illusions, but no obvious pattern was identified. However, two observations were identified in this visualization. It was found that more illusions were observed when yellow was compared. An individual difference was also observed; participants four and 23 had no errors throughout all trials, whereas participant nine made errors 100% of the time. Although participant nine can be treated as an outlier, participants five, sixteen, and 21 showed a pattern in which they made errors in both size and depth judgment, whereas participants one, ten, twelve, and eighteen showed a pattern that they made an error either in size or depth judgment.

5.5 Limitations and Future Research

There was a response time difference between the first quarter of experiment sessions and the other sessions, $F(3, 1224) = 9.83, p < .0001$. Response time was measured at each session and the mean of each quarter was compared. The first quarter took 26 ($M = 25.96, SD = 15.38, SEM = 0.87$) seconds, but other sessions took 22 ($M = 21.85, SD = 12.60, SEM = 0.71$), 21 ($M = 21.12, SD = 19.47, SEM = 1.10$), 20 ($M = 19.89, SD = 10.21, SEM = 0.58$) seconds respectively and the response time decreased (Figure 26). One possible explanation is a learning effect; participants became used to the questions, which reduced the response time. Since questions were the same throughout the experiments, it is possible that the learning effect reduced the response time to answer the questions. The other explanation is boredom or fatigue. Since the questions were repeated 52 times for all trials and only the color stimuli were changed slightly, participants may have become bored and answered less carefully. Landau (1987) found that eye fatigue was increased when an inadequate color contrast was given. In this study, several combinations of color stimuli were given, which may have caused visual fatigue. If the latter explanation is correct, then the resultant data will lose some reliability. Unfortunately the error rates were not comparable among the quarters, since the color comparison pairs were not distributed evenly and color was found to be a significant factor influencing the error rate and subjective difficulty.

The experimental design has limitations due to the assumption that LCD monitors would reproduce color illusions in much the same way as CRT monitors and slide projectors. Since red and green were perceived as the largest and smallest colors respectively in previous research (Tedford et al., 1977), all interventions were tested only with the red-green pair. However, the experiment showed that red-yellow was the most significant pair. To confirm that boundary confusion was the reason for the yellow illusion, it would be necessary to compare yellow with obvious borders or boundary contrast.

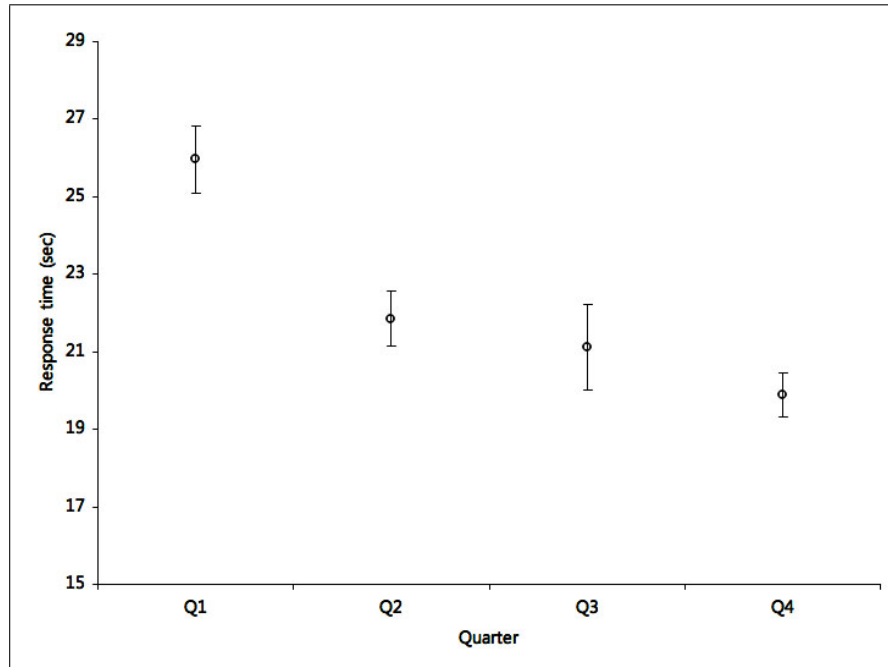


Figure 26: Average response time of each quarters

Another explanation, lateral inhibition on yellow brightness, also should be tested by comparing them in various background brightness levels. These experiments will strengthen our knowledge about the relationship between yellow and color illusions.

In order to simplify the experimental trials and keep them at a manageable size, the color size illusion was measured by asking whether two colored objects were identical and questions were repeated only twice per single hue pair. Several trials by manipulating size precisely would reveal more complete data about the order of apparent size, and those results would also reinforce our understanding of the difference between previously tested display devices and LCD monitors. In other aspects, having a control group such as a red-red comparison would indicate the baseline of human error rate and enrich the significance of the color size illusion.

In this study, participants were young and homogeneous. All participants were college and graduate students within a narrow age group ($M = 26.9, SD = 5.92$). This

sample may not well represent the population who use visualization tools, so designers should consider that users may have color blindness or worse visual acuity due to the presbyopia. A visualization should provide additional size information according to the recommendation of this study, since size judgment errors of colored objects can be caused not only by the color vision, but also by lower levels of visual acuity.

In addition to the limitation of population, this study has explored the influence of color on perceived size and depth under very controlled conditions. It is challenging to reproduce exact color in a practical display setting due to the variation of display devices and environmental settings that can influence the displayed color. For example, room illuminance can affect the perceived color. Besides the environmental control, it is also difficult to control properties of stimuli separately. If a colored object has a border to give boundary information, it can also influence the perceived brightness of the object according to the simultaneous brightness contrast theory or brightness assimilation (Wyszecki & Stiles, 1982). If the border was colored, the perceived hue of the object can be altered according to the simultaneous color contrast or color assimilation (Shapley & Reid, 1985). Because of these reasons, visual perception research should stand somewhere between controlled experiment and simulation to the extent that does not lose the context of a realistic working environment. The current study was simplified to compare only two colored objects and to manipulate limited factors (background brightness, border color, and background grid brightness). A chin-mount was used to fix the distance between the participant and display, but this is not a natural workplace setting and the visual angle was not controlled. Black display boards were set to block the peripheral visual stimuli and illuminance was kept consistent. As a result, the current research needs to be extended to simulate more realistic environment, where it can have more complex stimuli and interactions among the stimuli to be generalized.

Chapter 6

Conclusion

In its investigation of the influence of color on perceived size and depth, this study has utilized several color pairs to demonstrate that the color size illusion and the color depth illusion are both significant. Furthermore, this study has uncovered an illusion pattern that is unique to a white background on an LCD monitor. In contrast to earlier studies, this study found that yellow appears smaller and more distant than other colors. Two explanations were provided, but these will need to be strengthened with supplementary experimentation. Three types of interventions were tested to determine whether they minimized the color illusion, but there was no significant intervention. Subjective ratings of the judgment difficulty revealed that yellow made size comparisons difficult for participants.

Based on the experiment data and the literature survey, this study has determined design guidelines that could aid information visualization. First of all, this study found that it is better to avoid mapping color and size together when the size is critical, as a significant size illusion was observed and the study was not able to identify any effective interventions. For cases in which the visualization should map both size and color, the designer should provide supplementary information about either size or size difference so that user can easily determine the size information. Additionally, interaction techniques can be considered as alternatives to provide size information.

Table 13 summarizes design recommendations for visualizations. These address the color size and the color depth illusions.

Proposed design recommendations were implemented in a bioinformatics tool and evaluated by domain experts. Insights from the evaluations are presented. Avoiding color and size coding together is possible, but it has limitations because colors are used widely in the bioinformatics field. Additional size information can be delivered by reference line or exact numbers. Having both size and size difference would be helpful, since users can see the difference immediately and precisely. The interaction technique would be useful, since it does not occlude other information and it can provide very detailed information within the context of the existing display.

In addition to the design guidelines, the study was able to provide some evidence about the relationship between the color size illusion and the color depth illusion. It observed both illusions at the same time, and drew two pieces of controversial evidence. The illusion patterns were similar, but the occurrence pattern did not comply with the argument that the color depth illusion caused the color size illusion.

Considering the limitations of this study would be beneficial to future studies. User fatigue could not be compared due to the uneven hue distribution. Considering that color distribution must be randomized, alternative measures such as a physiological measure of visual fatigue (Murata, Uetake, Otsuka, & Takasawa, 2001) would be appropriate. However, the influence of visual fatigue on size judgment tasks should be demonstrated. According to Murata (2001), visual fatigue was observed, but the effect of visual fatigue on work performance was very minor within an hour-long VDT task.

As mentioned in Chapter 5.5, this study should be extended to understand the cause of the color size illusion, particularly why yellow seems smaller on a white background. In this study, all the interventions were tested with a red-green pair. Comparing yellow with an obvious border line will reveal whether the errors were caused

due to the confused boundary. Comparing yellow on various levels of background brightness will show whether it can be explained by the lateral inhibition theory. This study also can be extended to evaluate more interventions, including background hue, background saturation, border width, border style (solid or dashed), background grid hue, background grid saturation, background grid width, background grid frequency, background grid style, background grid pattern (horizontal, vertical, or both), and so on.

Finally, a validation study was conducted by interviewing domain experts with some screenshot examples due to technical issues. In addition to interviews, observing user performance with working prototypes will reveal more detail evaluations.

Table 13: Design guidelines

Design Recommendations	Reference
<p>Consider the color size illusion when you are using color and size mapping together and size judgment is important.</p> <p>(a) Try to avoid mapping on color and size together, if possible.</p> <p>(b) Convert the color coded information to other visual properties.</p> <p>(c) Avoid using high saturated yellow on a white background when either size or depth is compared.</p>	<p>Experiment Result.</p> <p>No design factors known from this study and literature survey</p> <p>(Mackinlay, 1986)</p> <p>Chapter 5.1</p>
<p>Provide additional information with redundant codings.</p> <p>(a) Provide additional size information with other visual cues such as text or reference line.</p> <p>(b) Consider providing size information via interaction techniques or other alternatives.</p>	<p>(Wickens & Hollands, 1999)</p> <p>Chapter 5.3.6</p> <p>Chapter 5.3.6, (Tufte, 1990)</p>
<p>To emphasize a target object, utilize the color illusions. Use a saturated warm color for the target image, and an unsaturated cool color for the background.</p>	<p>Chapter 5.2, (Campbell et al., 2004)</p>
<p>Test the colored visualization, since the color perception can be influenced by many factors.</p>	

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Appendix A

Informed Consent Form

Informed Consent Form

Virginia Polytechnic Institute and State University

Title of Project: Color influence on visual perception

Principal Investigator: Tonya L. Smith-Jackson, Ph. D.

Co-Principal Investigator: Hyun Seung Yoo.

I. THE PURPOSE OF THIS PROJECT

You are invited to participate in a study about color influence on visual perception. We are specifically interested in your perceived size and depth depends on color variation. This project will examine how you make decisions about size and depth by presenting several colors. There are no right or wrong answers. We are simply interested in your perception regarding several colors with varying conditions in order to build some guidelines for appropriate color use in visual display design. This project will take no more than 1 hour to complete.

II. PROCEDURES

You will be asked to complete, to the best of your ability, several questionnaires. You will also be asked to make size and distance judgment upon the objects displayed on a screen.

Finally, you will be asked to rate a level of difficulty to make the judgments. Everything is computer-administered with the exception of this informed consent sheet and an acuity-screening inventory.

III. RISKS

Participation in this project does not place you at more than minimal risk of harm. You may feel fatigue on your eye, but you can take a rest whenever you want for as long as you want.

IV. BENEFITS OF THIS PROJECT

You will be given research credit (1 credit) or the number of points allowed by your Professor or GTA for your participation. You will be given information to contact the principal investigator to get information about the outcomes of the study. You will also benefit from knowing that you have participated in worthwhile research that has immediate and positive applications.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. No one outside the research team will be able to connect any data with your name. The information you provide will have not be tied to your name. We will only use a two digit participant number to identify you during analyses and any written reports of the research. No reference will be made in oral or written reports that could link you to the data nor will you ever be identified as a participant in the project. The data from this research will be stored on a secure hard drive that is only accessible by the researchers. We will keep the data sets resulting from this study and the informed consent sheets for 5 years. The informed consent sheets will be stored in a locked metal cabinet in a research lab. After 5 years, both the data set and the informed consent sheets will be destroyed by deleting the files and shredding the informed consent sheets.

VI. COMPENSATION

You will be given 1 research credit at the completion of the experimental session. Or, you will be given the agreed upon credits or points if your instructor is giving extra credit as part of your course grade. There is no further compensation for participation in this study.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason. There is no penalty if you choose to withdraw from this study, but no research credits will be given if the study is incomplete.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering.

IX. PARTICIPANT'S RESPONSIBILITIES

It is very important that you keep the activities and information discussed confidential, since others will be participating in this research.

X. QUESTIONS

If you have questions, or do not understand information on this form, please feel free to ask them now.

XI. PARTICIPANT'S PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Signature

Date

Name (please print)

Contact: phone

XII. CONTACT

If you have questions at any time about the project or the procedures, you may contact the principal investigator, Tonya Smith-Jackson at (540) 231-4119 or smithjack@vt.edu (519-H Whittemore). If you feel you have not been treated according to the descriptions in this form, or your rights as a participant have been violated during the course of this project, you may contact Dr. David Moore, Chair of the Institutional Review Board Research Division at (540) 231-4991.

Appendix B

Demographic Questionnaire

1. Age: _____

2. Gender: _____ Female _____ Male

Appendix C

Acuity Screening Inventory

For each question you should select the response that best describes you and your behaviors.

You can select from among the following response alternatives: Never (or almost never), Seldom, Occasionally, Frequently, Always (or almost always). Simply circle the letter that corresponds to the letter of your choice.

1. Do you find most book print too small to read easily without glasses or contact lenses?

Never Seldom Occasionally Frequently Always

2. Can you recognize people if you see them at a distance when you are not wearing any corrective lenses?

Never Seldom Occasionally Frequently Always

3. Do you notice that far objects appear fuzzy when you are not wearing glasses or contact lenses?

Never Seldom Occasionally Frequently Always

4. Do you notice that near objects appear fuzzy when you are not wearing glasses or

contact lenses?

Never Seldom Occasionally Frequently Always

5. Do you wear glasses or contact lenses?

Never Seldom Occasionally Frequently Always

6. Can you read easily in dim light without any corrective lenses?

Never Seldom Occasionally Frequently Always

7. Do you think that you may need glasses?

Never Seldom Occasionally Frequently Always

8. Would you say that your vision is as good as most peoples?

Never Seldom Occasionally Frequently Always

Answer the following two questions using Good, Average, Slightly below average, Poor, Very Poor (circle the letter corresponding to your choice).

9. Without glasses or contact lenses, the clearness or sharpness of vision in my right eye is

Good Average Slightly below Average Poor Very Poor

10. Without glasses or contact lenses, the clearness or sharpness of vision in my left eye is

Good Average Slightly below Average Poor Very Poor

Appendix D

Instructions

D.1 Pre-experiment Instructions

1. Simply answer questions as you feel.
2. This is an example of this experiment (Figure 27). There are 4 questions and these questions will be same throughout the experiment. The first question is about size; which is longer than the other. The second question is about decision making difficulty of the first question; how much is it difficult when you answer the first question. The third question is about distance between an object and you; which is closer to you than the other. The last question is about difficulty of the third question.
3. You can take a rest as long as you want when you are at the intermediate session.
4. There is no time constraint. However, please answer the questions as quickly and accurately as possible. Those are equally important.

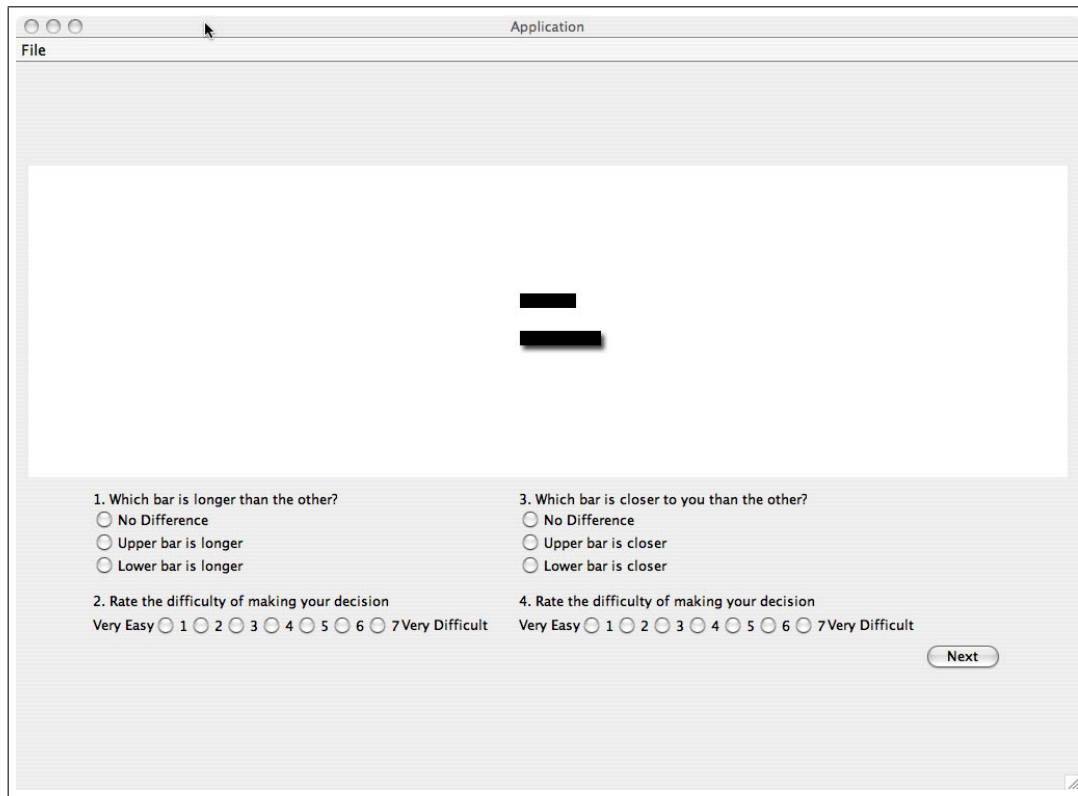


Figure 27: An example of experiment

D.2 Intermediate Session Instructions

1. Thank you for participating this study.

2. If you feel fatigue on your eyes, please take a rest as long as you want while this message is displayed.

3. The 'Next Session' button will be activated after 6 seconds.
You can move to next session after the activation.

Next Session

Appendix E

Experiment Conditions

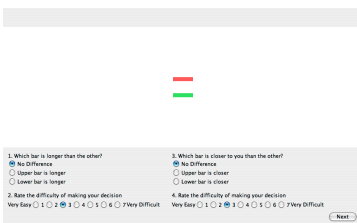
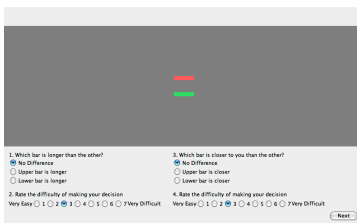
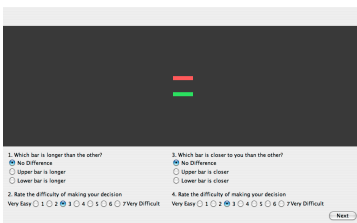
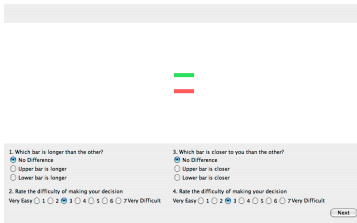
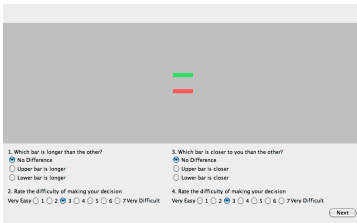
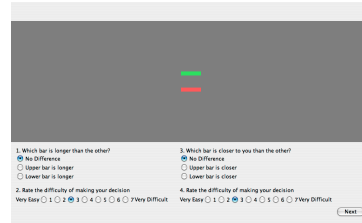
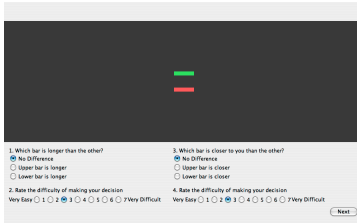
E.1 Experiment 1 conditions

The figure displays 12 experimental trials arranged in a 4x3 grid. Each trial consists of a visual stimulus and a set of four questions. The visual stimulus shows two horizontal bars: a blue bar and another bar in green, red, or yellow. The questions are:

1. Which bar is longer than the other?
 No Difference
 Upper bar is longer
 Lower bar is longer
2. Rate the difficulty of making your decision
Very Easy 1 2 3 4 5 6 7 Very Difficult
3. Which bar is closer to you than the other?
 No Difference
 Upper bar is closer
 Lower bar is closer
4. Rate the difficulty of making your decision
Very Easy 1 2 3 4 5 6 7 Very Difficult

The trials vary in the relative lengths and colors of the bars. For example, in the top-left trial, the blue bar is longer than the green bar. In the top-middle trial, the blue bar is longer than the red bar. In the top-right trial, the blue bar is longer than the yellow bar. The bottom row of trials shows different configurations, such as the green bar being longer than the blue bar in the bottom-left trial.

E.2 Experiment 2 conditions



E.3 Experiment 3 conditions

The image displays a 3x3 grid of experimental trials. Each trial consists of a visual stimulus and a set of four questions. The visual stimulus shows two horizontal bars: a green bar on top and a red bar on the bottom. In the top row, the green bar is longer than the red bar. In the middle row, the bars are of equal length. In the bottom row, the red bar is longer than the green bar. The questions for each trial are:

1. Which bar is longer than the other?
 No Difference
 Upper bar is longer
 Lower bar is longer
2. Rate the difficulty of making your decision
Very Easy 1 2 3 4 5 6 7 Very Difficult
3. Which bar is closer to you than the other?
 No Difference
 Upper bar is closer
 Lower bar is closer
4. Rate the difficulty of making your decision
Very Easy 1 2 3 4 5 6 7 Very Difficult

Each trial includes a 'Next' button at the bottom right.

Appendix F

Error Count

Table 14: Error count of color size illusion

Hue	Saturation	Longer Color	Count	Percentage
Green, Blue	High	Blue	9	18.75
Green, Blue	High	Green	2	4.17
Green, Blue	High	No Diff	37	77.08
Green, Blue	Low	Blue	13	27.08
Green, Blue	Low	Green	3	6.25
Green, Blue	Low	No Diff	32	66.67
Red, Blue	High	Blue	6	12.5
Red, Blue	High	No Diff	39	81.25
Red, Blue	High	Red	3	6.25
Red, Blue	Low	Blue	5	10.42
Red, Blue	Low	No Diff	39	81.25
Red, Blue	Low	Red	4	8.33
Red, Green	High	Green	1	2.08

Red, Green	High	No Diff	39	81.25
Red, Green	High	Red	8	16.67
Red, Green	Low	Green	3	6.25
Red, Green	Low	No Diff	40	83.33
Red, Green	Low	Red	5	10.42
Red, Yellow	High	No Diff	23	47.92
Red, Yellow	High	Red	24	50
Red, Yellow	High	Yellow	1	2.08
Red, Yellow	Low	No Diff	23	47.92
Red, Yellow	Low	Red	22	45.83
Red, Yellow	Low	Yellow	3	6.25
Yellow, Blue	High	Blue	22	45.83
Yellow, Blue	High	No Diff	24	50
Yellow, Blue	High	Yellow	2	4.17
Yellow, Blue	Low	Blue	17	35.42
Yellow, Blue	Low	No Diff	28	58.33
Yellow, Blue	Low	Yellow	3	6.25
Yellow, Green	High	Green	16	33.33
Yellow, Green	High	No Diff	27	56.25
Yellow, Green	High	Yellow	5	10.42
Yellow, Green	Low	Green	13	27.08
Yellow, Green	Low	No Diff	31	64.58
Yellow, Green	Low	Yellow	4	8.33

Table 15: Error count of color depth illusion

Hue	Saturation	Closer Color	Count	Percentage
Green, Blue	High	Blue	24	50
Green, Blue	High	Green	4	8.33
Green, Blue	High	No Diff	20	41.67
Green, Blue	Low	Blue	25	52.08
Green, Blue	Low	Green	3	6.25
Green, Blue	Low	No Diff	20	41.67
Red, Blue	High	Blue	9	18.75
Red, Blue	High	No Diff	34	70.83
Red, Blue	High	Red	5	10.42
Red, Blue	Low	Blue	6	12.5
Red, Blue	Low	No Diff	37	77.08
Red, Blue	Low	Red	5	10.42
Red, Green	High	Green	4	8.33
Red, Green	High	No Diff	27	56.25
Red, Green	High	Red	17	35.42
Red, Green	Low	Green	3	6.25
Red, Green	Low	NoDiff	28	58.33
Red, Green	Low	Red	17	35.42
Red, Yellow	High	No Diff	10	20.83
Red, Yellow	High	Red	37	77.08
Red, Yellow	High	Yellow	1	2.08
Red, Yellow	Low	No Diff	11	22.92
Red, Yellow	Low	Red	37	77.08

Yellow, Blue	High	Blue	37	77.08
Yellow, Blue	High	No Diff	10	20.83
Yellow, Blue	High	Yellow	1	2.08
Yellow, Blue	Low	Blue	36	75
Yellow, Blue	Low	No Diff	10	20.83
Yellow, Blue	Low	Yellow	2	4.17
Yellow, Green	High	Green	34	70.83
Yellow, Green	High	No Diff	13	27.08
Yellow, Green	High	Yellow	1	2.08
Yellow, Green	Low	Green	33	68.75
Yellow, Green	Low	No Diff	14	29.17
Yellow, Green	Low	Yellow	1	2.08

Appendix G

Expert Review Questionnaire

We are planning to use these prototypes to help visualization designers improve bioinformatics tool interfaces. For example, a designer who wishes to redesign a genome browser can integrate these examples to visualize genomic sequences. To help us to determine the usefulness of prototypes, please provide your comments and recommendations based on the questions below:

1. Have you experienced problems or confusions with the current tool? Especially in terms of size judgment when you are comparing genomic features?
 - (a) If you experienced problems, what were they? How often did you experience? What do you suggest to resolve the issue?
 - (b) Do you think displaying additional size information will be helpful?
2. Here are some examples of displaying additional information. (Iterate question 2 throughout examples.)
 - (a) What do you think about it?
 - (b) Do you have any concerns or suggestions?

- (c) What would be an example where this design recommendation fits better? Can you give me a specific example?
 - (d) What would be an example where this design recommendation will not fit or cause problems? Can you give me a specific example?
3. Do you have any other ideas to give size information more clearly?

Appendix H

IRB Approval



Office of Research Compliance
 Institutional Review Board
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 540/231-4991 Fax 540/231-0959
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FWA00000572(expires 1/20/2010)
 IRB # is IRB00000667

DATE: November 26, 2007

MEMORANDUM

TO: Tonya L. Smith-Jackson
 Hyun Seung Yoo

Approval date: 11/26/2007
 Continuing Review Due Date: 11/11/2008
 Expiration Date: 11/25/2008

FROM: David M. Moore 

SUBJECT: **IRB Expedited Approval:** "Color Influence on Visual Perception", IRB # 07-322

This memo is regarding the above-mentioned protocol. The previous exempt status was changed to expedited with the recently submitted amendment. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective November 26, 2007.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.
3. Report promptly to the IRB of the study's closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher's responsibility to obtain re-approval from the IRB before the study's expiration date.
4. If re-approval is not obtained (unless the study has been reported to the IRB as closed) prior to the expiration date, all activities involving human subjects and data analysis must cease immediately, except where necessary to eliminate apparent immediate hazards to the subjects.

Important:

If you are conducting **federally funded non-exempt research**, this approval letter must state that the IRB has compared the OSP grant application and IRB application and found the documents to be consistent. Otherwise, this approval letter is invalid for OSP to release funds. Visit our website at <http://www.irb.vt.edu/pages/newstudy.htm#OSP> for further information.

cc: File
 Department Reviewer: Thurmon E. Lockhart
 T. Coalson 0118

Invent the Future

Vita

Hyun Seung Yoo

- EDUCATION ◇ **Hanyang University**, Seoul, Republic of Korea.
B.A. in Industrial Engineering, *magna cum laude*, Feb 2005.
- HONORS AND AWARDS ◇ **Scholarships**
· Honor Scholarship: 5 semesters awarded (1998 – 2003)
· Excellent Scholarship(2004)
◇ **Awards**
· Hanyang Global Frontier (Summer 2003)
- RESEARCH INTERESTS Human Computer Interaction, Information Visualization, Bioinformatics, Usability, Evaluation Methodology
- PUBLICATION **PATRIC: The VBI PathoSystems Resource Integration Center**; Snyder EE, Kampanya N, Lu J, Nordberg EK, Rajasimha HK, Shukla M, Soneja J, Tian Y, Xue T, **Yoo H**, Zhang F, Dharmanolla C, Dongre NV, Gillespie J, Hamelius J, Hance M, Huntington KI, Jukneliene D, Koziski J, Mackasmiel L, Mane SP, Nguyen V, Purkayastha A, Shallom J, Yu G, Guo Y, Gabbard J, Hix D, Azad A, Baker SC, Boyle SM, Khudyakov Y, Meng XJ, Rupprecht C, Vinje J, Crasta OR, Czar MJ, Dickerman A, Eckart JD, Kenyon R, Will R, Setubal JC, Sobral BW; *Nucleic Acids Research* 35 (2007) D401-D406 (Extended abstract available as URL: http://nar.oxfordjournals.org/cgi/content/full/35/suppl_1/D401).
- SKILLS ◇ Programming Languages: PHP, Java, Python, Perl, C++, C, Ajax, XML
◇ DBMS: ORACLE, MySQL, MS-SQL, Sybase
◇ Sun Certified Java Programmer
- WORK EXPERIENCE ◇ **Research Assistant**, Virginia Bioinformatics Institute (Feb 2006 – Nov 2007)
BRC Student Programmer position
◇ **Web Application Programmer, DBA, and System & Network Administrator** (2000 – 2002)
· Thegolf, Co, Ltd., Seoul, Republic of Korea (Feb 2002 – Oct 2002)
· INQ, Co, Ltd., Seoul, Republic of Korea (Jan 2000 – Feb 2002)
- ACTIVITIES ◇ **Volunteer**
· Webmaster of Human Factors and Ergonomics Society Virginia Tech Student Chapter (Oct 2006 – Dec 2007)