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The Distance between Colors; Using DeltaE* to Determine Which Colors Are Compatible

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This thesis was prepared under the direction of the candidate's thesis committee chair, Jon French, Ph.D., Department of Human Factors & Systems, and has been approved by the members of the thesis committee. It was submitted to the Department of Human Factors & Systems and has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Human Factors & Systems.

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Abstract

The focus of this study was to identify colors that can be easily distinguished from one another by normal color vision and slightly deficient color vision observers, and then test those colors to determine the significance of color separation as an indicator of color discriminability for both types of participants. There were 14 color normal and 9 color deficient individuals whose level of color deficiency were determined using standard diagnostic tests. The colors were selected by avoiding co-linearity in the color confusion line graphs for deuteranopes, protanopes and tritanopes. The difference between each of the colors was then calculated. The chosen colors were presented to the participants in a Color Vision Discrimination (CVD) test, first as color boxes and then as color text made up of three letters followed by three numbers.

A one-tailed Spearman's non-parametric Rank Order Correlation was conducted. The results indicated that the difference between two colors does not determine the ability of a color normal observer to distinguish between two colors given that the color is presented as a color block (r_s = -.260, p = .234), but does determine their ability when presented as color text (r_s = -.644, p = .001). When it comes to color deficient individuals, the results show that for color blocks (r_s = -.558, p = .015) and color text (r_s = -.505, p = .002) their ability to distinguish between the candidate colors depends on the separation between the colors. Colors were selected on the basis that they were not confused with any other color. Those colors found to be most easily distinguished will be useful in many different applications

such as web site design, Internet displays of all types, and various other military and industrial applications.

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I would like to thank Dr. French for being a wonderful mentor and allowing me the opportunity to assist him in his research, which without, I would not have been able to complete this thesis.

Thank you to my family and friends for standing by and being so supportive and helpful throughout the course of this study. I know my thesis is better because of each and every one of you.

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Table of Contents

List of Tables

List of Figures

Introduction

Colors are an integral part of human life, from finding red berries on a green bush, to seeing a discoloration in the food we eat or appreciating the extra character to a painting. Color can add another dimension or be used to code information on computer displays. Some individuals have color vision deficiencies of differing intensity and have learned to adapt in today's world. Being in a world that relies so heavily on color can be problematic for those individuals.

With the increasing reliance on and use of computers and computer-like devices, it is also becoming increasingly important for designers of these products to design for the largest population possible. Whether it is a website, an advertisement or some other type of visual media; it is important for designers to be mindful of those people with color vision deficiencies, especially if the design contains color. Occupations that rely on computer displays, such as Air Traffic Control (ATC), may have difficulty accommodating people with color vision limitations in order to take full advantage of the dimension of color to code information.

In this study, theoretical procedures were used; lines of confusion and ΔE^*, to identify color candidates that should be distinguishable even by people with mild color vision deficiency. Empirical means were used to support the candidate color selection in color normal and color deficient populations. In this paper, the basics of color vision will be reviewed, followed by the theories used to select the color candidates. Finally, the empirical tests used to diagnose and down select the final color candidates will be described.

Human Color Vision

The human eye is composed of the cornea, lens, the aqueous humor - fluid between the cornea and the lens - the retina, the fovea and the optic nerve. The vitreous humor is a transparent fluid that fills the chamber of the eye between the lens and the retina. The cornea is transparent and lets light into the eye without reflecting or absorbing it. Once the light passes through the cornea and travels through the aqueous humor, it is refracted to the back of the eye by the lens. Small muscles attached to the lens control the amount of refraction and it is this process that allows the eye to focus on objects at different distances. After the light passes through the lens it travels to the retina and is absorbed by the eye's specialized sensory cells, called photoreceptors, in the fovea and close surrounding area. The human perception of sight comes from the information from the photoreceptors that is carried to the brain by neurons in the optic nerve. Figure 1 shows the structure of the eye and the two different types of photoreceptors, which will be discussed shortly.

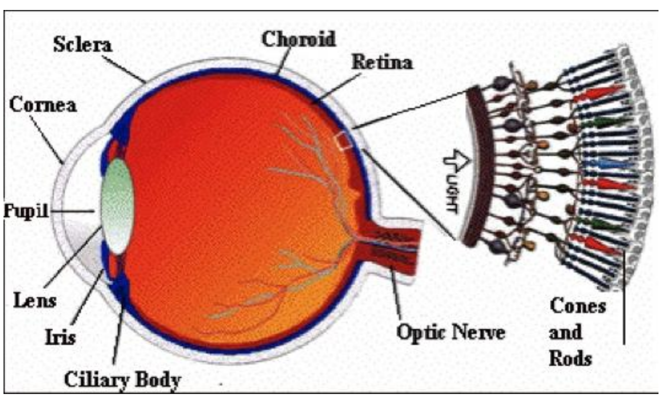

Figure 1. This figure illustrates the structure of the human eye as well as the two types of photoreceptors. Adapted from Simple anatomy of the retina [Online forum comment] by Kolb, 2005, retrieved from http://www.ncbi.nlm.nih.gov/books/NBK11533/

There are two types of photoreceptors: rods and cones. Rods respond best in low levels of light and detect movement. Cones respond best in bright light and allow for color vision. There are three types of cones, each with a different photopigment that responds best to long, medium, or short wavelengths of light. Short wavelengths appear blue, medium wavelengths appear green and long wavelengths appear red. Each type of cone is excited the most by its specific wavelength of light. Long wavelength cones are maximally excited by light in the 490-700 nanometers (nm) range, medium wavelength cones are excited by 450-620 nm, and short wavelength cones by about 400-520 nm. (Widmaier, Raff, & Strang, 2006) The combination of these three photopigments is called trichromatic vision and it is what allows normal color vision individuals, or trichromats, the ability to see all of the colors in the visible spectrum (400nm-700nm). While the actual wavelength range for each of the three photopigments varies slightly from person to person, typically those with normal color vision can see colors in just about the same way. (Wolfe, et al., 2009)

Color Vision Deficiency

Approximately 8% of males and 0.5% of females have some type of color vision deficiency, or what is most commonly referred to as “color blindness” (Wyszecki & Stiles, 2000a). Color vision deficiency generally occurs when there is a breakdown or shift in sensitivity in one of the three photopigments. The X chromosome contains the genes that code for two of the three types of photopigments; because females have two X chromosomes they have double the chance of having normal color vision. People that have all three photopigments but a shift in sensitivity are still considered trichromats, but are referred to as anomalous trichromats because they still cannot see colors the same way that a person with normal color vision can (Pitt, 1935). A color deficient person missing one of the three photopigments is called a dichromat. The three most common types of dichromatic color vision are protanopes, deuteranopes, and tritanopes. Protanope dichromats have difficulty seeing red, deuteranope dichromats have difficulty seeing green and tritanope dichromats have difficulty seeing blue. Each of these types of color vision are represented by the digital images in Figure 2. Out of these three types, protanope dichromats and deuteranope dichromats are the more common. Table 1 summarizes these deficiencies. (Wyszecki & Stiles, 2000a)

Table 1

Major color deficiencies and prevalence for dichromats in western races. Adapted from "Enhancing color representation for the color vision impaired," by Huang, Wu, and Chen, 2008, Proceedings of CVAVI.

Type	Name	Prevalence
	Protanopia	1%
Dichromacy	Deuteranopia	1.1%
	Tritanopia	0.002%

Figure 2. This figure illustrates what a set of 24 colored pencils looks like for normal color vision viewers (top-left), protanopes (top-right); deuteranopes (bottom-left); and tritanopes (bottom-right). Adapted from "Accommodating color blind computer users," by Jefferson and Harvey, 2006, *GECCO '08 Proceedings of the 10th annual conference on Genetic and evolutionary computation*, p. 40. Copyright 2008 by Association for Computing Machinery.

Color Vision Assessment

Now that the types of deficiencies have been discussed, it is important to briefly cover the ways to diagnose someone as color deficient to understand how to select color deficient participants. There have been many diagnostic tests designed to do just this. Some of these tests include the Ishihara, Dvorine, Colour Assessment and Diagnosis (CAD) test, and the Farnsworth-Munson. The Ishihara and Dvorine tests are similar in set up and the type of diagnosis they provide. The Ishihara pseudoisochromatic plate test is made up of numbers set in many different colored dots. The different versions of this test all take advantage of the colors that color deficient individuals typically confuse by using camouflage. In the 24-plate version of the test, the first plate is an example, plates 2-15 are used for the initial screening and then plates 16-17 are to classify deficiencies as either protanope or deuteranope. The diagnostic plates show a double-digit number in the circle, one is set up to be difficult for protanopes to see and the other for deuteranopes to see. An example of this test can be seen in the left half of Figure 3. The Dvorine test is also based on pseudoisochromatic principles. This test has 15 plates with numbers. The first plate is a demonstration plate, the other 12 plates are for screening and the remaining two for classifying the type of deficiency, either protanope or deuteranope. The font of the numbers in this test is slightly different than the font used in the Ishihara plates and is believed to be a little bit easier to see. An example of this test can be seen in the right side of Figure 3. (Barbur, Rodriguez-Carmona, Evans, & Milburn, 2009)

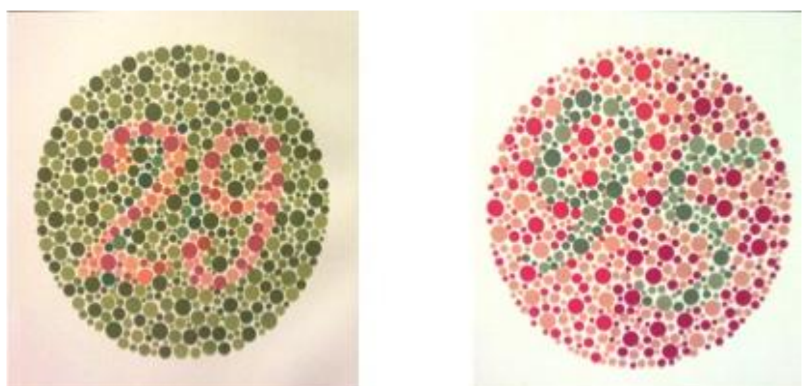

Figure 3. This figure illustrates the Ishihara pseudoisochromatic plate test (left) and the Dvorine test (right).

The CAD test is administered using a calibrated monitor. Different colored stimuli are presented on the display moving diagonally across the display area. The participant's job is to indicate which direction the colored stimuli are going toward, using a keypad. The CAD test is one of the more sensitive color vision diagnostic tests available because it evaluates color detection thresholds (Rodriguez-Carmona, Harlow, Walker, & Barbur, 2005). In one validation study, the CAD was compared with other diagnostic tests such as the Ishihara and Farnsworth Munsell 100 hue test and deemed a valid means of color vision diagnosis (Seshadri, Christensen, Lakshminarayanan, & Bassi, 2005). The CAD results indicate whether a person's red-green and yellow-blue color vision is considered normal or not. It also indicates if a person has a color vision deficiency and classifies the type and severity of deficiency. (Barbur, Rodriguez-Carmona, Evans, & Milburn, 2009)

Another color vision assessment test, used by the Federal Aviation Administration (FAA), is called the Air Traffic Color Vision (ATCOV) test. The use of this test in the current study will be discussed more in the methods section, however, it is important to note that the ATCOV is a practical test administered to ATC applicants that fail clinical color vision diagnostic tests to determine their ability to perform ATC related tasks (Ling, 2008). There are three parts to the test: Radar Identification, Alert Detection, and Weather Identification. Each of these three sub-tests were chosen based on a preliminary analysis that identified critical ATC job activities and tasks where color vision was important because of the color coding used on the displays. The ATCOV was designed, tested, and validated by the Civil Aerospace Medical Institute as tasked by the FAA and it adheres to the Uniform Guidelines on Employee Selection Procedures as set forth by the Equal Employment Opportunity Commission in 1978. (Chidester, et al., 2011)

The final color vision diagnostic test that will be presented here is the Farnsworth-Munson D15. There are also many versions of this test; some give a more specific diagnosis than others. The Farnsworth-Munson D15, which was used for this study is composed of 15 caps of incremental hues that the participant is asked to put in order given a starting hue. The results from this test diagnose color vision deficiency in terms of severity and type (protanope, deuteranope, or tritanope). The diagnosis from this test is a result of the ordering of the caps.

Purpose of Study

The purpose of the present work is to establish a list of candidate colors that can be easily discriminated by both normal and slightly color deficient individuals as well as test those colors on color normal and color deficient participants. The test results will be used to eliminate those colors that were confused to establish a list of final colors. Finally, the data will also be analyzed to determine a good indicator of color selection.

Background

Understanding the makeup of the eye, how color is measured, the more common types of color vision deficiencies and even the tests available to diagnose color vision deficiencies, is important. Equally important is understanding how this knowledge can be applied to the world around us, and how this knowledge can help to design in a more human-centered way. For these reasons, the next section will outline the purpose of this study and why it is important.

Many people would agree that computers are continuing to play an ever more important role in society. Many people depend on computers and computer-like devices to carry out daily tasks such as keeping in contact with others, deciding where to eat, shopping, looking up information, in addition to many other tasks.

Companies frequently rely on computers for interoffice communications, designing and presenting information, storing records, and even scheduling appointments. Because computer use is so widespread, the design of web displays is becoming increasingly important. When designing computer-based interfaces, it is essential to design keeping people with color vision deficiencies in mind. People with color vision deficiencies are at a disadvantage when it comes to web site displays because they do not see colors in the same way that people with normal color vision do.

While color vision deficiencies do not make up the majority of the population, with technology advancing as quickly as it is, designers should be more conscious of their designs and how they affect the population as a whole. Designing web sites and other computer displays with color deficient individuals in mind is something that would be beneficial not only to those individuals with color deficiencies, but also companies advertising online, and anyone with a webpage interested in reaching and retaining as many users as possible.

Kaufman-Scarborough (2001) did a study to identify issues that color vision deficient individuals commonly encounter in advertisement. In this study a survey was sent out to many different individuals in many different countries. The responses were carefully analyzed, common phrases were grouped, and common themes identified. Those common themes that were identified highlighted many of the issues that color deficient individuals face in advertisement today. Some of the issues identified included the inability to distinguish between colors when one was presented as the foreground text and the other as the background color; some reported that different color combinations create confusion, while still others stated that color, when used to attract attention, was generally ineffective. Based on the responses, Kaufman-Scarborough suggested some design techniques to accommodate for color deficient users. One such suggestion stated that designers should not use color as the only way to convey a message, or if it is, then there should be redundancies designed into the message so that color deficient individuals are not left out. Kaufman-Scarborough also noted some good design practices such as testing color combinations on color deficient users to see what works best before designing. Another option he listed was to use a computer program that allows designers to see what their page might look like to the different types of color deficient users. This type of program would allow the designer to see firsthand the colors that might be problematic to color deficient users and therefore design around them.

One computer program that does this is presented by Meyer and Greenberg (1988). Meyer and Greenberg tested and diagnosed color deficient individuals with one of the previously mentioned types of color vision diagnostic tests, the Farnsworth. The specific test used in their study is the Farnsworth-Munsell 100-hue test. Then using color confusion lines, they determined some additional colors they hypothesized would be better at diagnosing color vision deficiencies. They changed the Farnsworth-Munsell test to use their colors and retested participants. The results were used to create a program that transforms a picture into three other pictures. Each picture reflects what a color vision deficient individual would see, one color for each type of deficiency: protanopes, deuteranopes, and tritanopes. Similarly, Jefferson and Harvey (2006) did a study to design an algorithm to filter out key colors in an image and change those key colors into colors that a person with a specific color deficiency would be able to see normally. This algorithm was implemented using distance formulas and MATLAB. The algorithm created three pictures, one for each of the three common color vision deficiencies.

While both programs aim at designing with color vision deficient people in mind, they are not necessarily the best choices. In the program by Jefferson and Harvey, most of the image is changed over to colors that can be identified by a specific color deficient user, but only key colors are selected. This could be an issue in pictures where only sampling some of the colors does not give an accurate representation of the information in the picture. Finally, both programs only change the picture into one that can be seen by one type of color vision deficient user at a time. This makes it difficult for the designer to get a clear picture of which colors are problematic for each of the color deficiencies combined.

Another study that aims at solving the color sampling problem in the computer programs previously discussed was done by Vi´enot, Brettel, and Mollon (1999). In this study an algorithm was used to transform a color palette of 256 colors seen by a normal color vision observer into color palettes for both protanopes and deuteranopes separately. With these color palettes, the authors suggested changing the program palette when designing so that the designer can check for potential readability issues for those users with color vision deficiencies. Along those same lines, Troiano, Birtolo, and Miranda (2008) used genetic algorithms to come up with a color palette each for protanopes, deuteranopes, and tritanopes. This approach is advantageous because it allows the designer room to be creative and not worry about whether the colors picked will be appropriate for color deficient users. Additionally, it leaves room for the system identification of other palettes that can be used to adjust the user interface, even if it was not originally set up for color vision deficient users. While this approach does have some benefits, there is still the issue of three different color palettes. Again, having three separate color palettes means having three different display settings. While a good start to designing for color vision deficient users, it does not collectively accommodate for color normal and color deficient viewers. The current study aims at bridging the gap by creating a set of candidate colors that can be easily distinguished by color normal as well as slightly deficient observers. The theory behind the selection of these colors is discussed in the following sections.

Distance Between Colors

The internationally accepted way to evaluate color is based on trichromatic matching. Trichromatic matching was established based on color matching experiments that used additive mixtures of red, green and blue lights to match to a test color. In establishing the system for color measurement, the standard observer was decided to be a two-degree field size. The data from two separate experiments done by Guild and Wright were combined and mathematically transformed to yield the tristimulus values R, G, and B (Hunt, 1998). However, when using these values it is possible to have a negative number. Because of this, the International Commission on Illumination (CIE) felt that people may not be as willing to adopt this system so they established a new set of tristimulus values, X, Y and Z, that only yield positive numbers, to replace R, G, and B. (Hunt, 1998)

As previously mentioned, the CIE 1931 standard 2° observer uses the X, Y, Z color-matching functions. In these color matching functions, the Y tristimulus value approximately represents the lightness of a color, however, the X and Z values do not represent any perceptual attributes. Because of this, it was necessary to come up with a measure that related to the human perception of color. This was done through the chromaticity coordinates, x, y, and z, that are calculated from the color-matching functions. The chromaticity coordinates were chosen so that z can always be found if x and y are known. Having to only specify the two variables made it possible to construct the 1931 chromaticity diagram, see Figure 4. While the CIE 1931 chromaticity diagram was very useful in analyzing colors, the non-uniform color distribution created issues when trying to determine perceived color differences or the smallest color differences that can be seen by the human eye. Ideally, perceptual color differences of the same magnitude should be represented by equal length lines on the x,y chromaticity diagram. However, this is not the case with the CIE 1931 chromaticity diagram. (Hunt, 1998; Wright, 1941) For this reason, the CIE went on to establish a few other color spaces before finally establishing the 1976 CIELUV and CIELAB color spaces.

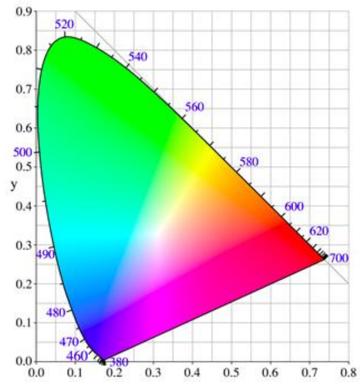

Figure 4. This figure illustrates the CIE 1931 chromaticity diagram. Adapted from CIE 1931 color space [Online forum comment] by Flück, 2007, retrieved from http://www.colblindor.com/2007/01/18/cie-1931-color-space/

The chromaticity diagrams up to 1976 were useful but only applicable to colors with the same luminance. Since colors typically differ in chromaticity and luminance, the CIE recommended two more color spaces: CIE 1976 (L*u*v*) color space or CIELUV color space and the CIE 1976 (L*a*b*) color space or CIELAB color space. Using the concept of the MacAdam ellipses, these color spaces make it possible to calculate perceived differences. The distance between two colors or the ΔE* value can be calculated from the CIELAB color space. This concept is based on a study done by MacAdam (1942). MacAdam created an apparatus that participants used to compare and ultimately attempt to match two colors. The apparatus consisted of a telescope-like device with a light source and prisms. The participant's job was to use a control dial to match the color from one prism to the color from another prism that was held constant. This was done with many different colors and the results were plotted as ellipses on the CIE 1931 chromaticity diagram. The colors inside each ellipse represented the colors that an observer with normal color vision would perceive to be the same color. The CIELAB color space was created to normalize these ellipses, yielding the concept of the distance between two colors or ΔE* where a ΔE* value of 1 is considered to be a just noticeable difference (JND) or the smallest color difference visible to the human eye. The CIELUV space has a uniform chromaticity diagram whereas the CIELAB space does not have a chromaticity diagram. There are other color spaces that have been developed since the CIELUV and CIELAB color spaces, CIE94 and CIEDE2000 for example, but they are simply modifications of the CIELAB formula and are generally more complex. (Hunt, 2004; Hunt, 1998; Mandic, Grgic, & Grigic, 2006) For the purposes of this study, the CIELAB color space was used.

Confusion Lines

While the ΔE* value between two colors gives an idea of the distinguishability between those two colors, this is only applicable to individuals with normal color vision. That being said, a method for determining those colors most often confused by color vision deficient individuals was established by earlier research. Pitt (1935) established confusion lines for protanopes and deuteranopes. Pitt used an apparatus called the Wright Colorimeter with modifications to allow for the requirements of his study. From this study he was able to chart on the CIE 1931 chromaticity diagram the color confusion lines for protanopes and deuteranopes. The lines on the color confusion graphs converge at a single point known as the confusion point or the copunctal point (Wyszecki & Stiles, 2000b). Farnsworth (1955) used similar methods to determine the copunctal point for triantopes. Thomson and Wright (1953) built on this work, and tested additional participants to arrive at the copunctal point for tritanopes. The copunctal point they arrived at was similar to the one Farnsworth found. The lines of confusion in each of the three confusion line graphs (Figure 5) indicate the colors that appear the same to a protanope, deuteranope or tritanope, depending on the graph. For example, looking at the confusion lines for a deuteranope, any two or more colors that are co-linear with the copunctal point would appear the same to a deuteranope dichromat. On the other hand, two or more colors chosen on the same graph that are not co-linear through the copunctal point would appear to be different colors to the same deuteranope dichromat. Theoretically then, colors that avoid colinearity with the copunctal points on each of the three graphs would be distinguishable to people with either of the three types of color vision deficiencies previously discussed.

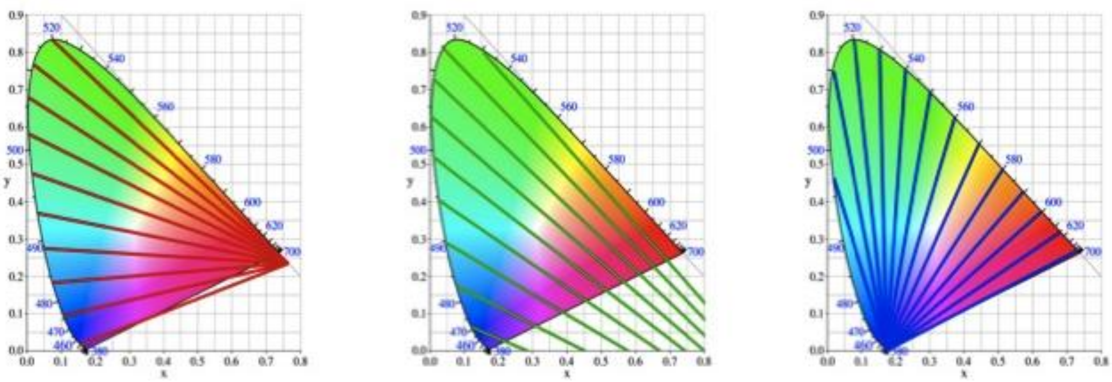

Figure 5. This figure illustrates color confusion lines drawn through the copunctal point for protanopes (left), deuteranopes (middle) and tritanopes (right). Adapted from Colorblind colors of confusion [Online forum comment] by Flück, 2009, retrieved from http://www.colblindor.com/2009/01/19/colorblind0colors-of-confusion/

In the present work, the candidate colors were first carefully selected to avoid collinearity in each of the color confusion line graphs. Once all the colors were selected and checked against each of the color confusion line graphs, the RGB values were converted to the CIELAB color space in an order to calculate the ΔE* values. Using the color confusion line graphs, a set of colors that should be easily discriminated from one another not only by those with normal color vision, but also by protanopes, deuteranopes and tritanopes were determined.

Summary

This study used theoretical and empirical approaches to identify colors that would not be difficult to discriminate from each other. As a starting point, the color candidate list initially began with the wavelengths corresponding to the three photopigments in the human eye or, short (blue), medium (green) and long (red) wavelength colors. These were plotted on the CIE 1931 chromaticity diagram along with the copunctal point for each of the three color deficient theoretical confusion line graphs. While the color confusion graphs are intended to identify colors that color deficient individuals would be most likely to confuse, this study assumed that the confusion graphs also identify some colors that individuals with normal color vision may also find problematic but to a lesser extent than a color deficient individual. For example, looking at the confusion line graph for a protanope (Figure 5), a person with normal color vision could easily have difficulties distinguishing two different shades of red that lie along one of the confusion lines. By the same standard, however, a protanope would find it nearly impossible to distinguish those same two shades of red. This presumes that color deficiency then, is a matter of degree not of type; normals being less affected than color deficients but still affected. After plotting the colors on each of the confusion line graphs and ensuring that the colors did not overlap on any of the charts, the theoretical ΔE^* values for each color candidate comparison was used to identify the distances between them. It was presumed this would help to identify a ΔE^* threshold above which colors could be easily discriminated. Finally, an empirical test was designed to determine how difficult the color candidates were to discriminate.

Statement of Hypotheses

It is hypothesized that a.) normal sighted individuals and b.) slightly color deficient individuals should be able to discriminate the color candidates because they were not collinear on any of the three confusion line graphs. It is additionally hypothesized that the lower the ΔE^* value the less likely that a.) normal color vision participants and b.) slightly color deficient individuals will be able to distinguish the candidate colors from each other regardless of whether the color is presented as a box or as text. This would mean that future candidate colors could be selected on the basis of ΔE^* alone.

Methods

Participants

Participants were recruited through advertisements in the college newspaper, flyers around campus and word of mouth. All participants were monetarily compensated for their time. There were 23 total participants, 14 of those participants were trichromats and nine were dichromats. There were 20 males and three females between 18 and 59 years of age. Out of the total color deficient participants, two were classified as dichromatic protanopes and seven as dichromatic deuteranopes; there were not any dichromatic tritanopes.

Materials and Apparatus

The study was conducted in two adjoined rooms, one room was a color vision diagnostic lab and the other was a human-computer color vision testing lab. Standard office lighting conditions were used for both adjoined rooms.

The vision diagnostics consisted of the Farnsworth-Munson D15, the Dvorine Pseudo-Isochromatic Plates, the Snellen visual acuity test, the ATCOV, and the CAD. Convention calls for the Farnsworth-Munson D15 to be conducted on a black background, however in this experiment it was placed on a desk with a white background. The test administrator placed the caps on the table in front of the participant in a random order and left the starting cap as an indicator of where to begin. The participant was given the test twice and the administrator recorded the results after each trial.

The Dvorine was set up at approximately 30 inches from the participant and the participant was given no longer than 5 seconds to identify the plate before it was changed. The administrator recorded the results. The Snellen visual acuity test is a standard eye test used to test fine detail vision. The eye charts used were found online and are included in Appendix A. This test was administered at a distance of 20 feet. Participants were asked to take the test with their glasses/contacts only if they normally wear them all day and would be using them on all other tests. There were three charts used because the participant was asked to read the first chart with both eyes open, the second chart with one eye closed and the other open, and the third chart with the second eye open and the first closed. The results were recorded on a pre-made record sheet and analyzed by the researcher.

The ATCOV was administered in the computer room. The participant was seated in front of the computer and asked to read the instructions, complete the practice test and then the actual test for each of the three sections of the ATCOV. As previously mentioned, this test is a practical test used by the FAA to determine the ability of a color deficient individual to perform their job as an air traffic controller. However, in this study, it was used as a diagnostic test to define those color deficient individuals who could be considered mildly color deficient based on their ability to perform ATC job functions. The results for this test were recorded by the computer and saved by the test proctor.

The final color diagnostic test used in this research was the Colour Assessment and Diagnosis (CAD) test. It was tested on a Dell Latitude E5400 with a ViewSonic E70fSB monitor, calibrated by the FAA, and placed at eye level. The participant was told that the test would present a color box moving from one corner of the screen to another and that their job would be to indicate which direction the color box was moving toward using a keypad. Results from this test were automatically generated by the computer and saved by the test proctor. This test identified those individuals that were color deficient and also indicated the severity of the deficiency. While there were other diagnostic tests used in this study, this was the test used to distinguish between color normal and color deficient participants for data analysis purposes. This diagnostic was chosen over the others because it is the most sensitive of the diagnostics used, does not require a proctor to record results which decreases the possibility of recording error, and the CAD accounts for luminosity in testing whereas the other diagnostic tests do not.

The Color Vision Discrimination test was created as part of an FAA research project and was determined to be a good measure of color discrimination. The diagnostic tests aim specifically at identifying the nature of the participant's color vision, whereas the test used for the FAA research project determines participants' ability to discriminate each candidate color when presented both as text and as a color block. The CVD test was run using Microsoft Office PowerPoint 2007 and it was a two-part test. In the first part of the test, the participant was presented with a screen that displayed the color they were to seek out and then the following screen displayed the candidate colors disbursed throughout the screen with a number to the right of the color box. It was the participant's job to indicate which color boxes were the same as the color they were presented with on the screen before. See Figure 6 for an example of the two screens just described. The participants were presented with the set of slides shown in Figure 6 for each of the candidate colors. Then, in the second part of the test, the procedure was the same, except the color was represented as text by three letters followed by three numbers, in Lucida 8 point font. The participant was instructed to state the number-letter combinations that corresponded to the same color initially presented to them. See Figure 7 for an example of what these screens look like.

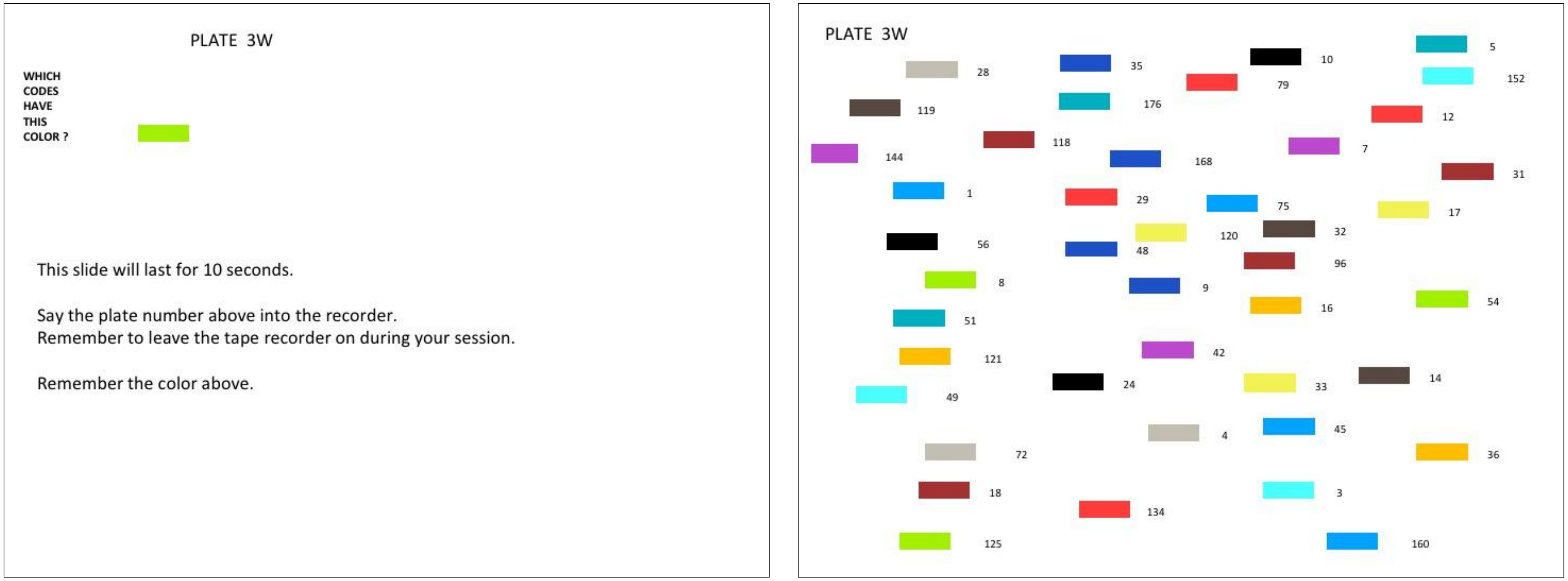

Figure 6. This figure illustrates the first part of the Color Vision Discrimination test. The left side of the figure represents the initial slide the participant is presented with and the right side of the figure is an example of the array of the candidate colors, in box form, from which the participant must pick out the previously indicated color.

Figure 7. This figure illustrates the second part of the Color Vision Discrimination test. The left side of the figure represents the initial slide the participant is presented with and the right side of the figure is an example of the array of the candidate colors, in text form, from which the participant must pick out the previously indicated color.

The computers used to conduct the CVD test and the (ATCOV) practical test were Dell Optiplex GX620 computers with Dell UltraSharp monitors and each screen was calibrated using an x-rite i1 Display 2 Colorimeter to a color temperature of 6500 K and a luminance of 85.7 cd/m^2. The ambient lighting had a color temperature of 3000 K and an illuminance of 360 Lux. To record responses on the CVD test, participants were issued a RadioShack voice-activated microcassette recorder along with a blank tape and instructed to record continuously and speak very clearly while taking the CVD test. To analyze this data, the participant responses were transferred to a spreadsheet. The CAD was administered in a room with a color temperature of 3000 K and an illuminance of 28 LUX. These results were later played back and recorded on data sheets before being entered into a spreadsheet. The CVD was the empirical test for final selection of the color candidates.

Procedure

On the day of testing, prior to the arrival of the participants, each of the computers in the computer testing lab were calibrated to assure that the colors displayed were the same from one computer test to the other using the x-rite i1 Display 2 Colorimeter. To calibrate, the procedure provided by the manufacturer was followed.

Upon arrival, each participant was briefed as to the nature of the testing and the goal of the project. They were each given a folder that included their participant number, the informed consent document, the demographics document, a list of the tests they would be taking and a place to indicate completion, as well as record sheets for the Farnsworth-Munson D15, the Snellen visual acuity test, the Dvorine, and a participant payment sheet. They were asked to read over the informed consent, ask any questions and, if they agreed, to sign their name at the bottom and date it. Next they were instructed to fill out the demographics questionnaire to the best of their ability. Once the informed consent and demographics questionnaire were complete, the participants were directed to their first station indicated by the test checklist in their folders. The order of each participant's testing was assigned in an effort to control for possible order of presentation effects. Participants rotated through the different tests as instructed by the order indicated on their list and, once the participants had completed all tests they were debriefed and then asked to fill out the Participant Payment sheet before receiving compensation.

Results

To analyze the data, the ΔE^* values were ranked for all colors and correlated with error rate by the participants, normal and mildly color deficient, using the Spearman rank order correlation coefficient (McDonald, 2009). The independent variables then, are the ranked ΔE^* values plotted along the abscissa and the dependent variables are the number of people to confuse colors for the specific ΔE^* values plotted on the ordinate.

The color candidates were selected based on the criteria that more than one person confused the color on the empirical test (CVD) with some other color. Given these criteria, formal statistical analysis was unnecessary.

The color candidates selected, based on their location on each of the color confusion graphs, are shown in Figure 8. The colors were first defined in RGB values because this is how color is defined on computers. The colors were then converted to Yxy tristimulus values to be plotted on the CIE 1931 chromaticity diagram to determine if they were collinear with the copunctal point of each of the three color confusion line graphs. Finally, the colors were converted to CIE LAB so that the ΔE* values could be calculated. The ΔE* values are presented in matrix form in Figure 9.

			R	G	B	Y	x	y	R	G	B
									L	A	B
101	Black		0	0	0	0	0	0	0	0	0
105	Blue		0	163	255	33.414	0.18995	0.20377	64.495	-2.244	-55.242
107	Cyan		0	175	192	34.466	0.21694	0.30095	65.331	-30.87	-19.261
106	D. Blue		30	80	200	10.183	0.1731	0.12746	38.17	29.491	-66.73
112	Blue 2		74	255	255	80.196	0.23217	0.32876	91.773	-43.795	-13.089
110	Brown 2		87	73	65	7.173	0.35549	0.35088	32.197	4.468	6.981
109	D. Mustard		128	107	41	15.265	0.42696	0.44762	45.995	0.315	38.902
103	Green		162	240	2	70.006	0.36214	0.55028	87	-51.198	84.039
108	Brown		165	50	50	10.511	0.54053	0.32968	38.744	47.03	27.144
117	Purple		189	74	206	20.173	0.3001	0.17509	52.032	63.687	-47.094
115	Gray		194	190	177	51.471	0.32608	0.34536	76.963	-0.886	7.05
118	Magenta		255	0	255	28.48	0.32092	0.15415	60.32	98.254	-60.843
104	Red		255	60	60	24.818	0.58033	0.32979	56.898	71.611	46.478
113	Pink 2		235	62	153	23.407	0.42761	0.23984	55.489	71.886	-10.342
111	Cad. Orange		255	97	18	29.853	0.57456	0.37595	61.527	57.321	67.573
116	Amber		255	191	0	58.522	0.47316	0.4625	81.028	10.386	83.036
114	Tan		255	215	92	70.634	0.42621	0.44618	87.307	0.744	64.043
102	White		255	255	255	100	0.31272	0.329	100	0.005	-0.01

Figure 8. This figure shows the list of candidate colors that were chosen based on their location in relation to the copunctal points of the three color confusion line graphs.

		101	102	115	104	111	108	110	114	116	118	113	117	112	105	106	107	103	109
		Black	White	Gray	Red	Cad. Orange	Brown	Brown 2	Tan	Amber	Magenta	Pink 2	Purple	Blue 2	Blue	D. Blue	Cyan	Green	D. Mustard
Black			100.00	66.57	52.20	56.43	36.70	22.83	85.15	77.44	56.71	50.18	47.87	91.42	56.87	38.06	56.85	86.16	38.86
White		100.00		15.90	42.14	31.36	54.00	55.58	27.36	31.36	42.18	42.01	44.85	25.14	34.57	55.71	32.62	31.64	45.37
Gray		66.57	15.90		35.35	31.90	43.84	43.29	23.09	25.69	43.74	38.99	43.05	27.73	35.17	50.75	26.70	28.67	30.99
Red		52.20	42.14	35.35		13.84	19.50	34.85	47.64	44.13	36.30	24.30	35.53	68.66	52.90	48.04	56.69	74.68	38.46
Cad. Orange		56.43	31.36	31.90	13.84		27.69	38.21	36.37	31.53	47.81	36.85	46.35	61.45	53.12	55.36	52.85	62.56	32.35
Brown		36.70	54.00	43.84	19.50	27.69		21.62	55.80	52.59	39.16	26.16	33.46	72.36	53.95	39.82	70.76	75.63	33.04
Brown 2		22.83	55.58	43.29	34.85	38.21	21.62		53.96	52.04	44.80	35.96	36.82	59.79	44.76	33.17	44.46	58.87	21.15
Tan		85.15	27.36	23.09	47.64	36.37	55.80	53.96		7.92	74.52	64.27	71.66	41.14	65.17	75.05	45.43	23.33	34.14
Amber		77.44	31.36	25.69	44.13	31.53	52.59	52.04	7.92		74.07	63.24	70.82	45.97	57.38	73.87	47.64	29.93	31.99
Magenta		56.71	42.18	43.74	36.30	47.81	39.16	44.80	74.52	74.07		15.54	10.62	55.77	48.44	34.88	46.64	101.26	63.83
Pink 2		50.18	42.01	38.99	24.30	36.85	26.16	35.96	64.27	63.24	15.54		14.76	72.58	51.32	36.45	63.81	88.32	52.14
Purple		47.87	44.85	43.05	35.53	46.35	33.46	36.82	71.66	70.82	10.62	14.76		57.22	43.26	25.68	45.01	94.16	57.73
Blue 2		91.42	25.14	27.73	68.66	61.45	72.36	59.79	41.14	45.97	55.77	72.58	57.22		32.93	57.19	19.95	36.69	50.97
Blue		56.87	34.57	35.17	52.90	53.12	53.95	44.76	65.17	57.38	48.44	51.32	43.26	32.93		30.94	20.42	69.42	57.50
D. Blue		38.06	55.71	50.75	48.04	55.36	39.82	33.17	75.05	73.87	34.88	36.45	25.68	57.19	30.94		39.97	79.58	55.30
Cyan		56.85	32.62	26.70	56.69	52.85	70.76	44.46	45.43	47.64	46.64	63.81	45.01	19.95	20.42	39.97		44.85	41.44
Green		86.16	31.64	28.67	74.68	62.56	75.63	58.87	23.33	29.93	101.26	88.32	94.16	36.69	69.42	79.58	44.85		40.64
D. Mustard		38.86	45.37	30.99	38.46	32.35	33.04	21.15	34.14	31.99	63.83	52.14	57.73	50.97	57.50	55.30	41.44	40.64	

Figure 9. In this figure, the ΔE* values between each of the candidate colors are displayed.

As previously stated, there were 23 total participants, 14 of those participants were trichromats and nine were dichromats. There were 20 males and three females between 18 and 59 years of age. Out of the total color deficient participants, two were classified as dichromatic protanopes and seven as dichromatic deuteranopes; there were not any dichromatic tritanopes.

Participant visual acuity, corrected and uncorrected, as defined by the Snellen visual acuity test, ranged from 10/20 to 15/20, with 26% of participants having 10/20 vision and 74% having 15/20. The results from the Farnsworth-Munson D15 indicated a diagnosis of normal color vision to 78% of the participants, strong deuteranopic vision to 13%, strong protanopic vision to 4% and moderate deuteranopic vision to 4%.

The Dvorine test indicated a diagnosis of normal color vision to 61% of the population, severe deuteranopic vision to 13%, severe protanopic vision to 4%, and moderate deuteranopic vision to 22% of the population. On average, those participants diagnosed as having normal color vision correctly identified 100% of the plates. Those diagnosed as severe deuteranopes correctly identified an average of 38% of the plates and those diagnosed as severe protanopes correctly identified 43% of the plates. Finally those diagnosed as moderate deuteranopes by the Dvorine test, on average, were able to correctly identify 53% of the plates.

The CAD indicated that 61% of the participants tested had normal color vision, 30% had deuteranopic vision, and 9% had protanopic vision. On average, those diagnosed as having normal color vision had a red-green threshold of 1.12 and a yellow-blue threshold of 0.87. Participants diagnosed as deuteranopes had an average red-green threshold of 12.98 and an average yellow-blue threshold of 0.86. Those participants classified as protanopes had an average red-green threshold of 10.43 and an average yellow-blue threshold of 0.93.

For this study the participants also took the ATCOV practical test which served as a cutoff point to differentiate between slight color vision deficiencies and extreme color vision deficiencies. As previously stated, this test is used by the FAA to determine if a potential air traffic controller, diagnosed with a color vision deficiency, will be able to do their job. Only data from those color deficient and color normal participants that were able to pass this practical test were used in determining the selection of the candidate colors. As can be seen in Table 2, the total number of participants that passed the ATCOV test was 17 with 13 of those participants having normal color vision and four having color deficient vision.

Table 2

Number and Percent of Participants to Pass the ATCOV

	Participants to take test	Participants to pass test	Total percent of participants to pass test
Normal	14	13	57%
Deuteranope	7	3	13%
Protanope	2	1	4%
Total	23	17	74%

The results from the first part of the CVD test indicated that 100% of normal color vision participants were able to correctly identify nine out of the 17 candidate colors as shown in Figure 10. On the other hand, 100% of the color deficient participants were able to correctly identify three of the 17 candidate colors, see Figure 11. On the second portion of the CVD test, 100% of the normal color vision participants were able to correctly identify three of the total number of candidate colors (Figure 12) and 100% of the color deficient participants were only able to correctly identify one color (Figure 13).

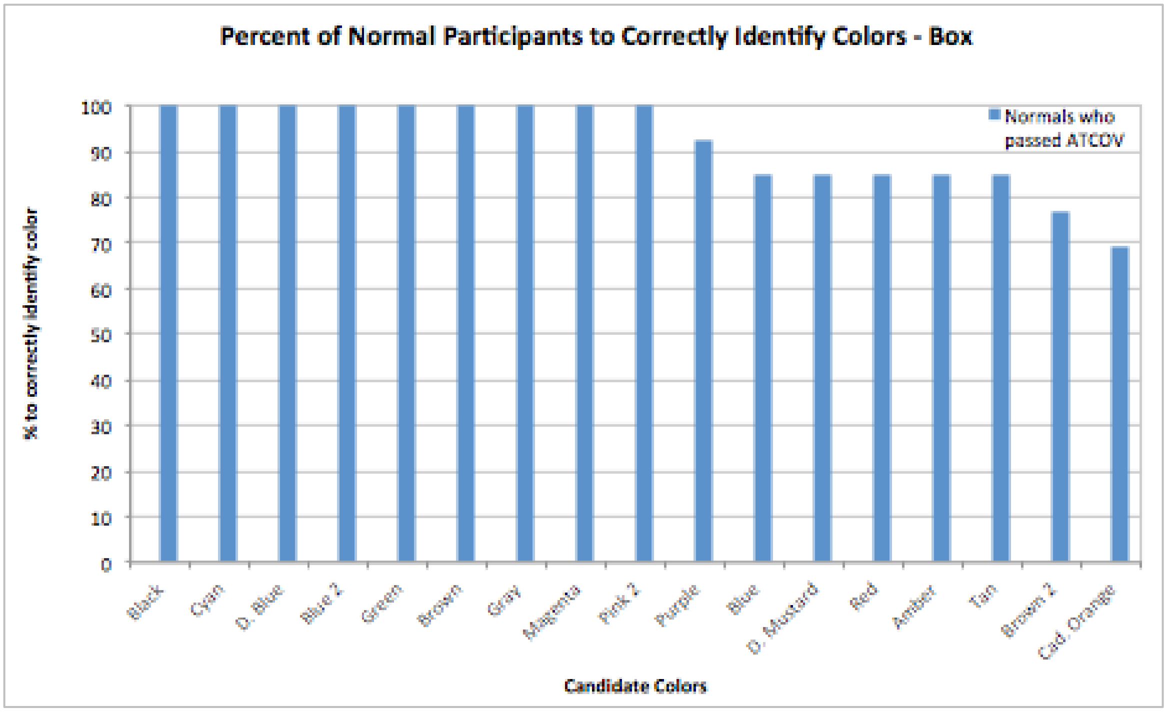

Figure 10. This figure illustrates the percentage of normal color vision participants to correctly identify the candidate colors in the first part of the Color Vision Discrimination test.

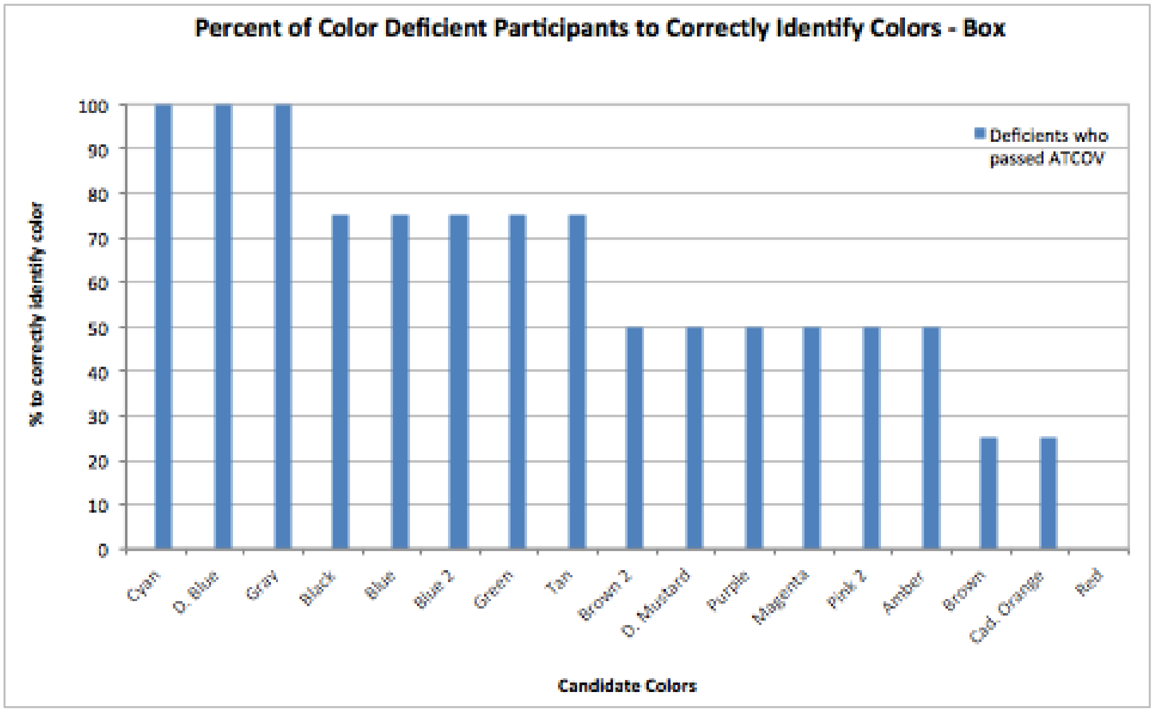

Figure 11. This figure illustrates the percentage of deficient color vision participants to correctly identify the candidate colors in the first part of the Color Vision Discrimination test.

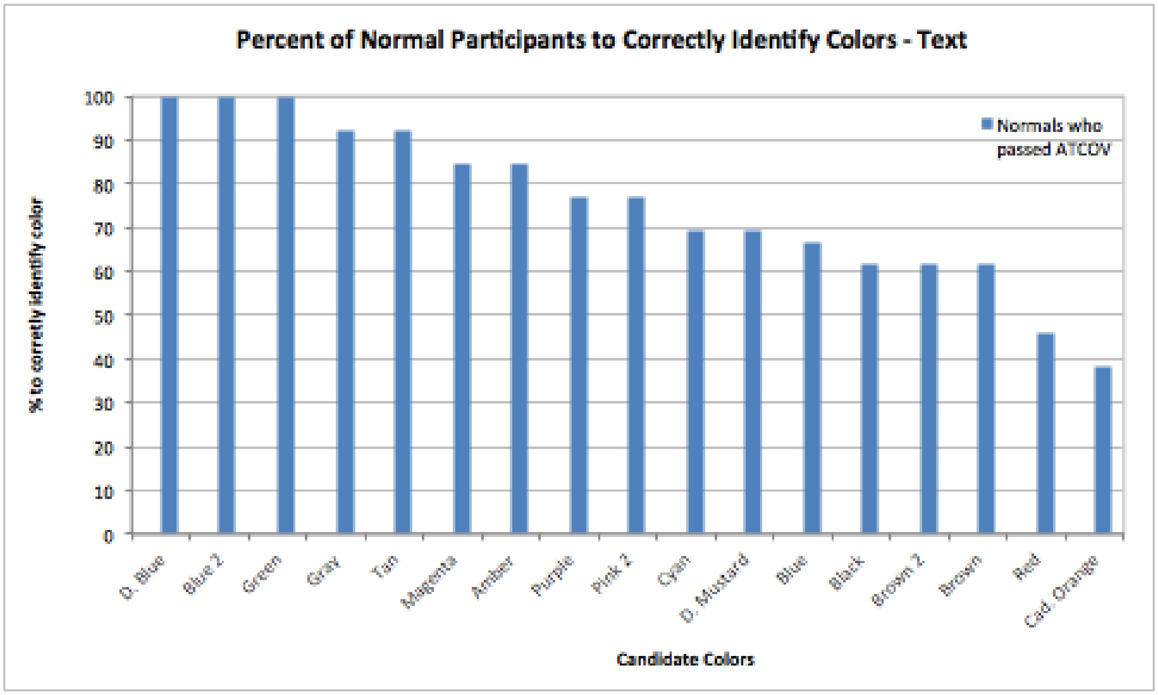

Figure 12. This figure illustrates the percentage of normal color vision participants to correctly identify the candidate colors in the second part of the Color Vision Discrimination test.

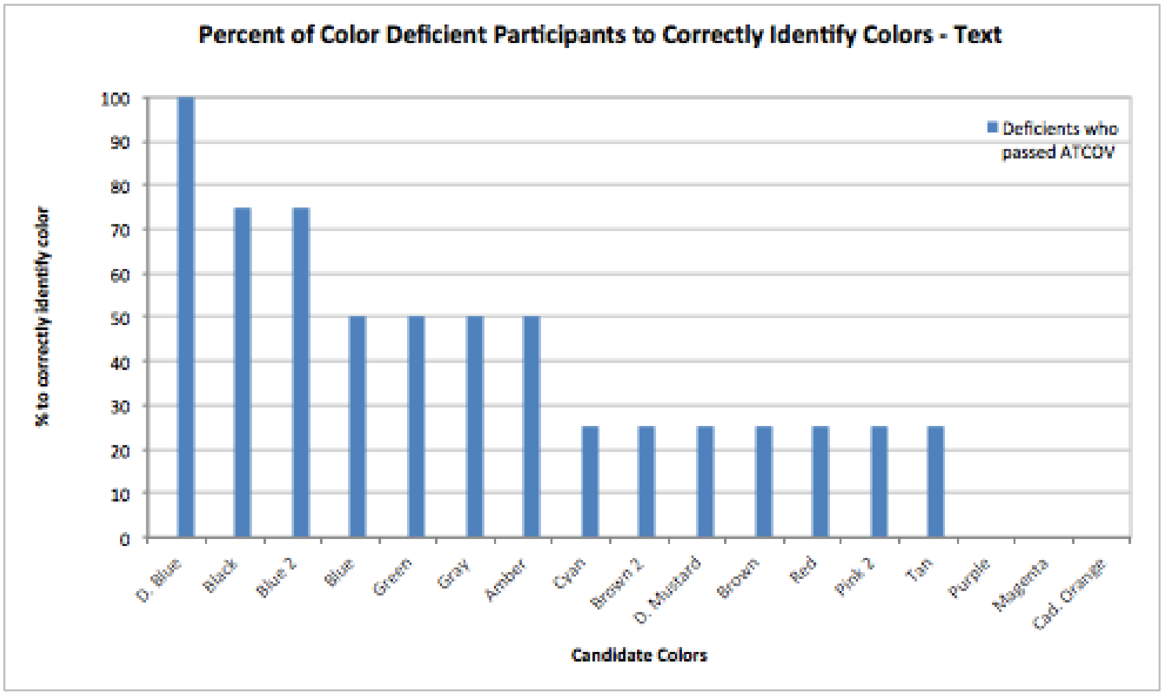

Figure 13. This figure illustrates the percentage of deficient color vision participants to correctly identify the candidate colors in the second part of the Color Vision Discrimination test.

As previously discussed, it was hypothesized that lower ΔE* values would result in fewer normal color vision participants being able to distinguish the candidate colors and that this would also hold true for color vision deficient participants. In the scenario where the color was presented as a colored box, it can be seen by the trend lines in Figure 14 and Figure 15 that there is a general decrease in the number of participants to confuse colors as the ΔE* values increase. Because of the small sample size, and to avoid violating the assumptions of a parametric test, a one-tailed Spearman's non-parametric Rank Order Correlation was done. For the color normal individuals (Figure 14) on the first portion of the CVD test, the Spearman's Rank Order Correlation did not reveal a significant correlation between ΔE* values and the number of participants to confuse colors with a given ΔE* value (r_s = -.260, p = .234). In the case of color deficient participants (Figure 15) on the first portion of the CVD test, Spearman's Rank Order Correlation revealed a significant correlation between ΔE* values and the number of participants to confuse colors with a given ΔE* value (r_s = -.558, p = .015).

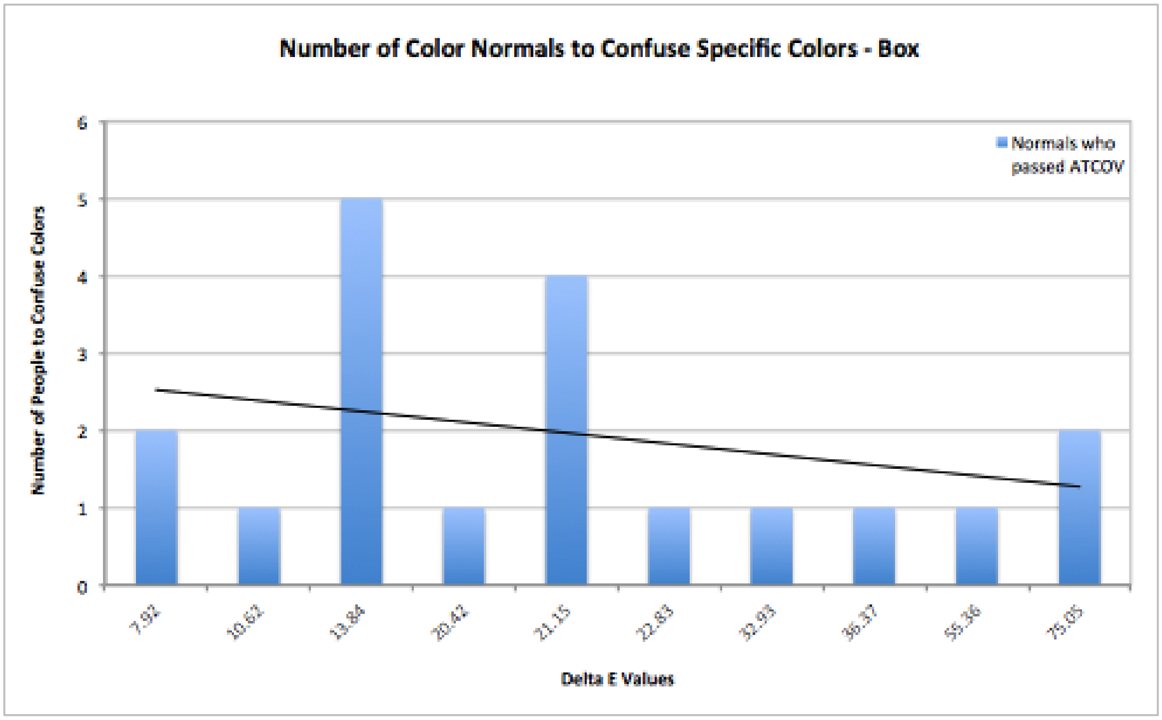

Figure 14. This figure illustrates the number of normal color vision participants to confuse colors in the first part of the Color Vision Discrimination test; the colors that were confused are represented by the ΔE* value. The trend line shows the general decrease in number of people to confuse colors as the ΔE* values increase, however, Spearman rho was not significant.

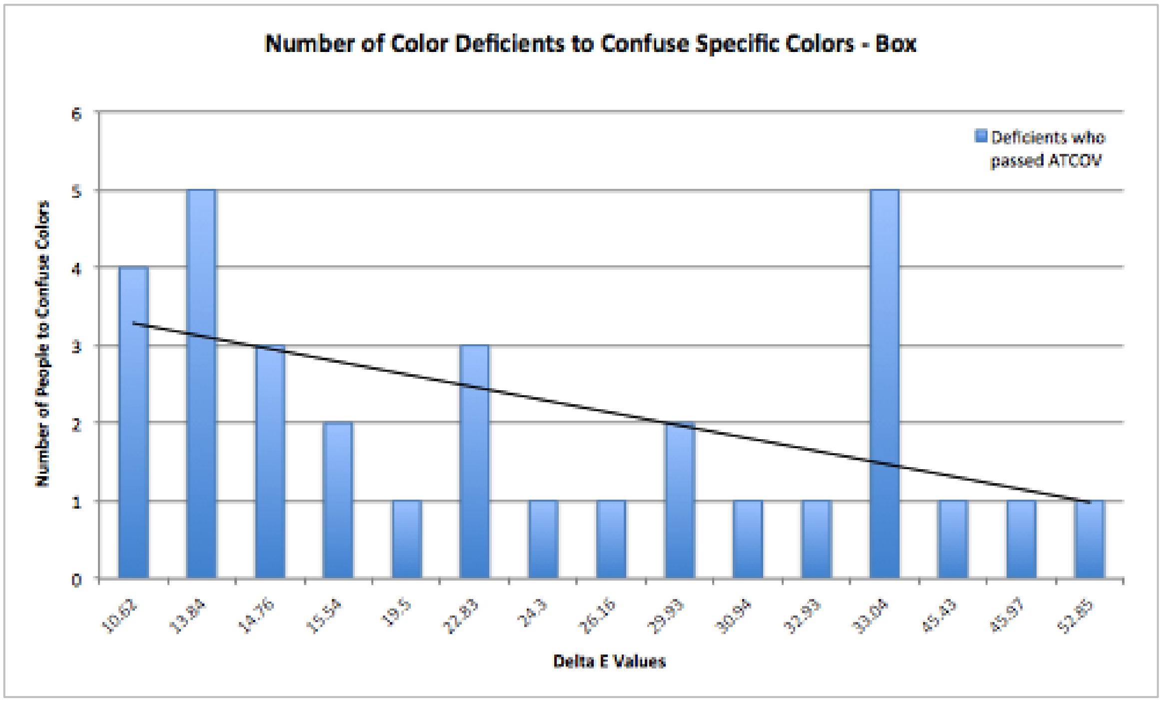

Figure 15. This figure illustrates the number of deficient color vision participants to confuse colors in the first part of the Color Vision Discrimination test; the colors that were confused are represented by the ΔE* value. The trend line shows the general decrease in number of people to confuse colors as the ΔE* values increase, however, the Spearman rho statistic was significant (r_s = -.558, p = .015) between ΔE* values and color confusion.

Looking at the trend lines in Figure 16 and Figure 17, it is apparent that for both color normal participants and color deficient participants, on the second half of the CVD test, there is a decrease in the number of participants who confused specific colors as the ΔE* values increased. The Spearman's Rank Order Correlation revealed a significant correlation between ΔE* values and the number of color normal participants (Figure 16) to confuse colors with a given ΔE* value (r_s = -.644, p = .001). This was also the case for color deficient participants (Figure 17) on the second portion of the CVD test;

Spearman's Rank Order Correlation revealed a significant correlation between ΔE* values and the number of participants to confuse specific colors with a given ΔE* value (r_s = -.505, p = .002).

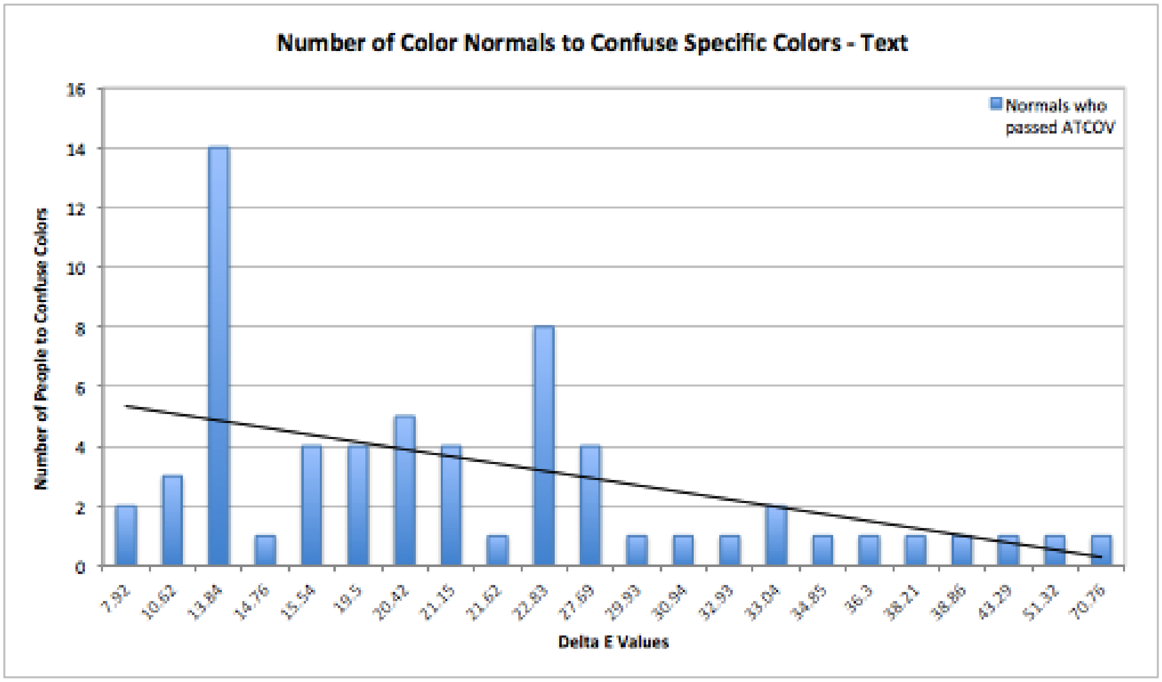

Figure 16. This figure illustrates the number of normal color vision participants to confuse colors in the second part of the Color Vision Discrimination test; the colors that were confused are represented by the ΔE* value. The trend line shows the general decrease in number of people to confuse colors as the ΔE* values increase. For this condition, the Spearman rho statistic showed significance (r_s = -.644, p = .001).

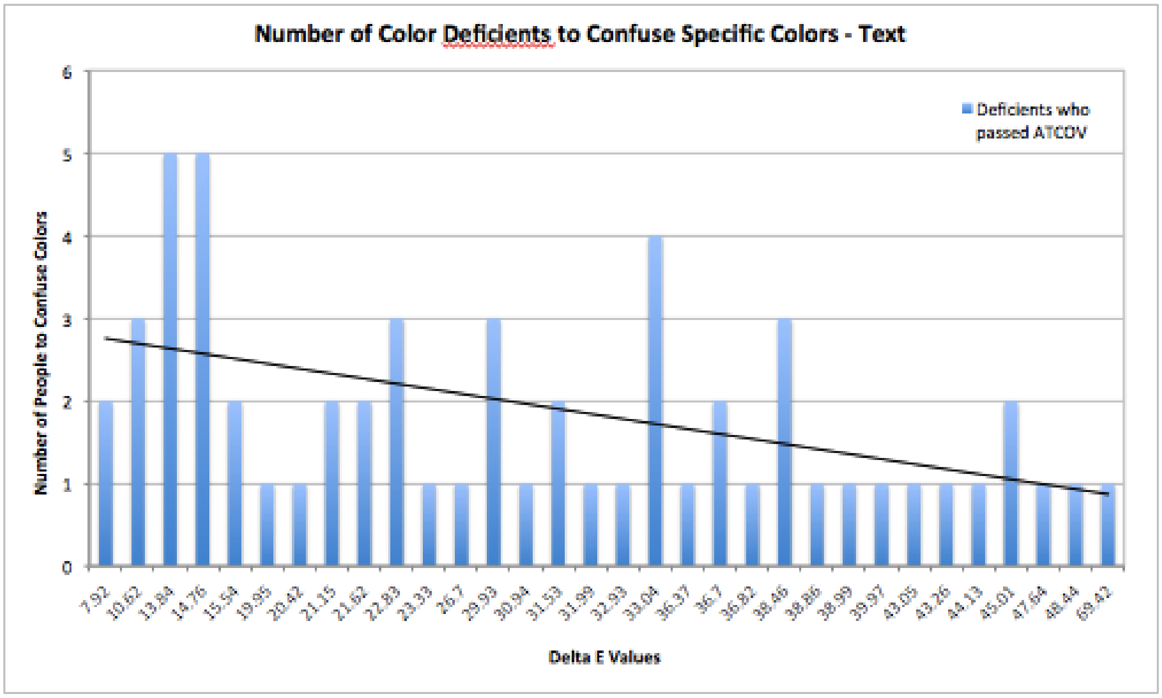

Figure 17. This figure illustrates the number of deficient color vision participants to confuse colors in the second part of the Color Vision Discrimination test; the colors that were confused are represented by the ΔE* value. For this condition, the Spearman rho statistic also showed significance (r_s = -.505, p = .002).

The final colors were selected based on the colors most commonly confused. The left side of Figure 18 shows the colors that were confused for the color deficient participants in the first part of the CVD test. The percentage listed next to each color is the percent of participants to confuse those colors. For example, looking at Green, 25 percent of the color deficient participants taking the first part of the CVD test confused Green with Amber. However, looking at the right side of Figure 18 shows that in the second part of the CVD test 50 percent of the participants confused Green with Amber and Tan. This result means that one participant confused each of those colors when presented with Green as the color they were to identify. Because each slide in the CVD test had more than one instance of the target color to be identified, so long as the participant selected at least one of the instances it was considered to be correct. If, however, a participant selected the color correctly once but identified the wrong color for the remaining instances of the target color then it was counted as incorrect and those colors that were incorrect were noted. In an alternate scenario, if a participant incorrectly selected the same color instead of the target color, it was considered to be an issue of memory rather than color discrimination and was not counted as an error. In this same manner, Figure 19 shows the colors that the participants with normal color vision confused as well as the percentage of those participants that confused the colors.

Deficient

	Box			
	Percent			
Gray	0			
Cyan	0			
D. Blue	0			
Green	25	Amber		
Blue	25	D. Blue		
Tan	25	Cyan		
Black	25	Brown2		
Blue 2	25	Blue		
Purple	50	Magenta	Pink2	
Amber	50	Green	Blue2	
Pink 2	50	Purple	Brown	
D. Mustard	50	Brown		
Magenta	50	Pink2	Purple	
Brown 2	50	Black		
Cad.Orange	75	Red	Cyan	
Brown	75	D. Mustard		
Red	100	Cad.Orange	Pink2	Brown

Deficient

	Text					
	Percent					
Gray	50	Pink2	Purple	Cyan		
Cyan	75	Purple	Blue2	D. Blue		
D. Blue	0					
Green	50	Amber	Tan			
Blue	50	Green	D. Blue	Cyan		
Tan	75	Amber	Red	Cad. Orange		
Black	25	Brown2				
Blue2	25	Blue				
Purple	100	Pink2	Brown2	Blue	Cyan	Magenta
Amber	50	Green	Red	Cad.Orange		
Pink2	75	Purple	Magenta			
D. Mustard	75	Brown	Black	Red	Amber	
Magenta	100	Purple	Blue	Pink2		
Brown2	75	Black	Brown	D. Mustard		
Cad.Orange	100	Red	Amber			
Brown	75	D. Mustard	Black			
Red	75	D. Mustard	Cad.Orange			

Figure 18. This figure shows the colors that were confused on the first half of the CVD test (left) and on the second half of the CVD test (right) by the color deficient participants who passed the ATCOV.

Normal

	Box	
	Percent	
Gray	0	
Cyan	0	
D. Blue	0	
Green	0	
Blue	15	Blue2 Cyan
Tan	15	D. Blue
Black	0	
Blue 2	0	
Purple	8	Magenta
Amber	15	Tan
Pink 2	0	
D. Mustard	15	Brown2
Magenta	0	
Brown 2	23	D. Mustard Black
Cad.Orange	31	Red D. Blue Tan
Brown	0	
Red	15	Cad.Orange

Normal

	Text	
	Percent	
Gray	8	Brown2
Cyan	31	Blue Brown
D. Blue	0	
Green	0	
Blue	38	Cyan D. Blue Blue2 Pink2
Tan	8	Amber
Black	38	Brown2 D. Mustard
Blue2	0	
Purple	23	Magenta
Amber	15	Green Tan
Pink2	23	Magenta Purple
D. Mustard	31	Brown2 Brown
Magenta	15	Pink2
Brown2	38	Black D. Mustard Red Brown Cad.Orange
Cad.Orange	62	Red
Brown	38	Red Cad.Orange
Red	54	Cad.Orange Magenta

Figure 19. This figure shows the colors that were confused on the first half of the CVD test (left) and on the second half of the CVD test (right) by the color normal participants who passed the ATCOV.

The criterion for eliminating a color was zero errors, where an error was defined as any instance in which a color was confused with another. However, if there was a target color that had more than one color confused with it, so long as the confused colors were eliminated, the target color could be used. For example, looking at Blue in the left side of Figure 19 it is shown that both Blue2 and Cyan were confused with it. If Blue2 and Cyan were eliminated then Blue could be a final color because it no longer would have colors that were confused with it. This same reasoning was applied to the data for color deficients and color normals separately to obtain a list of final colors for color deficients and a list of final colors for color normals. These two lists were then compared to each other and any colors that were not present on both lists were eliminated. Through this method of elimination, the final list of colors was selected and is shown in Figure 20.

		R	G	B	Y	x	y	R	G	B
								L	A	B
Gray		194	190	177	51.471	0.32608	0.34536	76.963	-0.886	7.05
D. Blue		30	80	200	10.183	0.1731	0.12746	38.17	29.491	-66.73
Green		162	240	2	70.006	0.36214	0.55028	87	-51.198	84.039
Black		0	0	0	0	0	0	0	0	0
Blue 2		74	255	255	80.196	0.23217	0.32876	91.773	-43.795	-13.089
Red		255	60	60	24.818	0.58033	0.32979	56.898	71.611	46.478

Figure 20. This figure represents the final list of colors chosen from the list of candidate colors based on the results from the CVD test.

Discussion

The 18 color candidates were selected based on their location on the CIE 1931 chromaticity diagram and their relation to one another when a line was drawn between them and the copunctal point for the color confusion graphs for each of the three types of color vision deficiencies: protanope, deuteranope, and tritanope. After the colors were plotted on the color confusion line graphs they were converted to the CIE LAB color scale and the ΔE^* values were calculated. While a ΔE^* value of one is considered to be a just noticeable difference, all of the selected colors had a ΔE* value greater than one. Before empirically testing these colors, participants were asked to take diagnostic tests to identify those participants with color deficient vision as well as the severity of their deficiency.

Some of the tests used to assess participant color perception included the Dvorine, CAD, and ATCOV. The CVD test was used to assess the discriminability of the candidate colors. Results from this test were analyzed using Spearman's Rank order correlation coefficient. Overall, there was a good relationship between ΔE* values and the percentage of colors with specific ΔE* values that were confused. This means that ΔE* seems to be a good indicator of color discriminability for both color normal individuals and slightly color deficient individuals depending on the way the color is presented, as a color block or as color text.

From the data presented, it can be stated that the difference between two candidate colors does not determine the ability of an observer with normal color vision to distinguish that color from the others, given that the color is presented as a color block. However, for a color deficient observer, the ability to distinguish between two of the candidate colors when the colors are presented as color blocks does depend on the ΔE* values of those colors. The greater the ΔE* value the less likely a color deficient observer is to confuse the colors corresponding to the ΔE* value. When it comes to color text, the results show that the ability of both color normal and color deficient observers to distinguish between the candidate colors depends on the separation between those colors. Based on this information, the hypothesis that stated the lower the ΔE* value the less likely that a.) normal color vision participants and b.) slightly color deficient individuals will be able to distinguish the candidate colors from each other regardless of whether the color is presented as a box or as text must be rejected. This is because there was not a significant correlation between ΔE* value and participant error for each of the four conditions: color deficient viewing the candidate colors as a box, color deficient viewing the candidate colors as text, color normal viewing the candidate colors as a box, and color normal viewing the candidate colors as text. The reason for the lack of significant correlation between ΔE* value and number of participant errors for the participants with normal color vision on the first part of the CVD test could be due to the fact that there is more color to detect when looking at colors presented in box form as opposed to colors presented in text form.

Some limitations in this study are the small sample size, use of the CVD test, lack of tritanope participants, and applicability to only the mildly deficient population as opposed to the moderately or severely color deficient. The use of the CVD test is a limitation because this was the first instance of the test being used and during testing there were areas identified where the test could be improved. For example, to reduce the number of errors that occurred because a participant could not remember the target color, it might be a good idea to keep the target color on the screen. This would allow the participant to have a reference and effectively change the nature of the task from a memory task to a discrimination task, which is more in line with the objective of this project. Similarly, the participant could be given the number of instances of the target color and asked to find all others matching that one. Additionally, the lack of dichromatic tritanopes in this study is a limitation because it reduces the reach of the results from this study. For example, the final list of colors determined in this study are only applicable to those individuals who are considered mildly color deficient, based on the ATCOV, and those participants with normal color vision who also passed the ATCOV. Whereas, if tritanopes were included in the study, the list of colors determined could be used for all of the three major types of dichromats.

The final list of six colors represents those colors that can be easily distinguished between by both normal and color deficient participants. Although the sample size was small, this list can still be considered valid because the criterion for eliminating a color was a single error. That being said, future work may be able to identify additional colors, using the same technique outlined in this work.

While this work is a good starting point in determining colors that can be easily distinguished by both color normal and color deficient users for computer based displays, further research is needed. This study only looked at a small number of participants, and, while appropriate measures were taken to account for this in the statistical analyses, testing a larger sample would be beneficial in identifying additional colors. Furthermore, because of the limited population available for sampling, this study did not include data from any dichromatic tritanopes. While the majority of the color deficient population is composed of protanopes and deuteranopes, for the findings of this study to be applicable to a larger population of color deficient observers, further research involving tritanopes is needed. Other areas that could be expanded upon are determining the best ΔE^* value that allows for discriminability between colors. As previously discussed, a ΔE^* of one is considered a just noticeable difference, however, knowing the optimal distance between colors that allows for easy discrimination would aid in display design as well as other areas of design involving color.

Current research being done on this topic reduced the list of candidate colors based on the results from this study and enlisted additional participants to further test the new list of colors. The new list of colors can be found in Appendix B along with the ΔE* matrix for those new colors.

The results from this study generally showed that as the ΔE* value increased the number of people to confuse colors with higher ΔE* values decreased. This indicates that ΔE* values could be a good indicator of easily distinguishable colors for even color deficient individuals. The only scenario in which the ΔE* value was not significant was for color normal participants when viewing the color as a color box. This could simply be the result of such a low number of participants or even because the normal participants made fewer errors in general which flattened the line of fit and resulted in no correlation. This study also identified a list of six colors that can be easily distinguished between by color deficient observers as well as observers with normal color vision. A list of colors such as this has many applications including other areas in aviation such as flight deck displays. There is some research aimed at identifying usable colors based on ΔE* values (Daniel & Byrd, 2003). Other research looks at designing displays in general and what users prefer in terms of color usage (Aragon, 2005; Beringer, 2000; Hart & Loomis, 1980; Kopala, 1979). In addition to ATC and flight deck displays, this list of colors would be helpful in webpage design and in designing other computer as well as hand held displays.

Conclusion

As technology advances and the general population reliance shifts more and more to the Internet and other computer based applications it is increasingly important to be mindful of those users who may not have normal color vision. While it is not yet possible to design an interface that automatically adjusts itself depending on the user, it is possible to design redundancies into displays or take a minimalist design approach when using colors. In addition to the colors discovered in this study, there are many ideas on how to design for a larger user group that includes color deficient users as well as color normal users. Some of the ideas discussed previously include algorithms, design rules and different color palettes. Each of these has benefits and limitations, but with continuing research, a seamless solution is within reach.

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Appendix A

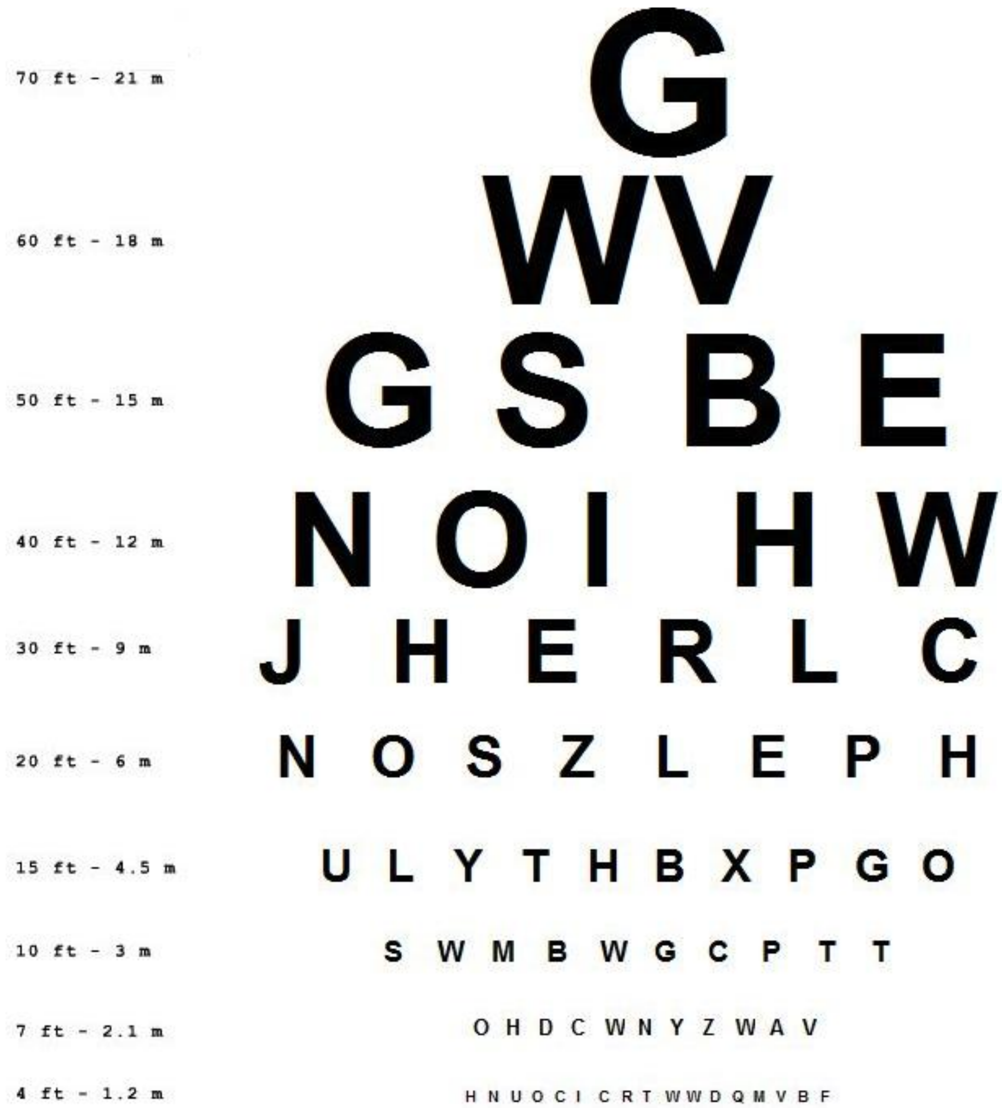
			R	G	B	Y	x	y	R	G	B
									L	A	B
201	Black		0	0	0	0	0	0	0	0	0
202	White		255	255	255	100	0.31272	0.329	100	0.005	-0.01
211	Gray		194	190	177	51.471	0.32608	0.34536	76.963	-0.886	7.05
204	Red		255	60	60	24.818	0.58033	0.32979	56.898	71.611	46.478
208	Brown		165	50	50	10.511	0.54053	0.32968	38.744	47.03	27.144
209	Brown 2		87	73	65	7.173	0.35549	0.35088	32.197	4.468	6.981
212	Amber		255	191	0	58.522	0.47316	0.4625	81.028	10.386	83.036
213	Purple		189	74	206	20.173	0.3001	0.17509	52.032	63.687	-47.094
210	Blue 2		74	255	255	80.196	0.23217	0.32876	91.773	-43.795	-13.089
205	Blue		0	163	255	33.414	0.18995	0.20377	64.495	-2.244	-55.242
206	D. Blue		30	80	200	10.183	0.1731	0.12746	38.17	29.491	-66.73
207	Cyan		0	175	192	34.466	0.21694	0.30095	65.331	-30.87	-19.261
203	Green		162	240	2	70.006	0.36214	0.55028	87	-51.198	84.039
214	Yellow		242	242	85	83.037	0.4024	0.47728	93.031	-18.406	72.555

This figure shows the second list of candidate colors that was selected by discarding those candidate colors that were most often confused based on the initial testing done in the current work.

			101	102	115	104	108	110	116	117	112	105	106	107	103	
			Black	White	Gray	Red	Brown	Brown 2	Amber	Purple	Blue 2	Blue	D. Blue	Cyan	Green	Yellow
201	Black			100.00	66.57	52.20	36.70	22.83	77.44	47.87	91.42	56.87	38.06	56.85	86.16	94.35
202	White		100.00		15.90	42.14	54.00	55.58	31.36	44.85	25.14	34.57	55.71	32.62	31.64	28.22
211	Gray		66.57	15.90		35.35	43.84	43.29	25.69	43.05	27.73	35.17	50.75	26.70	28.67	26.14
204	Red		52.20	42.14	35.35		19.50	34.85	44.13	35.53	68.66	52.90	48.04	56.69	74.68	60.60
208	Brown		36.70	54.00	43.84	19.50		21.62	52.59	33.46	72.36	53.95	39.82	70.76	75.63	66.08
209	Brown 2		22.83	55.58	43.29	34.85	21.62		52.04	36.82	59.79	44.76	33.17	44.46	58.87	58.46
212	Amber		77.44	31.36	25.69	44.13	52.59	52.04		70.82	45.97	57.38	73.87	47.64	29.93	18.41
213	Purple		47.87	44.85	43.05	35.53	33.46	36.83	70.82		57.22	43.26	25.68	45.01	94.16	82.96
210	Blue 2		91.42	25.14	27.73	68.66	72.36	59.79	45.97	57.21		32.93	57.19	19.95	36.69	38.55
205	Blue		56.87	34.57	35.17	52.90	53.95	44.76	57.38	43.26	32.93		30.94	20.42	69.42	69.45
206	D. Blue		38.06	55.70	50.75	48.04	39.82	33.17	73.87	25.68	57.19	30.94		39.97	79.58	83.86
207	Cyan		56.85	32.62	26.71	56.68	70.76	44.46	47.64	45.01	19.95	20.42	39.97		44.85	46.27
203	Green		86.16	31.64	28.67	74.68	75.63	58.87	29.93	94.17	36.69	69.42	79.58	44.85		13.01
214	Yellow		94.35	28.22	26.14	60.60	66.08	58.46	18.41	82.96	38.55	69.45	83.86	46.27	13.01	

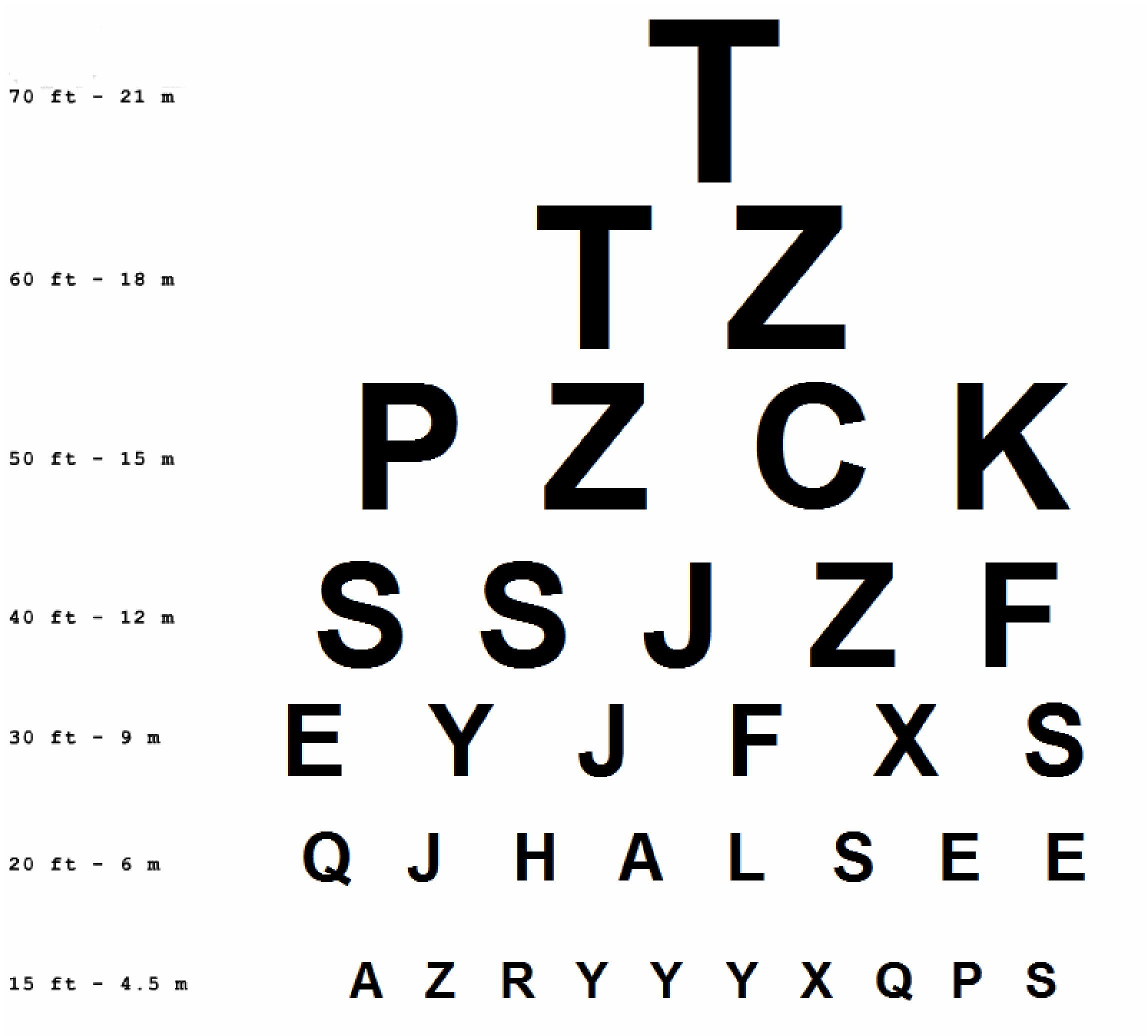
This is the ΔE* matrix for the second list of colors.

Appendix B



This is one of the three eye charts used to test visual acuity.

This is one of the three eye charts used to test visual acuity.



This is one of the three eye charts used to test visual acuity.