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# ASSESSING COLOR DISCRIMINATION 

## By:

Joshua R. Maxwell

A Thesis Submitted to the Department of Human Factors \& Systems in Partial Fulfillment of the Requirements for the Degree of Master of Science in Human Factors \& Systems

Embry-Riddle Aeronautical University<br>Daytona Beach, Florida

Spring 2012

## Assessing Color Discrimination

## By

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

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#### Abstract

The purpose of this study was to evaluate human color vision discriminability within individuals that have color normal vision and those that have color deficient vision. Combinations of 15 colors were used from a list of colors recommended for computer displays in Air Traffic Control settings, a population with some mildly color vision deficient individuals. After a match to sample test was designed to assess the limits of human color vision discrimination based on color saturation and hue, standard color diagnostic tests were used to categorize college students as having normal or deficient color vision. The results argue that color saturation and hue impact human ability to discriminate colors, particularly as the delta E is small. This evidence also indicates that the effect that hue and saturation have on discriminability is not predicted by standard color vision assessment tests. Our results show that there is no difference in discriminability based on hue or saturation of both color normal and color deficient individuals, but for one exception. The delta e for black was significantly higher than all other colors. This was true for both color normal and color deficient individuals. From this information, it can be determined that the tolerance threshold for black should be $\mathrm{dE}(00)=36.9$ and the tolerance for all other colors to be $\mathrm{dE}(00)=9.2$ for display on LCD displays. These results will have value for any computer display of critical information in which color discrimination is important for complete comprehension. The large number of individuals with color vision problems also makes these results a useful guide to color coding of information on web page design.


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## Introduction

The purpose of this study was to investigate the discriminability of human color vision within individuals that have color normal vision (CNV) and color deficient vision (CDV) for colors displayed on liquid crystal displays (LCD). ). The selected palette of colors was derived from a Federal Aviation Administration (FAA) study to determine a color set for information display in NextGen air traffic control (ATC) computers. The study attempted to determine the perceived just noticeable difference (JND), expressed as a delta E value, between the colors used in the FAA palette. These results may be useful in setting a standard for color display calibration and color coding design. These colors, and the use of delta E to select other colors, would enhance the information obtained from color coded displays.

## Color vision

The human eye is composed of a complex arrangement of lenses and photoreceptors that make it possible for people to perceive the world by detecting a very narrow band of radiation in the electromagnetic spectrum. Light first passes through a clear membrane known as the cornea and passes through the aqueous humor before being refracted by the lens (see Figure 1). Muscles attached to the lens allow the lens to change the amount of refraction and, therefore, altering the focal length allowing perception at varying distances. The light is focused on one small spot on the retina as it passes through the vitreous humor, the point of sharpest visual acuity called the fovea. It is within the retina that the light is detected by photoreceptors( rods and cones ). These rods and cones are responsible for light detection and are arranged in the direction away from incoming light. Rods simply detect the presence of light; not the wave length of light (Widmaier, Raff, \& Strang, 2006). Cones detect the wave length of light and are divided in to three types depending on the frequency of the wavelength of light they detect; long, medium, and short
wavelengths, commonly known as red, green, and blue cones, respectively. These photoreceptors contain photopigments such as rhodopsin for rods and one for each of the cone types that are selectively sensitive to the frequency of light energy. Rods respond across these specific wavelengths and are useful for night vision and detecting movement. The majority of cones are located near the fovea in the macular area of the retina; which is where the center of light focused by the lens hits the retina.


Figure 1. This figure illustrates the structure of the human eye as well as the two types of photoreceptors (Kolb, 2005).

Each cone type responds to a different wave length of light. Red cones are sensitive to long wave lengths which are 490-700 nanometers (nm), green cones respond to medium wave lengths of light which are $450-620 \mathrm{~nm}$, and blue cones respond to short waves lengths which are $400-520 \mathrm{~nm}$. Perception of light is thus limited to the wave length band of the electromagnetic spectrum of $400-700 \mathrm{~nm}$. Colors are perceived dependent on the firing rates of the red, green blue cone receptors (Widmaier, Raff, \& Strang, 2006). The genetic encoding responsible for cone pigmentations is located on the X chromosome for red and green cones and chromosome 7 for
blue (Widmaier, Raff, \& Strang, 2006). The close proximity of red and green genes on the X chromosome increase the likeliness that crossover may occur during meiosis. This would alter or eliminate the ability to produce these photopigments (Widmaier, Raff, \& Strang, 2006) Individuals may vary slightly in the exact range for each cone type; however it has been demonstrated with observation that colors are perceived the same way by essentially all with normal color vision (Wolfe, et al., 2009). Light signals are converted into action potentials by the interaction of rods and cones with nearby bipolar cells and ganglion cells. Photoreceptors interact with bipolar and ganglion cells in two different pathways. These pathways are known as the "ON-center" and the "OFF-center". The ON center carries the signal when the photoreceptor is stimulated and the OFF center carries the signal when the photoreceptor is not stimulated (Widmaier, Raff, \& Strang, 2006). This dynamic pathway action potential improves image resolution by increasing the brain ability to perceive contrast at edges and borders. The photoreceptors are interlaced with horizontal and amacrine cells. Horizontal and amacrine cells allow information to travel between ganglion cells and respond to variation in characteristics in the visual image such as motion, color, intensity, and form. This interconnectedness allows for fields to be set as "ON center/OFF surround" or "OFF center/ ON surround" (Widmaier, Raff, \& Strang, 2006). This organization allows clean edges for ON and OFF areas increasing the contrast of the image.

The ganglion cell releases the action potential into the optic nerve through the optic chiasm. The optic nerves of both eyes meet and cross at the optic chiasm near the base of the hypothalamus. It is at the point that information from both eyes are combined and split according to visual field. This sends information from the right half of the visual field information from both eyes to the left side of the visual cortex and vice-versa on the lift visual field as seen in figure 2 . A small region in the center of the visual field is redundantly processed by both halves of the brain (Nolte, 2002). Each optical track terminates in the lateral


Figure 2. Visual pathway (Scienceblogs, 2007)
geniculate nucleus (LGN). The LGN is composed of six layers. The inner two layers, 1 and 2, are called the magnocellular layers; while the outer layers, $3,4,5$, and 6 are called parvocellular layers. An addition set of neurons, known as the koniocellular layer, separates the six layers (Carlson, 2007) (Rosa, Pettigrew, \& Cooper, 1996). Layers 1 and 2 receive information from rods; while layers $3,4,5$, and 6 , receive information from red and green cones, koniocellullar cells receive information from blue cones (Xu, et al., 2001). The layers of the LGN also correspond distinctly to ipsilateral (same side) and contralateral (opposite side) eyes; the ipsilateral layers being 2, 3 , and 5 while the contralateral layers are 1, 4, and 6 (Rosa, Pettigrew, \& Cooper, 1996). The axons that leave the LGN led to V1 visual cortex. Both the magnocellular and parvocellular layer axons extend to layer 4 of V1. Layer 4 receives parvocellular input from corresponding layers of LGN, layer 4 receive input from magnocellular layers of LGN. The konincellular layers of the LGN output to layer 4 of V1. The visual cortex sends information to the LGN from axons in layer 6 of V1. The cortex magnifies the foveal area by correlating a large area of the cortex to a small area of the retina (Schmid, et al., 2010).

Within the cortex, there may exist regions responsible for color perception. This has been demonstrated in the case where an individual had cerebral achromatopsia (Goldstein, 2007). This condition is a form of color blindness due to damage to the cortex. Through studies of this condition, researchers hypothesize that the brain processes color information in two areas of the cortex separately; the first area being where wavelength information is processed and the other being where color is perceived. Individuals with cerebral achromatopsia are unable to perceive color. However, they are able to perceive the border between two adjacent colors even though they both appear the same shade of gray (Goldstein, 2007).

There are two theories of color vision; the first being the trichromatic, the other is the opponent theory. The combination of information from three color pigment receptors to explain color perception is known as trichromatic vision. It is the combination of intensity and wavelength that trigger the cones to fire and relay the information about color to the brain (Hecht, 1930). For example, the perceived color yellow is composed of strong firing of green and red cones with little or no firing of blue cones. This combination of cone signals to the brain indicates that the color is perceived as yellow.

The other theory of color vision perception is the opponent theory, which states that color is perceived as the difference in cone response rather than the direct individual cone response. This theory hypothesizes that there are three color channel red verses green, blue verses yellow and black verses white. The opponent colors are never perceived in combination (Hurvich \& Jameson, 1957). While the two theories may appear opposed to one another, quite the opposite is true. The trichromatic theory explains the mechanism for color detection and the opponent theory explains how the information is encoded to the brain. The opponent theory explains how the cones interaction with the bipolar and ganglion cell. As explained previously, the cones pass information to bipolar cell and they pass the information to the ganglion cells. It is during this passing of information the opponent process takes place and information is organized. Parvocellular ganglions are organized in two types. The first type relays information about the difference between red and green cones, while the second type relays the difference between the blue cones and the combination of red and green cones. This organization is responsible for the red-green channel and the blue-yellow channel, respectively (Hurvich \& Jameson, 1957).

With the understanding of the physiology of human color vision researchers are prepared to test capabilities of color vision. Researchers now understand that the human eye is capable of
detecting three different bandwidths a light. The combination of these bandwidths is interpreted by the brain into the perceived colors. By using three separate light sources with threes color filters researches have been able to replicate all discernible colors and measure the amount of each light source needed to replicate a color. This research became known as color space and is the mathematical representation of the visual spectrum based on human physiology.

## Color Spaces

Many uses of color such as paint, displays and design would benefit if color could be described in a quantitative manner, One, organization that set out to quantify color was the Commission Internationale de l'Eclaige or International Commission on Illumination (CIE). The CIE roots date back to a meeting of the International Gas Congress in 1900 when several members were in agreement that a major problem facing the industry was the photometry of gas mantels. These members then formed the International Commission on Photometry (CIP). This commission made progress in the standardization of photometry measures. With the growth of the electrical industry, it was realized that color quantification should be broadened to all aspects of light. By 1913, plans were formed for the establishment of a larger origination now known as the CIE. The CIE has made many advances in the field of color research and is recognized as a standardizing body by the International Organization for Standardization (ISO) (Commission Internationale de l'Eclairage, 2011).

Early in the late nineteenth century, vision scientists used different descriptions for the color space that described human color vision. A convention was needed to promote research and the CIE established the CIE RGB color space from research conducted by W, David Wright (Wright, 1928) and Guild (Smith \& Guild, 1931). These scientists independently conducted a series of experiments to measure and detail human color vision. Their work established a
standardized mathematical description of color that could be defined reliably using trichromatic additive mixtures of red, green, and blue light (RGB). Their experimental methods used the match to sample paradigm to develop numerical values for colors based on the amount of red, green, and blue light the color contained. The match to sample paradigm is an experimental method by which the participants match an experimental color to a sample color. By standardizing the primary color values for RGB, the CIE set the international standard for objective color notation. Now precise colors could be defined by the numerical amount of red, blue and green they contained. The CIE RGB values are based on the radiant power of the light and wavelengths of the light. This is not the same as the current sRGB color scale used by computer programs today; in which the scale is based on the percentage of each primary color. One issue with the CIE RGB tristimulus values is that the " $r$ " value is negative for light wave lengths between 450 nm and 550 nm . This region's negatives values makes it difficult conceptualize the color space because the mathematics allows for negative radiant power for one of the tristimulus values.

The CIE then set out to create a color space that was related to the CIE RGB color space but, would also follow several other guidelines for even more precise color descriptions. The guidelines for the development of the CIE1931 color space required that the color matching functions would use positive integer values to simplify computation. The color matching functions are numerical descriptions of chromatic response of the observer and are denoted as $\mathrm{X}, \mathrm{Y}$, and Z . The Y color matching function equates to the luminosity. The color space shall have a constant energy white point located at the center of the color space. Thus, the ratio $\mathrm{X}=\mathrm{Y}=\mathrm{Z}=$ $1 / 3$ is the center of the color space and the value of the constant energy white point. The gamut for colors would be constrained by the triangle with coordinates $(1,0),(0,0),(0,1)$, in the color
space as seen in figure 3, (Commission Internationale de l'Eclairage, 1931). The CIE commission developed the Yxy coordinate system to provide a means to represent color on a two dimensional chart known as the 1931 CIE diagram (Figure 3). The two dimensional chart is the color space at a constant luminosity $(\mathrm{Y})$ with x and y being derived parameter from $\mathrm{X}, \mathrm{Y}, \mathrm{Z}$. The coordinate system was developed in such a way that as long as two coordinate were known the third could be calculated. The non-linearity of the diagram presents a problem for the evaluation of differences in color and for determining a standard threshold of human color (Wright, 1941).


Figure 3. This figure illustrates the CIE 1931 chromaticity diagram (Flück, 2007).

One of the first studies to made use of the diagram involved color vision sensitivity research (MacAdam, 1942). Through the use of an apparatus; participants were able to view two different colors within a circle of the same luminosity. The apparatus used a constant luminance light source a filters to produce the desired light color. The light would then pass through a prism and split in to two beams of light one light beam would be the test color and the other beam the match color. Each beam would then pass through a second prism. The second prism would alter
the color of the light beam. The test colors prism was set by the research to produce and exact color for testing while the match color prism would be rotated by the observer until a match was made. The participant's goal was to match the sample to the target for colors dictated by the researcher's change of color filters and prism angle for the target color. The result of the study was a set of ellipses around the target color plotted on the CIE 1931 color diagram as seen in figure 4. The ellipses denote the threshold of just notable differences between the target color indicated by the center dot and the discriminable color of the ellipse (MacAdam, 1942).


Figure 4. MacAdam (1942) ellipses plotted on the CIE xy 1931 chromaticity diagram. Ellipses are 10 x actual size (MacAdam, 1942).

MacAdam's research is important for describing the range of color perception. The research finds that human color perception is very similar between individual and defines the threshold for color comparison. By defining the threshold of perceptive difference for colors
researchers were able to begin research for a uniform color space to more accurate describe color vision. Further research into color perceptual differences led the CIE to develop two new descriptions of color in 1976. These new descriptions of the color space, the Luv 76 and Lab 76 (as seen in figure 5), were built on mathematically attempting to linearize the color space, taking to account visual sensitivity and making the distance between colors meaningful.


Figure 5. Lab color space (Sensus, 2012)

The Luv scale was developed to describe color difference within small visual spaces such as photographs, and tv displays; while the Lab scale was developed for large visual spaces such as wall paint, and automobiles. Neither scale was able to fully normalize the entire color space, due to mathematical transformation and the lack of information describing the MacAdam's ellipses in the blue region of the CIE1931 color space. (Brainard \& Wandell, 1991). The major discrepancy between the two scales is the mathematical transformation used to compute the white point. (Alman, Berns, Snyder, \& Larson, 1989). White point adaption is the effect of light
source on color perception. An easy way to replicate this concept is to read a book under a florescent light for an hour and then look at the same book under a tungsten bulb. The observer would notice that at first the white page would appear to have a yellow-orange tint. This tint would eventually fade as the observers eyes adapted to the new light source. The LUV scale used a Judd-type white point adaption while the Lab scale uses a von Kries transformation (Alman, Berns, Snyder, \& Larson, 1989). The Judd-type and von Kries transformation are two mathematical models that describe this effect (Lee, 2005). In the debate between the two scales, standards writers in government applications have chosen the Luv scale while research has favored the Lab scale. Research has modified the equation of the Lab scale creating two more robust scales known as Lab 1994, and Lab2000. These new Lab scales improve the uniformity of the Lab color space making them viable for both additive and subtractive color application (Hunt, 2004: Fairchild, 1998: Mandic, Grigic, \& Grigic, 2006). No modifications have been made to the Luv scale and it is no longer as useful as the Lab scale.

With a linear color space established, researchers have a measurable difference in color relationship. The new color spaces have been able to transform the MacAdam ellipsis into uniform circle with a radius of one. This difference between colors is known as Delta E (dE), and is a mathematical expression that describes the distance between two colors within the color space (Mandic, Grigic, \& Grigic, 2006). The MacAdam ellipses were used to develop a uniform color space with a base unit of measurement as the measure of just noticeable difference. The original dE equation for both Luv and Lab color spaces is the simple Euclidian distance formula for two points in three dimensional a space (Melgosa, Hita, Romero, \& Jiménez, 1992). Research conducted with the Lab space has resulted in two modifications of the dE equation that weighs in the effects of luminance, distance from neutral axis and color hue angle (Mandic, Grigic, \&

Grigic, 2006). These modifications corresponded to the advancements in color spaces and are known as delta E 1994 and delta E 2000 with delta E 2000 (dE2000) varying the weighted luminance based of color hue. The dE 2000 equation is as follows in equation 1 (Melgosa, 2000). The threshold for color discrimination is current under investigation for a variety of application. One such study indicates that the just noticeable difference threshold is approximately one (Witt, 1990). Correlation studies looking into the varying color distance formulas indicate that the dE2000 formula shows the best correlation to the empirical data (Huang, Liu, Xu, \& Liao, 2009).

The color difference, or delta $\mathrm{E}(\Delta \mathrm{E})$, between a sample color $L_{2} a_{2} b_{2}$ and a reference color $L_{1} a_{1} b_{1}$ is (Sharma, Wu, \& Dala, 2005):

$$
\Delta E=\sqrt{\left(\frac{\Delta L^{\prime}}{K_{L} S_{L}}\right)^{2}+\left(\frac{\Delta C^{\prime}}{K_{C} S_{C}}\right)^{2}+\left(\frac{\Delta H^{\prime}}{K_{H} S_{H}}\right)^{2}+R_{T}\left(\frac{\Delta C^{\prime}}{K_{C} S_{C}}\right)\left(\frac{\Delta H^{\prime}}{K_{H} S_{H}}\right) .}
$$

- A hue rotation term $\left(R_{T}\right)$, to deal with the problematic blue region (hue angles in the neighborhood of $275^{\circ}$ )
- Compensation for neutral colors (the primed values in the $L^{*} C^{*} h$ differences)
- Compensation for lightness $\left(S_{L}\right)$
- Compensation for Chroma ( $S_{C}$ )
- Compensation for hue $\left(S_{H}\right)$

The full delta E equation can be found in appendix A. While many color spaces are used to describe color only CIE Lab and CIE Luv can be used to calculated delta E. programs exist that will covert tristimulus values from one color space to another color space and calculate delta E. Open RGB is one such program that will transform sRGB into CIE Lab and calculate dE2000 for comparing two colors.

## sRGB

The sRGB color space is by computer application and defimes colors for software applications. The color space was developed by Microsoft and Hewlet- Packard companies for
the use in color monitors and printers in 1996. The color space was widely accepted by the industry for its ability to be directly displayed by CRT monitors of the time. sRGB was designed with the intention to be used in a typical office light environment. The sRGB color space as seen in figure 6 is well within the visual color space as defined by CIE 1931. Most current software assumes 8 -bit per channel coding; this assumption in combination with 32 bit processing architecture limits the amount of colors to be 256 allocations per color channel (Stokes, Anderson, Chandrasekar, \& Motta, 1996).


Figure 6. sRGB color space displayed as the area of the triangle drawn in the CIE1931 color space (Thomas, 2007).

## Color Blindness

Color blindness is the generic term for color deficient vision and does not accurately describe color deficient vision because few individuals are totally blind to all color (Pitt, 1935).

Monochromatic vision is true color blindness because individuals with monochromatic vision cannot see color. There are three other types of color deficient vision, Protanopia is the vision condition in which individuals are unable to correctly perceive the color red; Deuteranopia is the vision condition in which individuals are unable to correctly perceive the color green, and Tritanopia is the vision condition in which individuals are unable to correctly perceive the color blue (Pitt, 1935). These individuals are not blind to color but have difficulty perceiving certain colors and possess dichromatic vision. These conditions affect $8 \%$ of the male population and $0.5 \%$ of the female population for dichromatic vision being protanopia and deuteranopia. . Individuals with dichromatic vision have a breakdown or sensitivity shift in one of the three photopigments (Wolfe, et al., 2009). Research conducted to establish how individuals with color deficient vision perceive colors developed color confusion lines (Wyszecki \& Stiles, 2000). These lines claim that for each of the color vision deficient types, lines can be draw within CIE color space that converge on a point known as the copunctal point see figure 7. Two colors that lie on the same line through the copunctal point are confused by an individual with dichromatic vision. (Thomson \& Wright, 1953). These confusion lines hold true for trichromatic vision for colors very close together on the confusion lines such as in the case of magenta and fuchsia. There also is the case of anomalous trichromatic vision. In this case, individuals have cones with a shift in sensitivity that does not allow them to perceive colors the same way that individuals with normal color vision perceive color. These individuals would be able to see some reds, greens, and blues; but not all of the shades of reds, greens, and blues (Pitt, 1935).


Figure 7. The color confusion lines for the 3 color deficiency types (Wyszecki \& Stiles, 2000).

## Color vision assessment

From research of human perception, many techniques for assessing color vision have been developed. These techniques vary in application, medium, and purpose based on the theory they were developed for. However, with the difference between each technique, similar results are concluded. Some of the more popular tests are the, and Colour Assessment and Diagnosis (CAD) test (Seshadri, Christensen, Lakshminarayanan, \& Bassi, 2005). There is also a unique test used by the FAA for the purpose of assessing color vision as it is applied to air traffic control; Air traffic color Vision test (ATCOV).

The CAD test makes use of calibrated computer displays. Upon the display, a square field is shown and a color dot moves towards one of the corners of the square. The participant is to indicate the corner to which the dot moves by pressing the corresponding key on the key pad. The CAD test is one of the more sensitive diagnostic test because it evaluate an individual's color detection threshold. This evaluation is based on the MacAdam ellipse centered on the white
point (Rodriguez-Carmona, Harlow, Walker, \& Barbur, 2005). The CAD test has been validated by comparison to more standard color tests such as the Ishihara and Farnsworth-Munson d100 and was deemed a valid method of color vision diagnostics (Seshadri, Christensen, Lakshminarayanan, \& Bassi, 2005). The CAD test is capable of diagnosing the type and severity of color impairment and plots the threshold value of just noticeable difference for the individual around the white point. The CAD test accounts for the detection of change in shading by rapidly altering pixels in the test field from white to gray randomly. This process controls perception of luminesce independent of color (Barbur, Rodriguez-Carmona, Evans, \& Milburn, 2009).

One specific test used by the FAA in the screening of air traffic controllers for color vision as it applies to job performance, is Air Traffic Color Vision (ATCOV) test. The ATCOV test consists of three sub test each test relates to controller task with color coded information (Ling, 2008). The three sub tests are designed to test color coded information in the field of Radar Identification, Alert Detection, and Weather Identification. For a participant to be considered for employment as an air traffic controller, they must be able to pass all three sub tests. The Civil Aerospace Medical Institute designed, tested, and validated the ATCOV test as to conform to the Uniform Guidelines on Employee Selection Procedures as set forth by the Equal Employment Opportunity Commission in 1978 (Chidester, et al., 2011).

Both methods of color vision assessment were used in the following experiment. Both tests allow the experimenter to assess the participant's color vision quantitatively with the CAD and qualitatively with the ATCOV. Color can be chosen so that individuals who were evaluated as color deficient can distinguish the color by selecting colors that do not lay along the same lines of color confusion for the three types of color deficiency. Testing can then be conducted to determine the distance threshold required for colors to be perceived as different for both
individuals that have color normal vision and color deficient vision. This testing will determine if color vision type, hue, and/or saturation affect noticeable difference threshold.

## Hypotheses

The primary focus of the research is to investigate the difference in discriminability between colors. It is predicted that the distance scores (DE) will be the same for all colors within both color vision groups(Hypotheses 1-2). We also expect that the difference between target and selected color to approximately 1 which is the just noticeable difference as predicted by the MacAdam ellipsis. It is expect our test will be sensitive to whether color discrimination is affected by color and saturation, Hypotheses 3-4. The tests specifically targets saturation by transitioning the sample colors through under-saturated and over-saturated conditions. Saturation is defined as the amount of opaqueness with in the color. A color that would appear faded when compared to the target color would be described as under-saturated while a color that was bolder when compared to the target color would be considered over-saturated. This differs from luminosity in that luminosity is the intensity of light. We predict that color saturation will have an effect on discrimination. Lastly, investigation of the affect color deficiency has on color discrimination. it is predicted that individuals with color deficient vision will have a delta e score for the selected colors high than those with normal color vision (Hypotheses 5). Those individual with color deficient vision should have greater difficulty discriminating colors that are similar due to proximity to color confusion lines.

## Color 1 vs. Color 2 vs. Color 3 vs. etc... Color n

1. It is hypothesized that there will be no difference in accuracy of color discrimination for those of color normal vision with dependence on target color. Individuals with normal color vision will be able to discriminate colors of similar shade to the same
accuracy for all shades of color. $(\mathrm{CNV}$ red $\mathrm{dE}=\mathrm{CNV}$ blue $\mathrm{dE}=\mathrm{CNV}$ green $\mathrm{dE}=$ etc.).
2. It is hypothesized that there will be no difference in accuracy of color discrimination for those of color deficient vision with dependence on target color. Individuals with color deficient vision will be able to discriminate colors of similar shade to the same accuracy for all shades of color. $(\mathrm{CDV}$ red $\mathrm{dE}=\mathrm{CDV}$ blue $\mathrm{dE}=\mathrm{CDV}$ green $\mathrm{dE}=$ etc.).

## White Start point vs. Black Start point

3. It is hypothesized that there will be no difference in accuracy of color discrimination for those of color normal vision with dependence of starting point being white or black. The ability to discriminate light hues from target color will be the equivalent to the ability to discriminate dark hues from target color for color normal individuals. $(\mathrm{CNV}$ Light dE $=\mathrm{CNV}$ Dark dE).
4. It is hypothesized that there will be no difference in accuracy of color discrimination for those of color deficient vision with dependence of starting point being white or black. The ability to discriminate light hues from target color will be the equivalent to the ability to discriminate dark hues from target color for color deficient individuals $($ CDV Light $\mathrm{dE}=\mathrm{CDV}$ Dark dE$)$ This hypothesis examines the difference in accuracy of color discrimination for those of color deficient vision with dependence of starting point being white or black.

## Color Normal Vision vs. Color Deficient Vision

It is hypothesized that there will be a difference in accuracy of color discrimination between those of color normal vision and color deficient vision based on individual color. Individuals with normal vision will be able to discriminate colors of similar shade more accurately than those with color deficient vision for all hues of color. (CNV red dE < CDV red dE, CNV green $\mathrm{dE}<\mathrm{CDV}$ green dE , etc.).

## Methods

## Participants

Participants were recruited from the student and staff population at Embry-Riddle University and the surrounding community. There were 38 total individuals who participated in the study; $78 \%$ were males and $22 \%$ were females. The average age was 24years. All participants were monetarily compensated for their time. Table 1 shows the number of individuals that were identified as color deficient based on the results of the CAD screening. All 38 individuals were tested in the CAD test in one room and then participants were tested on the ATCOV and the Color hue saturation test in an adjacent room, a large computer lab. Only the CAD was used for a determination of color deficiency. All subjects had visual acuity that was normal or correctable to normal as indicated by the Snellen test. Standard office lighting conditions were used for both adjoined rooms.

Table 1. Color deficiency was identified by the CAD test and the results of the ATCOV.

| Vision Rating | ATCOV |
| :--- | :--- |
| 04 Protan | 00 Passed |
| 06 Deutan | 05Passed |
| 00 Tritan | NA |
| 28 Normal Vision | 27 Passed |
| 38 Total | 32 Total |

## Apparatus

Both the ATCOV and Saturation tests were conducted on the following computers. The computers were Dell Optiplex 620's with 17" Dell UltraSharp LCD displays. Each display was calibrated using an x-rite iDisplay 2 Colorimeter to a color temperature of 6500 K and a luminance of $85.7 \mathrm{~cd} / \mathrm{m}^{2}$. The ambient lighting had a color temperature of 3000 K and a luminance of 360 Lux. The computers were setup in a computerized classroom. The room layout had six computers per row and three rows of desks all faced the same direction. The lighting conditions of the room were typical office lighting conditions. The CAD test was conducted on a Dell Latitude E5400 laptop with ViewSonic E70fSB crt monitor placed at seated eye level for each participant. Both were provided by and calibrated by the FAA. The room used to conduct the test was dimed to low lighting conditions.

## Design

The design of the experiment included 14 target colors shown in table 2 . Each color was tested twice with the exception of white and black. The tests had one of two starting conditions; white and black. Participants had their color vision diagnosed and be categorized as color normal or color deficient. The data collected during the experiment is the delta E value between the target color and the participant selected sample color for each test.

## Procedures

For the ATCOV test the participant was seated in front of the computer and was 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 performance. The results for this test were recorded by the computer and saved by the test administrator..

A more descriptive color diagnostic test was used in this research, the (CAD) test. 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 that was 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 in comparison to the Dvorine or Farnsworth testes, 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 hue saturation test was developed to determine color discrimination threshold for viewing colors displayed on an LCD screen. The test used a color palette suggested for use in FAA air traffic control displays (Table 2). These colors were determined empirically by using the color confusion lines and by using a dE greater than 20. The FAA also requested
that certain colors be examined such as red, amber and blue. Using the programing compiler Python, a program was developed to display a circle on a white background. The bottom half of the circle was set has the target color and the top half would start as white or black. The python code can be found in appendix B..

Table 2: Test colors, sRGB values, Lab values and sample

| Color name | sRGB value | Lab Value | Sample |
| :---: | :---: | :---: | :---: |
| Black | $(0,0,0)$ | $0,0,0$ |  |
| Gray | $(194,190,177)$ | $46.963,-0.886,7.05$ |  |
| Red | $(255,60,60)$ | $56.898,71.611,46.478$ |  |
| Amber | $(255,191,0)$ | $81.028,10.386,83.036$ |  |
| Blue | $(30,80,200)$ | $38.17,29.491,-66.73$ |  |
| Green | $(162,240,2)$ | $87,-51.198,84.039$ |  |
| Rudd | $(165,50,50)$ | $38.744,47.03,27.144$ |  |
| Light Blue | $(0,163,255)$ | $64.495,-2.244,-55.242$ |  |
| Brown | $(87,73,65)$ | $32.197,4.468,6.981$ |  |
| Cyan | $(74,255,255)$ | $91.773,-43.795,-13.089$ |  |
| Purple | $(189,74,206)$ | $52.032,63.687,-47.094$ |  |
| Yellow | $(242,242,85)$ | $93.031,-18.406,72.555$ |  |
| Teal | $(0,175,192)$ | $65.331,-30.87,-19.261$ |  |
| White | $(255,255,255)$ | $100, .005,-.01$ |  |

The participant would indicate whether or not the colors on the top half and bottom half of the circle matched. The test was design in this fashion to be similar to the design used by MacAdam. The major difference being that the apparatus used is a LCD screen in this experiment and not a beam of light through a prism as in the MacAdam study. If the participant indicated that the colors did not match, the color would slightly change in the direction of the target color in the color space by changing all three R, G, B values. The amount of change was randomized by the program. Participants were not timed and could take as long as they need to indicate whether the colors matched. This process would continue until the colors were identical or the participant indicated that they matched as depicted in figure 8 . When the participant
indicated that the colors matched, the sRGB values for the colors were recorded. If the participant indicate that two identical colors were not a match the program recorded this as an error. The data from the participants would who are unable to identify that the two colors were similar were excluded from the analysis. This process was repeated for all 12 colors starting with both white and black starting points with the exception in the cases where white and black were the target color. With the known sRGB values for target color, and indicated match color, researchers used the Openrgb program to convert the sRGB values into the Lab values and calculate the dE 2000 . The dE 2000 value calculated indicated the distance from the target the participant indicated the matching color was. Due to a low number of color deficient individuals in a population, a randomly selected group of color normal participant was selected to be compared to the color deficient individuals of equal number.


Figure 8: Color Saturation test, demonstration of how the colors transitioned from starting points to target

## Results

The data collected shown in figure 9 and figure 10 shows a graph of the mean dE and standard deviation for each color based on vision type. From this graph, it can be clearly seen that the dE threshold for black ( $C N v: M=17.34, s t d=5.56)(C D V: M=19.40, s t d=8.67)$ is much greater any other color for both color normal and color deficient participant groups. The mean scores for both participant groups are located in table 3 for the white starting point and table 4 for the black starting point.


Figure9: Graph of mean and standard deviation of CNV for each color.

Table 3: Mean and Standard devation of delta E values form white starting point

|  | Color deficient | Color normal | Std Color <br> deficient | Std Color <br> normal |
| :--- | :---: | :---: | :---: | :---: |
| Gray | 19.4 | 17.51 | 8.67 | 5.56 |
| Red | 3.08 | 1.61 | 1.62 | 1.06 |
| Amber | 2.09 | 2.05 | 1.18 | 1.69 |
| Blue | 1.76 | 0.81 | 1.66 | 0.69 |
| Green | 1.9 | 0.99 | 3.2 | 1.05 |
| Rudd | 1.74 | 1.12 | 1.03 | 0.82 |
| Light Blue | 1.61 | 2.15 | 1.62 | 1.93 |
| Brown | 1.79 | 1.42 | 1.58 | 1.39 |
| Cyan | 2.55 | 0.63 | 2.27 | 0.76 |
| Purple | 1.2 | 0.67 | 0.62 | 0.68 |
| Yellow | 0.97 | 0.82 | 0.89 | 1.54 |
| Teal | 1.17 | 0.79 | 0.86 | 0.84 |

An ANOVA statistical analysis was conducted with both sets of data, independently. The analysis detected a significant amount of variance within the sample $(\operatorname{CNV}: F(25,415)=22.73$, $p<0.001$; $C D V: F(25,181)=13.52, p<0.001)$. A post hoc Tukey's HSD was performed to investigate the cause of the variance. The Tukey's test indicated that the delta E threshold for black is significantly greater than any other color tested as seen in table 5 of CNV and table 6 for CDV. The Tukey's post hoc test also indicated that there are no significant differences in delta E between any other colors. The ANOVA analysis of the effect of color saturation showed no significant difference in delta E for both CNV and CDV .

| Table 4: Mean and Standard deviation of delta E values form black starting point |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: |
|  | Color <br> deficient | Color <br> normal | Std Color <br> deficient | Std Color <br> normal |
| White | 4.25 | 2.14 | 3.25 | 2.49 |
| Gray | 1.32 | 0.57 | 2.13 | 0.66 |
| Red | 2.88 | 2.7 | 1.89 | 2.78 |
| Amber | 3.57 | 1.17 | 4.17 | 1.2 |
| Blue | 0.67 | 2.34 | 0.84 | 7.32 |
| Green | 4.06 | 0.63 | 6.22 | 1.03 |
| Rudd | 2.9 | 1.93 | 4.29 | 2.21 |
| Light Blue | 2.73 | 0.94 | 2.62 | 1.35 |
| Brown | 4.62 | 2.17 | 7.18 | 2.99 |
| Cyan | 4.95 | 1.59 | 4.27 | 1.76 |
| Purple | 3.28 | 0.91 | 5.46 | 1.58 |
| Yellow | 3.52 | 0.58 | 6.91 | 0.67 |
| Teal | 1.88 | 1.04 | 3.91 | 0.96 |

Table 5: Color Normal Vision Tukey’s HSD results

|  | Mean <br> Difference (I- <br> (I) Color |  |  |  |
| :--- | :--- | :--- | :--- | :--- |
| (J) Color | Std. Error | Sig. |  |  |
| Black | Cyan | $16.2825^{*}$ | .94239 | .000 |
|  | Purple | $16.3169^{*}$ | .94239 | .000 |
|  | yellow | $16.3244^{*}$ | .94239 | .000 |
|  | Teal | $15.7694^{*}$ | .94239 | .000 |
|  | White | $14.9538^{*}$ | .94239 | .000 |
|  | Grey B | $16.5369^{*}$ | .94239 | .000 |
|  | Red B | $14.2369^{*}$ | .94239 | .000 |
|  | Amber B | $15.7888^{*}$ | .94239 | .000 |
|  | Blue B | $13.8119^{*}$ | .94239 | .000 |
|  | green B | $16.5075^{*}$ | .94239 | .000 |
|  | Grey | $15.5875^{*}$ | .94239 | .000 |
|  | Rudd B | $14.8819^{*}$ | .94239 | .000 |
|  | Light Blue B | $16.0963^{*}$ | .94239 | .000 |
|  | Brown B | $15.3525^{*}$ | .94239 | .000 |
|  | Cyan B | $15.6413^{*}$ | .94239 | .000 |
|  | Purple B | $16.1613^{*}$ | .94239 | .000 |
|  | Yellow B | $16.6863^{*}$ | .94239 | .000 |
|  | Teal B | $16.0406^{*}$ | .94239 | .000 |
|  | Red | $14.7856^{*}$ | .94239 | .000 |
|  | Amber | $16.3238^{*}$ | .94239 | .000 |
|  | Blue | $16.2119^{*}$ | .94239 | .000 |
| Green | $15.8300^{*}$ | .94239 | .000 |  |
|  | Rudd | $14.8706^{*}$ | .94239 | .000 |
| light Blue | $15.6681^{*}$ | .94239 | .000 |  |
| Brown | $16.7356^{*}$ | .94239 | .000 |  |



Figure 10: Graph of mean dE and standard deviation for color deficient participants.

A MANOVA analysis was conducted to compare CNV and CDV as seen in Figure 11. The results of the MANOVA indicated that CDV performed significantly different with higher delta E on only two colors (Brown Starting from White: $F(1,13)=5.55, p=0.036$; Cyan Starting From Black: $F(1,13)=6.828, p=0.023)$. There is no significance in the difference in delta E for Brown starting from black or Cyan starting from white between CNV and CDV. Overall no significant difference in color discriminability was detected between CNV and CDV for all color comparisions.


Figure 11: Graph comparison of mean dE and standard deviation between color normal and color deficient

These results can be used to determine design tolerances and criteria. Since it has been fully demonstrated that color discrimination is nearly independent of color and saturation, a broader color selection can be chosen. Choosing colors only requires that the color not be located along a color confusion line with another color and to be a defined distance from other colors in the color space. According to the results of this research, the defined tolerance distance is a delta E of 9.2, $(M=1.63, S D=2.52)$ this tolerance is inclusive of 99.7 percent of the population for all colors except Black. The tolerance for black is a delta E of 36.9 ( $M=18.31, S D=6.21$ ). With these two tolerances defined, designers will be able to select color and be confident that the colors will be significantly different on a LCD display.

Table 6: Color Deficient Vision Tukey's HSD results

|  | Mean <br> Difference (I- |  |  |  |
| :--- | :--- | :---: | :---: | :---: |
| (I) Color | (J) Color | J) | Std. Error | Sig. |
| Black | Cyan | $19.7600^{*}$ | 1.47373 | .000 |
|  | Purple | $19.9543^{*}$ | 1.47373 | .000 |
|  | yellow | $19.9300^{*}$ | 1.47373 | .000 |
|  | Teal | $19.1514^{*}$ | 1.47373 | .000 |
|  | White | $16.6471^{*}$ | 1.47373 | .000 |
|  | Grey B | $20.1443^{*}$ | 1.47373 | .000 |
|  | Red B | $18.0743^{*}$ | 1.47373 | .000 |
|  | Amber B | $18.8329^{*}$ | 1.47373 | .000 |
|  | Blue B | $20.3614^{*}$ | 1.47373 | .000 |
|  | green B | $17.5029^{*}$ | 1.47373 | .000 |
|  | Grey | $17.8514^{*}$ | 1.47373 | .000 |
|  | Rudd B | $18.4171^{*}$ | 1.47373 | .000 |
|  | Light Blue | $18.7686^{*}$ | 1.47373 | .000 |
|  | B |  |  |  |
|  | Brown B | $17.4143^{*}$ | 1.47373 | .000 |
|  | Cyan B | $16.6729^{*}$ | 1.47373 | .000 |
|  | Purple B | $18.4386^{*}$ | 1.47373 | .000 |
|  | Yellow B | $19.5000^{*}$ | 1.47373 | .000 |
|  | Teal B | $18.8300^{*}$ | 1.47373 | .000 |
| Red | $18.9357^{*}$ | 1.47373 | .000 |  |
|  | Amber | $19.4929^{*}$ | 1.47373 | .000 |
| Blue | $19.9571^{*}$ | 1.47373 | .000 |  |
| Green | $19.3686^{*}$ | 1.47373 | .000 |  |
|  | Rudd | $19.5186^{*}$ | 1.47373 | .000 |
| light Blue | $19.1257^{*}$ | 1.47373 | .000 |  |
| Brown | $18.3057^{*}$ | 1.47373 | .000 |  |
|  |  |  |  |  |

## Discussion

From this research two major conclusions can be made; the first being that an individual with color deficient vision are able to discriminate colors to the same level as individuals with color normal vision. That is to say that an individual with color deficient vision will be able to identify two shades of red as different to the same degree as an individual with color normal vision. The second conclusion is that the threshold for being able to tell when colors are different is dE200 greater than 9.2 for colors and 36.7 for black for color depicted on an LCD screen. These threshold values are important design criteria for determining if two colors can be distinguished from one another by both individuals with normal color vision and deficient color vision.

Prior Research

The colors selected to test were decided by a previous FAA study that used a match to sample method coupled with application. In that research, participants were asked to identify color blocks or text that matched the sample color or text. The researchers then kept colors that were confused equal to or less than two times. The set of colors that passed this test are seen in figure 12 (French, 2011).

| Color name | sRGB value | Lab Value | Sample |
| :---: | :---: | :---: | :---: |
| Black | $(0,0,0)$ | $0,0,0$ |  |
| Gray | $(194,190,177)$ | $46.963,-0.886,7.05$ |  |
| Red | $(255,60,60)$ | $56.898,71.611,46.478$ |  |
| Blue | $(30,80,200)$ | $38.17,29.491,-66.73$ |  |
| Green | $(162,240,2)$ | $87,-51.198,84.039$ |  |
| Cyan | $(74,255,255)$ | $91.773,-43.795,-13.089$ |  |
| Purple | $(189,74,206)$ | $52.032,63.687,-47.094$ |  |
| Yellow | $(242,242,85)$ | $93.031,-18.406,72.555$ |  |
| Teal | $(0,175,192)$ | $65.331,-30.87,-19.261$ |  |
| White | $(255,255,255)$ | $100, .005,-.01$ |  |

Figure 12. The recommended colors for displays using a white background. The RGB and the CIE-31 values are shown for the 9 color candidates on a white background. The colors were not confused by $100 \%$ of the participants. If the background is white, this is the color palette to use (French, 2011).

Brown was exclued form the final list because the delta E between brown and black is $\mathrm{dE}(00)=$ 22.83 , being less that the tolerance for black. A table of delta E distances between test color can be found in appendix C. Rudd should have been excluded for the same reason having a $\mathrm{dE}(00)$ $=36.7$ from black, however the color rudd was confused with was red having a $\mathrm{dE}(00)=19.5$ between them in the French 2011 experiment. Similar reasoning cannot be applied to the colors light blue and amber. Neither color had delta E values less than the tolerance when compared to the color set. For light blue, the closest color in the set is teal with a $\mathrm{dE}(00)=20.42$, and for amber the closest color is yellow with a $\mathrm{dE}(00)$ of 18.41 . The prior study has excluded colors because of confusion with each other whose $\mathrm{dE}(00)=32.93$ (light blue and cyan (French, 2011)) but keep two colors whose $\mathrm{dE}(00)=13.01$ (green and yellow) because of no confusion. This result seems contradictory because by definition delta E is the difference between colors and that the greater the delta E is the greater in difference to two colors should appear thus reducing confusion.

## Applications

Our world is ever expanding with information; each day we are bombarded with signals, posters, advertisements, warnings, directions, and other forms of communication. For most individuals, sight is the primary sense of perception. Through this sense, humans have devised many ways to visually communicate. The use of color to convey information is as old as cave paintings. Bold red text to indicate danger, imagery of light blue sky, and rich green meadows to allude to peace and serenity, are uses of color as a tool to transmit information. For 8\% of the population, this form of communication loses its effectiveness. The red bold text blends into the black text on the warning label for individuals that are protanopes, the rich green meadow appears as a dull brown to deuteranopes, and the light blue sky may be a stormy gray to tritanopes. The knowledge of color palettes that can be used to convey the same information to individuals that have color deficient vision, as those that have color normal vision, are of vast importance to advertisers, warning labels, web design, computer-software interface design, and safety management.

Studies have been conducted for the advertising industry to investigate the issues those with color deficient vision have with modern advertising. A list of common issues contains problems such as inability to distinguish foreground text from background color, confusion of information with color combinations, and ineffectiveness of attention grabbing colors. From researching this design, suggestions have been proposed. One such suggestion is to test color samples for ads with color deficient individuals (Kaufman-Scarborough, 2001). Since this population is fairly low, a computer research team has developed a program that is able to convert a normal picture into the same picture as seen by a color deficient individual as seen in figure 13. In 1988, researchers used the Farnsworth d100 test to compose a color analogue of
each color deficiency with the aid of a computer they were able to alter an image to appear as would to a color deficient individual (Meyer \& Greenberg, 1988). Further studies have yielded a computational algorithm that filters out colors that color deficient individual are unable to see and replace them with one they can see. This algorithm is performed with a computer program known as MATLAB and was used to produce figure 13 (Jefferson \& Harvey, 2006).The limiting factor of these two methods is that designers are unable to test color combination on the fly. Each design would have to be tested for color deficient compatibility for each of the color deficient types and then altered and retested. Another approach would be to apply the color algorithms directly to the application in which the design was created or by allowing the end user to adjust the color settings to compensate for the color deficiency. Both methods still contain the drawback of requiring three different setting for each of the color deficient palettes (Troiano, Birtolo, \& Miranda, 2008) (Vienot, Brettel, \& Mollon, 1999).


Figure 13. 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). (Jefferson \& Harvey, 2006). Copyright 2008 by Association for Computing Machinery.

One industry that relies heavily on the ability to perceive color is the aviation industry. This has become increasingly prevalent with the increase in glass cockpit designs and the development of next generation air traffic control software. Systems, such as highway in the sky programs for flight path information, rely heavily on color coded information. Such a system would use a combination of background colors with foreground informational color such systems would require a high level of separation between background and foreground in order to maintain low levels of confusion (Beringer, 2000). Pilots are required to have normal color vision. This has led the FAA to standardize the color vision requirements and color display requirement for flight systems (Barbur, Rodriguez-Carmona, Evans, \& Milburn, 2009).

However, individuals that may only pose a mild deficiency in color vision, or that have anomalous trichromatic vision, may be able to pass some color vision test. Because of this, the display and system must be robust enough to allow for these individuals, with mild color deficiency. The FAA is currently developing a color palette to use for air traffic control that is to be robust enough for these individual to be able to perform their assigned tasks. The development of this palette takes into account color distance and the three sets of color confusion lines. From these criterions, a set of 12 distinct colors has been suggested (French, 2011; Abeyta, 2011).

The military has its own needs and uses for color vision research. As more computer displays enter combat zones, they rely on color coded information to relay real time information to commanders. This color coded information needs to be easily understood by the user in high stress situations. Confusion, as to the meaning of a color, or the inability to see a color, could lead to horrific consequences (Kopala, 1979). Much like civil aviation, military aviation has similar concerns. The addition consideration is vision during high G-force maneuvers. During
these maneuvers, human vision is affected. Individuals with mild color deficiency may have their condition exacerbated by high G-force maneuvers because cyan merges with white at 0.9 G below blackout while green merges with yellow at 0.7 G below blackout (Chelette, et al., 1999). The military has also set design standards that set uniform criterion defined in the CIE 1931 color space but do not limit design creativity (Department of Defense, 1999).

## Conclusion

The world is seeing a revolution in computer technology where displays are getting smaller, lighter, and cheaper. This revolution is coupled with a desire for people to stay connected to information nearly constantly. GPS systems are becoming a standard feature of transportation, smartphones and tablet pc's are increasing in number and capability. These advancements are all dependent on LCD technology. The design of media to be displayed on these systems has yet to take into account those with color deficient vision. Dense information systems are in many other places-- power plants, train stations, stock market-- all of which must make color coded information needs to be clearly discriminable. The tolerances found by this research will assist graph designers and user experience designers decide what colors they are able to use to convey the highest amount of information clearly. More research is needed to discover those colors that highlight information for color deficient individuals in the same fashion that bright red stands out in normal color vision.

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## Appendices

## Appendix A: Delta E equation

$$
\begin{aligned}
& \Delta E=\sqrt{\left(\frac{\Delta L^{\prime}}{K_{L} S_{L}}\right)^{2}+\left(\frac{\Delta C^{\prime}}{K_{C} S_{C}}\right)^{2}+\left(\frac{\Delta H^{\prime}}{K_{H} S_{H}}\right)^{2}+R_{T}\left(\frac{\Delta C^{\prime}}{K_{C} S_{C}}\right)\left(\frac{\Delta H^{\prime}}{K_{H} S_{H}}\right)} \\
& \bar{L}^{\prime}=\left(L_{1}+L_{2}\right) / 2 \\
& C_{1}=\sqrt{a_{1}{ }^{2}+b_{1}{ }^{2}} \\
& C_{2}=\sqrt{a_{2}{ }^{2}+b_{2}{ }^{2}} \\
& \bar{C}=\left(C_{1}+C_{2}\right) / 2 \\
& G=\left(1-\sqrt{\frac{\bar{C}^{7}}{\bar{C}^{7}+25^{7}}}\right) / 2 \\
& a_{1}^{\prime}=a_{1}(1+G) \\
& a_{2}^{\prime}=a_{2}(1+G) \\
& C_{1}^{\prime}=\sqrt{a_{1}^{\prime 2}+b_{1}{ }^{2}} \\
& C_{2}^{\prime}=\sqrt{a_{2}^{\prime 2}+b_{2}{ }^{2}} \\
& \bar{C}^{\prime}=\left(C_{1}^{\prime}+C_{2}^{\prime}\right) / 2 \\
& h_{1}^{\prime}= \begin{cases}\tan ^{-1}\left(b_{1} / a_{1}^{\prime}\right) & \tan ^{-1}\left(b_{1} / a_{1}^{\prime}\right) \geq 0 \\
\tan ^{-1}\left(b_{1} / a_{1}^{\prime}\right)+360^{\circ} & \tan ^{-1}\left(b_{1} / a_{1}^{\prime}\right)<0\end{cases} \\
& h_{2}^{\prime}= \begin{cases}\tan ^{-1}\left(b_{2} / a_{2}^{\prime}\right) & \tan ^{-1}\left(b_{2} / a_{2}^{\prime}\right) \geq 0\end{cases} \\
& \bar{H}= \begin{cases}\left(h_{1}^{\prime}+h_{2}^{\prime}+360^{\circ}\right) / 2 & \left|h_{1}^{\prime}-h_{2}^{\prime}\right|>180^{\circ} \\
\left(h_{1}^{\prime}+h_{2}^{\prime}\right) / 2 & \left|h_{1}^{\prime}-h_{2}^{\prime}\right| \leq 180^{\circ}\end{cases} \\
& T=1-0.17 \cos \left(\bar{H}^{\prime}-30^{\circ}\right)+0.24 \cos \left(2 \bar{H}^{\prime}\right)+0.32 \cos \left(3 \bar{H}^{\prime}+6^{\circ}\right)-0.20 \cos \left(4 \bar{H}^{\prime}-63^{\circ}\right) \\
& \Delta h^{\prime}= \begin{cases}h_{2}^{\prime}-h_{1}^{\prime} & \left|h_{2}^{\prime}-h_{1}^{\prime}\right| \leq 180^{\circ} \\
h_{2}^{\prime}-h_{1}^{\prime}+360^{\circ} & \left|h_{2}^{\prime}-h_{1}^{\prime}\right|>180^{\circ} ; h_{2}^{\prime} \leq h_{1}^{\prime} \\
h_{2}^{\prime}-h_{1}^{\prime}-360^{\circ} & \left|h_{2}^{\prime}-h_{1}^{\prime}\right|>180^{\circ} ; h_{2}^{\prime}>h_{1}^{\prime}\end{cases}
\end{aligned}
$$

$\Delta L^{\prime}=L_{2}-L_{1}$
$\Delta C^{\prime}=C_{2}^{\prime}-C_{i}^{\prime}$
$\Delta H^{\prime}=2 \sqrt{C_{1}^{\prime} C_{2}^{\prime}} \sin \left(\Delta h^{\prime} / 2\right)$
$S_{L}=1+\frac{0.015\left(\bar{L}^{\prime}-50\right)^{2}}{\sqrt{20+\left(\bar{L}^{\prime}-50\right)^{2}}}$
$S_{C}=1+0.045 \bar{C}$.
$S_{H}=1+0.015 \bar{C}^{\prime} T$
$\Delta \theta=30 \exp \left\{-\left(\frac{\bar{H}^{\prime}-275^{\circ}}{25}\right)^{2}\right\}$
$R_{C}=2 \sqrt{\frac{\bar{C}^{17}}{\bar{C}^{7}+25^{7}}}$
$R_{T}=-R_{C} \sin (2 \Delta \theta)$
$K_{L}=1 \quad$ default
$K_{C}=1 \quad$ default
$K_{H}=1 \quad$ default

## Appedix B: Color Saturation test

```
from Tkinter import *
import tkMessageBox
import random
import sys
import csv
global outfileStr
global entryWidget
```

class colorCircleWindow(Tk):
\#Create A Window and save parent Tk
def __init__(self,parent,list):
\#Initialize tkinter frame
Tk.
_init_
(self,parent)
self.parent $=$ parent
self.colList $=$ list[:]
self.numCol $=0$;
def setUserCode(self):
print self.uCode.get()
self.ofile = open(self.uCode.get()+'_results.csv','wb')
self.initialize()
def getUserCode(self):
self.top $=$ self.parent
Label(self.top,text="Enter Your Participant Number").pack()

```
    self.uCode = Entry(self.top,width=50)
    self.uCode.pack()
    submit = Button(self.top,text="Submit",command=self.setUserCode)
    submit.pack()
```

\#Add app specifics here
def initialize(self):
\#Use a grid layout
self.grid()
\#Create canvas for circles
drawSurface $=$ Canvas(self,height $=650$, width $=1000, \mathrm{bg}=$ "white" $)$
drawSurface.grid(column=0,row=0,rowspan=1,columnspan=2)
\#Choose Colors
self.setColors()
topCol $=$ "\#\%02x $\% 02 \mathrm{x} \% 02 \mathrm{x} " \%$ self.topColor
botCol $=$ "\#\%02x\%02x $\% 02 \mathrm{x} " \%$ self.botColor
self.topStart $=$ self.topColor
self.botStart $=$ self.botColor
\#set the number of test
self.numTest $=0$;
self.maxTest $=$ len(self.colList)-1;
\#create arcs
circlePos $=350,150,650,450$
topArc $=$
drawSurface.create_arc(circlePos,start=0,extent=180,style=CHORD,fill=topCol,outline="")
bottomArc =
drawSurface.create_arc(circlePos,start=180,extent=180,style=CHORD,fill=botCol,outline="")

```
#Create Buttons
yesButton = Button(self,text=u"Yes",command=self.onYesPress)
noButton = Button(self,text=u"No",command=self.onNoPress)
```

\#Add buttons to grid
yesButton.grid(column=0,row=2)
noButton.grid(column=1,row=2)
\#Add Label
label = Label(self,text="Do the colors match?")
label.grid(column $=0$,row $=1$,columnspan $=2$,rowspan $=1$ )
\#configure row/column size
self.columnconfigure $(0$, minsize $=100)$
self.columnconfigure $(1$, minsize $=100)$
self.drawSurface $=$ drawSurface
self.topArc $=$ topArc
self.botArc $=$ bottomArc
self.resultWriter $=\operatorname{csv}$. writer(self.ofile)
self.resultWriter.writerow(['Top Color','End Top Color','Bottom Color']);

```
def setColors(self):
    if self.numCol < 13:
        self.topColor = int(255),int(255),int(255)
    else:
        self.topColor = int(0),int(0),int(0)
    self.botColor = self.colList[self.numCol]
    self.numCol = self.numCol + 1
def adjTopColor(self,r,g,b):
    self.topColor = tuple([sum(pair) for pair in zip(self.topColor,(r,g,b))])
    topCol = "#%02x%02x%02x"%self.topColor
    self.drawSurface.itemconfigure(self.topArc,fill=topCol)
def newOne(self):
    if ( self.numTest < self.maxTest ):
        #print "\n\nNew Color Circle Generated"
        self.setColors()
        topCol = "#%02x%02x%02x"%self.topColor
        botCol = "#%02x%02x%02x"%self.botColor
        self.topStart = self.topColor
        self.botStart = self.botColor
        self.drawSurface.itemconfigure(self.topArc,fill=topCol)
```

self.drawSurface.itemconfigure(self.botArc,fill=botCol)
self.numTest $+=1$
else:
print "Thanks for playing!"
self.ofile.close()
sys.exit()
self.destroy()
def printWrong(self):
\#print "Wrong\nStarting:"
\#print self.topStart
\#print self.botStart
\#print "Ending:"
\#print self.topColor
self.resultWriter.writerow([self.topStart,self.topColor,self.botStart])
def onNoPress(self):
\#Adjust this to make it more color aware and tween
\#along the lines that are important to the test
red $=$ self.botColor[0] - self.topColor[0]
grn = self.botColor[1] - self.topColor[1]
blu $=$ self.botColor[2] - self.topColor[2]
redrand $=\operatorname{int}(50 *$ random.random())+1
grnrand $=\operatorname{int}(50 *$ random.random())+1
blurand $=\operatorname{int}(50 *$ random.random())+1
if ( $\mathrm{red}==0$ and grn $==0$ and blu == 0 ):
self.resultWriter.writerow([self.topStart,self.topColor,self.botStart, "Error" ])
self.newOne()
return
if (red $==0$ ):
pass
$\operatorname{elif}(\operatorname{int}(\operatorname{abs}($ red $) /$ redrand $)<1)$ :
if ( red $>0$ ):
red $=1$
else:

$$
\text { red }=-1
$$

else:

$$
\text { red }=\text { red } / \text { redrand }
$$

if $($ grn $==0)$ :
pass
elif $(\operatorname{int}(\operatorname{abs}($ grn $) /$ grnrand $)<1):$
if ( grn > 0 ):
$\mathrm{grn}=1$
else:

$$
\operatorname{grn}=-1
$$

else:
grn $=$ grn/grnrand

```
        if ( blu == 0):
        pass
        elif ( int(abs(blu)/blurand) < 1 ):
            if (blu > 0):
                blu = 1
            else:
                blu = -1
        else:
            blu = blu/blurand
        self.adjTopColor(red,grn,blu)
    def onYesPress(self):
        if ( self.topColor == self.botColor):
            self.resultWriter.writerow([self.topStart,self.topColor,self.botStart, "Same"])
        else:
            self.resultWriter.writerow([self.topStart,self.topColor,self.botStart])
        self.newOne()
if
        __name__ == "_
```

$\qquad$

``` ":
    inf = open('TargetColors.csv','rb')
    colors=csv.reader(inf);
    colList = []
    for colorTuple in colors:
        colParts = colorTuple[0].split(',')
```

$\operatorname{red}=\operatorname{int}(\operatorname{colParts[0]}) ;$ blue $=\operatorname{int}(\operatorname{colParts[1]}) ;$ green $=\operatorname{int}(\operatorname{colParts[2]})$;
colList.append((red, blue, green))
inf.close()

```
\#print colList
colorTest \(=\) colorCircleWindow(None,colList)
colorTest.title('Color Sturation Test')
colorTest.getUserCode()
```

\#keeps the app persistent
colorTest.mainloop()

## Appendix C: Table of dE2000 distances between test colors



