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What You See Isn't Always What You Get: An Evaluation of Color Differences Across Different Devices

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What You See Isn't Always What You Get:
An Evaluation of Color Differences Across Different Devices

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ABSTRACT

The objective of this thesis was to examine color differences between different digital devices such as, phones, tablets, and monitors. New technology has always been the catalyst for growth and change within the printing industry. With gadgets like the iPhone and the iPad becoming increasingly more popular in the recent years, printers have yet another technological advancement to consider. Soft proofing strategies use color management technology that allows the client to view their proof on a monitor as a duplication of how the finished product will appear on a printed piece of paper. A possible problem can occur if clients are not using a calibrated monitor to view proofs.. Today's generation is obsessed with new technology and more importantly convenience. As the printing industry continues to evolve it is critical to consider the devices that clients are using to view proofs and the possible color differences that exist between those devices.

Within this thesis the following questions were the basis of the research:

- Do color differences exist between the phones, tablets, and monitors?
- If color differences are present, what is the Delta-E value compared to the standard?
- Do specific colors produce higher Delta-E values?
- Are certain brand devices more color accurate than others?

DEDICATION

I dedicate my thesis work my family and friends who I like to refer to as “my loves.” I would like to extend a special feeling of gratitude to my parents, Cynthia and Elmo Lewis, my sisters, Craijetta and Craijece Lewis, my niece and nephew, Christian and Craijaun Lewis, my aunt and uncle, Linda and Daniel Wyche, and my best friend Jessica James whose encouraging words, love, and support have been the fuel to my success. You guys are the reason why I work so hard. You all always support everything I do and I am forever grateful for that.

To my beautiful mother, you have helped me become the woman I am today. I thank you for instilling in me at a young age the importance of an education. Thank you for always being supportive of all my endeavors. You have always been my biggest cheerleader. I thank God for giving me a praying mother who knows and taught me to know that all things are possible through Christ. I would not be here if it wasn’t for you. I love you more than words can say. Thank you.

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Besides my advisor, I would like to thank the rest of my thesis committee. Dr. Weisenmiller and Professor Kern Cox. Your willingness to join my committee was greatly appreciated. You both were very kind, patient, and always willing to help. Words cannot express how much I appreciated your encouragement, insightful comments, and questions. This has been an arduous yet rewarding journey and I thank you all for helping make it through.

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CHAPTER ONE

INTRODUCTION

Color can be perceived differently from one person to the next (Beals 2002). Many factors can attribute to the presence of color differences. The first factor is light–the available illuminant in a specific environment. Light enables us to perceive color. Different wavelengths of light allow us to “see” what we know as color. Another factor that contributes to how people view color is the substrate it’s on. Color on a monitor will look differently compared to color on paper or a t-shirt (Color 2010). In order to keep color communication consistent and repeatable color can be assigned a specific number, which it can be identified by.

Color sensations are a function of human perception. Scientists have developed color spaces to represent how people perceive color. LAB is a color model that is perceptually uniform allowing change in color to produce the same amount of change visually (Bruno 2005). In the LAB color model the L component represents how light or dark the color is, the A component represents how green or red the color is, and the B component represents how blue or yellow the color is. People can define color numerically and visually through the LAB color model (Color 2010). The advantage of this color space is that it most accurately defines color the way the human eye sees color. These LAB values are gathered by measuring the color using a spectrophotometer.

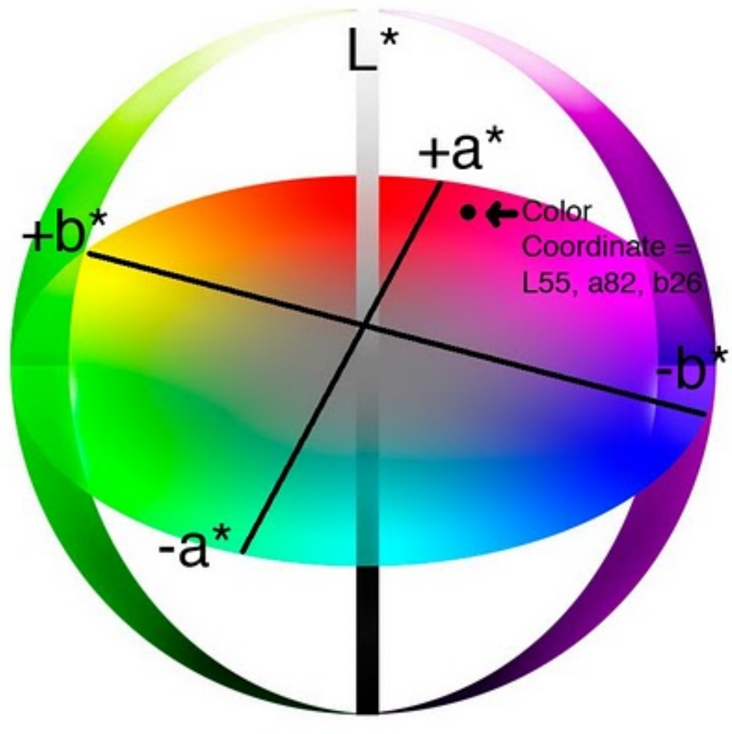

Figure 1: CIE L*a*b Color Model (Pritchard 2010)

When a color sample has been measured with LAB values obtained a Delta-E value can be produced. The measured color can be compared to a reference color. The Delta-E value shows how much difference there is between two colors and reveals how well a color has been duplicated. A Delta-E value of 1.0 is accepted as barely noticeable to the trained eye.

In the printing industry it is important to be able to reproduce color effectively. Printers use proofs to show their clientele how the color of a requested product will appear. The proof serves as a contract between the client and the printer. The client expects the proof to match finished product. The long-accepted and approved proofing method used are hard proofs. A hard proof is a proof that is on paper or other specified substrates. Currently many commercial printing companies use soft proofing. Soft proofing allows color accurate proofs to be viewed on a calibrated, (marked with standard readings) monitor (Hinderliter 2004). The problem with soft proofing is it doesn’t take into consideration other devices clients may use to view proofs. iPhones and iPads are becoming more popular and used more frequently to accomplish tasks that were once solely completed with computers. There is an emerging opportunity to utilize these devices for proofing–the questions of accuracy and reproducibility must be addressed.

CHAPTER TWO

THE PERCEPTION OF COLOR

In order to better understand how color is reproduced, one must first understand how color is perceived. Three elements must be present in order for color to exist: light, an object, and the observer. Light is energy that creates different wavelengths. The object absorbs and reflects light, without the object only white light would exist. The observer recognizes the wavelengths of light as color (X-rite 2005). Color and the communication of color can become very complex. Scientists have come up with different methods to help quantify, measure, and communicate color. When evaluating color it helps to start with the primaries; additive primaries and subtractive primaries are typically discussed. The additive primaries are red, green, and blue. The subtractive primaries used in print are cyan, magenta, and yellow (Field 2004). There are 3 dimensions involved in describing the appearance of these primaries or any other color. Those dimensions are hue, saturation, and lightness. Hue simply means what the color is, such as green, blue, or red. Saturation describes how vivid or dull a color appears to be. The lightness of a color depicts how dark or light the color is (X-rite 2005). Spectral data and tristimulus data are two other terms used to describe the appearance of color. Spectral data describes how the object absorbs or reflects light. Tristimulus data describes how the observer or sensor perceives the color of the object (Evans 1974). The International Commission on Illumination (CIE) is responsible for creating standards color spaces and lighting conditions to help make communicating color easier. In 1931 the CIE XYZ and the standard observer, the CIE LAB, and the CIE LCH were established to represent the visible spectrum (Field 2004). These color spaces assign a numerical value to color.

Defining lighting conditions is also an important part to understanding color perception. CIE established Illuminant A, a color temperature of about 2856°K, Illuminant B, direct sunlight at about 4874°K, and Illuminant C, indirect sunlight at about 6774°K. While all of these components help make up how color is perceived, it all starts with the eye.

"Color vision and color perception are unique subjects in several respects. First, they deal with one of the major sense receptors of the body, the eye, and its primary stimulus light" (Evans 1974). How the eye views color is very unique. The entire back half of the eye is made up of cells and neurons known as the retina. Rods and cones are cells that are sensitive to light–cones detect color and rods detect light. The fovea is the central part of the retina that contains cells with the sharpest color vision (Field 2004). Cones respond differently to various frequencies of light. The following diagrams illustrate the spectral response of the cones and the structure of the human eye.

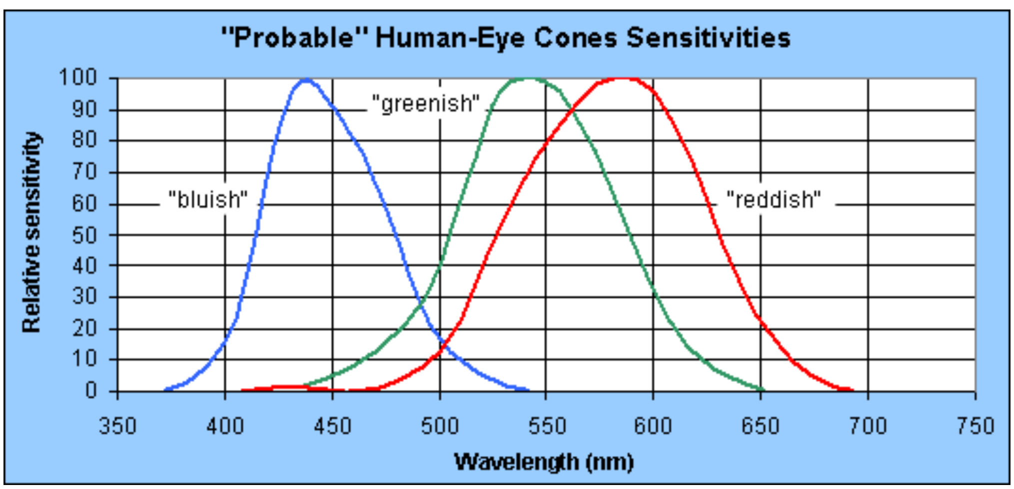

Figure 1.1 Cone Sensitivities (Pascale 2004)

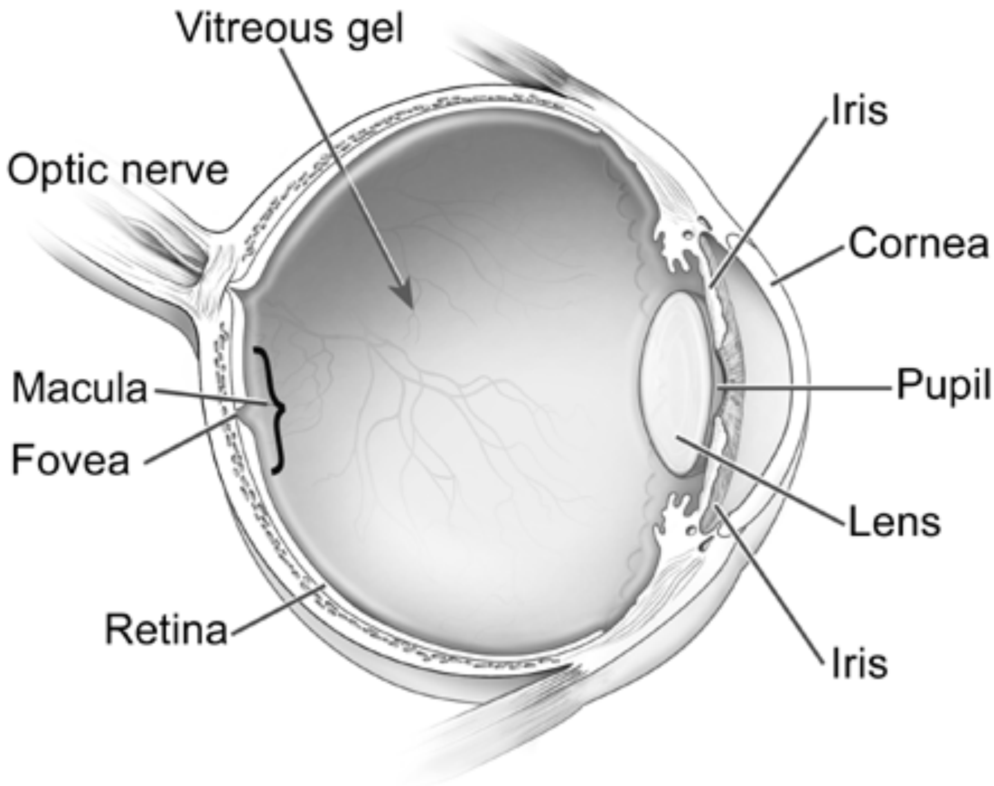

Figure 1.2 The Human Eye (The Human Eye 2013)

Light is radiant energy that is visible to the average human eye (X-rite 2005). Different wavelengths of energy detected by the human eye are known as the visible spectrum. The visible spectrum ranges from 400 nanometers to 700 nanometers (Field 2004). When all visible wavelengths are present, the human eye perceives that to be white light. When no visible wavelengths are present, the human eye perceives that to be black. The human eye never really sees “pure white light.” The observer witnesses light that has been modified, it is rare to witness all wavelengths or just one at a time (X-rite 2005). A wavelength near 700 nanometers is recognized as red, 450-500 nanometers is recognized as blue, and a 400 wavelength is perceived as violet. Color is perceived through these different wavelengths; however if objects were not present “color” would not exist.

Objects modify light by absorbing some wavelengths and reflecting others. When light is reflected from an object the sensors in the eye identify that light as color (Field 2004). Objects possess unique surfaces that modify light in different ways. Objects can be reflective like paper, transparent like film, or emissive like a monitor, tablet or phone. Light strikes a reflective object and passes through a transparent object allowing the light to be modified (Evans 1974). Emissive objects are unique. These objects are not only are affected by the light surrounding them, but they incorporate their own lighting conditions as well. With an object present light is reflected, transmitted or emitted which gives the object its "color" (X-Rite 2005). With this knowledge of how light, human perception, and objects affect color vision, scientist were able to create color systems, which quantify color.

In the 1920s, Wright and Guild conducted a series of experiments to better understand the human response to various colors. This experiment exposed a human subject to a field of illumination, half used spectral light and the other half used the three primaries, red, green, and blue. The Commission of International Illuminance (CIE) continued to conduct research based of the Wright and Guild experiments (Broadbent n.d.). In 1931, CIE developed a series of standards that represent the visible spectrum. The first attempt to produce a system of standards was The CIE XYZ and the Standard Observer.

The CIE XYZ color space was developed based upon the visual capabilities of the standard observer. An extensive study was conducted in order to identify the standard observer, a hypothetical viewer, representing human vision. This study used several subjects to determine the range of visible colors the human eye can recognize and to create functions to “match” color. This standard observer became also known as the 2° observer. In the 1950s, Stiles and Burch investigated a 10° observer in order to incorporate a larger field of view. The findings of the Stiles and Burch study were adopted as the 1964 Standard Observer. Both colorimetric observers the 1931 2°Standard Observer and the 1964 10° Standard Observer are used interchangeably as needed in the printing industry (Rosen 2013). The primaries, red green blue must be present for the human eye to perceive all colors in the visible spectrum. X, Y, and Z were assigned to each of the primaries (Evans 1974).

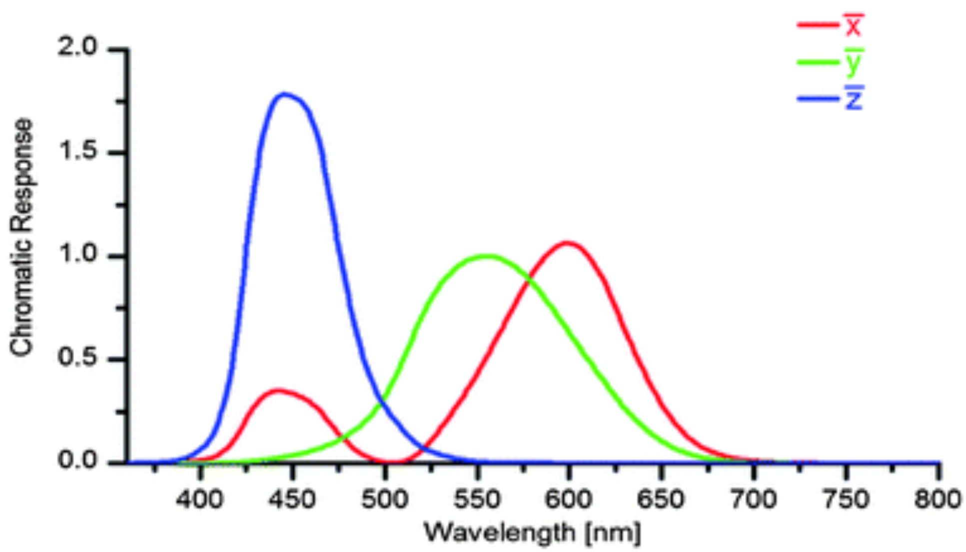

Figure 1.3 CIE XYZ Color Space (The CIE 2013)

During this study, CIE discovered the observer does not see all colors uniformly. The following diagram depicts the limitations of different color spaces:

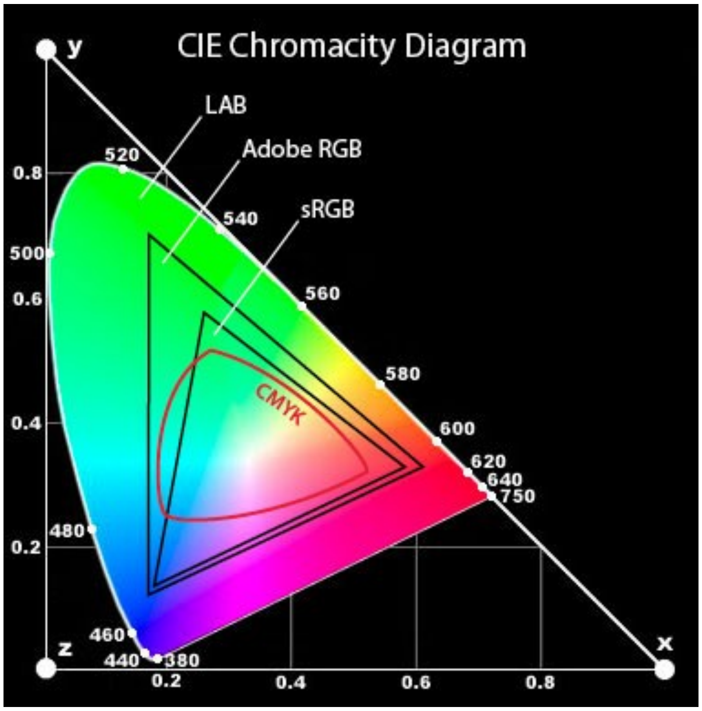

Figure 1.4 CIE Chromacity Diagram (Color Spaces 2010)

The creation of the CIE XYZ color space, allowed scientist to realize the model was unbalanced. By 1934, CIE made adjustments to the XYZ system to properly “map” how the human eye perceives color. This resulted in the creation of the CIE L*a*b and CIE L*u*v color spaces, in 1976 (Evans 1974). The CIE L*a*b, and the CIE L*u*v are color spaces that are device independent and use three coordinates to identify color (X-rite 2005). Since the color spaces are device independent the range of colors in this device are not limited to the observer or rendering capabilities of a device. CIE L*a*b is used most frequently, based off a theory that a color cannot appear to be blue and yellow at the same time or red and green at the same time. The L component represent lightness, the A represents red and green, and the B component represents blue and yellow. The CIE L*u*v color space, also known as the CIE LCH is a polar color system that uses cylindrical coordinates that represent lightness, chroma, and hue (X-rite 2005). The following figure is a representation of the CIE LCH color space:

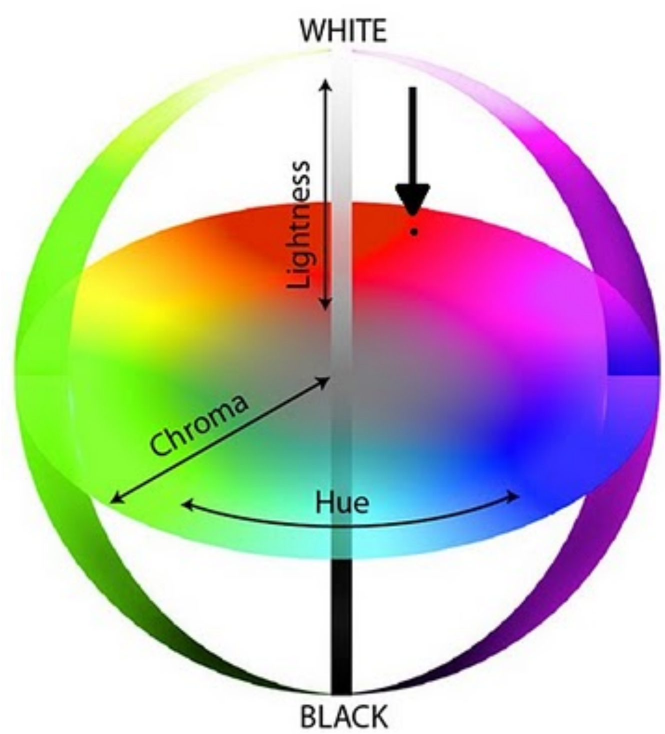

Figure 1.5 The CIE L*c*h Color Model (Pritchard 2010)

Both color systems can be formulated from collected spectral data, as a direct conversion from the XYZ values, or directly from colorimetric XYZ values (X-Rite 2005). Using these color models helps to compare how similar or different colors are in terms of perceptual color matching. These systems are the foundation for color reproduction and proofing.

CHAPTER THREE

HISTORY OF HARD PROOFING

Proofing is a key component to color reproduction. The proof serves as a representation of what the printed job will look like. Customers approve proofs in order to serve as a contract of how they expect the printed job to appear (Bruno 1986). A hard proof is the physical sample of the printed product.

"For many years the only way to create proofs was to print them on press (Bruno 1986)." This process could be very expensive and time-consuming. Plates had to be created, mounted, the press had to be set up and run. The advantage to this process was the equipment used, inks paper, press, were the actual materials that would be used to print the job.

Printers began to explore other alternatives in proofing, in hopes cutting down the time and cost associated with press proofs. These proofs became known as "off press proofs" made by photomechanical means (Bruno 1986). It was during World War II that these proofs were first introduced. The new proofing method allowed maps to be reviewed and checked in less time, however, this method wasn't very good with continuous tone images (Bruno 1986). Other methods such as the WATERCOTE® process, the FINAL PROOF® process, DuPont Cromalin®, and 3M Matchprint® were introduced to compensate for different printing techniques (Schmidt 1998). The development of proofs did not stop here. Off press proofs helped decrease cost and turn around time but there was still room for improvement. Printers continued to seek other alternatives to create proofs at a low cost and in a timely manner.

CHAPTER FOUR

INTRO TO SOFTPROOFING

In 2003, the development of “soft proofs” was a drastic change for the Printing Industry. Soft proofing eliminates the use of paper and inks, allowing the customer to view a simulation of how a printed product will appear on their monitor (Ward 2004). Printers were slow to adopt this new method and debated the quality of soft proofs. Some felt color could not be produced well on monitors; others wanted the physical proof to refer to during press-runs (Charnock 2010). However, soft proofing software addresses these concerns making the quality efficient and reliable.

High-quality monitors are an important factor in soft proofing. In 2004, The International Organization for Standards (ISO), finalized standards for high-end monitor displays. Standards allow comparisons to be made to see if a device is performing correctly or reproducing color accurately. Even though high-end monitors obtain a considerable amount of quality, these devices are incapable of reproducing products with little or no deviation. The standard of color deviation using the CIEDE2000 calculation should be less than 10 for white at a R=G=B=25 8-Bit monitor, for grey at a R=G=B=127 8-Bit monitor, and for dark grey at R=G=B=63 level. Standards have not yet been put in place for laptop monitors, phones, or tablets (ISO 2013). In order to reproduce a soft proof that meets standards one must first understand color management.

CHAPTER FIVE

COLOR MANAGEMENT

Color management involves understanding what the customer expects and being able to meet those expectations. Tools such as Photoshop curves, operator expertise and ICC profiles are used in order to manage color effectively. Effective color management provides consistency, repeatability, and predictability (Roszkiewicz 2006). A key to color management is measuring. The printer must first know what the input information is in order to create an output that reproduces color correctly.

Scientists have created different devices that measure color in the same way the human eye perceives color (X-Rite 2005). These different devices identify wavelengths of light as a numerical value. Each device is unique, providing different information for different measurements and controls of color (Roszkiewicz 2006). The densitometer provides density values, which simply indicates how much of a color is being printed on paper. A colorimeter measures tristimulus values based off the CIE XYZ color space. A spectrophotometer measures spectral data, which is the amount of light energy reflected from an object (Field 2004). Before taking any measurements it is important to make sure all instruments are calibrated.

Performance of devices can change over time, which is why it is important to perform calibration. Calibration of monitors, printers, and measuring devices is the first step to color management (Roszkiewicz 2006). Monitor calibration can be achieved using a colorimeter. Different devices and software such as iProfiler, ColorMunki, and MeasureTool, have been developed to determine and correct performance shifts (X-Rite

2005). To perform calibration these devices are placed on the front of the monitor as the software displays a color target. A series of colors flash across the screen, the instrument measures the color patches, then the measurements can be save and analyzed through the software. Once this data is obtained adjustments to the color balance, gamma, and white and black points can be made to correct the performance of the device (X-Rite 2005). These adjustments can be saved as profiles.

Profiles can be created after calibration is performed. Profiles are the key to a color-managed workflow (Roszkiewicz 2006). Profiles define the properties of the color spaces, identifying what colors can be reproduced. The profile describes the calibration or linearization of the device (Field 2004). When using profiles it is important to identify how the image is supposed to look, what output device will be used, and how to handle colors and tones that are out of gamut. The following figure shows a depiction of a color management workflow:

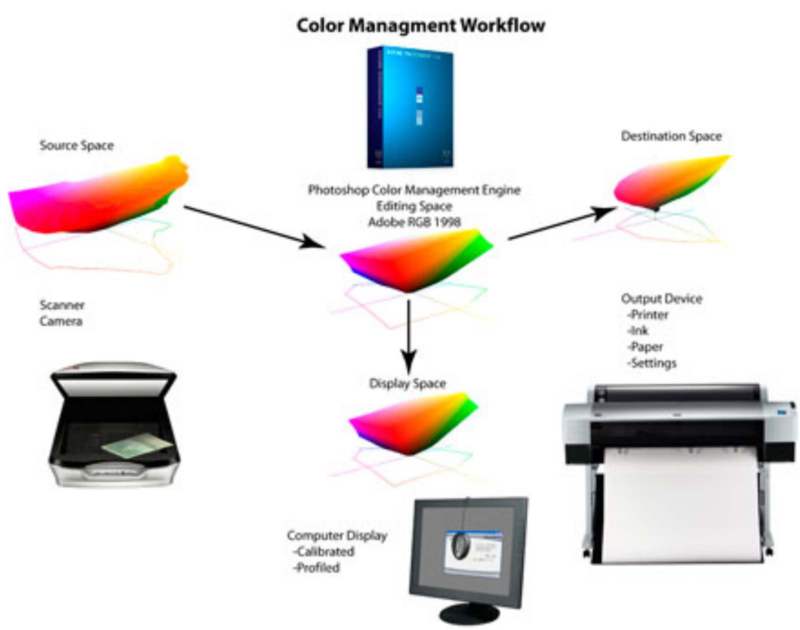

Figure 2: Color Management Workflow (Johnson 2011).

Software such as ColorSync, keep gamut compression controllable and predictable. An effective workflow consists of an optimized, controlled, and repeatable process. Profiles provide color communication across devices (X-rite 2005). When color management is implemented it becomes easier to produce color accurate soft proofs.

CHAPTER SIX

THE SOFT OPTION

Many publishers and advertisers have questioned the quality of soft proofs. However, soft proofing not only provides color accuracy, but it offers many advantages. For publishers and ad agencies soft proofing proves to be very desirable. Cox (2008) agrees, "The benefits of soft proofing are immense, offering the customer speed, accountability, and cost savings." For starters, the turn around time changed from days to hours (McClure 2004). Many rounds of soft proofs can be completed during the same time frame (Shaffer 2005). Once proofs are created they can be sent digitally. Companies no longer have to worry about mailing fees and delivery times (Charnock 2010). Costs go down tremendously. Companies gain a savings of about a "$25 to $50" in mailing fees alone (McClure 2004). Commercial printers, publishers, design agencies and pre-press houses are markets that implement the use of soft proofing strategies (Ward 2004). With constant change in technology, the markets using soft proofing have grown. The ICS Remote Director Software enables color shifts to be detected in "real time". This advancement in monitor proofing has allowed it to expand to web and packaging markets (Cox 2008).

There are many options to choose from when it comes to soft proofing. Software such as; ORIS Soft Proof™ Virtual Proofing System for the Eizo ColorEdge CG220 Display, Océ TrueProof, offer hardware calibration to provide consistent and predictable color (Felici 2004). Remote Director is said to be the world's number one soft proofing solution. The software is web-based so proofs can be created and shared with anyone using Internet Explorer, Firefox, or Safari on their Mac or PC. Color settings are verified across all users in order to manage color. Users can view and approve proofs in real time and easily sign off or make adjustments if needed (Remote Director 2013).

Since our society is constantly developing with new technologies, it is important for the printing industry to adapt and evolve. Nustream Europe has already begun to consider what the future holds for soft proofing. Nustream's Proofstream software now accommodates both the Apple iPhone and iPad. Colin Taylor states, "The technology of these products is a great fit with the immediacy of the proofing cycle, and the capabilities made available by our Proofstream software" (Proofstream 2011). Proofstream is offered in 3 different versions; Lite, Standard, Pro, and Enterprise. Prices start at about $3200 for the Lite version, and end at about $19,000 for the Enterprise version. Each version is user friendly, allowing a job to be approved after logging in, selecting a page that needs approval, and clicking approved. The software allows users to add notes and comments concerning the job, making it easier for printers to view and make needed changes (Creasey 2011). Once the changes to the proof have been made, the client can view the updated pages side by side to the original to compare. This software is very unique in several respects. Unlike most soft proofing solutions it doesn't put limits on storage or includes click-through charges. It is easy for users to get started with the program since the program is web-based and doesn't require the need for client applications (Proofstream 2011).

High-quality monitors are an important factor in soft proofing. In 2004, The

International Organization for Standards (ISO), finalized standards for high-end monitor displays. Standards allow comparisons to be made to see if a device is performing correctly or reproducing color accurately. Even though high-end monitors obtain a considerable amount of quality, these devices are incapable of reproducing products with little or no deviation. The standard of color deviation using the CIEDE2000 calculation should be less than 10 for white at a R=G=B=25 8-Bit monitor, for grey at a R=G=B=127 8-Bit monitor, and for dark grey at R=G=B=63 level. Standards have not yet been put in place for laptop monitors, phones, or tablets. There is prominent opportunity for these devices to be used in soft proofing. It is important to consider testing these devices to put standards in place and evaluate the color difference between each device.

CHAPTER SEVEN

METHODOLOGY

To test the research question a study was designed to create statistical data that could be used for comparison. Specifically, each device was measured to collect spectral data, which was used to formulate Delta-E values. The researcher performed several steps to conduct this study.

First a test file was created in Photoshop. Photoshop was used in order to create color patches using LAB values to serve as a standard. Since the test form was measured across different devices Photoshop, was the best program to use to create a file format compatible for each device. Color patches of red, green, blue, cyan, magenta, yellow, orange, violet, white, and 3 shades of gray were created in order to achieve a full gamut of colors. To create these patches, the researcher used the LAB sliders in Photoshop to enter LAB values under the color window. In order to ensure the colors measured adhered to standard qualifications, LAB values for each of the color patches were taken from the General Requirements for Applications in Commercial Offset Lithography (GRACoL) specifications. GRACoL is the preferred reference for commercial printing. Since soft proofs are prepared to represent a printed product it made sense to use these specifications. The Cyan, Magenta, and Yellow were created using the CMYK sliders in Photoshop making each color at 100 percent of that color then converting the color to LAB values in Photoshop. Cyan, Magenta, and Yellow were added to the test sheet later, which is why they were created differently. The following LAB values were used:

Table 1
Original LAB Values

	L	**A**	**B**
Red	47	68	48
Green	50	-66	26
Blue	25	20	-46
Orange	61	64	72
Violet	20	36	-36
Cyan	62	-44	-50
Magenta	52	81	-7
Yellow	95	-6	95
Gray 1	25	0	0
Gray 2	50	0	0
Gray 3	75	0	0
White	100	0	0

Table 1: Original LAB Values

Each patch was sized to be 2x2 inches. In Photoshop, the system used the Adobe 1998 RGB profile. Once the patches were created with LAB values specified by GRACol the test file was saved as a jpeg. Saving the file as a jpeg allowed for it to be opened on the other devices (phones and tablets) by sending the file through email. The following image is the test file that was used:

Figure 3: Test File

After the test sheet file was created, each device was calibrated. three laptops, three phones, and three tablets were used in this study to obtain enough information for comparison. The following devices with the following specifications were tested:

- IPhone4s

  3.5-inch (diagonal) Retina display

  960-by-640 resolution 326 ppi

  2 years old

- IPhone5

  4-inch (diagonal) Retina display

  1136-by-640 resolution 326 ppi

  Less than a year old

- Android Galaxy 3

  4.8 inch HD Super AMOLED

  (1280x720) display

  2 years old

- MacBook Pro 1

  Retina display: 13.3-inch (diagonal) LED-backlit display with IPS technology; 2560-by-1600 resolution at 227 pixels per inch with support for millions of colors

  1 ½ years old

- MacBook Pro 2

  Retina display: 13.3-inch (diagonal) LED-backlit display with IPS technology; 2560-by-1600 resolution at 227 pixels per inch with support for millions of colors

  Less than a year old

- HP

  HD display, Midsize, 15.6in, LED backlight

  1366 x 768 (HD) resolution

  1 year old

- IPad

  9.7-inch (diagonal) LED-backlit Multi-Touch display with IPS technology

  1024-by-768 resolution at 132 pixels per inch (ppi)

  2 years old

- IPad mini

7.9-inch (diagonal) LED-backlit Multi-Touch display with IPS technology

1024-by-768 resolution at 163 pixels per inch (ppi)

1 year old

- Nexus 7

  7” 1280x800 (216ppi)

  HD IPS

  2 years old

The researcher used the i1Pro to calibrate each monitor. Before the monitors were calibrated the i1Pro was calibrated. Using a program called MeasureTool, the researcher was prompted to calibrate the i1Pro device before calibrating the monitor. The device was then placed on the white point on the base of the device for measurement. Once the device was on the white point the researcher clicked ok to complete the calibration. Next, the i1Pro was used to calibrate each monitor. MeasureTool used the following settings: a gamma of 1.8, the standard Illuminant D65, the 2° observer, and the RGB Adobe 98 profile. The test target measured to complete calibration was the X-rite reference within the MeasureTool software. The monitor was then set to maximum contrast. Once these settings were applied the researcher placed the i1Pro on the monitor on the white patch, clicked start and made sure the arrows lined up in the quality indicator. The phones and tablets weren't calibrated since there is no calibration software compatible for those devices.

Next the researcher opened the test document on each device. Each device was set to 100 percent brightness. With the test file open on each device the researcher then wiped down each device. Since the phones and tablets are touchscreen devices, each screen was cleaned in order to remove fingerprints, smears, and such, which could interfere with correct readings.

After the screens were cleaned, the i1Pro spectrophotometer was used to collect LAB values. Using the MeasureTool software the researcher selected the i1Pro device under the device menu. Next the researcher checked the emission box to make sure the device would take readings from the monitor, the reflection option is used to gather measurements from paper, therefore, the emission box had to be selected. With the correct device and box selected the researcher then clicked on the spot measurement menu. Under this feature the researcher selected LAB under the drop down menu, to collect spectral data. The reference box was checked, the i1Pro was placed on the color patch, and start button was clicked. Once the patch was measured, LAB values were produced by the program and documented by the researcher. Each patch was read 3 times. The researcher placed the measurements in an excel file and used the average function to obtain an average of the 3 readings for each patch. Next, the average LAB values were compared the average to the original LAB values. The comparison of the original values versus the measured values allowed for a Delta-E value to be produced. The simple Delta-E calculation is as follows:

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}$$

Figure 3.1: The Simple Delta-E Calculation (ColorMine 2013)

However, a Delta-E2000 calculator from colormine.org was used to gather Delta-E values. The following formula was used:

$$\Delta E_{00}^{*} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}}$$

Figure 3.2: DeltaE2000 Calculation (ColorMine 2013)

Delta-E2000 was used because unlike prior Delta-E calculations, it compensates for chroma, hue, lightness, and neutral colors. The researcher evaluated the Delta-E values for similarities and differences across the different devices.

CHAPTER EIGHT

RESEARCH DESIGN AND ANALYSIS

This study employed the quasi-experimental research design. The X-Rite i1Pro Spectrophotometer was used to gather the LAB values of each color. LAB values were averaged and compared to the standard LAB values in order to calculate a Delta-E value utilizing a Delta-E2000 calculator. There were four research questions and one hypothesis that directed this study. The research questions asked:

- Do color differences exist between the phones, tablets, and monitors?
- If color differences are present, what is the Delta-E value compared to the specifications?
- Do specific colors produce higher Delta-E values?
- Are certain brand devices more color accurate than others?

Research Hypothesis: The devices will have different Delta-E values compared to a specification.

Null Hypothesis: The devices will not have different Delta-E values compared to a specification.

The hypothesis was designed to provide evidence that a variation of Delta-E values would be present across the devices. Spectral data was collected from each device using the i1Pro. The spectral data of each the 9 devices was compared to the original LAB values to produce Delta-E values. The Delta-E values allowed for the research of the null hypothesis to be rejected and the hypothesis to be accepted.

The data provided evidence that there is a considerable amount of color difference across the devices. The 50 percent Gray, Magenta, and Green proved to be colors with the greatest color differences across the devices. Both of the MacBooks and the Galaxy 3 had the least amount of color difference with average Delta-E values of 9.1, 9.5, and 9.7. The greatest color difference occurred on the Nexus Tablet, iPhone5, and the iPad with average Delta-E values of 26.3, 24.8 and 23.7. Both of the MacBooks produced spectral data and Delta-E values which were almost identical to one another. The iPad and the iPad mini produced similar spectral data as well, along with the iPhone5 and the iPhone4s. The HP, Nexus tablet, and Galaxy 3 were outliers. The following chart shows the original LAB values of the colors with the greatest color difference compared to the average LAB values of the devices:

Table 2
Comparison of LAB Values

Original LAB values	L	A	B
Green	50	-66	26
Magenta	52	81	-7
Gray 2	50	0	0

iPad

Green	93.6	-75.1	37.6
Magenta	94	127	-39.6
Gray 2	80.2	-1.9	-17.7

iPadMini

Green	80	-57.3	32.3
Magenta	91.5	91.5	-19.3
Gray 2	79.2	-2.7	-12.7

Nexus

Green	93.6	-75.1	37.6
Magenta	100	91.4	-25.9
Gray 2	91.7	-3.8	-17.7

iPhone5

Green	98.9	-86.2	37.9
Magenta	98	135.1	-48.9
Gray 2	40.3	-4.9	-34

iPhone4s

Green	70.5	-51.6	17
Magenta	84.2	77.9	-31.9
Gray 2	71.2	-6.6	-17.8

Galaxy

Green	51.8	-83.5	30.1
Magenta	56.4	88.5	-11.1
Gray 2	49.4	-8.5	-10.2

HP

Green	73.6	-48.7	6.3
Magenta	68	76.4	-36.3
Gray 2	63.3	3.5	-41.2

MacBook1

Green	75.6	-66.2	33.9
Magenta	71.3	100.3	10
Gray 2	53.3	0.9	-2.1

MacBook2

Green	75.6	66.2	33.9
Magenta	70.3	89.2	9.9
Gray 2	52.4	0.9	-3.1

Table 2: Comparison of LAB Values

The highlighted component is the coordinate, which had the greatest impact on the Delta-E value. The L coordinate had the greatest impact while reproducing green. Each of the devices produced greens that were lighter than the original values. Magenta produced higher A values on the iPad, iPhone5, and the Galaxy, which means the color appeared to be more red. The MacBook 2, iPhone5 HP, and Galaxy 3 produced a negative B value when reproducing the 50 percent gray, making the color have a bluish hue. The following charts show the original LAB values and the Delta-E values for each device:

Table 2.1
Original LAB Values

	L	**A**	**B**
Red	47	68	48
Green	50	-66	26
Blue	25	20	-46
Orange	61	64	72
Violet	20	36	-36
Cyan	62	-44	-50
Magenta	52	81	-7
Yellow	95	-6	95
Gray 1	25	0	0
Gray 2	50	0	0
Gray 3	75	0	0
White	100	0	0

Table 2.1: Original LAB Values

Table 2.2
Delta-E Values Across Devices

	iPad	iPadM	Nexus7	iPhone5	iPhone4s	Galaxy	HP	MB1	MB2
Red	25.1	26.6	28.6	29.9	15.6	5.5	13.9	2.9	2.9
Blue	23.9	23.5	34.7	25.5	17.8	4.1	4.1	4.4	5.4
Green	33.3	24.1	27.5	36.2	18.5	2.4	23.4	21.9	21.9
Cyan	28.3	27	27.6	29.2	23.7	5.8	17.2	13.2	13.8
Mag.	35.2	30.9	38.4	28.9	28.3	5.1	20	21.9	21.3
Yellow	3.2	3.5	2.9	7.9	3	3.6	3.9	5.9	5.9
Gray 1	20.4	14	26.4	22.9	21.6	14	23.4	5.6	5.6
Gray 2	27.8	26.2	34.6	21.6	25.1	20.2	24.6	3.8	3.7
Gray 3	22.8	20.9	23.3	25.5	26.9	18.43	25.5	12.4	9.74
Oran.	27.4	23.5	27.2	27.6	15.2	5.1	11.5	8.8	8.8
Violet	18.6	16.1	25.6	21.1	17.7	3.1	16.4	1.9	5.5
White	18.3	16.5	19.6	22.1	22.3	22.57	20.1	12.2	12.3

Table 2.2: Delta-E Values Across Devices

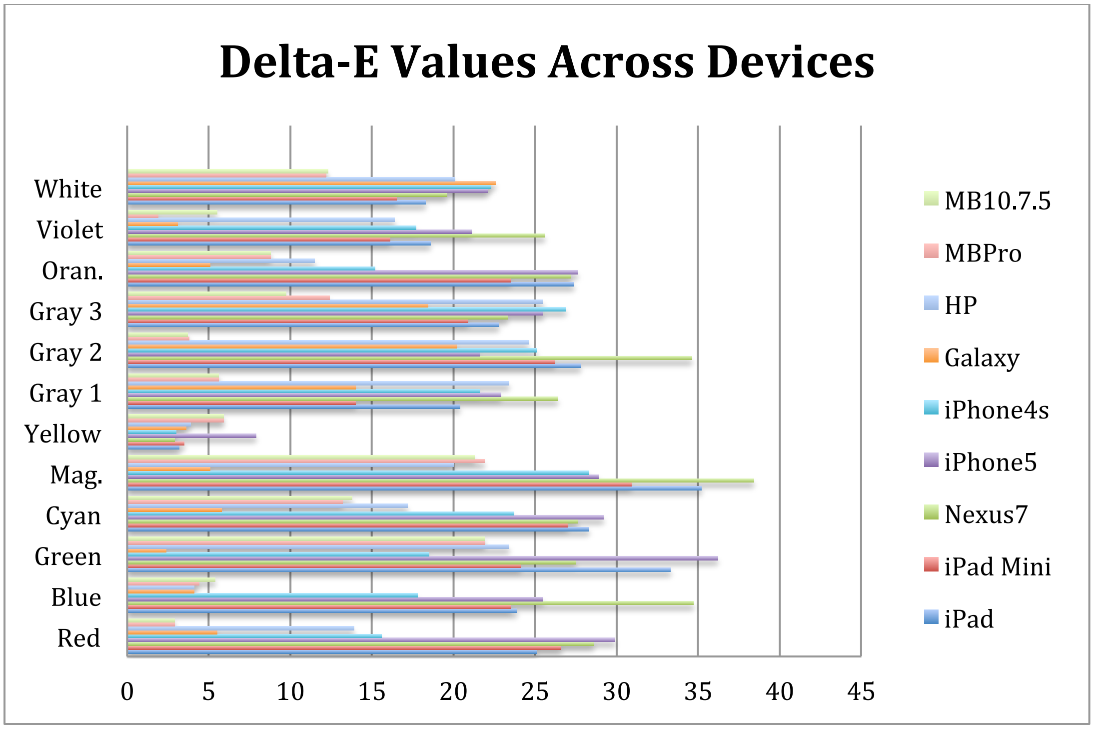

Figure 4: Delta-E Values Across Devices

CHAPTER NINE

FUTURE RESEARCH AND CONCLUSIONS

Due to limitations of resources on the subject and lack of materials the study was somewhat restricted. Standards of an acceptable amount of color difference have yet to be tested and set for phones and tablets. Along with not having a standard to compare these devices to, there is also no calibration software compatible for these devices. There is limited research on acceptable color difference on laptop monitors as well. Even with these limitations it is clear that the hypothesis of this study has been supported and accurate. Since there is limited research on the subject matter, it is recommended that further research be done to test a wider range of different device brands and profile conditions. It is also recommended that measurements be tested under D50 lighting conditions and the test sheet include color tints to provide a step by step view of color variation between the devices. Finally, further study is required to test if the age of the device affects the color or if the color shifts during different increments of time after being turned on.

In summary, color differences are present between these devices. Not only do color differences exist, the amount of difference appears to be significant at a first glance. However, there aren't standards to compare the data to which could mean the difference found wasn't significant at all. The data found could be the normal performance for these devices but the variation of difference between the devices becomes significant when we evaluate each brand. This can propose a major issue for companies in the Printing Industry using soft proofing to communicate color with their clients. If the customer is not using a calibrated monitor to view proofs they can be expecting colors that are drastically different from what will actually be reproduced by the printer. As the industry continues to move forward there is an emerging opportunity to use these devices for proofing. Today's generation is tech-savvy and all about convenience. As developments continue to be made in soft proofing software compatibility for these devices is must.

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APPENDIX

LAB Values for each device

<u>iPad Model MC 705LL/A Version 6.1 (10B141)</u>

Red
76.1 97.0 64.2
75.5 96.4 64.1
75.2 96.2 64.0

Average: 75.6 96.5 64.1

Blue
50.2 38.5 -91.3
49.8 38.6 -91.2
49.7 38.4 -90.9

Average: 49.9 38.5 -91.1

Green
93.2 -76.9 37.7
93.8 -72.2 37.4
93.1 -76.9 37.5

Average: 93.6 -75.1 37.6

Cyan
121.5 -23.8 -96.4
121.4 -24.2 -96.1
121.1 -23.9 -96.2

Average: 121.3 -23.9 -96.3

Magenta
94.2 127.0 -39.1
93.7 126.5 -39.4
94.0 127.1 -39.8

Average: 94 127.0 -39.6

Yellow
147.8 -28.1 121.8
157.8 -28.9 128.2
140.3 -24.8 90.4

Average: 137.6 -24.3 102.5

Gray 1
46.6 -2.0 -11.5
48.5 -2.0 -12.2
48.2 -2.1 -12.3

Average: 46.7 -2.0 -12.0

Gray 2
93.2 -2.2 -20.3
55.2 -1.8 -12.4
92.4 -2.2 -20.8

Average: 80.2 -1.9 -17.7

Gray 3
126.7 -4.7 -23.3
127.9 -4.7 -24.2
127.2 -4.8 -23.6

Average: 126.3 -4.7 -23.7

Orange
102.8 89.1 98.8
103.0 89.1 99.0
104.1 89.9 99.4

Average: 103.3 89.3 99.1

Violet
41.1 62.6 -79.3
39.9 61.3 -77.6
39.5 66.2 -76.3

Average: 39.3 63.4 -75.7

White
160.6 -2.0 -30.8
64.4 -1.0 -32.9
161.9 -1.9 -31.8

Average: 128.9 -1.8 -31.2

iPad mini Model-MD52LL/A Version 6.1(101341)

Red
78.2 86.5 58.2
78.2 86.6 58.2
78.1 86.5 58.1

Average: 78.2 86.5 58.2

Blue
51.8 8.8 -68.5
51.8 8.5 -68.8
51.3 8.6 -68.2

Average: 51.6 8.4 -68.6

Green
80.0 -57.2 32.1
80.0 -57.5 32.4
80.0 -57.3 32.2

Average: 80.0 -57.3 32.3

Cyan
108.6 -31.5 -79.2
109.0 -31.8 -79.1
108.9 -31.6 -79.3

Average: 108.7 -31.5 -79.2

Magenta
91.7 91.7 -20.3
91.7 91.6 -20.6
91.6 91.5 -18.9

Average: 91.5 91.5 -19.3

Yellow
141.9 -7.5 116.7
103.9 -5.6 89.1
140.3 -7.0 116.3

Average: 118.7 -5,7 106.3

Gray1
39.9 -1.2 -8.2
40.0 -1.4 -8.2
39.9 -1.4 -8.2

Average: 39.9 -1.3 -8.2

Gray 2
80.1 -2.6 -12.9
79.0 -2.7 -12.2
78.4 -2.7 -11.9

Average: 79.2 -2.7 -12.7

Gray 3
118.5 -4.3 -17.2
116.5 -4.2 -16.1
118.0 -4.1 -17.6

Average: 117.7 -4.2 -17.2

Orange
94.3 82.5 80.3
93.9 82.0 79.9
93.9 81.6 80.4

Average: 94.0 82.1 80.1

Violet
39.7 29.2 -53.5
40.0 29.2 -53.5
39.8 29.4 -53.9

Average: 39.9 29.3 -53.7

White
151.2 -5.0 -24.1
151.4 -4.6 -24.6
151.3 -4.3 -25.3

Average: 151.3 -4.5 -24.8

Nexus 10 Android version 4.2.2

Red
82.6 86.6 58.4
81.8 85.8 58.0
79.5 83.6 56.3

Average: 81.3 85.2 57.6

Blue
61.5 4.0 -73.7
61.6 4.1 -73.7
62.2 4.1 -74.4

Average: 61.7 4.1 -73.9

Green
84.4 -58.8 24.4
83.3 -58.1 24.3
85.5 -59.5 24.8

Average: 84.4 -58.8 24.5

Cyan
126.7 -42.3 -88.0
126.9 -42.4 -88.1
124.8 -42.1 -87.4

Average: 126.1 -42.3 -87.83

Magenta
100 91.4 -25.8
100 91.4 -25.8
100 91.3 -26.2

Average: 100 91.4 -25.9

Yellow
114.2 12.9 140.3
116.2 -9.3 89
109.2 -10.1 94.5

Average: 113.3 -9.7 97.8

Gray 1
53.2 -1.2 -12.4
53.1 -1.1 -12.5
53.3 -1.2 -12.6

Average: 53.2 -1.2 -12.5

Gray 2
91.4 -3.9 -17.6
91.7 -3.8 -17.7
91.7 -3.8 -17.7

Average: 91.7 -3.8 -17.7

Gray 3
124.7 -6.0 -22.1
124.0 -6.0 -21.8
124.0 -6.1 -21.5

Average: 124.2 -6.0 -21.7

Orange
104.6 81.9 92.9
105.0 82.3 93.4
105.0 82.4 93.3

Average: 104.9 82.2 93.2

Violet
50.8 25.7 -36.3
50.9 25.8 -36.5
51.0 25.9 -36.7

Average: 50.9 25.8 -36.5

White
156.8 -6.0 -32.4
158.5 -6.0 -32.0
158.0 -5.9 -32.2

Average: 157.8 -6.0 -32.2

<u>iPhone 5 Model MD655LL/A Version 7.0 (11A465)</u>

Red
83.5 107.6 61.3
82.4 106.8 60.9
83.5 107.3 62.4

Average: 83.1 107.2 61.3

Blue
49.5 51.5 -111.1
50.1 50.5 -110.2
49.9 50.2 -109.9

Average: 49.8 50.7 -110.3

Green
99.2 -86.5 37.1
98.1 -85.5 38.4
99.5 -86.8 38.3

Average: 98.9 -86.2 37.9

Cyan
125.8 -21.8 -113.3
125.8 -21.4 -113.6
125.8 -21.6 -113.5

Average: 125.8 -21.6 -113.5

Magenta
98.1 136.1 -48.9
98.2 136.3 -49.0
97.9 135.9 -48.7

Average: 98.0 135.1 -48.9

Yellow
172.1 -36.6 141.5
171.9 -36.7 141.3
171.1 -36.6 141.1

Average: 171.7 -36.6 141.3

Gray 1
47.2 -2.1 -19.0
47.6 -2.3 -18.9
47.3 -2.3 -18.9

Average:47.4 -2.3 -18.9

Gray 2
40.5 -4.9 -34.0
40.3 -4.9 -33.9
40.2 -4.8 -34.0

Average: 40.3 -4.9 -34.0

Gray 3
140.1 -2.3 -37.1
143.4 -2.3 -36.9

142.0 -2.3 -36.1

Average: 141.8 -2.3 -36.7

Orange
108.8 96.1 104.6
108.6 96.0 104.6
108.7 95.6 104.5

Average:108.7 95.9 104.6

Violet
40.6 71.0 -89.5
40.4 71.0 -89.6
40.3 70.9 -89.7

Average: 40.4 71.0 -89.5

White
179.0 -3.8 -43.9
177.4 -3.9 -44.0
177.6 -3.8 -44.0

Average: 178 -3.8 -44.0

iPhone 4s Model MD277LL/A Version 7.0.4(11B554a)

Red
57.7 64.7 44.6
66.4 70.6 48.2
66.7 72.7 49.6

Average: 63.6 69.3 47.5

Blue
38.8 3.2 -55.2
49.5 12.0 -57.2
49.8 8.6 -60.0

Average: 46.0 7.9 -57.6

Green
70.0 -52.5 17.6
70.5 -51.6 16.8
70.5 -51.6 16.7

Average: 70.5 -51.6 17.0

Cyan
87.3 -30.6 -62.6
99.9 -37.7 -71.8
98.2 -32.2 -70.2

Average: 95.1 -33.5 -68.2

Magenta
84.3 78.1 -32.0
84.2 77.8 -31.9
84.1 77.9 -31.9

Average: 84.2 77.9 -31.9

Yellow
123.9 -15.2 92.4
123.9 -15.2 92.3
121.8 -13.5 88.2

Average: 123.1 -14.6 90.9

Gray1
41.3 -4.3 -12.2
47.2 -9.3 -26.9
39.5 -5.2 -13.2

Average: 42.5 -6.3 -17.4

Gray 2
72.6 -6.8 -18.1
65.8 -6.1 -16.8
75.3 -6.9 -18.5

Average: 71.2 -6.6 -17.8

Gray 3
102.1 -8.8 -23.3
102.7 -8.8 -23.2
102.6 -8.9 -22.9

Average: 102.4 -8.8 -23.1

Orange

81.1 61.0 73.9
81.1 61.0 74.0
81.0 60.7 73.7

Average: 81.0 61.0 73.9

Violet
40.6 22.1 -54.4
40.4 22.6 -55.0
40.6 22.4 -54.6
Average: 40.6 22.4 -54.6

White
134.5 -11.0 -28.9
107.0 -5.3 -29.7
134.2 -11.0 -28.6

Average: 124.6 -9.1 -29.1

<u>Galaxy 3 Android Model -Samsung</u>

Red
47.3 71.2 60.6
48.0 73.2 73.3
49.2 74.8 64.4

Average: 48.1 73.1 66.1

Blue
24.8 20.6 -60.7
24.9 20.7 -60.5
24.8 20.6 -60.8

Average: 24.8 20.6 -60.6

Green
51.2 -81.8 29.0
52.1 -83.6 30.0
52.0 -85.1 30.6

Average: 51.8 -83.5 30.1

Cyan
65.5 -37.6 -65.3
66.3 -38.4 -66.0
66.5 -38.3 -65.9

Average: 66.2 -38.1 -65.7

Magenta
56.4 88.4 -10.7
56.4 88.6 -11.1
56.3 88.7 -11.1

Average: 56.4 88.5 -11.1

Yellow
96.6 -29.1 114.7
96.8 -29.1 115.0
96.9 -29.1 115.0

Average: 96.7 -29.1 115.0

Gray 1
22.8 -6.1 -4.9
22.7 -6.6 -5.2
22.8 -6.6 -5.0

Average: 22.8 -6.3 -5.1

Gray 2
49.1 -8.4 -10.2
49.6 -8.5 -10.4
49.6 -8.5 -10.3

Average: 49.4 -8.5 -10.2

Gray 3
77.4 -12.3 -13.7
77.4 -12.1 -13.6
77.3 -12.1 -13.7

Average: 77.4 -12.1 -13.7

Orange
62.5 69.4 94.6
62.2 70.2 97.2
62.6 70.6 96.6

Average: 62.3 70.3 95.8

Violet

20.2 36.4 -42.4
20.4 38.8 -45.5
20.4 38.5 -44.5

Average: 20.3 37.9 -44.1

White
96.3 -13.9 -17.3
99.6 -14.6 -17.4
99.8 -14.7 -17.4
Average:98.5 -14.3 -17.4

<u>HP Protect smart Windows 7 home Prem HP</u>

Red
45.0 61.8 16.3
51.1 62.1 15.3
51.2 62.2 14.5

Average: 49.1 62.0 15.3

Blue
38.1 41.9 -90.0
37.8 43.3 -92.0
43.2 45.1 -95.2

Average: 39.7 43.4 -92.4

Green
75.4 -49.3 4.8
77.2 -49.3 3.0
68.1 -47.9 11.2

Average: 73.6 -48.7 6.3

Cyan
80.0 -9.4 -83.5
82.9 -12.2 -82.0
81.7 -11.0 -82.6

Average: 81.5 -10.9 -82.7

Magenta
68.7 77.0 -39.9
68.3 76.4 -39.2
67.2 75.9 -33.5

Average: 68.0 76.4 -36.3

Yellow
116.1 -24.4 82.4
113.8 -26.1 80.1
114.6 -25.6 81.0

Average: 115.2 -23.5 81.3

Gray 1
44.5 2.6 -31.2
42.9 2.6 -30.4
42.5 2.7 -30.4

Average: 43.2 2.6 -30.6

Gray 2
66.5 3.3 -42.3
62.1 3.7 -40.9
61.3 3.6 -40.4

Average: 63.3 3.5 -41.2

Gray 3
97.0 .2 -47.7
92.2 1.3 -40.9
92.2 1.4 -49.1

Average:93.8 .9 -44.9

Orange
65.5 59.0 36.7
66.2 58.5 36.3
66.7 58.8 36.1

Average: 66.4 58.6 36. 4

Violet
35.8 43.2 -73.5
36.5 43.2 -73.6
37.4 43.9 -74.8

Average: 36.5 43.5 -73.9

White

124.6 -7.5 -28.1
124.6 -7.5 -28.3
123.2 -7.5 -28.4

Average: 124.3 -7.5 -28.2

<u>MacBook Pro Version 10.9</u>

Red
42.4 54.7 40.1
43.7 63.4 49.1
46.0 65.5 51.4

Average: 44.0 61.2 45.9

Blue
32.2 32.0 -66.2
23.5 31.9 -61.4
23.0 31.0 -60.1

Average: 26.2 31.6 -62.6

Green
75.8 -66.6 34.7
75.5 -65.9 33.1
75.4 -66.2 34.0

Average: 75.6 -66.2 33.9

Cyan
86.9 -18.1 -71.2
79.3 -15.8 -68.1
70.2 -12.7 -64.6

Average: 77.8 -15.5 -68.1

Magenta
73.7 103.7 4.5
68.7 96.5 19.4
71.5 100.6 9.2

Average: 71.3 100.3 10.0

Yellow
140.7 -20.7 129.3
140.1 -21.0 127.6

140.4 -24.0 120.3

Average: 140. 3 -20.9 125.7

Gray 1
25.1 1.0 -2.6
38.7 .4 -5.5
17.2 1.8 -.3

Average: 26 .9 -8.4
Gray 2
57.7 1.1 -4.4
47.7 1.1 -1.3
54.7 .9 -3.6

Average: 53.3 .9 -2.1

Gray 3
102.4 -2.2 -9.2
86.2 -1.4 -1.7
91.3 -1.6 -3.9

Average: 92.3 -1.7 -4.9

Orange
74.1 90.2 90.1
72.1 88.1 88.0
67.1 89.8 85.1

Average: 71.1 88.4 87.3

Violet
15.3 31.3 -32.8
21.7 38.3 -41.2
17.3 33.3 -35.2

Average: 17.1 34.3 -36.4

White
135.8 -4.6 -11.0
138.7 -4.6 -11.8
134.6 -5.0 -15.5

Average:135.4 -4.7 -12.8

MacBook Pro Version 10.7.5

Red
42.4 54.7 40.1
43.7 63.4 49.1
46.0 65.5 51.4

Average: 44.0 60.2 45.9

Blue
52.2 32.0 -66.2
23.5 31.9 -61.4
23.0 31.0 -60.1

Average: 25.9 32.3 –62.5

Green
75.8 -66.6 34.7
75.5 -65.9 33.1
75.4 -66.2 34.0

Average: 75.6 -66.2 33.9

Cyan
86.9 -18.1 -71.2
79.3 -15.8 -68.1
70.2 -12.7 -64.6

Average: 78.8 -15.5 -68.1

Magenta
73.7 103.7 4.5
68.7 96.5 19.4
71.5 100.6 9.2

Average: 70.3 89.2 9.9

Yellow
140.7 -20.7 129.3
140.1 -21.0 127.6
140.4 -24.0 120.3

Average: 140.3 -21.9 125.7

Gray 1
25.7 1.0 -2.6
38.7.4 -3.5

17.2 1.8 -.3

Average: 26.2 1.0 -2.1

Gray 2
57.7 1.1 -4.4
47.7 1.1 -1.3
54.7.9 -3.6

Average: 52.4 .9 -3.1

Gray 3
102.4 -2.2 -9.2
86.2 -1.4 -1.7
91.3 -1.6 -3.9

Average: 83.3 -1.7 -4.8

Orange
74.1 90.2 90.1
72.1 88.1 88.0
67.1 89.8 85.1

Average: 71.1 88.4 87.7

Violet
15.3 31.3 -32.8
21.7 38.3 -41.2
17.3 83.3 -35.2

Average:17.1 49.9 -35.4

White
135.8 -4.6 -11.0
138.7 -4.6 -11.8
134.6 -5.0 -15.5

Average:134.4 -4.8 -12.7