Impact of Substrate Weight and Brightness on Color Quality of Electro-photographic Digital Color Printing

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Keywords: substrate, digital color, gamut, profile, ANOVA

Abstract

Print reproduction involves physical/mechanical interaction between the imaging cylinder, dry/liquid toner, and the substrate. Most photographic technology prints will heavily degrade after about fifty to one hundred years after their initial printing. This allows for determining which factors, including the paper, play the most crucial role in the longevity of printed images. Other distortions may happen to images during the printing process. Printing paper or substrate is considered to be the fifth color for process color printing. Paper is considered a commodity but its properties are a long way from being standardized. The perception of color quality evaluation is strongly influenced by the properties of the paper (weight and brightness), and it is one of the most important factors in judging the color appearance of the printed material. Substrate thickness can influence the paper weight also. Color can be viewed as a science where the optical aspects of color are quantitatively analyzable and measurable. The human eye, however, perceives color more subjectively, which poses a challenge at times for the printing and image reproduction industry.

The experiment was conducted in a digital color printing workflow (DCPW) to determine the effect (impact or influence) of paper properties (thickness and brightness) on the color quality based on the statistical evaluation among nine (K = 9) different types of substrates (printing papers). Each substrate (paper) in the experiment was considered as a group, noted by letter “K” (K = 9). Paper samples with different properties (weight and brightness) were used (or selected) for the experiment. This study was focused on the measurement of color prints, printed on multiple types of substrates by using dry-toners on a digital color printing device which uses a color electrophotographic (color laser) printing technique.

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Color quality was determined by carefully evaluating the printed primary colors hue. Colorimetric, denstometric, and spectrophotometric computations were used to determine the printing colors (solid CMYK) and gray color (overlap of C = 50%, M = 40%, and Y = 40%) "*hue variation*" (ΔH) among the nine (K = 9) types of substrates with various thickness/brightness. Type of paper used for the printing will have a significant impact on the print attributes, in turn they affect the print quality/visual appearance of colors (hue). This research demonstrates the use of ANOVA to determine the influence of substrate property (thickness/weight) in the *primary colors and gray color hue variation among the nine types of papers/ substrates, printed in a digital color printing workflow*. The findings of this study represent specific printing or testing conditions.

Introduction

Over the past two decades, the printing (or the graphic arts) industry has been revolutionized. Technology, workflow, management strategy, markets, and customer expectations have changed. Today, print is just one of many media channels which consumers can access. Advancements in science and engineering field are enabling the printing and graphic professionals to apply scientific research methods across prepress, press-room, and quality control areas for quality color reproduction on a wide variety of substrates (papers). The value and role of printing is changing. The use of print is merged across multiple communications channels, such as: web, mobile, and social media. Due to advancements in computer networking and digital printing technologies, print media has become a powerful multi-channel marketing and communications tool. Modern printing has evolved from a craft-oriented field toward a color management science. This is demanding a greater color control among the devices (printing and non-printing) and substrates used in the printing and imaging industry. The quality of color image reproduction of any type of printing (digital or traditional), is largely influenced by the properties of paper. Paper is considered a commodity but its properties are a long way from being standardized (Wales, 2009).

A continuous-tone color (or grayscale) photograph is composed of a full spectrum of shades and colors, from near white to dense black. The method by which a continuous-tone photographic image is transformed to a printable image is called halftoning. In this method, varying percentages of the printed sheet are covered with halftone dots to represent the varying tones in the image. Digital printing technologies can be described as methods that do not use image carriers such as printing plates. Today, most digital printing environments utilize a digital halftoning process for color printing. A simple digital image could be a binary picture, [h(x, y)], with each point being either completely black or completely white (Pnueli & Bruckstein, 1996). A digital halftone is a pixel map, with bit depth, that gives the impression of an image containing a range of gray shades or continuous tones. An 8-bit grayscale image contains 256 different levels of gray (from white to black).

Advancements in digital technology enable the industry to engage in short-run color printing that can achieve levels of color quality comparable to that of the traditional offset printing process.

Print reproduction involves physical/mechanical interaction between the imaging cylinder, dry/liquid toner, and the substrate (Avramoci & Novakovia, 2012). Most photographic technology prints will heavily degrade after about fifty to one hundred years after their initial printing. This allows for determining which factors, including the paper, play the most crucial role in the longevity of printed images. Other distortions may happen to images during the printing process. Printing paper or substrate is considered to be the fifth color for process color printing. The perception of color quality evaluation is strongly influenced by the properties of the paper (weight and brightness), and it is one of the most important factors in judging the color appearance of the printed material. Substrate thickness can influence the paper weight also. Color can be viewed as a science where the optical aspects of color are quantitatively analyzable and measurable. The human eye, however, perceives color more subjectively, which poses a challenge at times for the printing and image reproduction industry.

Literature Review

Literature summarized in this section was found to be important as it relates to the paper properties effect on the color/print attributes (*primary colors/gray hue, gamut volume, etc.*), which enables this research to examine/evaluate to determine the quality of color printing. Digital printing methods differ in that they usually do not have a direct physical impact on a substrate. Color electrophotography, or color laser printing, is commonly used and employs charged toner particles that transfer electrostatically to a substrate and create an image that is fused to the surface. The advantage of dry, toner-based digital print technology is that it can create varying images from one sheet to the next and it is more cost-effective for shorter production runs. In 2003, McIlroy posited "all printing processes exhibit dot gain, or more correctly, tone value increase, to varying extents." McIlroy continued by stating, "this includes desktop inkjets, laser printers, digital presses, and any conventional printing press" (p. 261). This establishes not only that dot gain is likely to be a measurable factor in digital printing but provides a basis for defining dot gain and how to measure it. Leurs supports this definition and further refines it by stating "Dot gain is sometimes referred to as TVI (tone value increase). TVI is a more generic description of the difference in tone value between a requested value and the final output. It is also a more suitable name for processes in which, some devices may not actually deliver a dot in the final output" (2013).

Gray balance is a useful measure of color reproduction because it indicates problems that will impact all other colors. Correct gray balance is a fundamental measure for proper color balance. Printing that does not maintain gray balance will have a color cast that does not only show in the gray area but throughout the entire image. Grays produced using the primary CMY toner colorants must be measured and adjusted regularly to avoid color shifts. The value of a stable, predictable printing process is essential to any color-managed digital printing workflow. The color gamut is defined as the range of colors producible (captured or displayed) or printable on a particular device such as: digital camera/scanner, monitor, or printer. A monitor, which displays red, green, and blue (RGB) signals, typically has a greater color gamut than that of a printer, which uses CMYK dry-toners or liquid inks. Since the paper or the substrate is considered to be the fifth color of multi-color printing, it has a direct effect on the printed colors. For example, image/colors printed from the same device on different types of paper substrates will have a different color appearance (color hue). A simple scenario could be, printing on 75 LBS coated paper vs. 75 LBS un-coated paper, the color results will be different by showing the significant variation visually and quantitatively among the print attributes. Color gamut volume (CGV) is quantifiable in the colorimetric color space. The CGV is generally examined in the CIE L* a* b* color space, and it can be interpreted as the number of colors that are discernable within a tolerance of $\Delta E=\sqrt{3}$ (Fleming & Veronica, 2009).

CIE L* a* b* Color Model

The Commission Internationale de l'Eclairage (CIE), also known as the International Commission on Illumination, is responsible for international recommendations for colorimetric measurements (ANSI/CGATS.5-2003). In 1976, the CIE developed the CIE L*a*b* or CIELAB color model (scale) for quantifying color values numerically. It was intended to provide a standard, approximately uniform color model that could be used by the industry so that color values could be easily compared or expressed (ANSI/CGATS.5-2003). The CIE color model utilizes three coordinates to locate a color in a color model. In a uniform color model, the differences between points plotted in the color model correspond to the visual differences between the colors plotted (Hunter Lab, 1996). The CIELAB color space is organized in a cube form. The L* axis runs from top to bottom. The maximum for L* is 100, which represents a perfect reflecting diffuser. The minimum for L* is zero (0), which represents black. The +/-a* and +/-b* axis have no specific numerical limits. +a* is indication of red color and –a* is green color in the color model. Additionally, +b* is yellow and –b* is blue (see Figure 1). The center of this model represents the neutral or gray colors. These color scales are based on the opponent color theory of color vision, which means that one cannot be both green and red at the same time, nor blue and yellow at the same time. As a result, single values can be used to describe the red/green and the yellow/blue attributes (X-Rite, 2002).

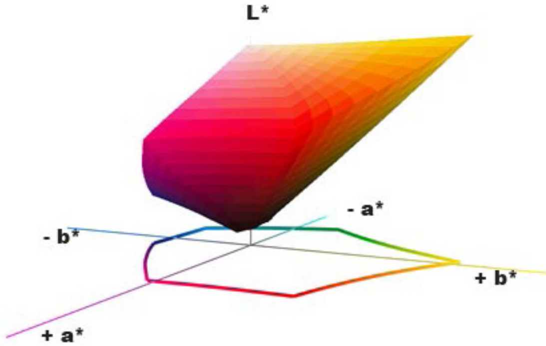

Figure 1: *Schematic Diagram of CIE L* a* b* Color Model*

The following equations are used by a spectrophotometer to calculate the CIE L* a* b* values from a color or any colors (ANSI/CGATS.5-2003, p.28).

$L^* = 116\ (Y/Y_n)^{1/3} - 16$

$a^* = 500\ [(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$

$b^* = 200\ [(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$

where: X_n, Y_n, Z_n: tristimulus values of XYZ for 2˚ standard observer

CIE Color Difference (ΔE)

Assessment of color is more than a numeric expression. Usually it's an assessment of the difference in the color sensation (delta) from a known standard. In CIELAB color model, two colors can be compared and differentiated. The expression for these color differences is expressed as ΔE (Delta E or Difference in Color Sensation). The following equation is used to calculate the ΔE (ANSI/CGATS.5-2003, p.29)

$\Delta E = \sqrt{} L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2$
where: 1 = Color 1 and 2 = Color 2

CIE Lightness, Chroma, Hue (L* C* H*) and Gray

Each color has its own distinct appearance based on hue, chroma (saturation), and value or lightness (X-Rite, 2007). By describing a color in terms of these three attributes, one can accurately identify a particular color and distinguish it from others. When asked to describe the color of an object, most people mention its hue first. Quite simply, hue is how people perceive an object's color, such as red, orange, or green (X-Rite, 2007). Chroma describes the vividness or dullness of a color: how close the color is to either gray or to the pure hue. For example, the red of the tomato is vivid, but the red of the radish is dull (X-Rite, 2007). The luminous intensity of a color (i.e., its degree of lightness) is its value. Colors can be classified as light or dark when their values are compared. For example, when a tomato and a radish are placed side by side, the red of the tomato appears to be much lighter. In contrast, the red of the radish seems to have a darker value (X-Rite, 2007). The L* c* h* color space uses the same coordinates as those of the L* a* b* color space, but it uses cylindrical coordinates instead of rectangular coordinates. In this color space, L* indicates lightness and is the same as the L* of the L* a* b* color space, C* is chroma, and h* is the hue angle. The value of chroma C* is 0 at the center and increases according to the distance from the center (See Figure 2). Hue angle h* is defined as starting at the +a* axis and is expressed in degrees; 0° would be +a* (red), 90° would be +b* (yellow), 180° would be –a* (green), and 270° would be b* (blue). Metric chroma C* and the metric hue angle h* are defined by the following formulas (Morovic, et al. 2002).

Metric chroma $C^* = \sqrt{(a^*)^2 + (b^*)^2}$

Metric hue angle: $h^*_{ab} = \tan^{-1}\left(\frac{b^*}{a^*}\right)$

where: a*, b* are chromaticity coordinates in L* a* b* color space

Gray balance is the proper percentages of "overlap/combination" of cyan, magenta, and yellow inks that produce neutral shades of gray. Hue shifts will occur when there is any imbalance of one of the components. The imbalance is due in large part to ink impurities. Gray balance is a significant factor in determining overall color gamut. Gray balance can be determined by careful evaluation of a full set of tint charts printed with process inks. Colorimetric method is used to determine *if the hue of gray* is desirable in order to make sure that the black ink scale is neutral.

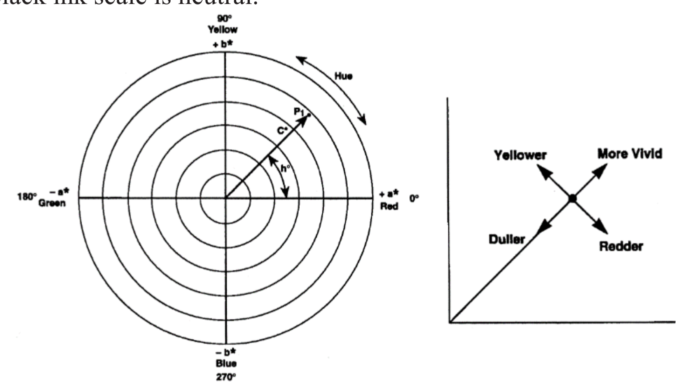

Figure 2: Schematic of L* c* h* Coordinates

Hue difference (ΔH*) is calculated by the following formula (Morovic et al., 2002).

$$\Delta H^* = \sqrt{(\Delta E^*\ ab)^2 - (\Delta L^*)^2 - (\Delta C^*)^2}$$

$$= \sqrt{(\Delta a^*)^2 + (\Delta b^*)^2 - (\Delta C^*)^2}$$

Purpose of the Research

The experiment was conducted in a digital color printing workflow (DCPW) to determine the effect (*impact or influence*) of paper properties (thickness and brightness) on the color quality based on the statistical evaluation among nine (K = 9) different types of substrates (printing papers). Each substrate (paper) in the experiment was considered as a group, noted by letter "K" ($K = 9$). Paper samples with different properties (weight and brightness) were used (or selected) for the experiment. This study was focused on the measurement of color prints, printed on multiple types of substrates by using dry-toners on a digital color printing device which uses a color electrophotographic (color laser) printing technique.

Color quality was determined by carefully evaluating the printed *primary colors hue* [Cyan, Magenta, Yellow, and Black (CMYK) and *gray hue* (overlap of CMY)]. Colorimetric, denstometric, and spectrophotometric computations were used to determine the printing colors (solid CMYK) and gray color (overlap of C = 50%, M = 40%, and Y = 40%) "*hue variation*" (ΔH) among the nine (K = 9) types of substrates with various thickness/brightness. Type of paper used for the printing will have a significant impact on the print attributes, in turn they affect the print quality/visual appearance of colors (hue). In order to print a quality halftone image, the printer (or press operator) must carefully manage several variables and attributes which are associated with the printing process. The technology of interest for this study is dry-toner color electrophotography. The following one-tailed non-directional hypothesis was established, because of the multiple types of substrates (*groups, K = 9*).

H_o: There is no significant difference (or relationship) in the printing CMYK ΔH and Gray ΔH (CMY overlap) of multiple types of substrates, when the printed colorimetry is compared against the reference colorimetry.
H_a: There is a significant difference (or relationship) in the printing CMYK ΔH and Gray ΔH (CMY overlap) of multiple types of substrates, when the printed colorimetry is compared against the reference colorimetry.

Limitations of the Research

For this experiment, there were limitations to the technology used within the graphics program laboratory. Prior to printing and measuring the samples, the digital color output printing device and color measuring instruments (spectrophotometer and densitometer) were calibrated against the recommended reference. The print condition associated with this experiment was characterized by, but not restricted to, inherent limitations. For example: colored images (ECI2002, ISO300, and

ISO12647-7) chosen for printing, desired rendering intent applied, type of digital printer for proofing/printing, type of paper for printing, type of toner, resolution, and screening technique, use of predefined color output profiles, calibration data applied, and so on. Several variables affected the facsimile reproduction of color images in the DCPW, and most of them were mutually dependent. The scope of the research was limited to the color laser (electrophotographic) digital printing system (printing proof/printing) and other raw materials and the multiple types of color measuring devices and color management and control applications (data collection, data analysis, profile creation, and profile inspection) used at the university graphics laboratory. Findings were not expected to be generalizable to other DCPW environments. It is quite likely, however, that others could find the method used and the data of this article meaningful and useful. The research methodology, experimental design, and statistical analysis were selected to align with the purpose of the research, taking into account the aforementioned limitations.

Research Methodology

The digital color printing device used in this experiment is a Konica-Minolta bizHub C6000 Digital Color Press. It uses a Creo IC-307 raster image process (RIP) application (front-end system). This study utilized an experimental research method. Nine ($K = 9$) different types of substrates with various properties (weight/thickness and brightness) were used for the printing. Two page custom test image (12" x 18" size) was created for proofing and printing use for the experiment (*See Figure 3 & 3A*). The test target contained the following elements: an ISO 300 and generic images for subjective evaluation of color, and an ISO 12647-7 Control Strip, and an ECI 2002 target for gamut/profile creation. Table 1 presents the variables, materials, conditions, and equipment associated.

Colorimetric, Densitometric, and Spectrophotometric data were extracted by using an X-Rite Eye-One Spectrophotometer and X-Rite i1iO Scanning Spectrophotometer from the color printed samples for the statistical analysis to determine the significant differences that exist among the nine different types of substrates primary colors and gray hue. Print/Color attributes (primary colors and gray hue) from each group were analyzed/compared with one another. For all the nine groups ($K = 9$), a total of 900 samples of target color images were printed, 100 prints for each substrate group, noted by letter "N" ($N = 100$). Of 100 samples of each group, 80 samples (n = 80) were randomly selected from each substrate group, and measured, noted by the letter "n" (n = 80). Glass, G.V. & Hopkins, K.D. (1996), provides an objective method to determine the sample size when the size of the total population is known. Thefollowing formula was used to determine the required sample size, which were 80 (n) printed sheets of each type of substrate for this study.

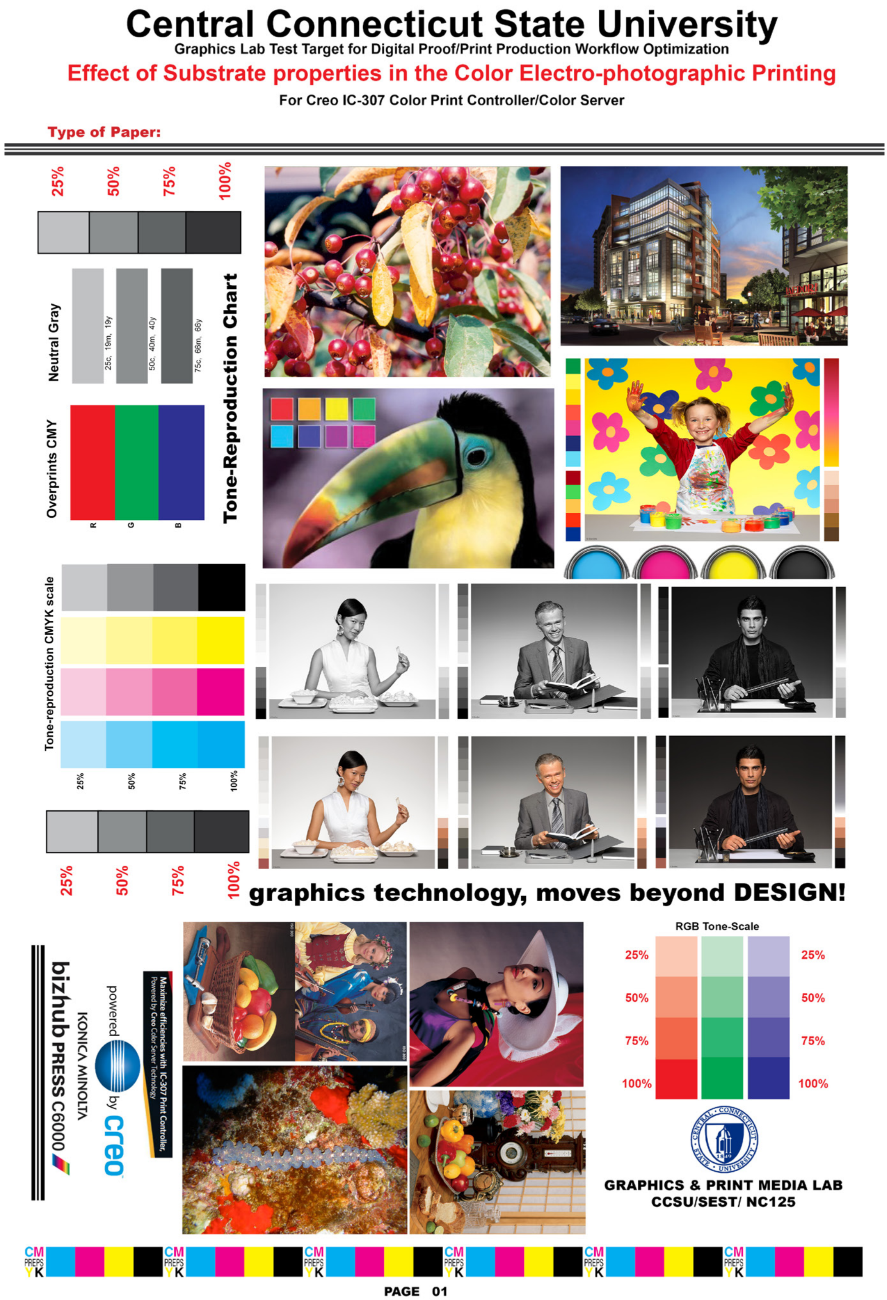

Figure 3: *Page one of the Test Image for the experiment*

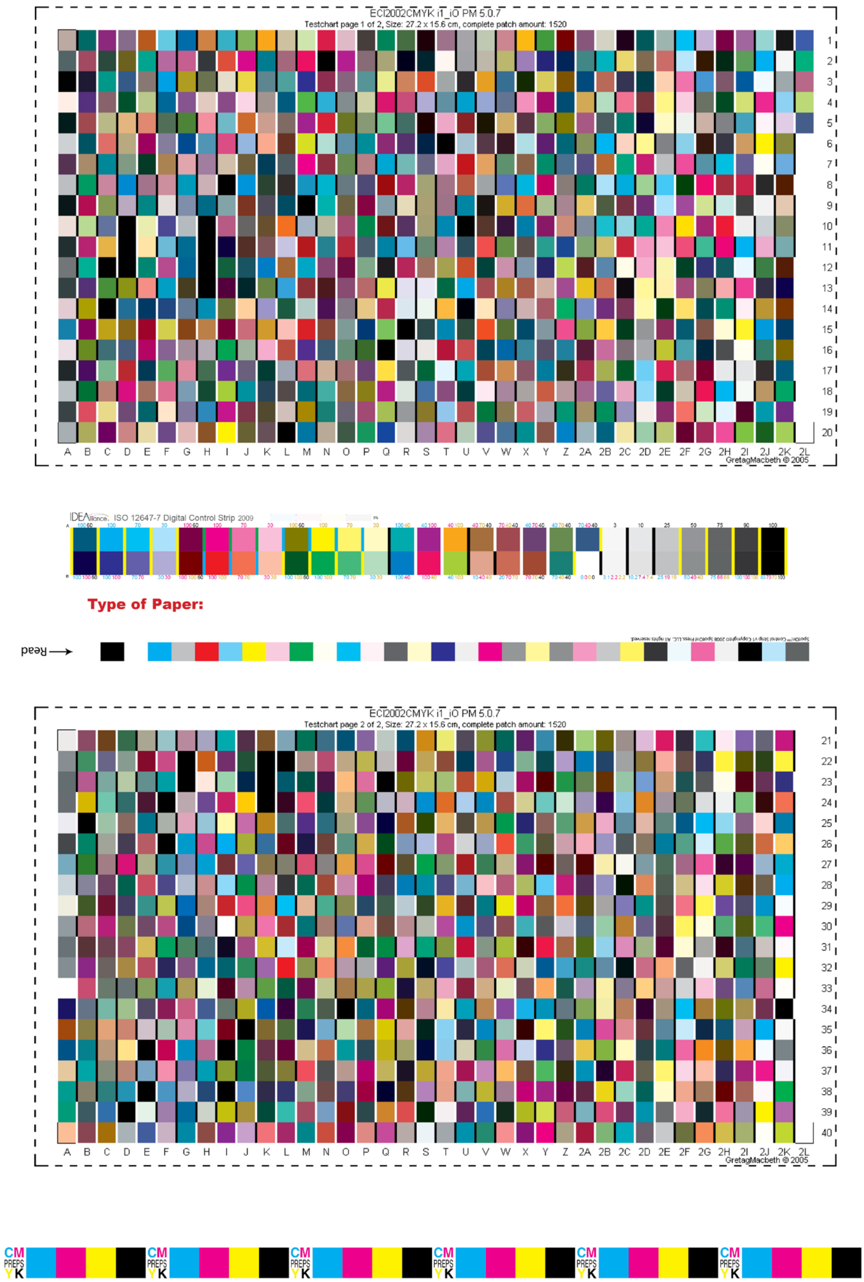

***Figure 3A:** Page two of the Test Image for the experiment*

Variable(s)	*Material/Condition/Equipment*
Test images	Custom Test Target
Control strips	ISO 12647-7, and SpotOn!Press
Profiling Software	X-Rite ProfileMaker 5.0.10
Profile Inspection Software	Chromix ColorThink-Pro 3.0
Image Editing Software	Adobe PhotoShop CS-6
Page Layout Software	Adobe InDesign CS-6
Source Profile (RGB)	Adobe 1998.icc
Emulation Profile (CMYK)	None
Destination Profile (CMYK)	Custom, Konica-Minolta.icc
Color Management Module (CMM)	Adobe (ACE) CMM
Rendering Intents	Absolute
Computer & Monitor	Dell OPTIPLEX/LCD
Raster Image Processor (RIP)	Creo IC-307 Print Controller
Printer	Konica-Minolta bizHub C6000 Color Laser
Achieved CMYK SID for both print runs	C = 1.24; M = 1.27; Y = 0.89; and K = 1.59
Screen Ruling	200 LPI
Print Resolution for AM Screen	1200 x 1200 DPI
Print Resolution for FM Screen	600 x 600 DPI
Toner	Konica-Minolta Color Laser
Paper (sheetfed)	***See Figures 4 & 5***
Type of Illumination/Viewing Condition	D50
Color Measurement Device(s)	X-Rite Eye-One-PRO Spectrophotometer with Status T, 2˚ angle, and FD-5 Spectrodensitometer
Data Collection/Analysis Software	FUJIFILM ColorPath Verified, SpotOn! Press, and MS-Excel

Table 1. *Experimental and Controlled Variables*

$$n = [\ \chi^2 NP (1-P)\ ] / [\ d^2 (N-1) + \chi^2 P (1-P)\ ]$$

n = the required sample size
χ^2 = the table value of chi-square for 1 degree of freedom at the desired confidence level (3.84)
N = the total population size
P = the population proportion that it is desired to estimate (.50)
d = the degree of accuracy expresses as a proportion (.05)

Statistical method applied for the experiment data analysis

The total population for this study was 100 (N) printed sheets for each type of paper. Total printed sheets for all the groups, $N_i = 900$, and total randomly selected printed samples from all the groups, $n_i = 720$. Data for this study was collected from ISO 12647-7 Control Strip, and an ECI 2002 target from the test image (part of printed samples). Microsoft Excel and Statistical Package for Social Sciences (SPSS) were used to analyze the collected data to determine the colorimetric variation (COLVA) among the multiple substrates. Since K = 9, inferential statistics were used to determine the significant differences that exist among the ($K = 9, n_i = 720, and N_i = 900$) group mean color deviations of the various substrates.

Collected data was arranged in an analyzable format for each attribute of each/ every substrate. A Statistical Package for Social Sciences (SPSS) was used for inferential analysis from the *collected data* (color hue variation and gamut volume) of all these nine types of substrates to determine the significant differences that exist in the quantifiable print/color attributes of these nine types of paper substrates. Since K = 9, a one-way Analysis of Variance (ANOVA) with equal n's method (at $\alpha = 0.05$) was employed to determine the significant differences that exist between (K = 9, n = 80, and N = 100) printed attributes means/averages for each group. The F-test can be calculated by using the following equation (Glass & Hopkins, 1996).

$$F = \frac{\sigma_b^2}{\sigma_w^2} = \frac{MS_b}{MS_w} = \frac{SS_b / V_b}{SS_w / V_w} = \frac{\sum n_k \left(\bar{X}_k - \bar{X}\right)^2 / K-1}{\sum \left(X_{ik} - \bar{X}_k\right)^2 / N-K}$$

The F distribution and a probability value p, which is derived from F, will be used to determine if significant differences exist in the print attributes of multiple groups of substrates. F is a ratio of two independent estimates of the variance of the sample, namely between the groups and within the groups (K = 9, N = 100). A low p value (or higher F value) is an indication that one of the substrates means (an attribute's average) is significantly different. It would suggest that there is a strong support that at least one pair of the substrate means is not equal. A higher p value (or lower F value) indicates that the means of attributes/substrates are not statistically different. The value of q is the difference between the larger and smaller means of the two samples. Differences among the means at $p \leq 0.05$ will be considered to be statistically significant among all the groups (K = 9) or multiple substrates.

Analysis

The descriptive and inferential statistical methods were usedto analyze the data and presented in the following pages/tables. Subjective judgment on color difference/ deviation was not used in this study. The subjective judgment of color difference could differ from person to person. For example, people see colors in an image not by isolating one or two colors at a time (Goodhard & Wilhelm, 2003), but by mentally processing contextual relationships between colors where the changes in lightness (value), hue, and chroma (saturation) contribute independently to the visual detection of spatial patterns in the image (Goodhard & Wilhelm, 2003). Instruments, such as colorimeters and spectrophotometers, could eliminate the subjective errors of color evaluation perceived by human beings.

Paper property "weight" was tested against the color hue deviation and gamut volume. A total of nine different thicknesses/weights (9 types of papers) were used for the color print quality analysis. Paper weight is commonly identified as grams per square meter (g/m^2). In North America, paper weights are given as the weight in pounds (LBS) of 500 sheets of paperin basic size. Paper brightness is a measure of the amount of light, of a specific wavelength, that a sheet of paper reflects. The higher the light reflection,the higher the paper brightness.Color printing with higher paper brightness provides more contrast by allowing colors to stand out.

Printing Colors (CMYK) Hue Deviation (ΔH): Reference Vs. Printed Colorimetry

The average primaries ΔH were different from one substrate to the other. As such, the ANOVA test was conducted to determine if there was any significant difference, $p \leq 0.05$ among the primaries ΔH of the multiple substrates. An ANOVA test revealed that there was a significant difference among the CMYK primaries ΔH produced by each (multiple) paper/substrate, $F (9, 891) = 133.44, p = 0.000$. Data indicated that each of the paper used shows the printed primary colors differently (hue deviation). As such, the effect was significant at the $p < 0.05$ for all nine substrates/papers. Post-hoc ANOVA analysis was NOT employed to determine which group (K) of paper means (averages) were significantly different (a*mong the multiple substrates means/average primaries ΔH*), when compared two sample means/averages at a time (Glass & Hopkins, 1996). Descriptive statistical analysis was used to compare the means/averages of multiple substrates means/average primaries ΔH. Color gamut volume (CGV) was extracted from the created profile of each paper (K = 9). ColorThink Pro software was used to extract the numerical information of CGV (*see Figure 4*).

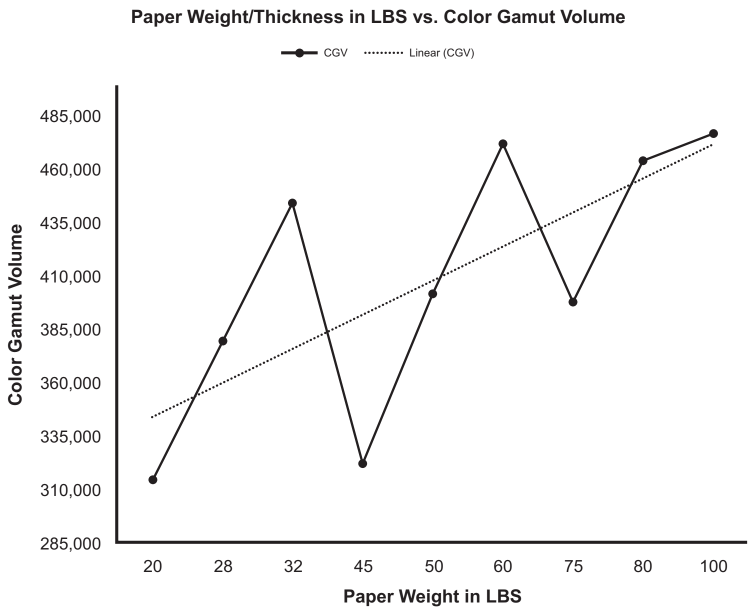

Figure 4: *Comparison of Paper Weight VS. Color Gamut Volume*

CMYK primary colors hue deviation was significant among the paper groups from 20 LBS to 50 LBS, and 75 LBS. No significant hue deviation was detected among the paper groups of 60 LBS coated, 80 LBS coated, and 100 LBS coated. Comparison of primary color hue deviation (ΔH) with printed vs. reference colors, the 80 LBS coated paper produced the least deviation, while 20 LBS uncoated paper produced the highest color deviation (see Figure 5).

Gray Color (Overlap of CMY) Hue Deviation (ΔH): Reference Vs. Printed Colorimetry

An ANOVA test revealed that there was a significant difference among the gray ΔH produced (gray hue appearance) each (multiple) substrate/paper, $F(9, 891) = 1309.77, p = 0.000$. Data indicated that on each paper/substrate surface, the gray colors look differently (see Figure 5). As such, the effect was significant at $p < 0.05$ for all the nine substrates/papers of various thickness/weight (see Table 5). Post-hoc ANOVA analysis was NOT employed to determine which group (K) of paper means (averages) were significantly different (*among the multiple substrates means/ average Gray ΔH*), when compared two sample means/averages at a time (Glass & Hopkins, 1996). Descriptive statistical analysis was used to compare the means/ averages of multiple substrates means/average Gray ΔH.

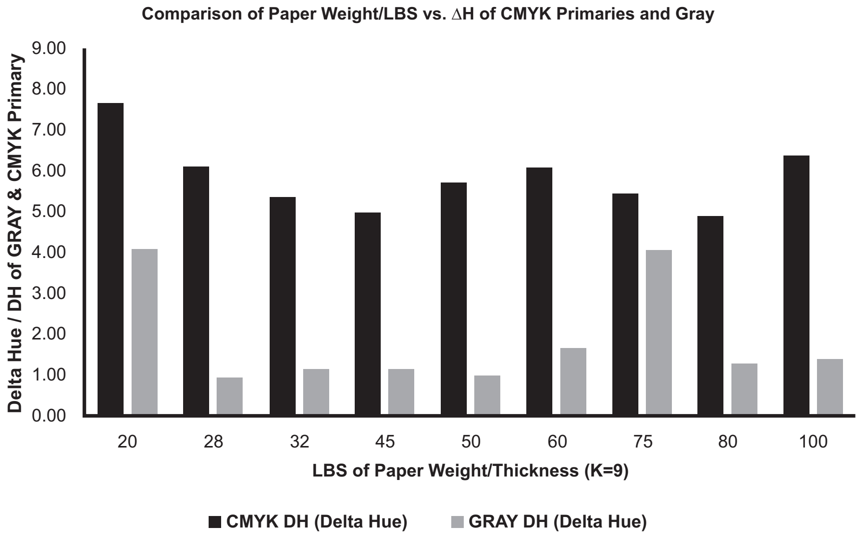

Figure 5: *Comparison of Paper Weight/LBS VS. CMYK Primaries ΔH & Gray ΔH*

Gray hue deviation was significantly higher among the paper groups from 20 LBS and 75 LBS. No significant hue deviation was detected among the remaining paper groups of 60 LBS coated, 80 LBS coated, and 100 LBS coated. Comparison of gray hue deviation (ΔH) with printed vs. reference colors, the 28 LBS matte-coated paper produced the least deviation, while 20 LBS uncoated paper produced the highest gray hue deviation. As the thickness of paper increased, the color gamut volume also increased.

Summary

This research demonstrates the use of ANOVA to determine the influence of substrate property (thickness/weight) in the primary colors and gray color hue variation among the nine types of papers/substrates, printed in a digital color printing workflow. The findings of this study represent specific printing or testing conditions. The images, printer, instrument, software, and paper that were utilized are important factors to consider when evaluating the results. The findings of the study cannot be generalized to other digital printing workflow. However, other graphic arts educators, industry professionals, and researchers may find this study meaningful and useful. For example, educators can implement similar models, the presented model, or this method to teach. The colorimetric data of this experiment led to the conclusion that the selection of a suitable paper is an important step for printing colors of choice for a desired use/purpose.

The conclusions of this study are based upon an analysis of the ANOVA test data and major findings (data and experience of the experiment). The data from the ANOVA test revealed that there were significant differences in the color reproduction among the multiples types of substrates used. As such the null hypothesis were rejected. There were significant differences that were found in gray color hue and primary color hue variation. Furthermore, the experience of the experiments (visual comparison) and analyzed data proved that there were noticeable color differences among the printed samples (photographs, commercial, and digital printing) of various substrates. One could **NOT** achieve the same color output with various types of paper substrates and should be cautioned to identify color hue on coated vs. uncoated papers. Higher color deviations (ΔE or ΔH) mean that the printed colors could be out of established deviation tolerances.

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