May 2020

Evaluating Hue Shifts in Spot Color Tints in Flexographic Package Printing

Himanshu Rana
Clemson University, himanshurana24@gmail.com

Recommended Citation

Rana, Himanshu, "Evaluating Hue Shifts in Spot Color Tints in Flexographic Package Printing" (2020). *All Theses*. 3316.
https://tigerprints.clemson.edu/all_theses/3316

EVALUATING HUE SHIFTS IN SPOT COLOR TINTS IN FLEXOGRAPHIC PACKAGE PRINTING

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Packaging Science

by
Himanshu Rana
May 2020

Accepted by:
Dr. Duncan Darby, Committee Chair
Dr. Kay Cooksey
Dr. Liam O'Hara

ABSTRACT

Packaging helps to preserve, protect, dispense, communicate, and sell a product. Color is a key contributor to the communication and selling functions. In order to achieve a specific color appearance on a given packaging substrate, spot color printing uses custom formulated inks. The standard colorimetric values for solids of spot colors are well defined by either Pantone® specifications, International Commission on Illumination (CIE) L*a*b*C*h° values, spectral data, or with a combination of these. While the colorimetric standards for tints of spot colors exist in the form of digital libraries such as PantoneLIVE or as Color Exchange Format (CxF-4a) data, spot color tints are commonly managed using tone value measurements. Additionally, these spot color inks can be manufactured as mixtures of different combinations of the base pigment inks. This may cause a hue difference in the tints printed with different ink recipes. Some spot colors are also known to exhibit a shift in hue angle at different tint percentages (e.g. Reflex Blue). It is also important to understand this problem from a designer's viewpoint who is using a digital standard as reference. This study focuses on evaluating the extent and nature of hue shifts in spot color tints. The study is also intended to address how different these hue shifts are from a digital reference commonly used by designers. The second part of the study evaluates the visual perceptibility and acceptability of these hue shifts in spot color tints. Three versions of spot color tints were evaluated – print, PantoneLIVE, and hue-corrected. The visual results were also correlated to the results obtained from spectrophotometer measured data. The results suggested high hue shifts with spot colors that had a high chromaticity. The study also highlighted the limitations of hue angle and hue difference in characterizing hue shifts for colors with low chromaticity. The visual study showed that there were visually perceivable and potentially unacceptable hue shifts between the tested spot color tints. Although, the visual difference between print and PantoneLIVE samples was consistently recognized by the observers, it was not enough to change their intent to purchase in most of the cases.

ACKNOWLEDGMENTS

I would like to thank my advisory committee - Dr. Duncan Darby, Dr. Kay Cooksey, and Dr. Liam O'Hara for guiding me through this project. I want to express my gratitude towards Dr. Patrick Gerard from the Statistics and Mathematics Consulting Center (SMCC) for advising me on the statistical design and analysis aspects of this project. I would like to thank the department chairs and faculty members of Packaging Science and Graphic Communications for their contribution and support during the course of this project. I want to express my gratitude to the staff and student interns at The Sonoco Institute of Packaging Design and Graphics for their constant support throughout this project. I also want to thank the Flexographic Technical Association, the people who participated in the study and the industry experts who helped me with this project Mark Samworth, and Mr. John Seymour. I would like to thank the industry partners at The Sonoco Institute of Packaging Design and Graphics for their contribution of materials and equipment needed in this project. I would like to thank Mr. Wade Harris and Westrock for their donation of the paperboard substrate for this study. I want to thank Siegwerk inks for donating the color-matched inks for this project. I would also like to thank the pre-press software, consumables and equipment suppliers—Esko Graphics Inc., DuPont Advanced Printing, and MacDermid Graphics Solutions. I also want to thank Xrite for providing the Xrite eXact spectrophotometer, Colorcert and Ink Formulation Software. I would also like to thank Epson US for the proofing devices used in this study.

Finally, I would like to thank my family and friends for their constant support and inspiration through this journey.

TABLE OF CONTENTS

Page

CHAPTER

Table of Contents (Continued)

Page

LIST OF TABLES

Table Page

List of Tables (Continued)

Table Page

LIST OF FIGURES

Figure Page

List of Figures (Continued)

List of Figures (Continued)

Figure Page

List of Figures (Continued)

List of Figures (Continued)

Figure Page

CHAPTER ONE

INTRODUCTION

Introduction to problem

Packaging plays an important role in the modern world. It helps to preserve, protect, dispense, communicate and sell a product. Hellström and Saghir (2007) and Mohebbi (2014) stated that packaging serves three primary communication functions – communicating product handling and use related information, promoting the product , and improving consumer connection. Garber, Burke, and Jones (2000) cited Hine (1996) suggesting that the package has assumed the role of salesperson, as the primary mode of communication with the consumer at the point of purchase. Printing and color are key components of the communication and selling functions. Mohebbi (2014) suggested that graphics and color can influence purchase decisions. Despite the importance of visual cues such as color in market research applications, limited work has been done on its use in packaging (Kauppinen-Räisänen, 2014; Kauppinen-Räisänen, 2011; Labrecque & Milne, 2012).

Printing can be broadly classified into two categories based on how the color is achieved, process and spot color printing. Process color printing involves use of combinations of process colors—Cyan, Magenta, Yellow and Black (CMYK). Expanded gamut printing is a special case of process printing where additional colors, typically orange, green and violet, are used to achieve a larger color gamut. Spot color printing uses specially formulated inks that are designed to achieve a particular color appearance on a given substrate. High volume brand colors are commonly printed as spot colors. Different brands use characteristic colors that allow consumers to relate to their products and brand identity (e.g. a Coca-Cola® red or a Pepsi® blue).

The spot colors in the printing and packaging industry are usually printed with custom formulated spot inks. The colorimetric standards for solids of spot colors are well defined by either Pantone specifications, colorimetric coordinates, spectral data, or with a combination of these. However, spot color halftones (or tints) are commonly managed using tone value and dot gain, which does not provide colorimetric information. Some of these spot color inks can show hue shifts in printed tints. A common example of such an ink is Reflex Blue that tends to shift towards a purple hue as the tone value goes down. The extent of this shift is difficult to predict and may depend upon factors such as the colorimetric properties of the spot color, ink mixture composition, substrate, and the tone values. These spot color inks are mixtures of different combinations of the base pigment inks. Different ink manufacturers may use different ink recipes and base pigments for making the same spot ink while trying to achieve a reference colorimetric value for the solid. While this approach may work well for achieving a color match in the solids, tints may show hue differences between the differently formulated inks. Another aspect of the problem involves the use of a standard to simulate the color appearance of a spot color tint. The color appearance from the standard may not necessarily match with the print results. The nature and extent of these hue shifts needs to be evaluated. Moreover, the measured hue shifts need to be correlated to visual perception.

This study focused on using three different hue shift metrics to characterize the extent and nature of hue shifts in spot color tints. The maximum hue shifts and the corresponding SCTV were noted. The study was also intended to address how different these hue shifts were from a digital reference commonly used by designers. The three metrics used to characterize hue shift were also compared with each other. A visual study was also conducted in the second part of this project. The visual study was designed to evaluate perceptible and acceptable differences between spot color tints. The results of the instrument-based approach were compared with the visual study results.

Scope of the study

The study was limited to six spot colors on a single paperboard packaging substrate. The study was conducted with six different water-based inks. Water-based inks are commonly used for printing paperboard packaging. The PantoneLIVE dependent library Flexo Water-Based Coated

Paper (FWCP) was used as the digital reference. Other software solutions, although available, were not evaluated under this study. The substrate was chosen based on substrate white point in the PantoneLIVE FWCP library.

CHAPTER 2

LITERATURE REVIEW

Definition of terms

This section provides basic terminology and brief explanation that would be helpful in understanding the content.

- Spot color ink – An ink that is custom formulated to achieve a specific color appearance on a given substrate. A spot color refers to the colorimetric appearance that is desired in this case.
- Spot color solid – An area or patch where the spot color is printed with 100% area coverage.
- Spot color tints or tones or halftones – An area or patch where spot color is printed with partial (1 to 99%) area coverage.
- Spot Color Tone Value (SCTV) or spot color tint percentage – A metric to quantify the percentage area covered by spot color ink out of a given area (1 to 99%). The SCTV is also generally referred to as tone value or tint percentage.
- Spectral Reflectance – The reflectance response of a sample over a spectrum of wavelengths, typically in the visible region of the electromagnetic spectrum.
- Tristimulus Values (XYZ) – CIE XYZ tristimulus values are colorimetric coordinates to define color. The Y value represents the luminance or brightness, the Z value can be related to the response of S cone function of human eyes and/or the blue color perception. The X value is a set of non-negative response curves (Wikipedia, 2020).
- Colorimetric Values (CIE L*a*b*C*h°) – The colorimetric values are used to quantify, define and communicate colors.
    - L* stands for lightness. 100 means purest white and 0 means pure black.

  - a* defines the redness or greenness of a sample. A positive a* value indicates red while a negative a* indicates the extent of green.
  - b* defines the yellowness or blueness of a sample. A positive a* value indicates yellow while a negative a* indicates the extent of blue.
  - C* is the chromaticity of a sample. It refers to the saturation of a color.
  - h^{o} stands for the hue angle of a color in a 360^{o} polar coordinate space.

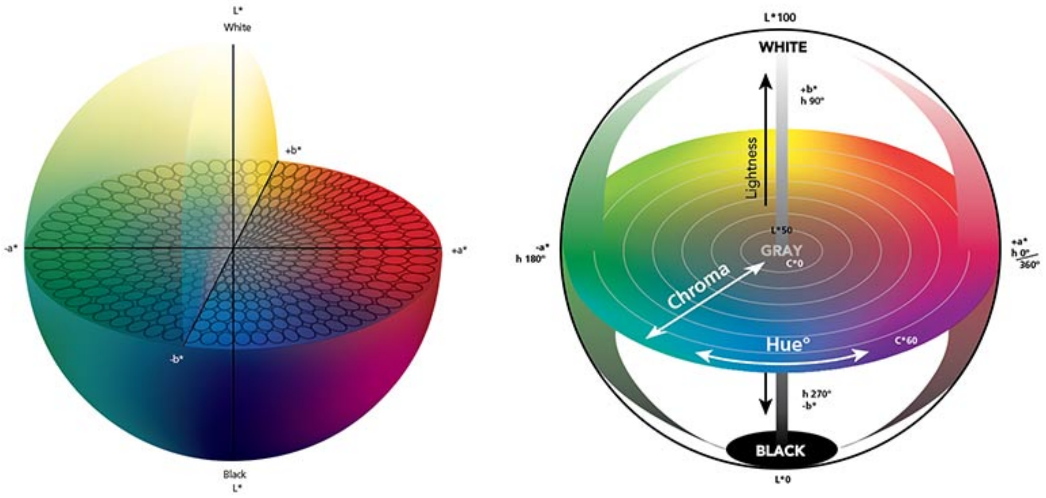


Fig. 2.1. Colorimetric coordinates in CIELAB and CIELCH models (Mouw, 2018)

- White point – The colorimetric values of the substrate that is used for printing.
- PantoneLIVE Flexo Water-based Coated Paper (FWCP) Library – A PantoneLIVE dependent library containing colorimetric standards (L*a*b*C*h^{o} values) for paperboard with a specific white point, printed with water-based inks using the Flexography process.
- Hue shift - In this study hue shift refers to the change in the hue appearance of a spot color tint. Three metrics have been used in this study to characterize hue shift. These metrics have been defined with the formulae used in the methods and materials section.
  - Hue angle difference – The arithmetic difference between hue angle of spot color solid and the spot color tint.

  - Hue difference or Delta H - The component of color difference calculation that quantifies the hue difference component.
  - Orthogonal Distance – The orthogonal distance between a spot color tint and the line joining the substrate white point and the spot color solid.
- Proofing – Proofing is the process of reproducing a color or an artwork on a color accurate digital printing device to simulate a specific colorimetric appearance.
- Tone scale – It refers to a sequence of tints printed in an array (generally 1 to 100% in steps of 10% tone value)
- Tonal range – The range of tone values that can be reproduced on an output device.
- Highlights – The lighter region of the tone scale (generally 1%-20%)
- Midtones – The middle region of the tone scale (generally 20% to 75%)
- Shadows – The dark region of the tone scale (generally 75% to 99%)
- Spectral Power Distribution (SPD) – SPD represents the radiant power of an illuminant as a function of wavelength or a band of wavelength of light in the visible region (Taylor, 2000).
- Color measurement mode M0 – International Organization for Standardization (ISO) 13655-2 (2017) suggests M0 mode relates to the measurements made with a light source which closely resembles an incandescent lamp and has a relative spectral power distribution close to the CIE (International Commission on Illumination) Illuminant A. The CIE illuminant A light source resembles the output of an incandescent lamp with a correlated color temperature of 2856K (ISO/TC 130, 2017).
- Color measurement mode M1 – ISO13655-2 (2017) suggests M1 mode relates to the measurements made with a light source which closely resembles the CIE Illuminant D50. The CIE illuminant D50 corresponds to a correlated color temperature of 5000K (ISO/TC 130, 2017).

- Color gamut – Range of colors that can be reproduced using an output device such as a printing machine or a desktop monitor.

Review of literature

The role of packaging in the modern world has evolved from just a means to protect and preserve a product to something much more. Modern-day packaging acts as a silent salesman interacting directly with consumer at the point of purchase. Various studies have related packaging to product marketing, brand building and sales.

Kauppinen-Räisänen (2014) and Clement (2007), while citing a study by Urbany, Dickson, and Kalapurakal (1996) reported that up to 90% consumers purchased products based on a visual examination of the face of a package even before picking up the product. However, the author of the current study could not trace the origin of this claim in the primary study published by Urbany, Dickson, & Kalapurakal (1996). Kauppinen-Räisänen (2014), Inman, Winer, & Ferraro (2009), and Point of Purchase Advertising Institute (POPAI) (1995) reported that in mass merchandisers and supermarkets across the United States (US), more than 70% of purchase decisions involved in-store decision making. It has been reported by multiple authors that majority of purchase decisions for non-durable products are made at the store shelf (Mohebbi B., 2014; Prone, 1993; Rosenfeld, 1987; Underwood & Ozanne, 1998; Vartan & Rosenfeld, 1987). Underwood & Ozanne (1998) and Mohebbi B. (2014) suggested that higher in-store decision making allowed for more decision influencing potential for the packaging. The author cited a study by Simms & Trott (2010), where they suggested that packaging had an effect on consumers' buying decisions and consequently the success of a product in fast-moving consumer goods market (Mohebbi, B., 2014; Simms & Trott, 2014). It was suggested that since packaging is generally the most visible representation of the brand at the point of purchase, it can influence consumers' brand decision-making (Kauppinen-Räisänen, 2014; Madzharov & Block, 2010; Silayoi & Speece, 2007; Simms & Trott, 2014). This potential to influence consumer purchase decisions has reportedly led to an increase in the point-of-purchase marketing efforts and focus on product packaging (Inman, Winer, & Ferraro, 2009; Kauppinen-Räisänen, 2014).

Mohebbi (2014), Simms and Trott (2010), Wansink and Huffman (2001) stated that packaging is an important contributor to product success, especially in fast-moving consumer goods market. Mohebbi (2014) said that packaging could be effectively used as an advertising tool to promote sales. Packaging is also seen as a key marketing and brand promotion tool (Mohebbi, B., 2014; Rundh, 2005; Simms & Trott, 2014).

Stoll, Baecke, & Kenning (2008) conducted a study to correlate consumer behavior towards package aesthetics and their brain activity. They used functional Magnetic Resonance Imaging (fMRI) to map the consumers' brain activity while judging attractive versus unattractive or neutral packages. The authors began by conducting pre-tests and confirmed that packages did, in fact, affect consumer decision-making and preferences for the tested subjects. They reported that changes in package (e.g. changing Nivea cans changed to red from blue) led to changes in consumer preference. The authors asked 51 random observers to rate 86 paper-based packages on attractiveness scale where 1 represented very unattractive and 10 represented very attractive. The product packages were grouped into three categories – attractive (scored above 6), neutral (scored between 5 and 6), and unattractive (scored lower than 6). The researchers then picked the top 10 packages from each category. The fMRI study was conducted with eleven subjects (four male and seven female), all aged between eighteen and twenty-six years. While being monitored in the MR device, the subjects were shown images of packages and asked to judge it as attractive or unattractive. The authors reported that the percentage of positive responses (judged attractive) for attractive, neutral, and unattractive package categories were 87.95%, 63.18%, and 24.32%, respectively. The authors observed different neural activation patterns and active brain regions for attractive and unattractive packages. The authors suggested that choice of attractive packages could be related with areas in the brain associated with reward processing, decision making, and episodic memory. Based on the activity observed in the regions of the brain, it was suggested that attractive packages triggered stronger emotions, attention, information processing with background knowledge, emotional response, and were seen as a rewarding stimulus as compared to the unattractive stimuli. The active brain regions for unattractive packages corresponded to uncertain and negative response. Through this study, the authors provided a neurophysiological basis for packaging. They concluded that attractive packages were more likely to contribute to brands due to the associated attention and memory effects (Stoll, Baecke, & Kenning, 2008).

Mohebbi (2014) suggested that packaging, when effectively combined with branding, could improve the likelihood of consumers purchasing a product and could provide a competitive edge in the market. Aurier & de Lanauze (2012) suggested that packaging and the perceived quality affected the consumers’ trust and commitment to a brand and influenced attitudinal loyalty. (Aurier & de Lanauze, 2012; Mohebbi, B., 2014).

Packaging aesthetics play a vital role in gaining and retaining consumer attention, and influencing purchase decisions. Packaging color is a critical component of the package aesthetics. Various studies have related packaging color with brands and marketing, and have discussed its effect on consumers’ decision to invest in a brand or product.

Priluck Grossman, R. and Wisenblit, J. (1999) presented a review of literature on marketing applications of color from an associative learning perspective. The authors discussed multiple studies where color was applied towards marketing and/or product promotion and differentiation. The authors cited Shimp (1991) while stating that associative learning occurred when observers made connections between different events occurring in their environment. For instance, Owens Corning associated the color pink with the image of Pink Panther to represent their brand of fiberglass insulation (Grossman & Wisenblit, 1999; Shimp, 1991). Priluck Grossman, R. and Wisenblit, J. (1999) offered that such strategies had a long-term benefit potential. It was suggested that color preferences for objects were affected by the situation and associations that people may have developed. The authors discussed a study by Holmes and Buchanan (1984) on color preferences as a function of objects being judged. The subjects were asked to report their color preferences for a few products such as automobiles, clothing, and furniture. They were also asked to report their overall favorite color. It was observed that people reported different preferred colors for different objects and the reported overall favorite color was independent of object-associated preferences. It was conclude that color preferences were linked to the objects being judged (Grossman & Wisenblit, 1999; Holmes & Buchanan, 1984). Priluck Grossman, R. and Wisenblit, J. (1999) also suggested that color preferences were also affected by cultural association factors. While reporting the findings of Beatty (1997), the authors suggested that colors could affect perception of product characteristics. Citing the example of Hewlett-Packard, the white packaging of their computers was found to denote accuracy and scientific prowess. However, the users also viewed it as plain and emotionless and not attractive(Beatty, 1997; Grossman & Wisenblit, 1999). The use of color for product differentiation was also discussed. The authors cited the study by Heath (1997), where it was reported that while the color red was generally associated with soft drinks, Pepsi chose the color blue for its brand. This strategy was designed to form a new product and color association and help the consumer easily identify their product on the shelf (Grossman & Wisenblit, 1999; Heath, 1997). The authors stated that the level of involvement towards a product affected the decision-making process and attitudes. It was suggested that color could be more of an influential factor in low involvement decision-making rather than a high-involvement one, especially where competing products were not significantly different (Grossman & Wisenblit, 1999). Kardes (1988) reported that the brand attitudes were more favorable towards ads with explicitly stated conclusions, and implicit conclusion – high involvement conditions, than with implicit conclusion – low involvement condition. The conditions with explicitly stated conclusion, the brand attitudes were found to be independent of the involvement. However, for the conditions where the conclusion was implicit, the brand attitudes were observed to be more favorable for high involvement condition than the low involvement condition (Kardes, 1988).

Mohebbi (2014) also conducted a review of literature to investigate the role of color in packaging. The author, while citing Labrecque, Patrick, & Milne (2013), stated that there were examples where color similarity was used by marketers in package design (Garber, Burke, &

Jones, 2000; Labrecque, Patrick, & Milne, 2013; Mohebbi, B., 2014) to attract consumer attention and promote brand recognition. Venter et al. (2011) reported that the visual attributes of packages, especially shape and color, help attract consumer attention, build product perception and influence consumers’ buying decision (Venter, Van der Merwe, De Beer, Kempen, & Bosman, 2011). The author stated that graphics and color affected consumers’ decision to buy a product. (Mohebbi, B., 2014).

Kauppinen-Räisänen (2014) in the literature review on strategic use of color in brand packaging suggested that while color was not the only visual cue at play, it was reported to be one of the most powerful ones in packaging as it could help build deeper perceptions beyond just first impressions (Danger, 1987; Kauppinen-Räisänen, 2014). Brand packaging was reported to be an extrinsic product cue (Kauppinen-Räisänen, 2014; Méndez, Oubina, & Rubio, 2011). Extrinsic attributes do not have an effect on the physical characteristics of a product (Miyazaki, Grewal, & Goodstein, 2005), but may affect quality perceptions (Kauppinen-Räisänen, 2014; Olson & Jacoby, 1972). Miyazaki, Grewal, & Goodstein (2005) stated that consumers relied more on intrinsic product cues as these provide more useful information and product associated details. However, there can be multiple cases where the consumer may prefer extrinsic cues over intrinsic ones. For example, the cases where consumer did not have experience with the product, intrinsic information was not available, or useful or there was insufficient time, or incentive to process this information, consumers were said to rely more on the extrinsic product cues. (DeBerry-Spence, Dadzie, Ferguson, & Johnston, 2008; Kauppinen-Räisänen, 2014; Miyazaki, Grewal, & Goodstein, 2005; Veale & Quester, 2009). While high involvement purchase decisions were related to intrinsic product cues, low involvement purchases relied more on visual extrinsic product cues. Summarizing the state of existing relevant color research in marketing, the author stated that packaging color helped attract the attention of consumers (Dantas, Minim, Deliza, & Puschmann, 2004; Grimes & Doole, 1998; Kauppinen-Räisänen, 2014), and had the ability to communicate and influence preferences (Kauppinen-Räisänen & Luomala, 2010; Kauppinen, 2005; Kauppinen-Räisänen, 2014). It was stated that color did not only have the physiological ability to attract attention, but also to retain it. This could assist in cognitive processing of information and forming product perception (Kauppinen-Räisänen, 2014; Schoormans & Robben, 1997). This attraction of visual attention could be involuntary (which could be triggered by unfamiliar and color differentiated cues) or voluntary (which are typically stored in memory) (Kahneman, 1973; Kauppinen-Räisänen, 2014; Kauppinen-Räisänen & Luomala, 2010). The author also discussed the perspective that the response to packaging colors in consumers could be unconscious (instinctive) , semi-conscious (culturally-learned, daily behavior pattern), or conscious (based on personalities and personal experiences) (Kauppinen-Räisänen, 2014; Lee & Lee, 2006). While the general notion suggested that packaging colors could affect consumers' emotion, Chan and Andrade (2010) proposed that the consumers' current emotions could affect their color preferences (Chan Jean Lee & Eduardo Andrade, 2010; Kauppinen-Räisänen, 2014).

Garber, Burker, & Jones (2000) investigated the effect of packaging color on consumer choice using a computerized grocery store simulation. The authors stated that package color could be used as an effective tool to attract consumer attention and achieve product differentiation at the point of purchase. The importance of package was especially higher for products, categories or brands for which the consumer had no prior experience. The author cited a study by Cheskin (1957) stating that color was a salient element of a package because it is vivid, memorable, and can create an effect. It was suggested that a package's color could significantly affect the brand recognition and message. It could also affect the overall communication of the product and its novelty compared to other brands in the market. In their study, the authors reported an increase in brand consideration with changes in package color for consumers that were not brand loyal. However, for brands with a loyal customer base, it was suggested to keep the package color consistent with the original package or introduce only minor variations. This was suggested to avoid confusing the customer at the point of purchase (Garber, Burke, & Jones, 2000).

It is also important to understand that while packaging color is important, it does not work in a vacuum. Color combines with other elements of packaging, branding and marketing efforts to build brand identity, product perceptions, and personal associations for a consumer over time. Mohebbi (2014) discussed a study by Singh & Srivastava (2011), stating that the influence of color was affected by consumers' personal characteristics, including their physiological and mental notions, previous experiences, ethnographic and demographics. Räisänen (2014) cited Danger (1987) suggesting that while the color was not the only visual cue at play, it was one of the most powerful ones in packaging as it could help build deeper perceptions beyond just first impressions.

Given the relevance of package color in this study, it is important to discuss the basics of color, its measurement and communication. The discussion below pertains to reflectance based measurements and does not necessarily apply to the transmittance based measurements.

Color can be described as a combination or interaction of three elements – an illuminant or a light source, an object, and a receiver or an observer. The light emanates from an illuminant, reflects from an object and is received and interpreted by observers. Color can be defined using colorimetric coordinates in a 3-Dimensional (3D) CIELAB space (Fig. 1). The L* represents lightness or darkness, a* stands for redness or greenness and b* indicates the yellowness or blueness of a color. These colorimetric coordinates can also be represented in CIELCH space using $L^*C^*h^o$ values, where C* is the chromaticity and h^o represents the hue angle of a color. Chromaticity represents the saturation of a color, or how vivid or dull a color is e.g. vivid red, or dull green. Hue is defined as the color appearance itself, e.g. red, green, blue. Color measurement instruments, specifically spectrophotometers, try to simulate the human visual data collection. In order to align measurement results with visual results, International Commission on Illumination (CIE) proposed standard light sources and a standard visual observer function. The instruments illuminate an object with a standard light source and measure the reflectance at different wavelengths (bands). The plot of data representing the measured reflectance values against the corresponding wavelength is called a spectral curve. (X-rite Pantone, 2016)

A technical note by Whetzel (2015) explained the standard observers with simplicity. The author stated that standard observer functions published by CIE in 1931 were based on color-matching research conducted by David Wright and John Guild in the 1920s. The researchers asked human observers to match given colors using combinations of red, green and blue lights. The observers were looking at colors through a hole that provided a 2° field of view. This field of view was selected as it was believed at the time that the color-sensing cones were located within 2° arc of the fovea, which is a region of the eye. The curves generated from these research were termed as the standard observer (Whetzel, 2015). Each curve in figure 2.2 represents the response function of one of the primary colors of light (approximately red, green and blue) (Konica Minolta, n.d.).

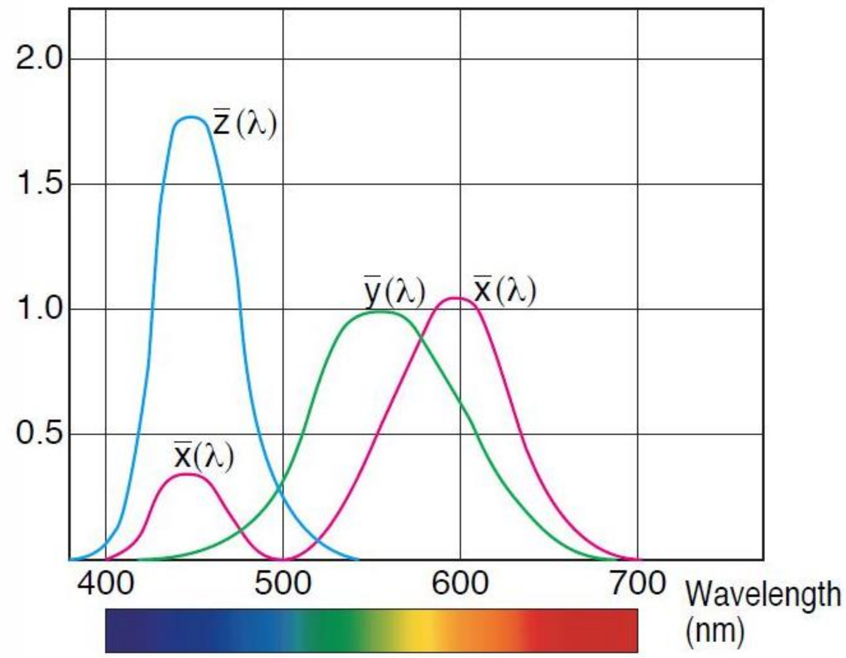


Fig. 2.2. 2-degree standard observer function (Konica Minolta, n.d.)

ISO 13655 (2017) describes the recommended data collection procedures and calculations to determine the colorimetric coordinates. The recommended wavelength range for measuring the reflectance data was 380 nm to 780 nm. The minimum acceptable wavelength range for data measurements was prescribed to be between 400 nm to 700 nm. Similarly, the data measurements were ideally recommended to be taken at 5 nm intervals, but 10 nm intervals were deemed acceptable. The recommended measurement geometry were (0^o:45^o) or (45^o:0^o), where these represent the angle between incident light and the measurement angle. The reflectance at each wavelength (or wavelength band) was recommended to be reported to the third decimal place (0.001) with a scale of zero to one. The reflectance data could also be presented as percent reflectance (reflectance factor multiplied by 100%). However, full resolution of data was recommended for further calculations and transformations on data to avoid accumulation of round-off errors. The CIE tristimulus values (CIE X, CIE Y, CIE Z or XYZ) calculations were recommended to be made using CIE D50 as the illuminant and CIE 1931 2^o as the standard colorimetric observer. The weighting factors for each wavelength band (at interval of 10 nm) to be used under this set of conditions were also provided in the standard document. The calculations recommended in ISO13655 (2017) for obtaining CIE tristimulus values (XYZ) from the spectral data are as follows:

$$X = \sum_{\lambda=380}^{780} R(\lambda) * W_X(\lambda) \qquad \text{Eq. 2.1}$$

$$Y = \sum_{\lambda=380}^{780} R(\lambda) * W_Y(\lambda) \qquad \text{Eq. 2.2}$$

$$Z = \sum_{\lambda=380}^{780} R(\lambda) * W_Z(\lambda) \qquad \text{Eq. 2.3}$$

where λ is the wavelength in nanometers (nm),

$R(\lambda)$ = spectral reflectance factor at wavelength λ,

$W_X(\lambda)$ = weighting factor at wavelength λ for CIE X,

$W_Y(\lambda)$ is the weighting factor at wavelength λ for CIE Y,

$W_Z(\lambda)$ is the weighting factor at wavelength λ for CIE Z.

The values of these weighting functions for wavelengths 380 nm to 780 nm at intervals of 10 nm were presented in Table I.2 in the ISO 13655 (2017) standard. These values were referenced from ASTM E308-13, Table 5.9. In cases where the spectral data was only available from 400 to 700 nm, the weighting functions were recommended to be added from 380 nm to 400 nm and used as the revised 400 nm weighting function. Similarly, the sum of weighting functions from 700 to 780 nm was to be used as the revised weighting function for 700 nm. The formulae to calculate CIELAB from CIE XYZ values were also discussed in the ISO 13655 (2017) standard. These calculations are summarized below:

$$L* = 116\left[f\left(\frac{Y}{Y_n}\right)\right] - 16 \qquad \text{Eq. 2.4}$$

$$a* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right] \qquad \text{Eq. 2.5}$$

$$b* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right] \qquad \text{Eq. 2.6}$$

The functions f(X/X$_n$), f(Y/Y$_n$) and f(Z/Z$_n$) were defined as follows:

$$f\left(\frac{X}{X_n}\right) = \left(\frac{X}{X_n}\right)^{1/3}, if \left(\frac{X}{X_n}\right) > \left(\frac{6}{29}\right)^3 \qquad \text{Eq. 2.7}$$

$$f\left(\frac{X}{X_n}\right) = \left(\frac{841}{108}\right)\left(\frac{X}{X_n}\right) + \left(\frac{4}{29}\right), if \left(\frac{X}{X_n}\right) \leq \left(\frac{6}{29}\right)^3 \qquad \text{Eq. 2.8}$$

$$f\left(\frac{Y}{Y_n}\right) = \left(\frac{Y}{Y_n}\right)^{1/3}, if \left(\frac{Y}{Y_n}\right) > \left(\frac{6}{29}\right)^3 \qquad \text{Eq. 2.9}$$

$$f\left(\frac{Y}{Y_n}\right) = \left(\frac{841}{108}\right)\left(\frac{Y}{Y_n}\right) + \left(\frac{4}{29}\right), if \left(\frac{Y}{Y_n}\right) \leq \left(\frac{6}{29}\right)^3 \qquad \text{Eq. 2.10}$$

$$f\left(\frac{Z}{Z_n}\right) = \left(\frac{Z}{Z_n}\right)^{1/3}, if \left(\frac{Z}{Z_n}\right) > \left(\frac{6}{29}\right)^3 \qquad \text{Eq. 2.11}$$

$$f\left(\frac{Z}{Z_n}\right) = \left(\frac{841}{108}\right)\left(\frac{Z}{Z_n}\right) + \left(\frac{4}{29}\right), if \left(\frac{Z}{Z_n}\right) \leq \left(\frac{6}{29}\right)^3 \qquad \text{Eq. 2.12}$$

where, L* represents the lightness of a specimen

a* defined how red or green a specimen is,

b* defines how yellow or blue a specimen is.

X, Y, Z are the CIE tristimulus values

X_n, Y_n and Z_n are the white points (96.422, 100, and 82.521, respectively, as provided in Table I.2 in the ISO standard)

The chromaticity (CIE C*) and hue angle (CIE h_{ab}) were defined using the CIELAB 1976 coordinates as follows (ISO, 2017):

$$C^*_{ab} = (a^{*2} + b^{*2})^{1/2} \qquad \text{Eq. 2.13}$$

$$h_{ab} = \arctan\left(\frac{b^*}{a^*}\right) \qquad \text{Eq. 2.14}$$

The SCTV values were calculated on the basis of ISO 20654 (2017) recommendations. The calculations used in this study are presented in equations 2.15 to 2.18.

$$SCTV = 100 * \sqrt{\frac{(V_{xt} - V_{xp})^2 + (V_{yt} - V_{yp})^2 + (V_{zt} - V_{zp})^2}{(V_{xs} - V_{xp})^2 + (V_{ys} - V_{yp})^2 + (V_{zs} - V_{zp})^2}} \qquad \text{Eq. 2.15}$$

$$V_x = f\left(\frac{X}{X_n}\right) * 116 - 16 \qquad \text{Eq. 2.16}$$

$$V_y = f\left(\frac{Y}{Y_n}\right) * 116 - 16 \qquad \text{Eq. 2.17}$$

$$V_z = f\left(\frac{Z}{Z_n}\right) * 116 - 16 \qquad \text{Eq. 2.18}$$

where $V_{xs}, V_{ys}, V_{zs}\ are\ V_x, V_y, V_z$ values calculated for the solid of spot color,

$V_{xp}, V_{yp}, V_{zp}\ are\ V_x, V_y, V_z$ values calculated for the paper,

$V_{xt}, V_{yt}, V_{zt}\ are\ V_x, V_y, V_z$ values calculated for the spot color tint,

X, Y, Z and Xn, Yn, Zn and f(X/X_n), f(Y/Y_n) and f(Z/Z_n) are as defined in equations 2.7 to 2.12 as per ISO 13655 (2017) (ISO, 2017).

A study by Danilove and Mollon (2016) suggested that the human visual system has a higher sensitivity towards hue than chromaticity. The authors conducted a study comparing the hue and saturation discrimination threshold using a self-luminous CRT display. The thresholds were defined on geometric and chromaticity terms, instead of being subjective appearance based. It was noted that the hue threshold was lower than the saturation threshold at same reference chromaticity levels. The authors concluded that there was a higher hue discrimination capability than saturation discrimination amongst the tested subjects under the examined conditions (Danilova & Mollon, 2016). Baribeau and Robertson (2005) conducted a study to evaluate visual hue discrimination thresholds across different hue regions. Three human subjects were shown four color quadrants arranged in the shape of a circle on a high resolution Cathode Ray Tube (CRT) display. Three of the four quadrants were filled with one color and the remaining quadrant was filled with the other color. The observers were asked to identify the different color out of the four options. The authors investigated hue discrimination thresholds for eighteen hues around the hue circle at constant L* and C* values. The hue discrimination thresholds were observed to be different in the different hue regions. Moreover, an abrupt change in hue discrimination threshold was reported while moving from the blue to purple region(Baribeau & Robertson, 2005).

These studies highlight that the viewers have higher sensitivity in some color regions than others. Since hue is a critical aspect of color appearance, research in the field of characterization of hue and hue differences should be discussed.

McLaren (1980) discussed anomalies in hue angle calculations from XYZ and b*,a* values based on CIE1976 recommendations. It was stated that hue angles were not completely independent of the Y value (from tristimulus values X,Y and Z). The author calculated hue angles for colors on the spectrum locus and in the purple region for Y values of 10, 1, and 0.1. Two versions of hue angles were calculated – a) using the CIE1976 recommendations and b) using the CIE1974 recommendations. It was suggested that low luminance factors (also meaning lower L value i.e. darker colors) could amplify the hue angle anomaly. The hue itself had a complex effect on this anomaly. This anomaly was attributed to the replacement of a cube root function with a linear function which was used in the conversion of XYZ tristimulus values to the b* and a* values (equations 2.4 to 2.12). This linear function was applied as decrease in Y value led to one or more of the tristimulus ratios (X/X_n, Y/Y_n or Z/Z_n) falling below 0.00856 or $(6/29)^3$. The author stated that this change also affected the Delta H_{ab} (ΔH_{ab}) and Delta C_{ab} (ΔC_{ab}) (McLaren, 1980).

CIE/ISO 11664-4 (2019) also stated that the use of linear functions in place of cube root functions of X/X_n, Y/Y_n and/or Z/Z_n could lead to anomalous hue angle values (equations 2.7 to 2.12). This anomaly could be observed with transparent colors in the purple region or near the spectrum locum having low luminance values (ISO, 2019).

Durmus and Davis (2019) studied hue shifts of 24 color samples under different light source spectral power distributions (SPDs) in the 1976 CIELAB and Color Appearance Model 2002 (CAM02) color spaces. The luminance was adjusted to be the same for all light sources. The hue shifts under these light sources were compared to two standard light sources – CIE standard illuminant D50 and white phosphor-converted LED. The authors used two hue shift formulae for CIELAB color space. The hue shift formulae used were based on recommendations from Seve (1991). This formula was also recommended by CIE Technical Committee (CIE, 2018) and are explained below:

$$\Delta H^*_{ab} = 2\left(C^*_{ab,1}.C^*_{ab,2}\right)^{0.5} Sin\left(\frac{\Delta h_{ab}}{2}\right) \qquad \text{Eq. 2.19}$$

where, ΔH^*_{ab} = Hue Difference or Delta H or Delta Hue, C*= Chromaticity = $(a *^2 + b *^2)^{1/2}$,

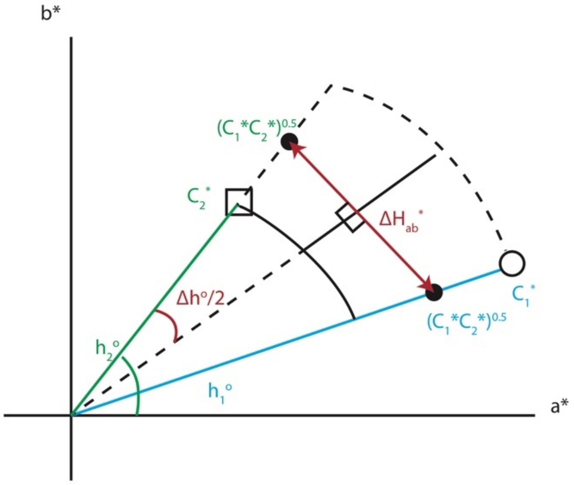
$C^*_{ab,1}$ = Chromaticity of test (tint),

$C^*_{ab,2}$ = Chromaticity of solid reference,

Hue Angle Difference (Δh_{ab}) = Hue angle of solid – Hue Angle of tint (in radians),

$$\Delta h_{ab} = h_{ab,2} - h_{ab,1} \qquad \text{Eq. 2.20}$$

(CIE Technical Committee, 2018; Séve, 1991).



$(C_1^*C_2^*)^{0.5}$ represents the geometric mean of C_1* and C_2*

Fig. 2.3. Geometric interpretation of Delta H (Stokes and Brill, 1992)

The second formula was based on the recommendations by Stokes and Brill (1992):

$$\Delta H^*_{ab} = s[2(Q - a^*_1.a^*_2 - b^*_1.b^*_2)^{1/2}] \qquad \text{Eq. 2.21}$$

where

$$Q = C^*_{ab,1}.C^*_{ab,2} = [(a *_1^2 + b *_1^2)(a *_2^2 + b *_2^2)]^{1/2} \qquad \text{Eq. 2.22}$$

if $a^*_1.b^*_2 > a^*_2.b^*1$, s = 1,

otherwise, s= -1,

$C^*_{ab,1}$ = Chromaticity of test (tint),

$C^*_{ab,2}$ = Chromaticity of solid reference,

a^*_1 = a* value of test (tint),

a^*_2 = a* value of solid reference,

b^*_1 = b* value of test (tint),

b^*_2 = b* value of solid reference.

The geometric representation of Del H is shown in figure 2.3.

It should be noted that the numerical notation depicted here is consistent with notation used by Seve (1991) and Durmus and Davis (2019), but different from CIE/ISO 11664-4 (2019) and CIE Technical report notation. Hence, the signs have been adjusted in the presented formulae to adjust for that change. Durmus and Davis (2019) also submitted that CIELAB space had poor hue uniformity. A study by Durmus and Davis (2018) stated that the hue difference (Delta H) can show large variation even for small color difference (Delta E). To reduce this non-uniformity, Chromatic Adaptation Transforms (CATs) are recommended (Durmus & Davis, 2019; Li & Melgosa, 2013). CMCCAT2000 transform was reported as the better option out of few other CATs tested (Luo, Rigg, & Smith, 2003) and has reported application in a study (Davis & Ohno, 2010; Durmus & Davis, 2019). The authors concluded that the hue shifts calculated with the reported formulae may result in significantly different results even for light sources that had similar PSDs. A good correlation was not found between the two hue shift metrics used by the authors. The authors mentioned that the color space uniformity and scale differences could contribute to calculated hue shifts (Durmus & Davis, 2019).

American Standard Test Methods (ASTM) D2244 stated that the difference in hue angle between a reference sample and specimen can be correlated to the differences in visual perception of these hues, with an exception of very dark colors (ASTM, 2016).

In packaging applications, the graphics and the visual elements on the package are printed using different printing methods. A market research report in packaging printing suggested that the global market size is projected to grow to USD 440.6 billion by 2024 from USD 350.6 billion in 2019. The projected Compound Annual Growth Rate (CAGR) for the market was projected to be 4.7%. The report also suggested that flexographic printing would account for the largest market share amongst the competing print processes, and will continue to grow at moderate CAGR in the forecast duration (MarketsandMarkets, n.d.). This study focuses on Flexographic printing with water based inks because of its popularity in the package printing industry.

Spot colors are frequently used to achieve a desired color on a given substrate in the packaging industry. The colorimetric standards for solids of spot colors are well defined by either Pantone specifications, colorimetric coordinates, spectral data, or with a combination of these. However, spot color halftones (or tints) are commonly managed using tone value and dot gain. ISO 20654 (2017) recommends use of Spot Color Tone Value (SCTV) as the preferred metric to measure tone values of spot colors. The presence of tonal data standards for spot colors would help in soft proofing, digital contract proofs and managing the colorimetric expectations from design to the print production stages (O'Hara et al., 2014). However, the colorimetric appearance of spot color tints are difficult to predict and standardize. The extraction, simulation, and prediction of spot color tints solely on the basis of spot color solids can be problematic and presents accuracy challenges (Jodra, Such, & Soler, 2009; Sawatzki, Roesch, & Specht, 2017). A recommendation to address this problem of communication and consistency of spot color tint information was provided in ISO17972-4 (2018). The standard provides guidelines on the exchange of spot color characterization data. The standard recommended the use of spectral reflectance data and opacity to characterize spot color inks. The conformance level CxF-4a required spectral characterization with at least 11 patches (including tints) of spot color ink on a single substrate (ISO/TC 130, 2018). However, the standard does not completely address some concerns that are typical to printing of spot color tints and overprints. One of these challenges is the tendency of some spot colors to exhibit a hue shift as the printed tone value decreases. A common example of such a color is Pantone Reflex Blue, which tends to shift towards a purple hue as the tone value decreases. The figure below shows the hue shift in printed tint results compared to the reference hue corrected line. The hue corrected line consists of the same L*C* value as the printed tints, but the hue angle is replaced by the hue angle of the solid.

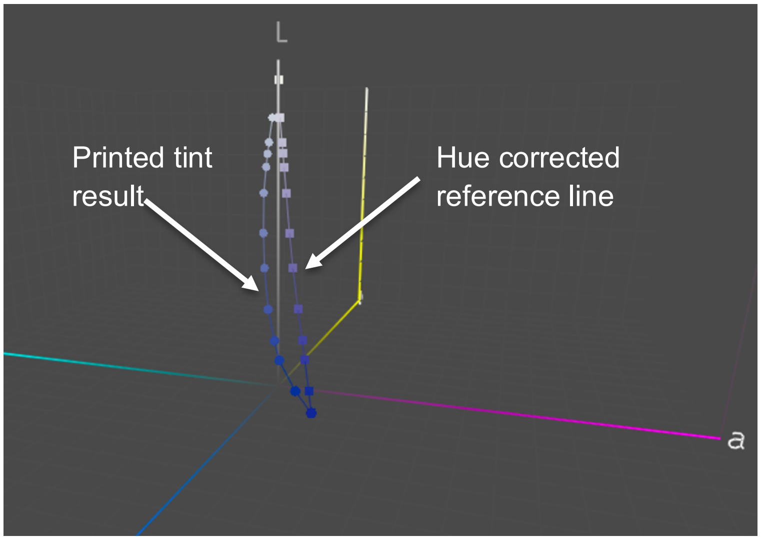


Fig. 2.4. Print and hue corrected curves for PReflexBlue-FWCP in CIELAB space

The potential primary factors affecting and/or contributing to these hue shifts are ink characteristics (lightness, chromaticity, hue, spectral curve shape), differences in ink recipe, printed tint percentage and substrate effects. The nature and extent of these hue shifts in some spot colors could be difficult to predict or reproduce consistently, especially if any of these primary factors are changed. It is also worth noting that spot color inks can be mixed using multiple combinations of different base pigments. Different ink manufacturers may use different ink recipes and base pigments for making the same spot ink, especially if a spectral match is not required. While this approach may work well for achieving a color match in the solids, halftones may show differences in hue for the differently formulated inks (O'Hara, et al., 2014). These color shifts may be even more apparent in case of spot color overprints (printing of spot colors on top of each other). This also presents a decision point in conversion of spot color tints to Expanded Color Gamut (ECG) separations. The question to be answered here is if the ECG separation should simply reproduce the results observed while printing a true spot color ink or aim to adjust and correct this hue shift. As seen in figure 2.5, the spot color printed to linear SCTV shows a hue shift towards purple hue. The other two variants are Esko Equinox (Esko ECG software) converted renditions of the same color, printed with and without linearizing to SCTV. The image without any curve correction (b) shows a 50% patch which appears too dark, perhaps due to the dot gain. The image (c) appears to be relatively hue normal and the 50% appears as a midway point between the paper and the solid.

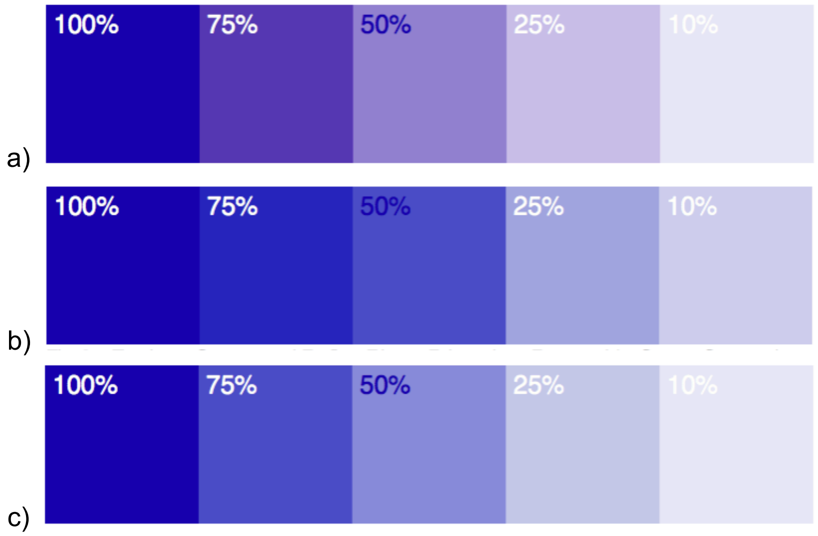


Fig. 2.5. Three variants of Reflex Blue – (a)Spot Color – Reflex Blue – Printed on Press to Linear SCTV, (b) Esko Equinox converted Reflex Blue – Printed on Press – No curve correction, (c) Esko Equinox converted Reflex Blue – Printed to Press – Corrected to Linear SCTV (Images courtesy of Mark Samworth – Esko Graphic Inc. (Samworth, 2017))

Even if the hue shift is accurately matched to the reference print output with a specific ink formulation, it may not necessarily align with the designers' and brand owners' perceptions and preferences of the desired color appearance. If the digital view of the spot color tints is not accurately represented in the prepress software systems, there can be a gap between the designer or a brand owner's view and the printed results. Color-accurate visual representation of tint or overprint is not supported in many software systems (Sawatzki, Roesch, & Specht, 2017).

There are, however, a few pre-press software solutions that help in simulating the spot color tints in the proofing environment. This study uses the Pantone-Live dependent library data as a digital standard.

O’Hara et al. (2014) evaluated the reproducibility of spot color solids and tints from PantoneLIVE dependent libraries. These dependent libraries contained standards for the substrate and printing process in addition to the inks. Moreover, dependent standards also contained colorimetric values for 11 tone values across the tone scale. The tonal data was captured from print results with an ink formulation that had the closest possible spectral match and lowest colorimetric difference from the standard color. This tonal colorimetric data helped manage color appearance expectations at the design stage and helped achieve close results through soft proofing till print production. The need of a colorimetric standard for spot color tints was highlighted by the authors (O'Hara et al., 2014). Jodra, Such, and Soler (2009) stated that characterization of spot color tints based on solids was inaccurate. In order to achieve an accurate representation of different spot color mixtures, a device-independent description of each of the spot color combinations was recommended (Jodra, Such, & Soler, 2009).

ISO17972-4 (2018) provides recommendations on exchange of spot color characterization data. The standard suggested the use of spectral reflectance data and opacity to characterize spot color inks. The standard described three conformance levels - CxF/X-4, CxF/X-4a and CxF/X-4b. Level CxF/X4 required spectral characterization of ink on the substrate and a black background (with L* value less than 20 and a* and b* between -3 and +3). Level CxF-4a required spectral characterization with at least 11 patches (including tints) of spot color ink on a single substrate. CxF/X-4b needed spectral characterization of only a 100% patch (solid) on a single substrate (ISO/TC 130, 2018)

While instrumental data provides an approximation of the visual perception and the associated color and hue differences, it is important to validate the differences with visual evaluation studies. These studies help validate the instrument-based results and can be used to build a correlation between the visual and instrumental methods.

A study conducted by Lin, Huang et al. (2015) on denture based resins correlated the perceptible and acceptable visual color differences to Delta E2000 and Delta Hue. The study suggested a strong correlation between Delta Hue and Delta E2000. The authors reported that at a 50% acceptance ratio, the perceptible and unacceptable differences corresponded to DeltaE00 of 1.71 and 4.0, respectively. Similarly, it was reported that perceptible and unacceptable visual differences based on hue corresponded to Delta E2000 of 1.57 and 4.70 respectively (Ren, 2015). Moreover, the human visual system has a different sensitivity to detect differences in color at different densities and hues (Ren, Lin, Huang, & Zheng, 2015). Baribeau and Robertson (2005) conducted a study to evaluate visual hue discrimination thresholds across different hue regions. Three human subjects were shown four color quadrants arranged in the shape of a circle on a high resolution Cathode Ray Tube (CRT) display. Three of the four quadrants were filled with one color and the remaining quadrant was filled with the other color. The observers were asked to identify the different color out of the four options. The authors investigated hue discrimination thresholds for eighteen hues around the hue circle at constant L* and C* values. The hue discrimination thresholds were observed to be different in the different hue regions. Moreover, an abrupt change in hue discrimination threshold was reported while moving from the blue to purple region. The authors pointed out that the CIELAB and CIEDE2000 color difference formulae did not effectively account for these differences (Baribeau & Robertson, 2005).

It is also important to understand this process from a designers' viewpoint. The designers are often the first ones in the process to look at a color and adjust it to achieve color harmony with the rest of the artwork or a specific brand color. If the digital view of the spot color tints is not accurately represented in the prepress software solutions, there would be a gap between what the designer / brand owner's desire and how the print actually looks. There are few pre-press software solutions that help in simulating the spot color tints. This study uses the Pantone-Live dependent library data as a digital standard. This study focuses on evaluating the extent and nature of these hue shifts in spot color tints. The study is also intended to address how different these hue shifts are from a digital reference commonly used by designers.

CHAPTER 3

EVALUATING HUE SHIFTS IN SPOT COLOR TINTS IN FLEXOGRAPHIC PACKAGE PRINTING

Introduction

Packaging plays an important role in the modern world. It helps to preserve, protect, dispense, communicate and sell a product. Hellström and Saghir (2007) and Mohebbi (2014) stated that packaging serves three primary communication functions – communicating product handling and use related information, promoting the product , and improving consumer connection. Garber, Burke, and Jones (2000) cited Hine (1996) suggesting that the package has assumed the role of salesperson, as the primary mode of communication with the consumer at the point of purchase. Printing and color are key components of the communication and selling functions. Mohebbi (2014) suggested that graphics and color can influence purchase decisions. Despite the importance of visual cues such as color in market research applications, limited work has been done on its use in packaging (Kauppinen-Räisänen, 2014; Kauppinen-Räisänen, 2011; Labrecque & Milne, 2012).

Printing can be broadly classified into two categories based on how the color is achieved, process and spot color printing. Process color printing involves use of combinations of process colors—Cyan, Magenta, Yellow and Black (CMYK). Expanded gamut printing is a special case of process printing where additional colors, typically orange, green and violet, are used to achieve a larger color gamut. Spot color printing uses specially formulated inks that are designed to achieve a particular color appearance on a given substrate. High volume brand colors are commonly printed as spot colors. Different brands use characteristic colors that allow consumers to relate to their products and brand identity (e.g. a Coca-Cola® red or a Pepsi® blue).

Color can be defined using colorimetric coordinates in a 3-Dimensional (3D) CIELAB space as shown in figure 3.1. The L* represents light to dark, a* stands for red to green and b* indicates the yellow to blue characteristics of a color. These colorimetric coordinates can also be represented in CIELCH space using L*C*h^{o} values, where C* is the chromaticity and h^{o} represents the hue angle of a color. While chromaticity represents the saturation or vividness of a color, hue refers to the color appearance itself (e.g. red, green, blue, etc.). Studies have suggested a higher visual sensitivity towards hue as compared to saturation and lightness (Danilova & Mollon, 2016; Durmus & Davis, 2019).

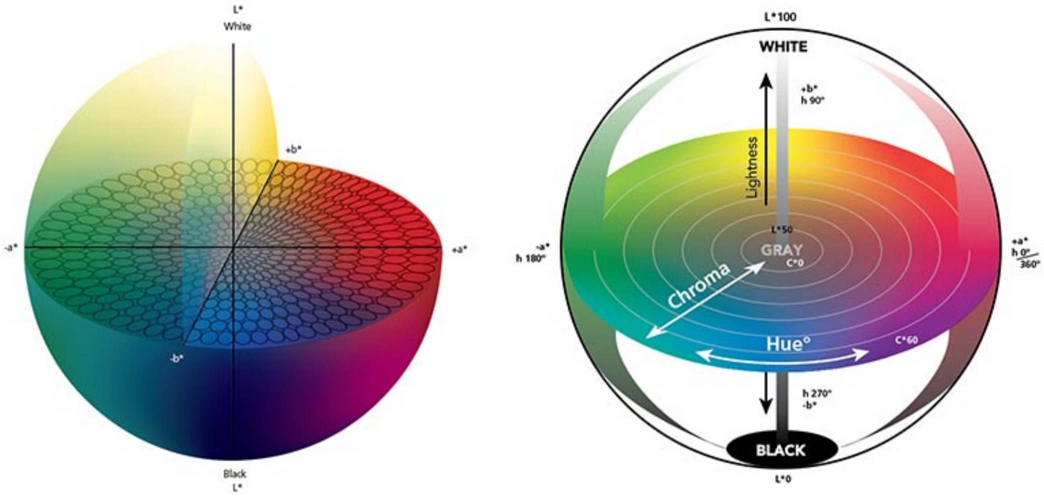


Fig. 3.1. Colorimetric coordinates in CIELAB and CIELCH models (Mouw, 2018)

The standard colorimetric values for solids of spot colors are well defined by either Pantone specifications, L*a*b*C*h^{o} values, spectral data, or with a combination of these. However, spot color halftones (or tints) are commonly managed using tone value and dot gain. International Organization for Standardization (ISO) 20654 (2017) recommends use of Spot Color Tone Value (SCTV) as the preferred metric to measure tone values of spot colors. The presence of tonal data standards for spot colors would help in soft proofing, digital contract proofs and managing the colorimetric expectations from design to the print production stages (O'Hara, et al., 2014). However, the colorimetric appearance of spot color tints are difficult to predict and standardize. The extraction, simulation, and prediction of spot color tints solely on the basis of spot color solids can be problematic and presents accuracy challenges(Jodra, Such, & Soler, 2009; Sawatzki, Roesch, & Specht, 2017). A recommendation to address this problem of communication and consistency of spot color tint information was provided in ISO17972-4 (2018). The standard provided guidelines on exchange of spot color characterization data. The standard recommended the use of spectral reflectance data and opacity to characterize spot color inks. The conformance level CxF-4a required spectral characterization with at least 11 patches (including tints) of spot color ink on a single substrate. However, the standard does not completely address some concerns that are typical to printing of spot color tints and overprint. For instance, some spot colors are known to exhibit a hue shift as the printed tone value decreases. An example of such a color is Reflex Blue, which tends to shift towards a purple hue as the tone value decreases. Figure 3.2 shows the hue shift in printed tint results compared to the reference hue corrected line. The hue corrected line consists of the same L*C* value as the printed tints, but the hue angle is replaced by the hue angle of the solid.

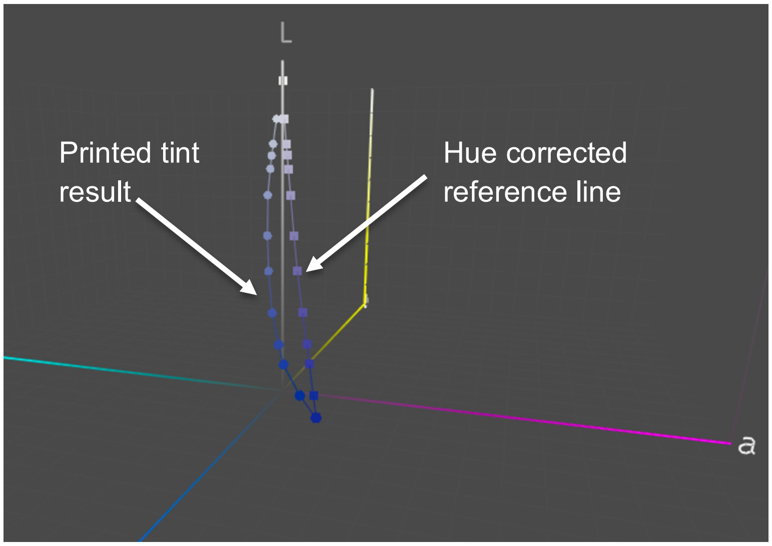


Fig. 3.2. Print and hue corrected curves for PReflexBlue-FWCP in CIELAB space

The potential primary factors affecting and/or contributing to these hue shifts are ink characteristics (lightness, chromaticity, hue, spectral curve shape), differences in ink recipe, printed tint percentage and the substrate effects. The nature and extent of these hue shifts in some spot colors could be difficult to reproduce consistently, especially if any of these primary factors are changed. It is worth noting that spot color inks can be mixed using various possible combinations of the different base pigments. Different ink manufacturers may use different ink recipes and base pigments for making the same spot ink, especially if a spectral match is not required. While this approach may work well for achieving a color match in the solids, halftones may show differences in hue for the differently formulated inks (O'Hara, et al., 2014). These color shifts may be even more apparent in case of spot color overprints (printing spot colors on top of each other). This also presents a decision point in conversion of spot color tints to Expanded Color Gamut (ECG) separations. The question to be answered here is if the ECG separation should simply reproduce the results observed while printing a true spot color ink or aim to adjust and correct this hue shift. As seen in figure 3.3, the spot color printed to linear SCTV shows a hue shift towards purple hue. The other two variants are Esko Equinox (Esko ECG software) converted renditions of the same color, printed with and without linearizing to SCTV. The image without any curve correction (b) shows a 50% patch which appears too dark, perhaps due to the dot gain. The image (c) appears to be relatively hue normal and the 50% appears as a midway point between the paper and the solid.

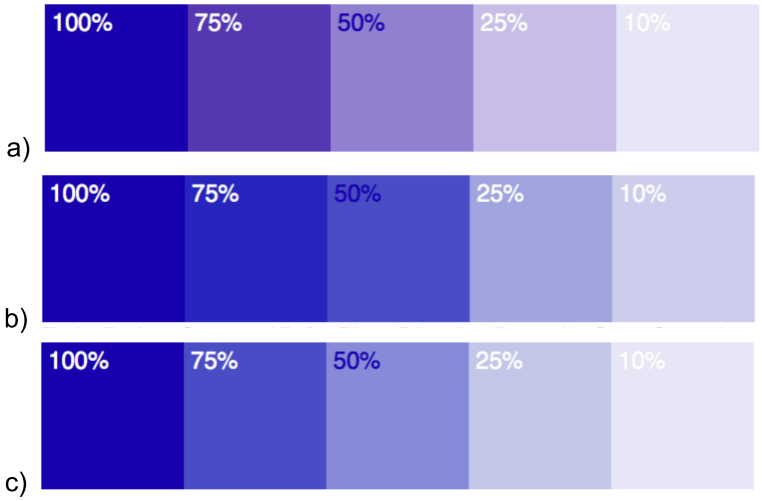


Fig. 3.3. Three variants of PReflexBlue – (a)Spot Color – Reflex Blue – Printed on Press to Linear SCTV, (b) Esko Equinox converted Reflex Blue – Printed on Press – No curve correction, (c) Esko Equinox converted Reflex Blue – Printed to Press – Corrected to Linear SCTV (Images courtesy of Mark Samworth – Esko Graphic Inc. (Samworth, 2017))

Even if the hue shift is accurately matched to the reference print output with a specific ink formulation, it may not necessarily align with the designers' and brand owners' perceptions and preferences of the desired color appearance. If the digital view of the spot color tints is not accurately represented in the prepress software systems, there can be a gap between the designer or a brand owner's view and the printed results. Color-accurate visual representation of tint or overprint is not supported in many software systems (Sawatzki, Roesch, & Specht, 2017). There are, however, a few pre-press software solutions that help in simulating the spot color tints in the proofing environment. This study uses the PantoneLIVE dependent library data as a digital standard.

This study focused on using three different hue shift metrics to characterize the extent and nature of hue shifts in spot color tints. The maximum hue shifts and the corresponding SCTV were noted. The study was also intended to address how different these hue shifts were from a digital reference commonly used by designers. The three metrics used to characterize hue shift were also compared with each other. A visual study was also conducted in the second part of this project. The visual study was designed to evaluate perceptible and acceptable differences between spot color tints. The results of the instrument-based approach were compared with the visual study results.

Scope of the study

The study was limited to six spot colors on a single paperboard packaging substrate. The study was conducted with water-based inks as these are common for paperboard packaging. Pantone-Live dependent library Flexo Water-Based Coated Paper (FWCP) was used as a digital reference. Other software solutions, although available, were not evaluated under this study. The substrate was chosen based on substrate in the Pantone-Live FWCP library.

Methods and Materials

Experimental Design

The input variables included six different spot colors, a range of tonal values and two different ink recipes for one of the six spot colors. The selection method and standard values for each color are described in the ink section of methods and materials. The two different ink recipes for the color P4975-FWCP were used to evaluate the effect of different ink recipes on hue shift behavior. The tone scale from 10% to 100% was printed at increments of 10% (with addition of 25, 50 and 75% patches). The tone scales were printed for all the colors over paper, over a printed black background and in randomized order. The print over black was conducted for opacity calculations, if needed in the future. The patches were also printed in randomized order for use in case any bias was recognized in the data. The test chart design and components can be seen in figure 3.7.

The SCTV of tint patches was calculated from measured X, Y, Z values based on ISO 20654 (2017) recommendations. In terms of the output metrics, this study involved quantification of hue shift with three different metrics. ASTM D2244 states that the difference in hue angle between a sample and specimen could be correlated to the differences in visual perception of these hues, with an exception of very dark colors (ASTM, 2016). Hence, a difference between hue angles of solid and the tints (Δh_{ab}) was used as the first metric. The calculations were corrected for hue angle shift between quadrants e.g. hue angle moving from 359° to 1°. This metric is referred to as 'hue angle difference' in this study. The second metric used in this study was the hue difference also called Delta H (ΔH_{ab}^{*}). The formula used for calculations was selected based on International Commission on Illumination (CIE)/ISO11664-4 (2019) recommendations.

$$\Delta H_{ab}^{*} = 2\left(C_{ab,2}^{*}.C_{ab,1}^{*}\right)^{0.5} Sin\left(\frac{\Delta h_{ab}}{2}\right) \qquad \text{Eq. 3.1.}$$

where, ΔH^{*}_{ab} = Hue Difference or Delta H or Delta Hue as a measure of hue difference,

C*= Chromaticity $= (a *^{2} + b *^{2})^{1/2}$,

$C^{*}_{ab,1}$ = Chromaticity of test (tint),

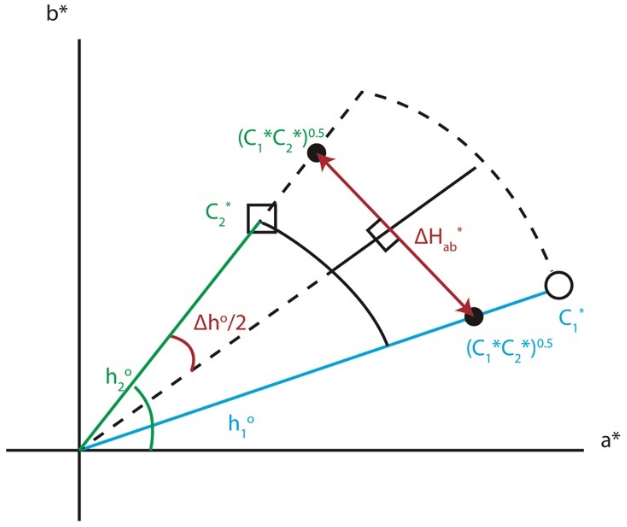
$C^{*}_{ab,2}$ = Chromaticity of solid reference,

Hue Angle Difference (Δh_{ab}) = Hue angle of solid – Hue Angle of tint (in radians),

$$\Delta h_{ab} = h_{ab,2} - h_{ab,1} \qquad \text{Eq. 3.2}$$

(CIE /ISO, 2019; CIE Technical Committee, 2018; Séve, 1991).

Figure 3.4 shows a geometric representation of Delta H as explained by Stokes and Brill (1992).



$(C_1^{*}C_2^{*})^{0.5}$ represents the geometric mean of C_1* and C_2*

Fig. 3.4. Geometric interpretation of Delta H (Stokes and Brill, 1992)

While the hue angle difference (Δh_{ab}) as an individual metric was calculated and analyzed in degrees, the hue difference (ΔH^{*}_{ab}) formula requires the (Δh_{ab}) to be in radians.

A new metric was also developed in this study to characterize hue shift. The third metric used in the study was the shortest distance between the tint and a line joining paper white point and the solid in a CIELAB space. The orthogonal distance calculation is depicted in the figure 3.5.

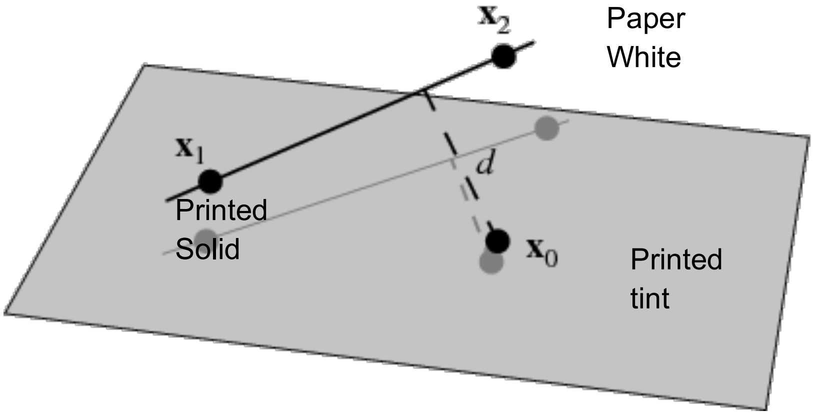


Fig. 3.5. Paper white point (X_2), solid point (X_1) and tint (X_0) of spot color plotted in three-dimensional (3-D) space (Weisstein, 2020)

In figure 3.5, X_1 = L*a*b* coordinates of solid = (L^*_1, a^*_1, b^*_1)

X_2 = L*a*b* coordinates of paper = (L^*_2, a^*_2, b^*_2)

X_0 = L*a*b* coordinates of tint = (L^*_0, a^*_o, b^*_o)

The shortest distance between the point X_0 and the line connecting the solid to the paper white point in 3D space is represented by the orthogonal distance between the point X_0 and line vector $\overrightarrow{X_1X_2}$. This distance is calculated using the formula below:

$$d = \frac{|(X_2 - X_1) \times (X_1 - X_0)|}{|(X_1 - X_0)|} \quad \text{Eq. 3.3}$$

where, $|(X_2 - X_1) \times (X_1 - X_0)|$ is the magnitude of the cross product of the two terms and

$$|(X_1 - X_0)| = \sqrt{(L_1 - L_0)^2 + (a_1 - a_0)^2 + (b_1 - b_0)^2} \qquad \text{Eq. 3.4}$$

which is the magnitude of the substraction of vector X_0 from X_1 (Weisstein, 2020).

The input variables and their corresponding levels along with the output variable and corresponding metrics are summarized in table 3.1.

Table 3.1. Summary of input and output variables with corresponding levels and metrics

Input Variables	**Levels**
Color	6 Spot Colors – Red (P485-FWCP), Green (P357-FWCP), Blue (PReflexBlue-FWCP), Orange (POrange021 – FWCP), Purple (P261-FWCP), and Brown (P4975-FWCP)
Ink Recipe	2 ink recipes with different base pigments (for P4975 – FWCP only)
Tone Value	11 levels - 10, 20, 25, 30, 40, 50, 60, 70, 75, 80 and 90%
Output Variables	**Metrics**
Hue Shift	Hue Angle Difference (Δh_{ab}), Hue Difference or Delta H (ΔH^*_{ab}), Orthogonal Distance (OD)

Substrate

The study was conducted on Westrock 12 point (pt) PrintKote paperboard substrate. This paper was selected in accordance to the white point of the PantoneLIVE digital library used as a reference in this study. Paperboard substrates are widely used in packaging applications.

Inks

Paperboard substrates are commonly printed with water based inks for a wide variety of packaging applications, mainly in the food industry. The colors of the inks for this study were selected based on the data collected from a preliminary press run, PantoneLIVE (PL) data, and spot color usage statistics obtained from three industry package printing sources. The colorimetric data from the preliminary study involving six different spot colors were analyzed for hue shift across the tonal range. The six spot colors printed in the preliminary study were

P135C(light yellow), P2706C (light blue), P1485C (light orange), P187C (dark red), P357C (dark green), and P2685C (dark violet). Hue angle difference and Delta H were used as metrics. These data are presented in figure 3.6.

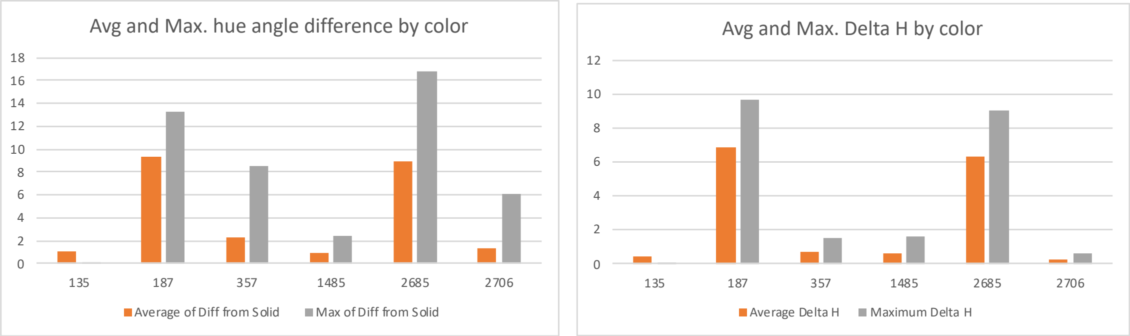


Fig. 3.6. Absolute average and maximum hue angle difference and Delta H data from preliminary study

As seen in figure 3.6, the maximum hue angle difference of more than 10 degrees was observed in the spot color tints of Pantone (P)187 (dark red) and P2685 (dark violet). The Delta H data agreed with the hue angle difference data with better differentiation between high and low hue shift colors. The data from this study suggested higher hue shift in darker and more chromatic colors than lighter colors. The highest hue shifts were seen in the red and violet regions. It should be noted that the data from the preliminary study were collected under M1 measurement mode while the all the data collected in the present study were collected in M0 measurement mode. The preliminary data were only meant to serve as a precursor to the actual study and no direct comparisons were drawn between these data and the data collected under the current study.

PantoneLIVE library provides the colorimetric information for spot color tints in addition to the solids. The top twenty-five most used spot colors from the usage statistics were selected and their colorimetric data, including tints, were extracted from the PantoneLIVE Library. The data were analyzed for hue angle difference. Colors showing a maximum hue angle difference of more than 10 degrees across the tonal range were selected for this study. The PantoneLIVE dependent library - Flexo Water-Based Coated Paper (FWCP) library was used in this study. The colors were also segregated based on their hues and only one color from each segment was selected (i.e. one color each from orange, red, purple, blue, and green regions). The inks selected for the print trials based on the conditions mentioned above are presented in table 3.2. The maximum hue angle difference and the corresponding spot color tone value (SCTV) data from PantoneLIVE – FWCP library are also listed in table 3.2.

Table 3.2. Target colors, maximum hue angle difference and corresponding SCTV from PantoneLIVE data

Color	Maximum Hue Angle Difference (degrees)	Spot Color Tone Value at maximum hue angle difference
P357-FWCP (Dark Green)	46	3
P261-FWCP (Purple)	86	6
POrange021-FWCP (Orange)	16	25
P4975-FWCP (Brown)	-69	5
P485-FWCP (Red)	11	34
PReflexBlue-FWCP (Blue)	10	25

For simplicity, the spot colors may be used without the FWCP suffix in this report. The inks were formulated and donated by an ink manufacturer. However, the reflex blue ink was reformulated with the Xrite Ink Formulation Software v6 using an ink recipe suggested by ink company’s color matching experts. The inks’ viscosities and pH were measured but left unadjusted to avoid any changes in the hue angle due to dilution.

Test chart

The test chart consisted of tonal patches of the 6 inks arranged along machine direction and cross-direction. A randomized chart with the same patches was also included in the target. The layout of the test chart is as shown in figure 3.7.

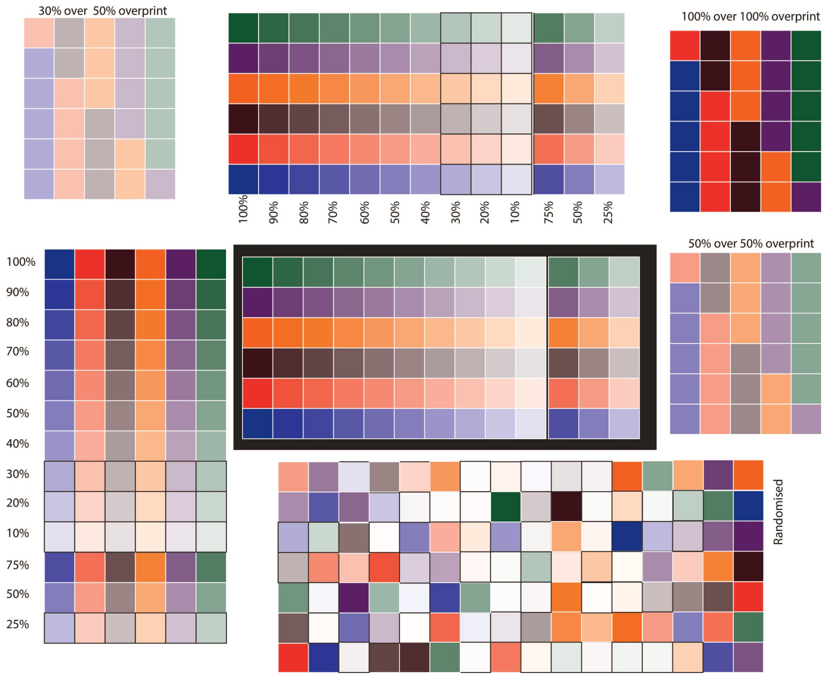


Fig 3.7. Test Chart Layout

Print setup and run

The plate files were launched though workflow, arranged and imaged using Esko (Esko Graphics Inc., Miamisburg, USA) Automation Engine, Merger and Exposer software. Dupont (Dupont Advanced Printing, Wilmington, USA) EPR 067 photopolymeric plates were made on an Esko Crystal Cyrel Digital Imager (CDI) and XPS system. The plates were solvent processed, dried, and post-exposed and light-finished on an Evo (Vianord Engineering, Carros, France) 3A machine. The plates were output with a linear curve without any compensation curve applied. However, a 2 to 1 bump curve was applied to the file while launching the workflow. Since the minimum anilox resolution was 500 lpi (lines per inch), a 120 lpi screening was applied to all the plates and the Esko crystal CDI resolution was set to 4000 dpi. The print trials were conducted on an Omet (Omet Srl, Lecco, Italy) Varyflex 7 color press at 150 feet-per minute (fpm). The first station was used for printing black and the remaining six stations were used to print six different spot color inks. The impression settings were set at minimum impression. The ink sequence and the anilox used for each station are listed in table 3.3.

Table 3.3. Ink sequence and anilox setup used

Station No.	Ink	Anilox Configuration
1	Process Black	500 lpi/5.0 bcm
2	Pantone 357	900 lpi /2.2 bcm
3	Orange 021	800 lpi/2.8 bcm
4	Pantone 261	600 lpi /4.0 bcm
5	Pantone Reflex Blue	500 lpi /4.0 bcm
6	Pantone 485	800 lpi /2.8 bcm
7	Pantone 4975	900 lpi /2.2 bcm

The Delta E2000 tolerance was set at 5.00 due to anilox availability limitation and inks being formulated to a standard ink film thickness. Xrite (Xrite, Grand Rapids, USA) Colorcert software was used for achieving and monitoring color on the press. The standard and the measured print results during setup are described in table 3.4. The hue angle difference from the standard was under 2.5 for all colors except P357. The Delta E2000 was under 5 for all colors except P4975. However, the hue angle for P4975 was within 1° of the hue angle of the standard.

Table 3.4. Colorimetric standard and printed values for each color with color differences (Deltas)

Color	Standard	Print Result	Deltas
P357- FWCP	L*: 33.96 a*: -23.08 b*: 13.06 C*: 26.52 h°: 150.50	L*: 32.28 a*: -28.82 b*: 11.17 C*: 30.91 h°: 158.82	L*: -1.68 a*: -5.74 b*: -1.89 E00 = 3.39 C*: 4.39 h°: 8.32
P261 - FWCP	L*: 26.53 a*: 31.83 b*: -22.33 C*: 38.88 h°: 324.95	L*: 21.39 a*: 26.77 b*: -17.51 C*: 31.99 h°: 326.81	L*: -5.14 a*: -5.06 b*: 4.82 E00 = 4.63 C*: -6.89 h°: 1.86
POrange021 - FWCP	L*: 62.71 a*: 57.65	L*: 64.96 a*: 53.30	L*: 2.26 a*: -4.35

	b*: 73.79 C*: 93.64 h^o: 52	b*: 74.09 C*: 91.27 h^o: 54.27	b*: 0.30 E00 = 2.75 C*: -2.37 h^o: 2.27
P485 - FWCP	L*: 50.43 a*: 61.13 b*: 47.18 C*: 77.22 h^o: 37.66	L*: 47.85 a*: 66.33 b*: 48.54 C*: 82.19 h^o: 36.20	L*: -2.59 a*: 5.20 b*: 1.37 E00 = 3 C*: 4.98 h^o: -1.46
PReflexBlue - FWCP	L*: 24.01 a*: 30.22 b*: -62.47 C*: 69.40 h^o: 295.81	L*: 20.91 a*: 29.81 b*: -66.06 C*: 72.48 h^o: 294.29	L*: -3.1 a*: -0.41 b*: -3.59 E00 = 2.86 C*: 3.08 h^o: -1.52
P4975-FWCP – Recipe 1	L*: 20.07 a*: 6.94 b*: 3.19 C*: 7.64 h^o: 24.69	L*: 20.01 a*: 14.14 b*: 6.69 C*: 15.64 h^o: 25.32	L*: -0.06 a*: 7.19 b*: 3.50 E00 = 6.42 C*: 8.00 h^o: 0.66
P4975-FWCP – Recipe 2	L*: 20.07 a*: 6.94 b*: 3.19 C*: 7.64 h^o: 24.69	L*: 23.27 a*: 5.62 b*: 2.59 C*: 6.19 h^o: 24.77	L*: 3.20 a*: -1.32 b*: -0.60 E00 = 2.67 C*: -1.45 h^o: 0.08

Data collection

Fifteen sheets were randomly selected from the printed roll and measured. The measurements were taken with an Xrite eXact Standard + Scan instrument using the Xrite DataMeasure tool. Measurements were taken in M0 mode as the PantoneLIVE data was available in M0 mode. The measured tristimulus values and L*a*b* values were used to calculate SCTV, chroma and hue values. The data from printed sheets were averaged over fifteen sheets for each color. The average hue angle and hue shifts of fifteen sheets per color were used for drawing graphs and corresponding inferences.

Output metrics and statistical analysis method

The hue angle difference, Delta H and orthogonal distance were used as metrics to quantify the hue shift in spot color tints. These metrics were plotted against the measured SCTV value for all the printed colors. The curve shapes for each metric were compared between the digital reference (PantoneLIVE data) and the print output. The maximum hue shift for print and PantoneLIVE (PL) and the SCTV corresponding to these maximum shifts were compared. It was expected that the print and PantoneLIVE data would show maximum hue shifts in the same tint range or halftone region—highlight, midtone or shadows). The plotted curves were also examined for the trends in hue shift and the tonal areas most susceptible to hue shift. A general linear model (glm) was used to fit the hue shift curves for print and PantoneLIVE data. Subsequently, the least squares means were compared for statistically significant differences at five different SCTV values—10, 25, 50, 75 and 90%. The significance level (α) was set at 0.05 for the test. The p-values below 0.05 showed statistically significant difference between the least square means.

Results and discussion

The statistical null hypothesis was that the least square means for print and PantoneLIVE were not statistically significantly different.

$$H_0: LSMeans_{print} = LSMeans_{PantoneLIVE} \qquad \text{Eq. 3.5}$$

$$H_a: LSMeans_{print} \neq LSMeans_{PantoneLIVE} \qquad \text{Eq. 3.6}$$

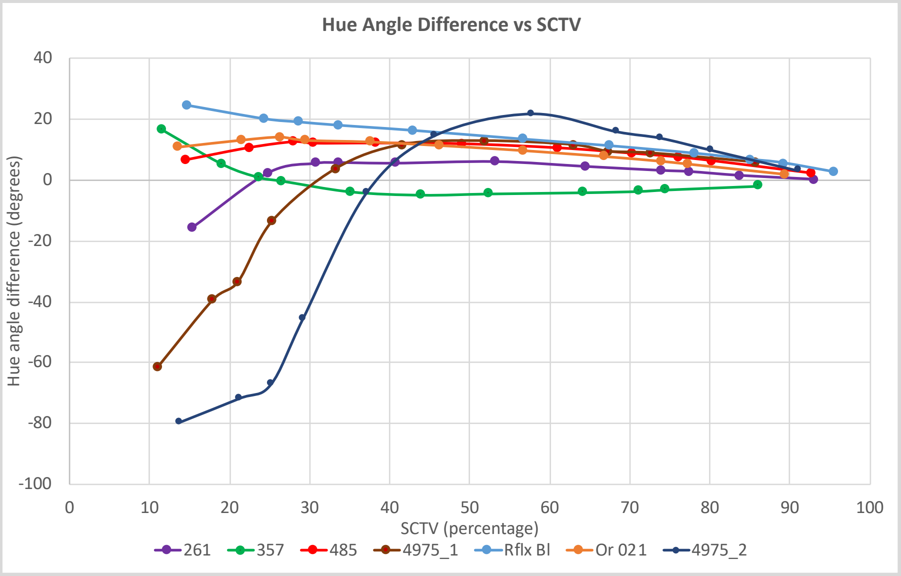


Fig. 3.8. Overview of hue angle difference data versus measured SCTV in print

Figure 3.8 shows the hue angle difference in the measured printed samples. The general trend suggested an increase in hue angle difference as the measured SCTV decreased. P261 and P357 showed maximum hue shifts below 10 degrees between 30% and 50% SCTV. The most significant hue shift was seen in P4975. This was followed by PReflexBlue, POrange021 and P485. P4975 distinctly stood out on the graph. This color showed a high negative hue angle difference which changed to positive at approximately 30% SCTV and above. This was due to the low chromaticity of the color and proximity to the achromatic axis. Even small changes in a* and b* values can show high hue shifts near the achromatic axis.

An overview of Delta H is presented in the figure 3.9. Unlike the hue angle difference graph, a clear distinction can be seen between two sets of colors. While some colors showed Delta H close to 0 throughout the tonal range, a few colors showed Delta H around 10 in the midtone region. The curve shape for Delta H was also different from the curve shape for hue angle difference. An increase in Delta H can be seen as the SCTV approaches midtone from either end of the tone-scale. The colors showing a low maximum Delta H, between 3 and -3, are P261, P357, P4975-1C (P4975 printed with ink recipe 1) and P4975-2 (P4975 printed with ink recipe 2). The color P4975 showed low Delta H despite showing a high hue angle difference. This was due to the chromaticity term in the Delta H calculation. Since, the Del H calculation includes a chromaticity term and the low chromaticity of P4975, the Delta H value was less dramatic than the hue angle difference for this color. The colors P485, PReflexBlue and POrange021 showed maximum Delta H of more than 10. The curve for these colors have a characteristic shape where the highest Delta H is seen in the midtones.

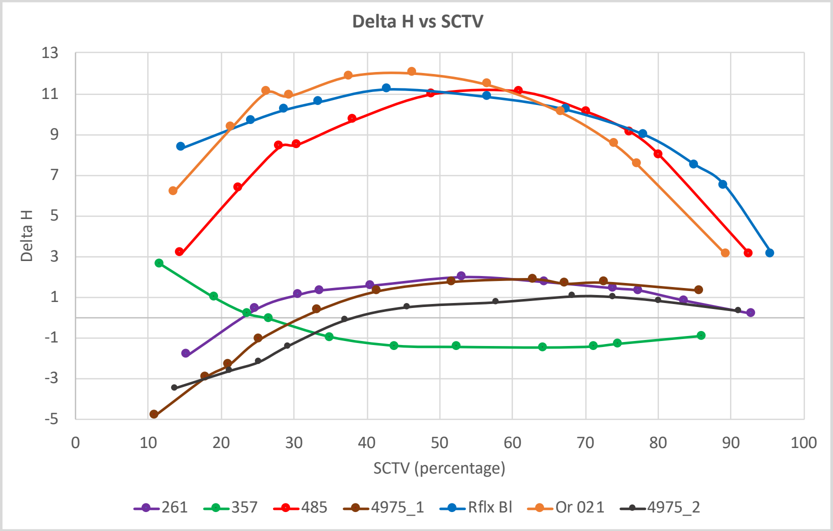


Fig. 3.9. Overview of Delta H data versus measured SCTV in print

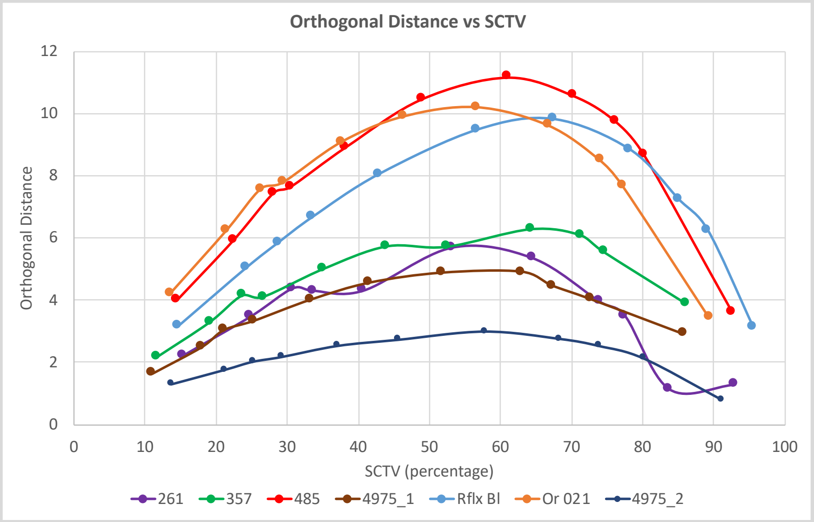


Fig. 3.10. Overview of orthogonal distance data versus measured SCTV in print

Figure 3.10 presents the orthogonal distance results in graphical form. While colors P261, P357, P4975-1 and P4975-2 showed low orthogonal distances, colors P485, PReflexBlue and POrange021 showed maximum orthogonal distances above 10. The curve shape resembled that of Delta H where the orthogonal distance increases and showed peak in the midtones.

The hue angle difference, Delta H and orthogonal distance results are presented and discussed for each color below. The L*C*h° values from the print measurements were plotted in CIELAB color space using ColorThinkPro v3.0.7. Another series was added to the ColorThink plots as the hue corrected series. The hue corrected series contained the same L*C* values as the printed tints, but the hue angle was kept the same as the solid. This series was used as a reference to visually highlight the hue shift observed in the printed results. The print data series can be identified by spherical shaped points while the hue corrected data series is represented by cube shaped data points (as was shown in figure 3.2)

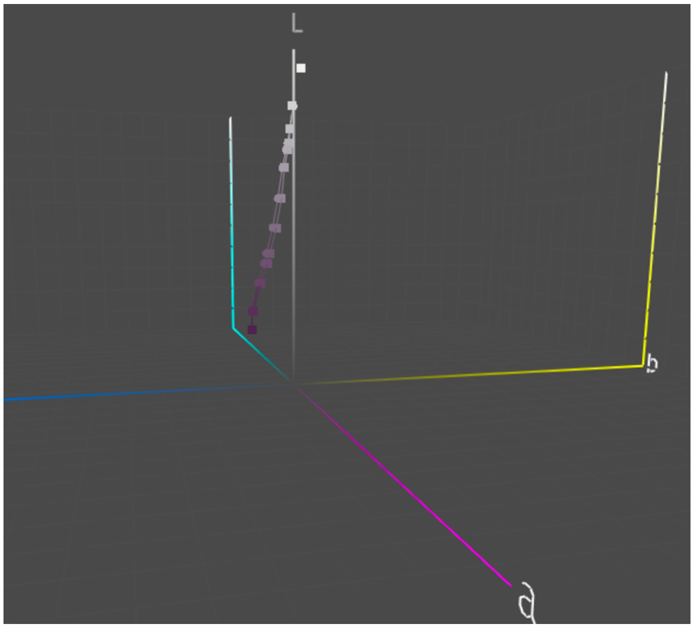
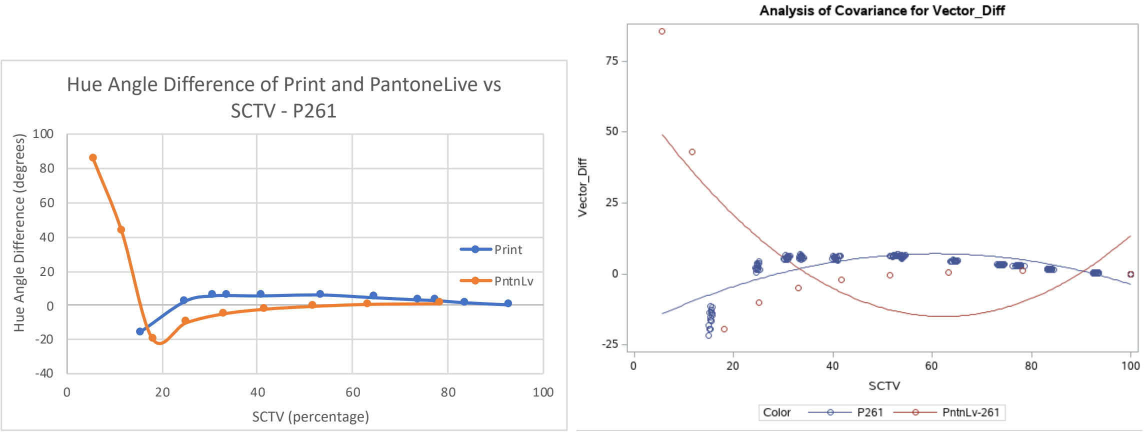
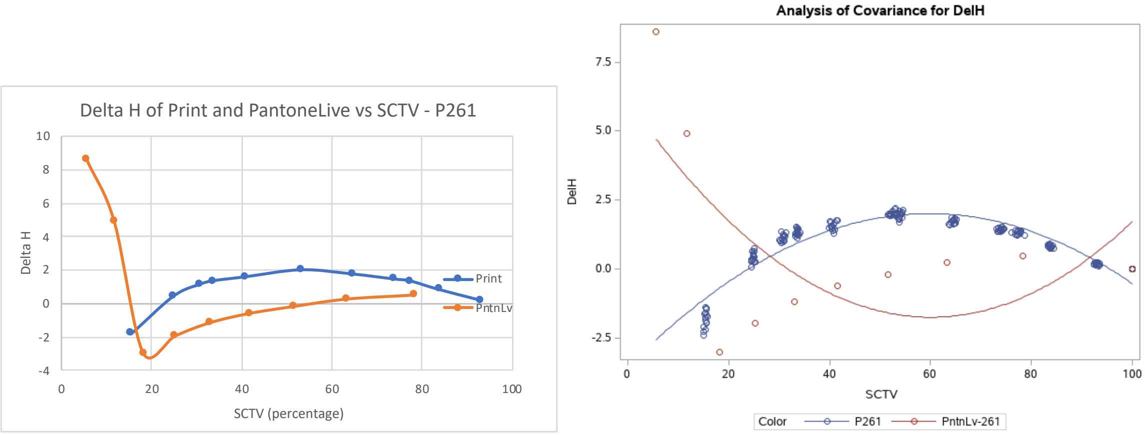


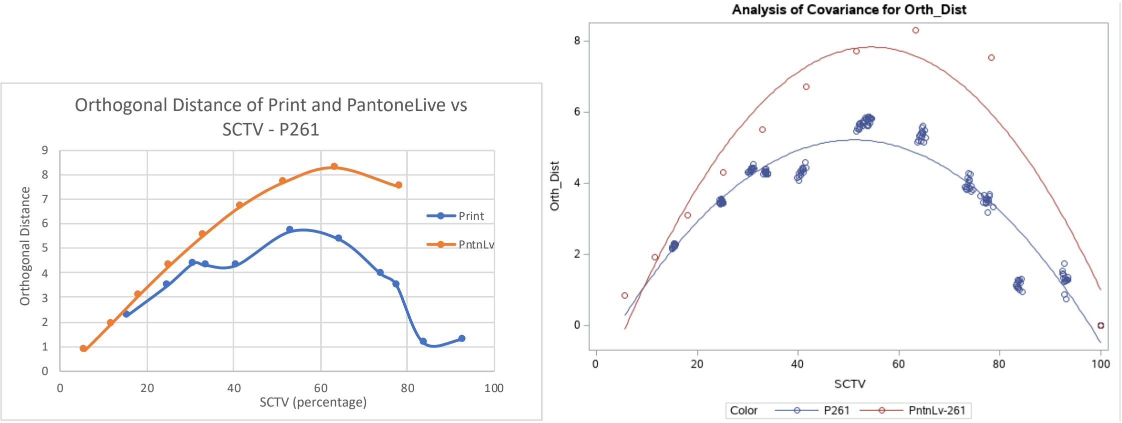
Fig. 3.11. Print and Hue Corrected data for P261-FWCP in CIELAB space



(a)



(b)



(c)

Fig. 3.12. Hue Shift curves for P261 FWCP – (a) Hue angle difference, (b) Delta H, and (c) Orthogonal Distance – measured data curves for Print and PantoneLIVE (PntnLv) (left); Fitted curves using general linear model for print (P261) and PantoneLIVE (PntnLv-261) data (right)

As seen in figure 3.11, the print line did not deviate significantly from the hue corrected line for P261-FWCP. The two lines are difficult to distinguish on the plot due to negligible hue shift. The plots in figure 3.12 suggest that the hue angle difference and Delta H for the PantoneLIVE (PL) data and the print results for P261 were not similar. While the maximum hue angle difference predicted by the PL data was around 85 degrees, the maximum hue angle difference observed in the print was around 6 degrees. The PL data showed the magnitude of hue angle difference and Delta H to be increasing with decrease in SCTV. On the other hand, the print data reached maximum hue angle difference and Delta H at 50% SCTV. This behavior was more distinctly seen with the Delta H metric than with the hue angle difference. An abrupt increase in hue angle difference and Delta H was also seen in the PL data below 15% SCTV, but was not observed in the print results. The maximum orthogonal distance in print and PL data was observed between 50 and 60%. The orthogonal distance curves from print and PL data were similar in shape and showed peaks in the same tonal range. Moreover, the abrupt increase seen in the hue angle difference and Delta H PL data was not observed with orthogonal distance (OD).

Table 3.5. Print vs PantoneLIVE data hypothesis test results at different SCTV values– P261

Hue Angle Difference		Hue Difference (Delta H)		Orthogonal Distance	
Model R^2	0.5390	Model R^2	0.7064	Model R^2	0.9014
SCTV	Pr > |t|	SCTV	Pr > |t|	SCTV	Pr > |t|
10	<0.0001	10	<0.0001	10	0.8634
25	<0.0001	25	0.0033	25	<0.0001
50	<0.0001	50	<0.0001	50	<0.0001
75	<0.0001	75	<0.0001	75	<0.0001
90	0.8633	90	0.4033	90	<0.0001

As seen in table 3.5, the model R^2 for the hue angle difference (denoted as Vector_Diff in graphs) showed that the data did not fit the curve well. The P261 curve (for print data) showed a good fit to the data (figure 3.12). However, the fit for the PantoneLIVE data was not good. This was because the hue angle difference below 15% SCTV deviated significantly from the curve followed by rest of the points. The Delta H curves for P261 were similar to the hue angle difference curves (figure 3.12). However, the model had a better R^2. This was due to the fact that the Delta H values were much smaller as compared to the hue angle difference values. This resulted in a lower root mean square error (Root MSE) value and a better model R^2. The R^2 value for the model with orthogonal distance metric was significantly better. The curve shapes fitted well to the data. The orthogonal distance was not affected by the significant hue angle shifts below 15% SCTV. This could explain a higher R^2 and a better curve fit to the data. The fitted curves for all the orthogonal distance suggested a maximum hue shift between 50 and 60% SCTV.

The p-values (table 3.5) indicate that the print, PL hue angle difference and Delta H fitted data were statistically significantly different at 10, 25, 50, and 75% SCTV, but not at 90% SCTV. On the other hand, the orthogonal distance curves showed statistically significant difference at all the tested SCTV values except 10%. This observation was opposite to that suggested by the hue angle difference and Delta H curves.

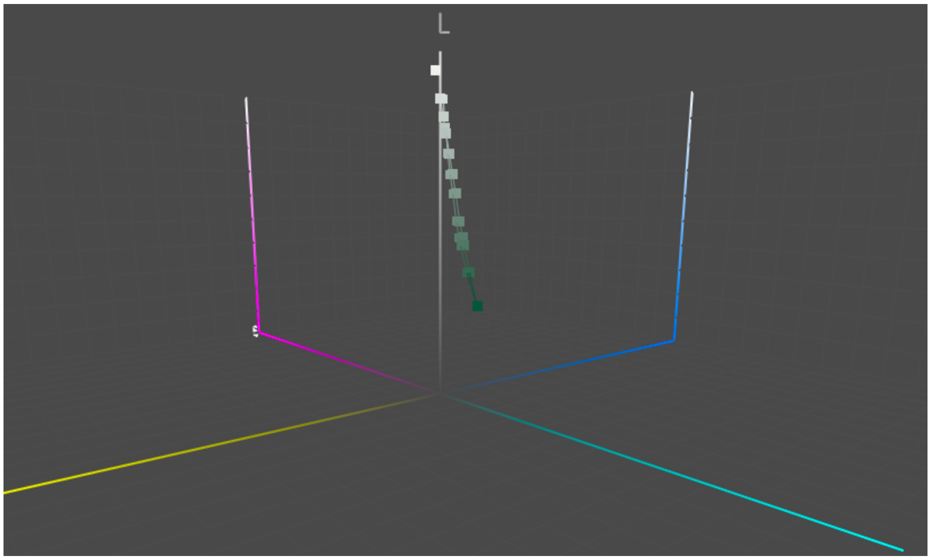
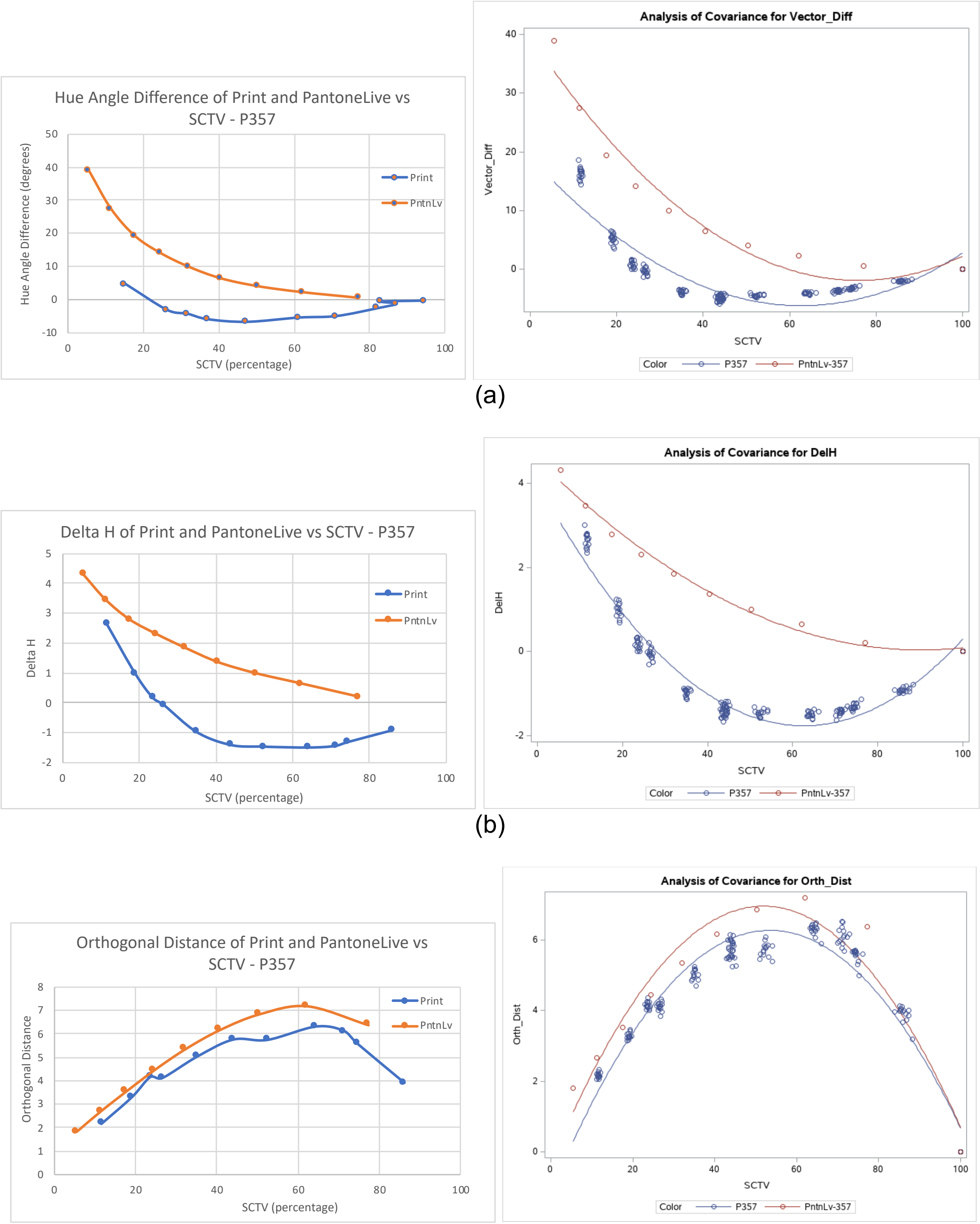


Fig. 3.13. Print and Hue Corrected data for P357-FWCP in CIELAB space



(a)

(b)

(c)

Fig. 3.14. Hue Shift curves for P357 FWCP – (a) Hue angle difference, (b) Delta H, and (c) Orthogonal Distance – measured data curves for Print and PantoneLIVE (PntnLv) (left); Fitted curves using general linear model for print (P357) and PantoneLIVE (PntnLv-357) data (right)

The print and hue corrected lines for P357-FWCP data did not show any noticeable hue shift (figure 3.13). The two lines are difficult to distinguish on the plot due to negligible hue shift. As seen in figure 3.14, the observed hue angle difference and Delta H in print were lesser than the PL predictions. These metrics suggested an increase in hue shift as the SCTV reduced. Moreover, the PL data showed positive hue angle difference and Delta H, while the print data showed some negative values. The orthogonal distance curves for print and PantoneLIVE appeared similar. The maximum orthogonal distance was observed between 60 and 65% SCTV for both, print and PL.

Table 3.6. Print vs PantoneLIVE data hypothesis test results at different SCTV values– P357

Hue Angle Difference		Hue Difference (Delta H)		Orthogonal Distance	
Model R^2	0.8628	Model R^2	0.9535	Model R^2	0.9348
SCTV	Pr > |t|	SCTV	Pr > |t|	SCTV	Pr > |t|
10	<0.0001	10	<0.0001	10	0.0024
25	<0.0001	25	<0.0001	25	<0.0001
50	<0.0001	50	<0.0001	50	0.0022
75	0.0106	75	<0.0001	75	0.0613
90	0.6026	90	0.0004	90	0.5071

The model R^2 showed good fit to the data for all the three metrics. The hue angle difference for the print and PL data was statistically significantly different at all the tested values of SCTV except 90%. The print and PL curves for Delta H were statistically significantly different at all the tested SCTV values. The orthogonal distance data showed a statistically significant difference between print and PL only at 10, 25, and 50% SCTV. These results can be visually related to the shape of fitted curves and the difference in hue shift seen in print as against the prediction using PL data.

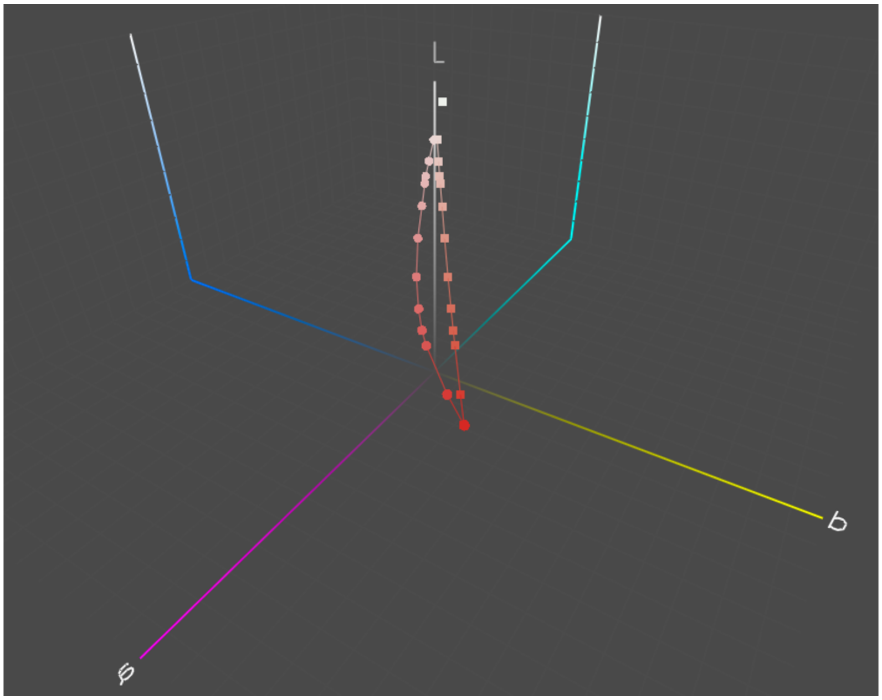
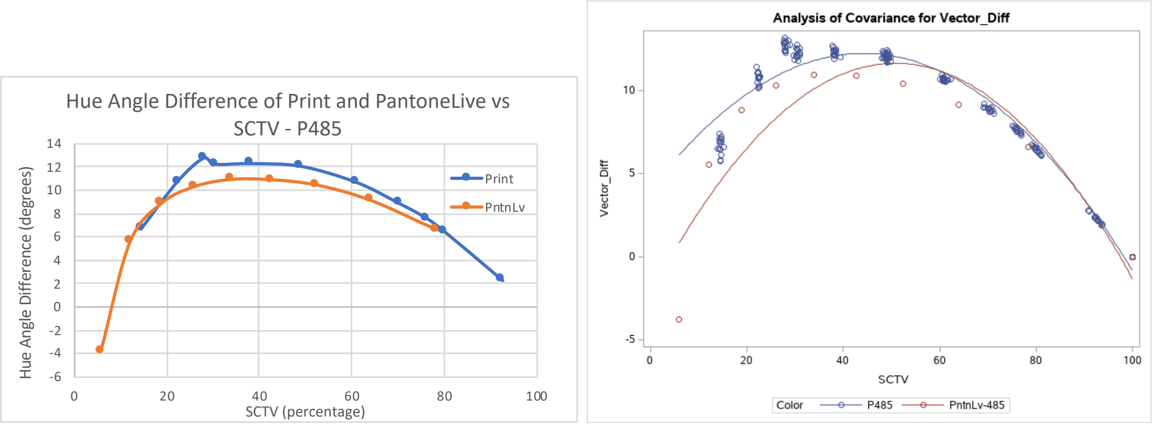
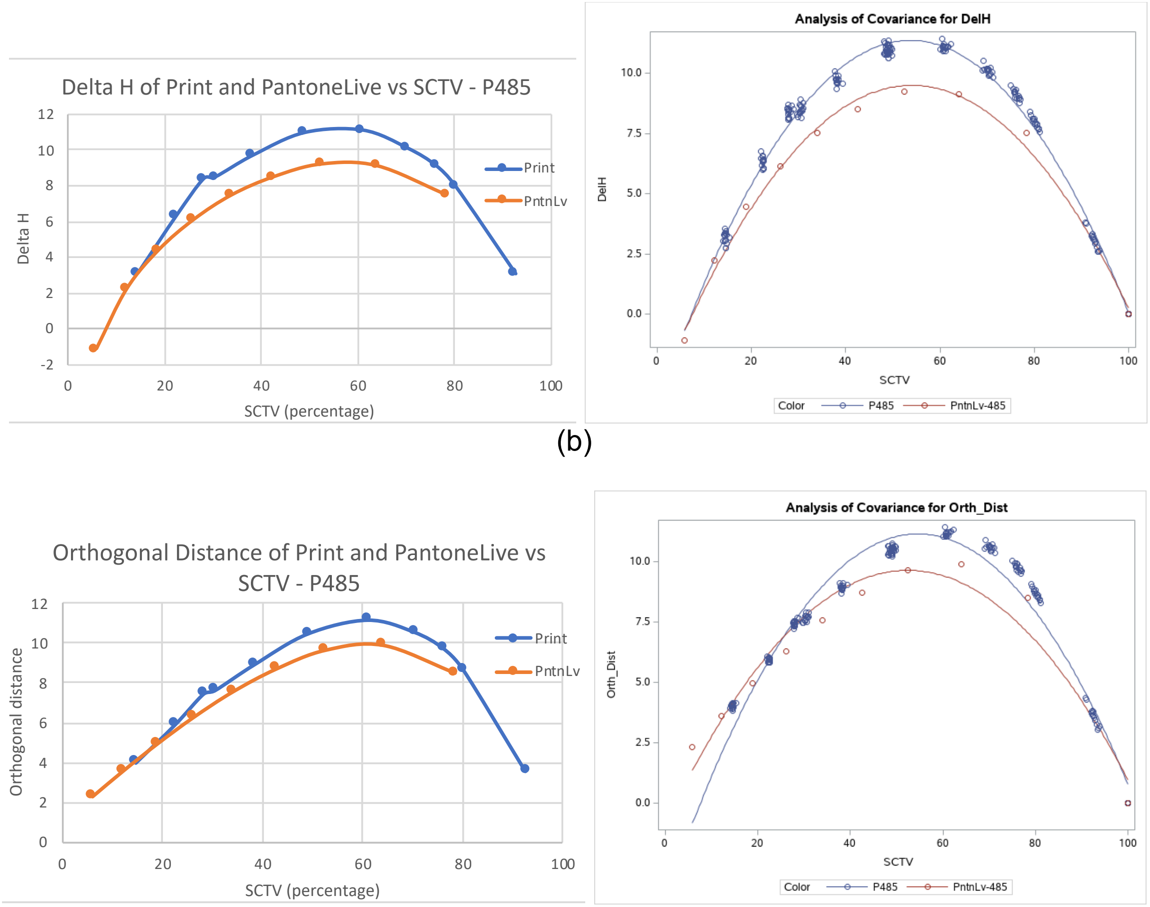


Fig. 3.15. Print and Hue Corrected data for P485-FWCP in CIELAB space



(a)



(b)

(c)

Fig. 3.16. Hue Shift curves for P485 FWCP – (a) Hue angle difference, (b) Delta H, and (c) Orthogonal Distance – measured data curves for Print and PantoneLIVE (PntnLv) (left); Fitted curves using general linear model for print (P485) and PantoneLIVE (PntnLv-485) data (right)

The print and hue corrected lines for P485-FWCP data showed a noticeable hue shift (figure 3.15). The hue shift curve suggested highest hue shift in the midtone region with decreasing shift towards highlights and solids. The hue shift behavior seen in the hue shift metrics' curves (figure 3.16) was observed to be consistent with the CIELAB plot (figure 3.15). As seen in figure 3.16, the hue angle difference, Delta H and orthogonal distance for print and PL data showed similar curve shape and amplitude of hue shift. While the hue angle difference curves suggested maximum hue shift between 30 and 40% SCTV, the Delta H and orthogonal distance curves showed peaks between 55 and 65% SCTV.

Table 3.7. Print vs PantoneLIVE data hypothesis test results at different SCTV values– P485

Hue Angle Difference		Hue Difference (Delta H)		Orthogonal Distance	
Model R^2	0.9454	Model R^2	0.9912	Model R^2	0.9599
SCTV	Pr > |t|	SCTV	Pr > |t|	SCTV	Pr > |t|
10	<0.0001	10	0.1317	10	<0.0001
25	<0.0001	25	<0.0001	25	0.8550
50	0.3261	50	<0.0001	50	<0.0001
75	0.5887	75	<0.0001	75	<0.0001
90	0.9661	90	0.0065	90	0.1502

The model R^2 for the all the three metrics showed excellent curve fit to the data (table 3.7). Based on the p-values listed in table 3.7,the hue angle difference fitted curves did not show a statistically significant difference between print and PL above 50% SCTV. The Del H fitted curve suggested a statistically significant difference between print and PL at all the tested SCTV values. The orthogonal distance fitted curve showed statistically significant differences at 10, 50, 75% SCTV. While the statistical tests suggested a statistically significant difference at most SCTV values, the maximum difference between the hue shift for print and PL data was not more than three. Hence, these differences were not practically significant.

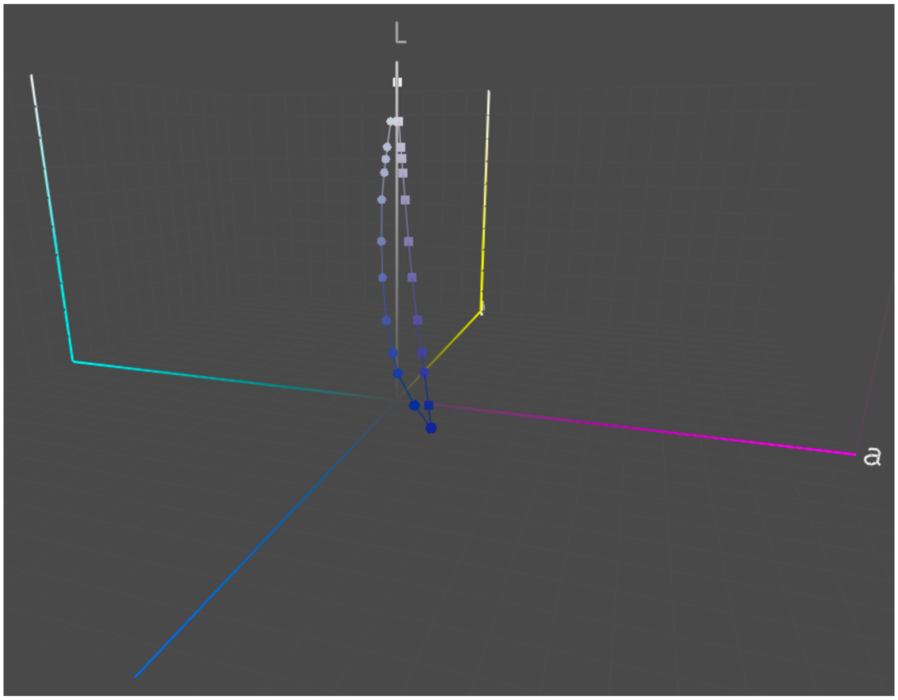
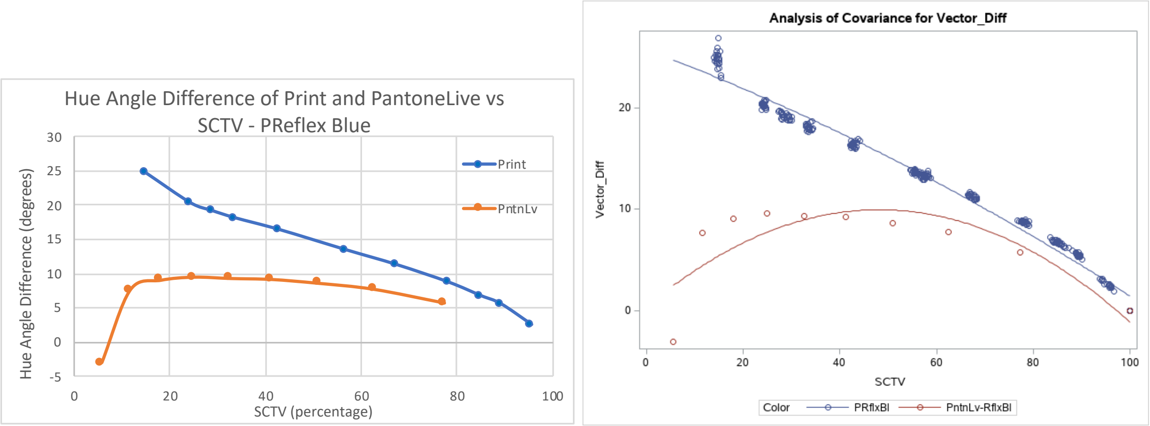
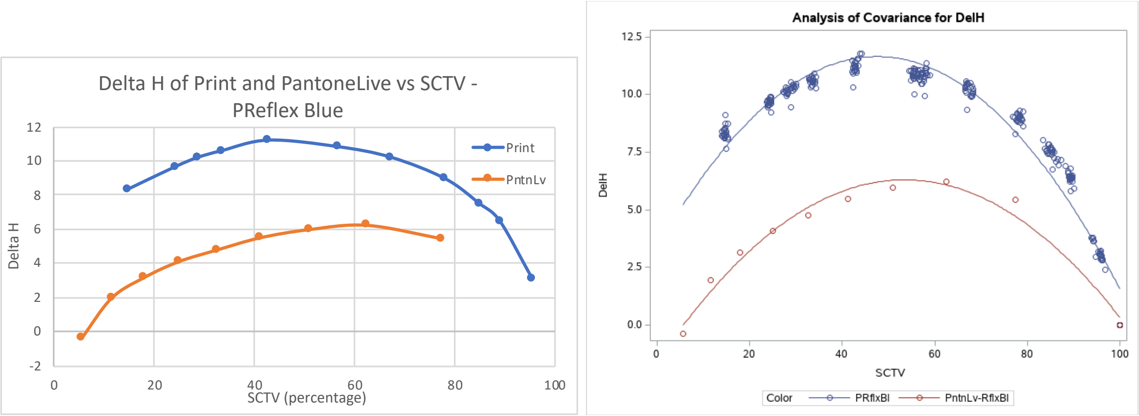


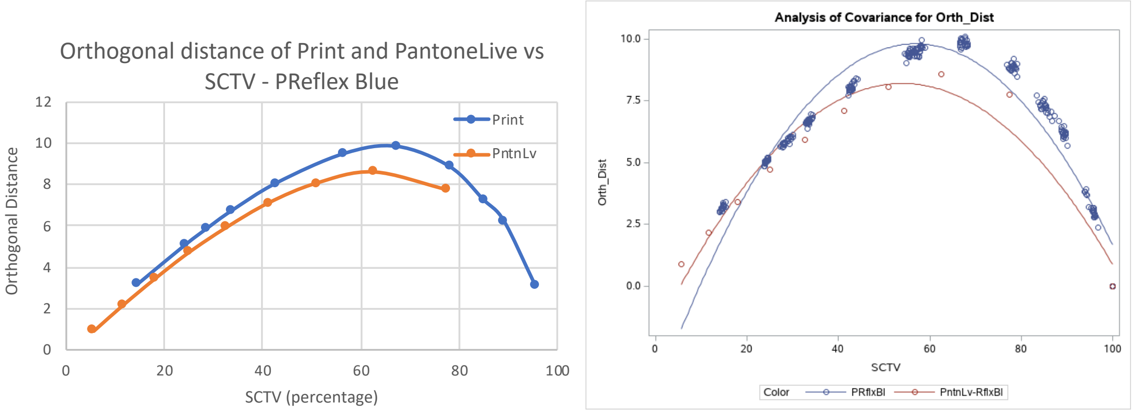
Fig. 3.17. Print and Hue Corrected data for PReflexBlue-FWCP in CIELAB space



(a)



(b)



(c)

Fig. 3.18. Hue Shift curves for PReflexBlue FWCP – (a) Hue angle difference, (b) Delta H, and (c) Orthogonal Distance – measured data curves for Print and PantoneLIVE (PntnLv) (left); Fitted curves using general linear model for print (PRflxBl) and PantoneLIVE (PntnLv-RflxBl) data (right)

Figure 3.17 showed a noticeable hue shift in the print curve as compared to the hue corrected curves for PReflexBlue-FWCP. The hue shift curve suggested highest hue shift in the higher end of midtone region. The hue angle difference curves for print and PL data (figure 3.18) indicated an increase in hue angle difference with a decrease in SCTV. However, curve shapes were not similar in the highlight region. While the PL data suggested a sharp decrease in hue angle difference below 15% SCTV, an almost linear increase was observed in the print results. The maximum hue angle difference was observed at around 15% SCTV for both print and PL. The Delta H and orthogonal distance curves showed similar shapes for print and PL data (figure

3.18). The maximum Delta H and orthogonal distance were observed in the midtone region (45 to 65% SCTV) for both print and PL data. Overall, the fitted Delta H and orthogonal distance curves showed similar trend as that seen in the print data CIELAB plot.

Table 3.8. Print vs PantoneLIVE data hypothesis test results at different SCTV values– PReflexBlue

Hue Angle Difference		Hue Difference (Delta H)		Orthogonal Distance	
Model R^2	0.9796	Model R^2	0.9515	Model R^2	0.9139
SCTV	Pr > |t|	SCTV	Pr > |t|	SCTV	Pr > |t|
10	<0.0001	10	<0.0001	10	0.0086
25	<0.0001	25	<0.0001	25	0.8636
50	<0.0001	50	<0.0001	50	0.0005
75	0.0009	75	<0.0001	75	<0.0001
90	0.0122	90	<0.0001	90	0.0209

The model R^2 for all the three metrics were above 90% (table 3.8), which indicated very good curve fit to the data. Based on the p-values listed in table 3.8, the hue angle difference curves for print and PL were statistically significantly different at all the tested SCTV values. Table 3.8 suggested similar results with Delta H curves. The orthogonal distance fitted curves showed statistically insignificant differences between print and PL data at 25%. The difference between orthogonal distance fitted curves of print and PL was relatively lesser than that seen with Delta H and hue angle difference.

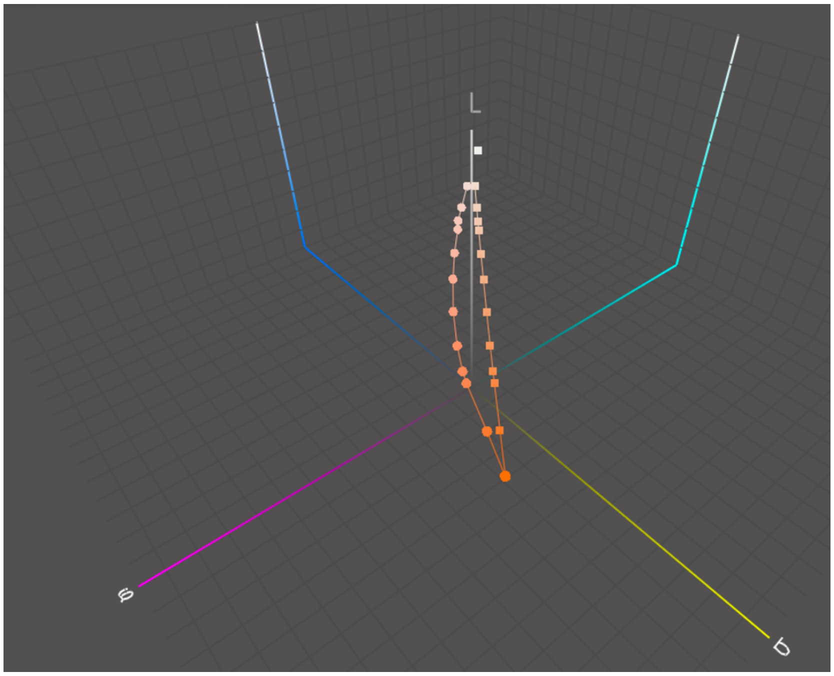
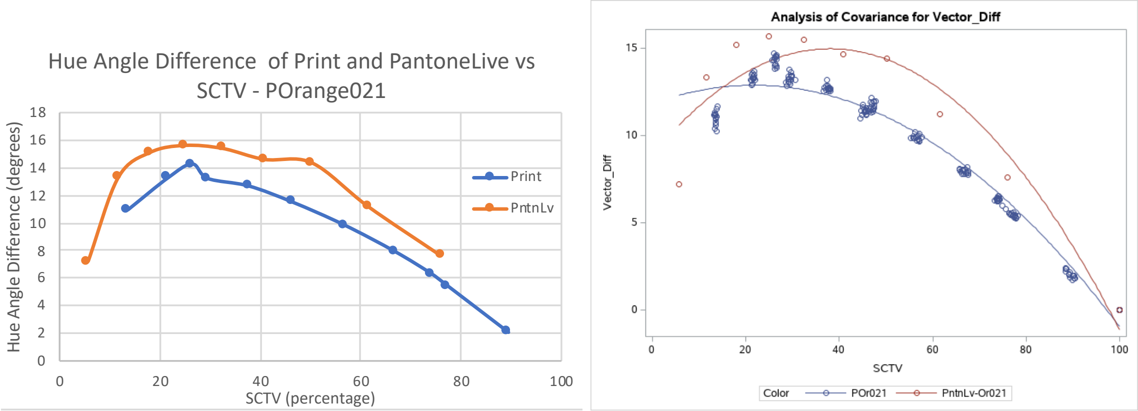


Fig. 3.19. Print and Hue Corrected data for POrange021-FWCP in CIELAB space



(a)

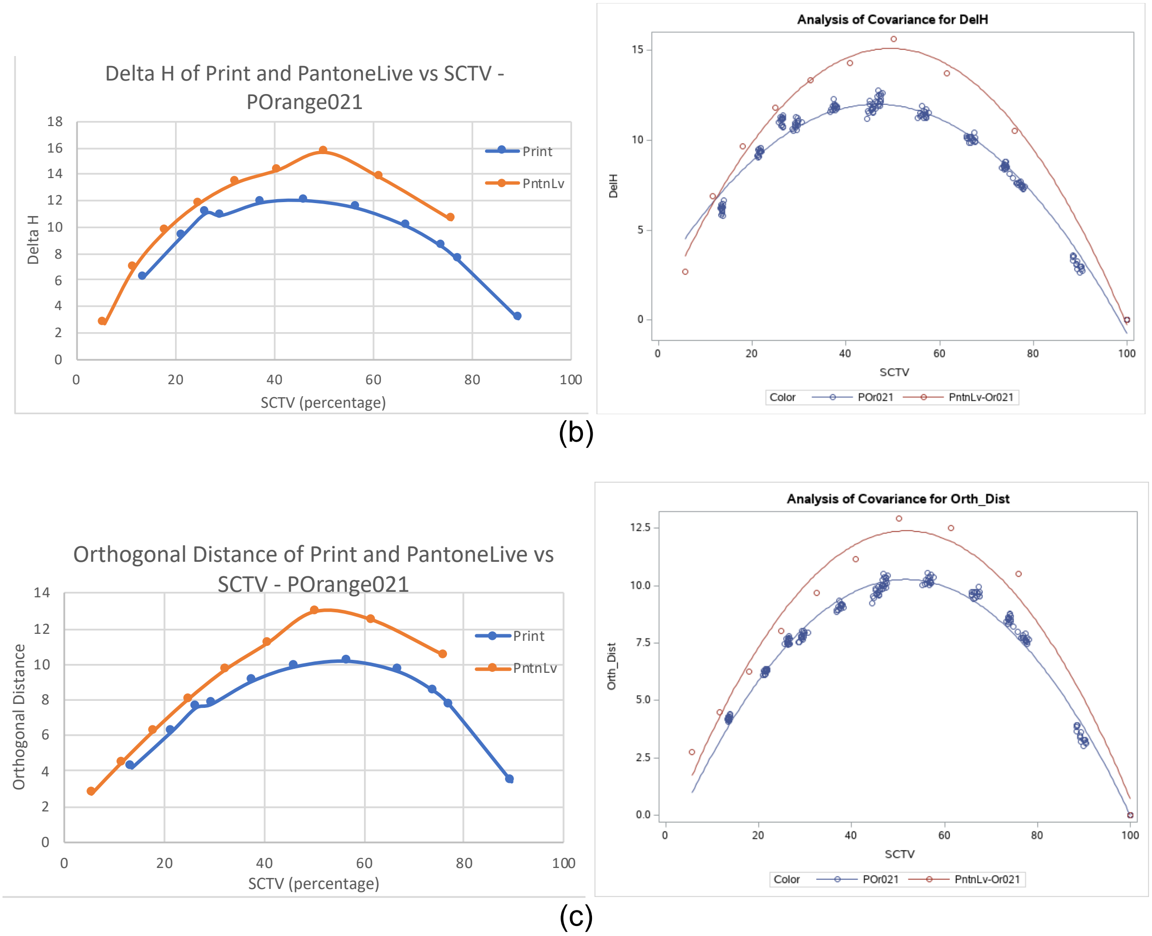


Fig. 3.20. Hue Shift curves for Porange021 FWCP – (a) Hue angle difference, (b) Delta H, and (c) Orthogonal Distance – measured data curves for Print and PantoneLIVE (PntnLv) (left); Fitted curves using general linear model for print(POr021) and PantoneLIVE (PntnLv-Or021) data (right)

Figure 3.19 showed a noticeable hue shift in the print curve as compared to the hue corrected curve of POrange021-FWCP data. The print curve suggested highest hue shift in the midtone region. The hue angle difference, Delta H and the orthogonal distance curves for print and PL data of POrange021 showed similar shapes (figure 3.20). While the maximum hue angle difference was observed around 30%, the maximum Delta H and orthogonal distance were observed between 40 and 60%. The hue shift observed in print was lesser than the PL predictions.

Table 3.9. Print vs PantoneLIVE data hypothesis test results at different SCTV values– POrange021

Hue Angle Difference		Hue Difference (Delta H)		Orthogonal Distance	
Model R^2	0.9633	Model R^2	0.9802	Model R^2	0.9854
SCTV	Pr > |t|	SCTV	Pr > |t|	SCTV	Pr > |t|
10	0.0867	10	0.3353	10	<0.0001
25	<0.0001	25	<0.0001	25	<0.0001
50	<0.0001	50	<0.0001	50	<0.0001
75	<0.0001	75	<0.0001	75	<0.0001
90	0.0282	90	<0.0001	90	<0.0001

The model R^2 for all the three metrics was above 90% (table 3.9). This indicated good curve fit to the data. The hue angle difference and Delta H showed statistically insignificant difference between print and PL fitted curves at 10%. The fitted curves to the hue shift metrics at all the other tested SCTV values showed statistically significant difference between the print and PL results.

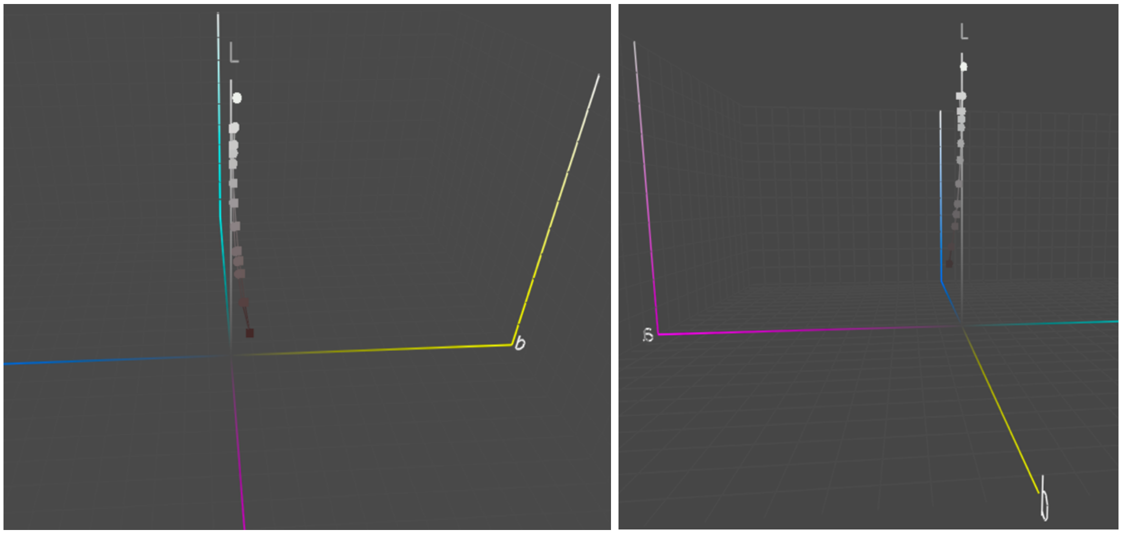


Fig. 3.21. Print and Hue Corrected data for P4975-FWCP in CIELAB space a) Recipe 1; b) Recipe 2

Figure 3.21 did not show a noticeable hue shift in the print when compared to the hue corrected line for both recipes of P4975 data. On comparing the two recipes with each other, a similar hue shift behavior was observed between them (figure 3.22). The deviation towards the solid is seen due to the difference in measured chromaticity of the printed samples with the two recipes.

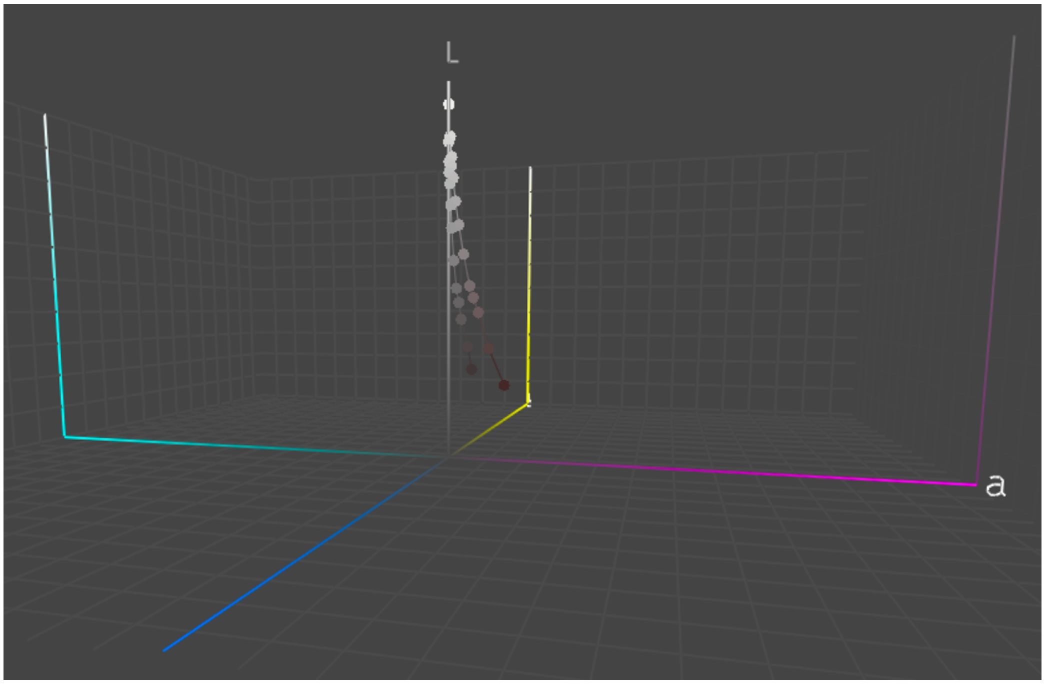
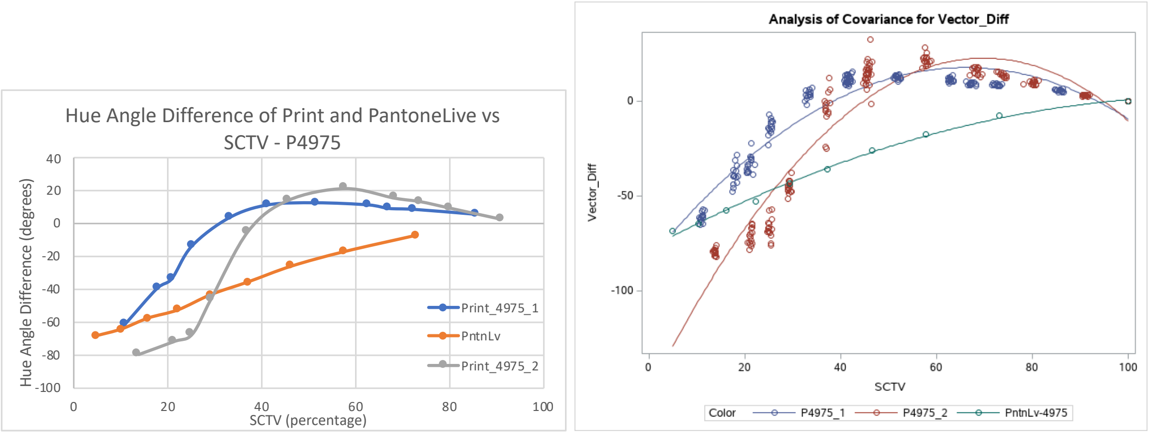
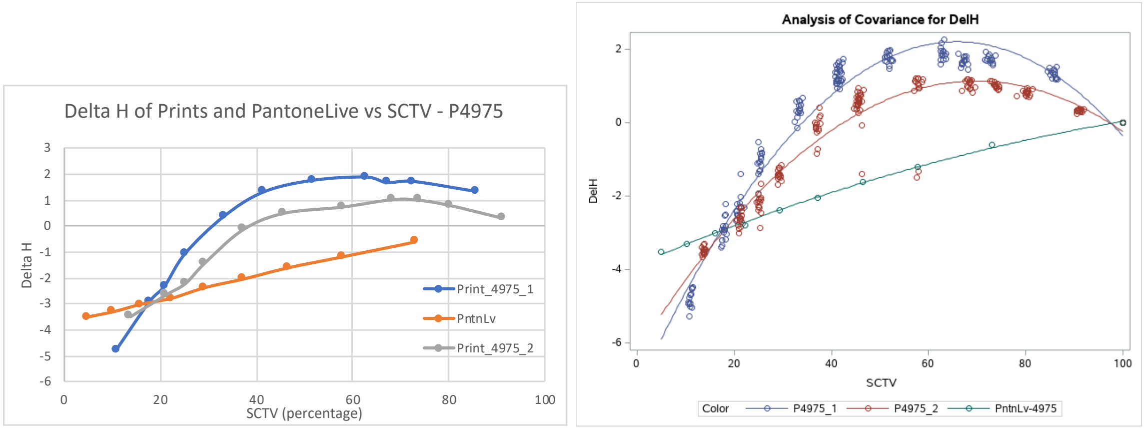


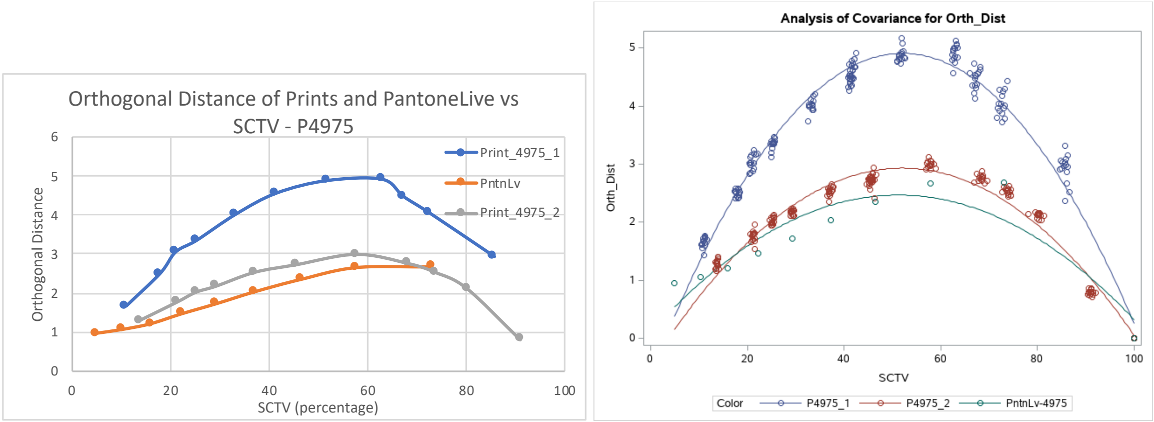
Fig. 3.22. Print data for the two recipes of P4975-FWCP in CIELAB space (series on the outside represents recipe 1 and the other is recipe 2)



(a)



(b)



(c)

Fig. 3.23. Hue Shift curves for P4975FWCP – (a) Hue angle difference, (b) Delta H, and (c) Orthogonal Distance – measured data curves for Print and PantoneLIVE (PntnLv) (left); Fitted curves using general linear model for print (P4975_1, P4975_2) and PantoneLIVE (PntnLv-4975) data (right)

The hue shift plots for P4975 (figure 3.23) contain three data series – print from ink recipe 1, print from ink recipe 2 and the PL data. The hue angle difference curves for print and PL data of P4975 were different. The hue angle difference curve for PL suggested a linear negative increase in hue angle difference with a decrease in SCTV. On the other hand, the print data followed a curve showing knee-shaped change in hue shift around 40percent SCTV. The maximum hue angle differences were observed in the highlight region at or below 15% SCTV. The print curves show the hue angle difference moving from negative to positive between 30 and

40% SCTV. This change in sign can be attributed to the low chromaticity of the color. Since the points were close to the achromatic axis, small shifts in the CIELAB space caused large shifts in the hue angle (CIE/ISO, 2019; Durmus & Davis, 2019).

The Delta H for print data from both ink recipes showed similar curve shape with maximum hue shift between 60 and 70% SCTV (figure 3.23). However, the Delta H curve shape for PL data was different from that of the print data. The magnitude of hue shift suggested by the Delta H metric was much lower than that seen in the hue angle difference. This was due to the chromaticity factor included in the Delta H formula and low chromaticity of P4975-FWCP. The Delta H curves for PantoneLIVE showed a straight line indicating a linear negative increase in magnitude of hue shift with decrease in SCTV.

The orthogonal distance curve for print recipe 2 was much closer to the PantoneLIVE prediction than the ink recipe 1 results (figure 3.23). It is worth noting that the chromaticity of print with ink recipe 2 was much closer to the PL standard than the ink recipe 1. The ink recipe 1 showed higher orthogonal distance than the ink recipe 2 and PL. The orthogonal distance curve shapes for both the ink recipes showed similar shapes with a maximum hue shift around 60% SCTV.

While comparing the two ink recipes of P4975, the hue shift curve shapes were similar (figure 3.23). However, the extent of hue angle difference and orthogonal distance observed with ink recipe 1 and ink recipe 2 were different. The three metrics unanimously showed higher hue shift for ink recipe 1 than for ink recipe 2. It is worth noting that the L* and h^{o} values for both the recipes were similar. However, the C* for printed solid with ink recipe 1 was 15.64 while that for ink recipe 2 was 6.19. This supported the finding that higher chromaticity resulted in a higher hue shift.

Table 3.10. Print vs PantoneLIVE, and print with ink recipe 1 vs ink recipe 2 data hypothesis test results at different SCTV values – P4975

Hue Angle Difference		Hue Difference (Delta H)		Orthogonal Distance	
Model R^2	0.9086	Model R^2	0.9572	Model R^2	0.9800
Ho: $\text{LSMean}_{\text{print\_recipe1}} = \text{LSMean}_{\text{PantoneLIVE}}$					
SCTV	Pr > $\lvert t\rvert$	SCTV	Pr > $\lvert t\rvert$	SCTV	Pr > $\lvert t\rvert$
10	0.0782	10	<0.0001	10	0.0009
25	<0.0001	25	<0.0001	25	<0.0001
50	<0.0001	50	<0.0001	50	<0.0001
75	<0.0001	75	<0.0001	75	<0.0001
90	0.3588	90	<0.0001	90	<0.0001
Ho: $\text{LSMean}_{\text{print\_recipe1}} = \text{LSMean}_{\text{print\_recipe2}}$					
SCTV	Pr > $\lvert t\rvert$	SCTV	Pr > $\lvert t\rvert$	SCTV	Pr > $\lvert t\rvert$
10	<0.0001	10	0.0018	10	<0.0001
25	<0.0001	25	<0.0001	25	<0.0001
50	0.0222	50	<0.0001	50	<0.0001
75	<0.0001	75	<0.0001	75	<0.0001
90	0.0490	90	<0.0001	90	<0.0001

The model R^2 values were greater than 90% for all three metrics (table 3.10). This suggested a good curve fit to the data. The fitted curves of hue angle difference for print and PL data were statistically significantly different at 25, 50 and 75%. The Delta H and orthogonal distance fitted curves showed statistically significant difference between print and PL data at all the tested SCTV values. When comparing the two ink recipes, the hue shift metrics were statistically significantly different at all the tested SCTV values. This indicated that the results from the two ink recipes were statistically significantly different.

An analysis of spectral reflectance information indicated a trend in the hue shift behavior of the tested spot color inks.

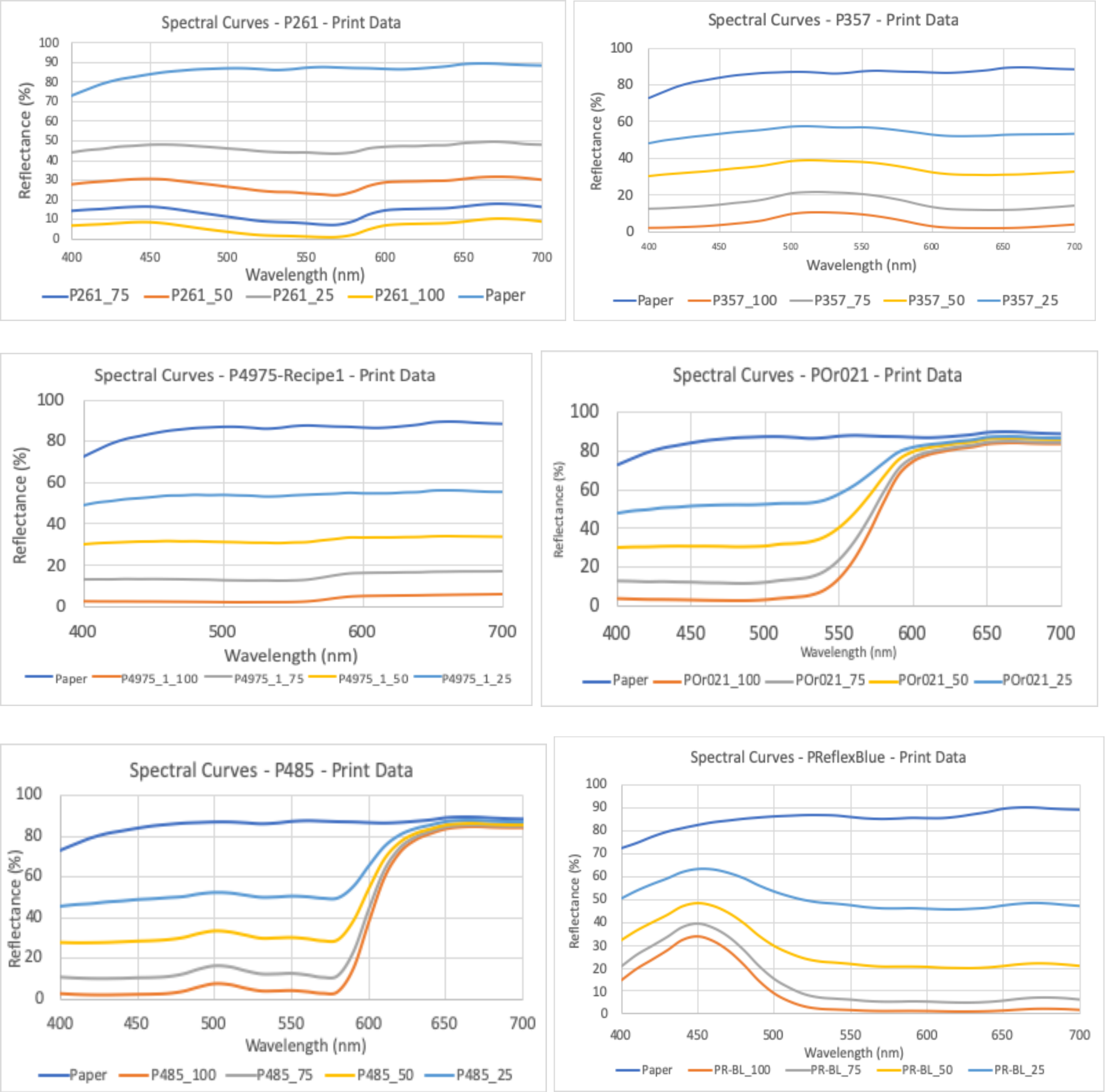


Fig. 3.24. Spectral reflectance curves of paper, solid, 25, 50, and 75% tints of tested spot colors

The tested colors can be grouped into categories based on the spectral reflectance curve shapes as seen in figure 3.24. While the colors P261, P357, and P4975 showed relatively flat spectral curves, the spectral curves for POrange021, P485, and PReflexBlue showed distinct peaks and large changes in reflectance. While the colors with peaks in their spectral curves showed high hue shift in this study, the colors with relatively flat spectral curves did not show practically significant hue shifts.

The efficacy of the three metrics in characterizing the hue shifts for print and PantoneLIVE data was evaluated. For each metric, the absolute value of difference between maximum hue shift for print and PantoneLIVE was calculated. The calculation is as defined below:

Maximum hue angle difference between print and PantoneLIVE data = | Maximum hue angle difference for print data – Maximum hue angle difference for PantoneLIVE data | Eq. 3.7

This difference was used as an indicator of how each hue shift metric performed in terms of predictability of print with PantoneLIVE data. A higher difference indicated poor predictability for that metric.

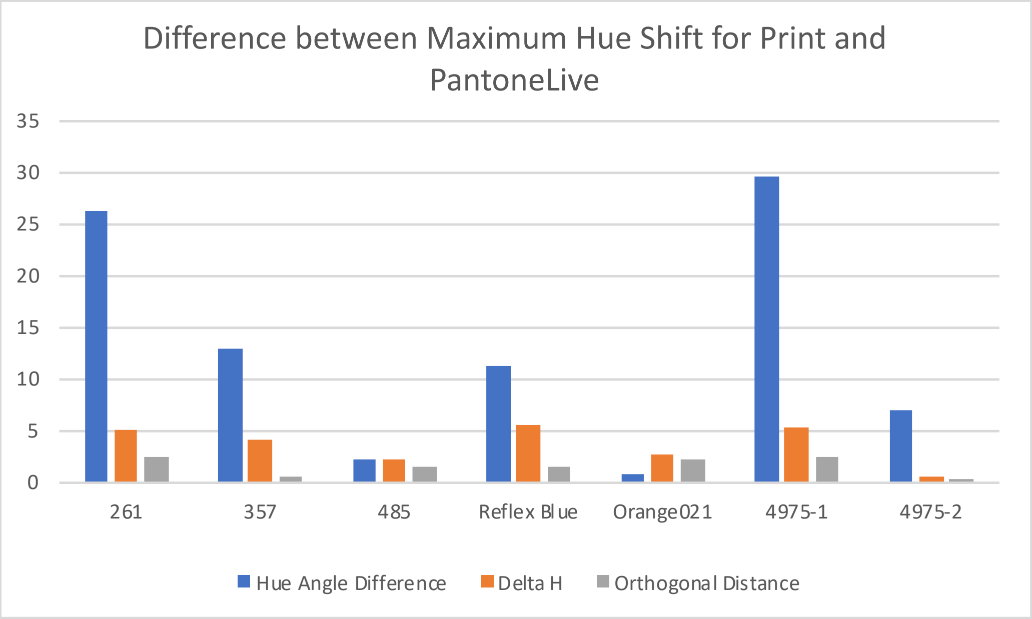


Fig. 3.25. Maximum difference between hue shift metrics for Print and PantoneLIVE data

Figure 3.25 clearly showed that hue angle difference showed the highest difference between the print and PantoneLIVE data. The lowest difference was seen with the orthogonal distance. The difference for Delta H was between hue angle difference and orthogonal distance. The limitation of hue angle difference as a hue shift metric were highlighted with low chromaticity color i.e. P4975- FWCP. The metric overestimated the hue shift and showed sign changes as well. Orthogonal difference showed the closest results to the PantoneLIVE data. In terms of predictability of print results with PantoneLIVE data, orthogonal difference appeared to be a better metric than the rest. However, orthogonal distance is a strictly positive quantity and does not indicate the direction of shift. On the basis of observations from the CIELAB plots and the individual metric curves, Delta H appeared to the best metric in terms of distinguishing between low and high hue shift colors.

Summary of Results

Hue Shift Behavior

Based on the results of preliminary and main study, the extent of hue shift was observed to be higher for spot colors with high chromaticity. Spot colors with C* higher than 70 showed practically significant hue shift. Moreover, spot colors with distinct peaks and large reflectance changes in their spectral curves showed high hue shifts. The yellow hue region showed negligible hue shifts, while the violet, red, orange and reflex blue hues showed a noticeable hue shift. The midtone region was observed to be the most susceptible to hue shifts. Table 3.11 lists the spot colors in decreasing order of hue shift based on the three metrics used in this study.

Table 3.11. Spot color ranked in decreasing order of hue shift

Metric	Spot Color ranked in decreasing order of hue shift
Hue Angle Difference	P4975-Recipe 2 > P4975- Recipe 1 > PReflexBlue > POrange021 > P485 > P261 > P357
Delta H	POrange021 > PReflexBlue > P485 > P4975- Recipe1 > 4975-Recipe2 > P261 > P357
Orthogonal Distance	P485 > POrange021 > PReflexBlue > P357 > P261 > P4975-Recipe1 > P4975- Recipe2

Print versus Digital (PantoneLIVE) comparison

The statistical tests on the print and PantoneLIVE fitted curves showed statistically significant differences at multiple SCTV values for all the tested colors. However, the largest number of statistically insignificant differences was found in P485. Moreover, the extent of difference in hue shift between print and PL data was practically insignificant for P485. The midtone region (25, 50 and 75% SCTV) consistently showed statistically significant differences in hue shift between print and PL data for all the rest of the colors (P357, PReflexBlue showed one exception each). The hue angle difference and Delta H curves for print and PantoneLIVE were observed to differ practically and statistically significantly for P261, PReflexBlue and P4975.

Effect of different ink recipe

The fitted hue shift curves for the two ink recipes of P4975 were statistically significantly different. Moreover, the extent of hue shift was observed to be higher in printed with recipe 1 than with recipe 2. This was attributed to the higher chromaticity of the print with recipe 1 than with recipe 2.

Comparison of metrics

Hue angle difference showed limitations for colors close to the achromatic axis. Hue angle difference was observed to increase with a decrease in SCTV while the Delta H and orthogonal distance showed peaks in the midtone region. The hue shift behavior seen in Delta H and orthogonal distance plots was similar to that seen in CIELAB plots of the print data. In terms of agreement between the print and PantoneLIVE data, orthogonal distance showed the best results. It is worth noting that orthogonal distance was not exclusively a hue shift measurement and could include small amounts of L* and C* variations. However, since the study was designed to have primarily hue shifts with minimal lightness and chromaticity variations, orthogonal distance was considered to approximate hue shift in this study.

Conclusion

The nature and extent of hue shift for tints of six spot colors were characterized using three hue shift metrics. The study showed that spot colors with high chromaticity and peaks in their spectral reflectance curves showed higher hue shifts than spot colors with lower chromaticity and flatter spectral curves. Spot color tints of P485, PReflexBlue, and POrange021 showed noticeable hue shift while the colors P261, P357 and P4975 did not show practically significant hue shifts. The hue shift, as suggested by Delta H, orthogonal difference and CIELAB plots, was observed to be the highest in the midtone region. The print and PantoneLIVE data for P357, P485 and POrange021 showed similar hue shift behaviors and magnitude. The print data for rest of the tested colors differed noticeably from the PantoneLIVE data. Orthogonal distance as a hue shift metric showed better correlation between print and PantoneLIVE data than the other two metrics. It was observed that hue angle difference as a hue shift metric could exaggerate hue shifts while characterizing low chromaticity colors near the achromatic line. Delta H was observed to perform better than the other two metrics in showing the distinction between high and low hue shift colors. The two ink recipes for P4975 did not show a significant difference in hue shift behavior. This observation was attributed to the low chromaticity of the color. Hence, it is recommended to repeat the different ink recipe exercise with a higher chromaticity spot color.

Further study

This study evaluated the hue shift in spot color tints with three different metrics. A visual analysis study is recommended as the next phase of this project. The visual study results will help establish if the measured hue shifts are visually perceptible and acceptable. If the observers do detect a visual difference between the print, PantoneLIVE and the hue corrected versions, it would be worth evaluating which version of the spot color tints do they choose as a more natural tint of a given spot color solid. It would also be worth repeating this study with high chromaticity colors in other hue regions to see if the relationship is replicated across the different regions. The study assumed hue uniformity in the CIELAB space. It would be worth repeating this study with other color spaces that are more perceptually uniform. Moreover, the performance of Delta H based on Delta E2000 recommendations needs to be evaluated against the Delta E1976 based formula. Additionally, a chromatic adaptation transform could also be tested with these hue shift metrics to check if the accuracy of these metrics improves. It would worth investigating the hue shift behavior of mono-pigment versus multi-pigment ink with same solid target but different spectral curves.

CHAPTER 4

VISUAL ANALYSIS OF HUE SHIFT IN SPOT COLOR TINTS IN FLEXOGRAPHIC PACKAGE PRINTING

Introduction

Packaging plays an important role in the modern world. It helps to preserve, protect, dispense, communicate and sell a product. Packaging graphics and color are key parts of the communication and selling functions. Package printing can be broadly classified into two categories based on how the color is achieved – process and spot color printing. Process color printing involves use of combinations of process colors – Cyan, Magenta, Yellow and Black (CMYK). Expanded gamut printing is a special case of process printing where additional colors, typically orange, green and violet, are used to achieve a larger color gamut. Spot color printing uses specially formulated inks that are designed to achieve a particular color appearance on a given substrate. Spot colors are commonly used as brand colors. Different brands use characteristic colors that the consumers can relate to their products and brand identity (e.g. a Coca-Cola® red or a Pepsi® blue).

The appearance of spot colors influences brand recognition. The standard colorimetric values for solids of spot colors are well defined by either Pantone specifications, $L^*a^*b^*C^*h^o$ values, spectral data, or with a combination of these. The extraction, simulation, and prediction of spot color tints, solely on the basis of spot color solids, can be problematic and presents accuracy challenges (Jodra, Such, & Soler, 2009; Sawatzki, Roesch, & Specht, 2017). While the colorimetric standards for spot color tints exist in the form of digital libraries such as PantoneLIVE or as Color Exchange Format (CxF-4a) data, spot color tints are typically managed using tone value measurements.

The tints of some spot colors tend to show hue shifts as the spot color tone value (SCTV) changes. A common example of such a color is reflex blue, which tends to shift towards a purple hue as the tone value decreases. Figure 4.1 shows the hue shift in printed tint results compared to the reference hue corrected line. The hue corrected line consists of the same L*C* value as the printed tints, but the hue angle of the solid is preserved.

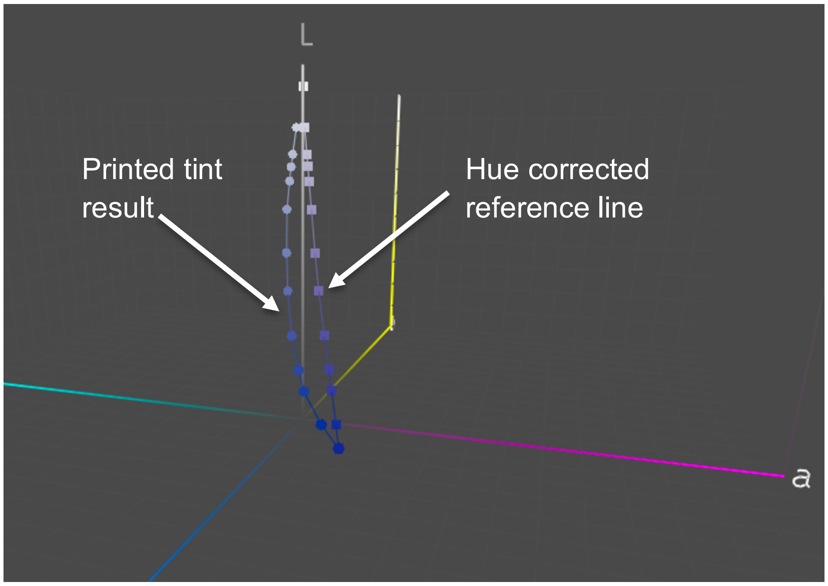


Fig. 4.1. Print and hue corrected curves for PReflexBlue-FWCP in CIELAB space

It is worth examining how closely the hue shift behavior of the printed tints resembles the reference data from the digital library or CxF data. Moreover, these spot color inks can be mixed using various possible combinations of the different base pigment inks. Different ink manufacturers may use different ink recipes and base pigments for making the same spot ink if a spectral match is not required. While this approach may work well for achieving a color match in the solids, halftones may show differences in hue for the differently formulated inks (O'Hara, et al., 2014).

The intent of the study is to visually compare the printed results of four spot color tints with their digital reference and hue corrected samples. The objective was to examine whether the hue shifts in tints of these four spot colors are visually perceivable or not. The appearance of a printed tint of these spot colors was visually compared to the appearance of the same tint from a digital reference library. Moreover, the intent of the study was to examine if the reported visual differences would cause a change in observers’ intent to purchase the product. The study correlates the visual difference results to the color and hue difference results measured using a spectrophotometer. The study also examined if the observers viewed one of the tint versions (printed tint, digital library tint or hue corrected tint) as the most natural tint of a given spot color reference solid.

Methods and Materials

Spot Color selection

The colors evaluated in this study were selected on the basis of results from a previous study. The previous study involved evaluation of hue shift in spot color tints using colorimetric data collected with a spectrophotometer (measurement instrument-based approach). Six spot colors were printed with the flexographic printing process on a paperboard substrate using water-based inks. The previous and the current study used the PantoneLIVE Flexo Water-based Coated Paper (FWCP) library from Xrite Pantone (P) as the digital reference. These spot colors were P261 – FWCP, P357 – FWCP, P485 – FWCP, P4975 – FWCP, POrange021 – FWCP, and PReflexBlue – FWCP. This library was chosen because paperboard packaging is commonly printed with Flexography using water-based inks. In this study, these colors are also referenced without the FWCP suffix in some places for simplicity.

In order to study the effect of different ink recipes on hue shift behavior of tints, one of the spot colors (P4975) was printed with two differently formulated inks in the previous study. Solids and tint-scales of six spot colors (with distinctly different hues) were printed. The colorimetric data (spectral, L*a*b*C*h° values) at each of the printed tint percentages were measured. Hue shifts at different tint percentages across the tonal range were calculated from the colorimetric data. Hue angle difference (Δh_{ab}) and hue difference (Delta H or ΔH^*_{ab}) were used as the metrics to quantify hue shift. These were calculated on the basis of International Commission on Illumination (CIE)/International Organization for Standardization (ISO) 11664-4 (2019) recommendations. The highest hue shifts across the tonal range were noted, along with the corresponding measured spot color tone value (SCTV). The colorimetric data pertaining to the maximum hue shift for each of the colors (in both, print and PantoneLIVE) were used for the visual evaluation study. An overview of hue shift data from the print results is presented in the figure below.

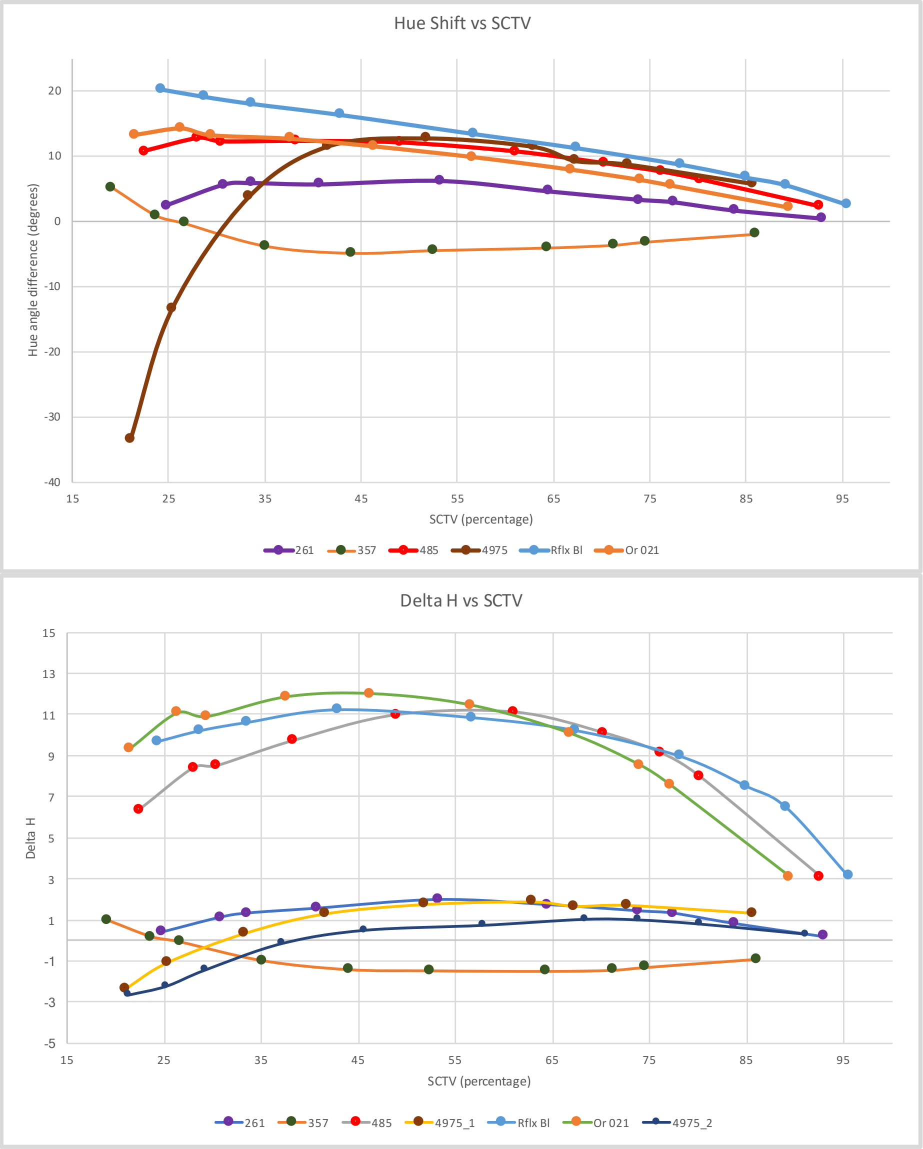


Fig. 4.2. Overview of Hue Angle Difference (top) and Hue Difference (bottom) – print results

Figure 4.2 indicates high hue shifts in the colors P485, P4975, POrange021, and PReflexBlue. The color P4975 showed highest hue angle difference (Δh_{ab}) but very low hue difference (Delta H or ΔH^*_{ab}). Hence these colors were selected for the visual study.

Sample identification

The visual evaluation study included six samples for each color. The first sample was a reproduction of the PantoneLIVE reference solid (100%). The remaining five samples were reproductions of different versions of spot color tints. The tint percentages were chosen on the basis of Delta H calculations from the previous study. The colorimetric values for the tint percentages which showed the highest Delta H across the tonal range were noted. Three samples were unique tint variants while the remaining two were random duplicates of the three tint samples (except P4975). The duplicate samples were included to check the accuracy of subjects in detecting the difference between samples and the probability of type I error. Type I error, in this case, refers to the condition where subjects report a difference between samples when the samples were actually identical.

The samples for the colors P485, POrange021 and PReflexBlue are explained below:

1. Reference Sample – The reference sample was a proof reproduction of the solid from the PantoneLIVE FWCP standards. Hence, the L*C*h^{o} value from the PantoneLIVE FWCP library was extracted for each color and reproduced on a proofing device.
2. Print Tint – The print tint sample reproduced the colorimetric measurement of the tint from printed sheets. The tone value with the highest Delta H in instrument-based analysis was used for this and the following samples.
3. PantoneLIVE tint – The PantoneLIVE tint sample was a proof reproduction of the PantoneLIVE L*C*h^{o} data at the same tone value as that used for the print.
4. Hue Corrected tint – The hue corrected sample used the L* and C* values from the printed tint sample. However, hue shift was corrected by using the h^{o} value of the printed solid reference.
5. Sample 5 was a duplicate of either of the samples 2,3 or 4. The duplicate sample was randomly chosen.

6. Sample 6 was a duplicate of either of the samples 2,3 or 4. The sample already duplicated as sample 5 was not picked as sample 6.

Figure 4.3 is an example of a set of samples.

Fig. 4.3. Six samples for POrange021 – FWCP

Unlike the other three colors, the six samples used for the P4975-FWCP study were different from each other. This color included samples from two different ink recipes to check how the observers responded to different ink recipes. The samples for P4975- FWCP are explained below:

1. Reference Sample – The reference sample was a proof reproduction of the solid from the PantoneLIVE FWCP standards. Hence, the L*C*h^{o} values for the solids were extracted from the PantoneLIVE FWCP library and reproduced on a proofing device.
2. PantoneLIVE tint – The PantoneLIVE tint sample was a proof reproduction of the PantoneLIVE L*C*h^{o} data at the same tone value as that used for the print.
3. Ink Recipe 1 Print Tint – The printed tint sample 1 reproduced the colorimetric measurement of the tint from printed sheets with the first ink recipe. The tone value with the highest Delta H in instrument-based analysis was used for this and the other tint samples.

4. Ink Recipe 2 Print Tint – The printed tint sample 2 reproduced the colorimetric measurement of the tint from printed sheets with the second ink recipe.
5. Hue Corrected tint recipe 1 – The hue corrected sample 1 used the L* and C* values from the printed tint sample 1 but corrected for the hue shift in print by using the h^o value of the solid reference printed with ink recipe 1.
6. Hue Corrected tint recipe 2 – The hue corrected sample 2 used the L* and C* values from the printed tint sample 2 but corrected for the hue shift in print by using the h^o value of the solid reference printed with ink recipe 2.

All the samples with their identification, description and standard are provided in table 4.1. The samples with suffix R represent the reference PantoneLIVE solid (100%) samples. The print, PantoneLIVE and hue-corrected tint samples are referred to with the suffix P, PL, and HC, respectively. The samples with suffix P2, PL2, HC2 were the duplicates of their respective samples. The suffix notation R1 and R2, specific to P4975, refers to the ink recipe 1 and ink recipe 2.

Table 4.1. List of samples with identification and description

Label	Identification	Description	L*	C*	h^o
AR	P485_R_PL	100% – P485-FWCP PantoneLIVE	50.44	77.46	37.52
A1	P485_P	60% - P485 FWCP – Print	63.12	43.28	25.73
A2	P485_PL	60% - P485 FWCP – PantoneLIVE	63.57	42.70	28.40
A3	P485_P2	60% - P485 FWCP – Print	63.12	43.28	25.73
A4	P485_PL2	60% - P485 FWCP – PantoneLIVE	63.57	42.70	28.40
A5	P485_HC	60% - P485 FWCP – Hue Corrected	63.12	43.28	36.39
BR	PRB_R_PL	100% – PReflexBlue – FWCP PantoneLIVE	24.04	69.35	295.79
B1	PRB_PL	40% - PReflexBlue FWCP – Print	67.24	16.80	286.57
B2	PRB_HC	40% - PreflexBlue FWCP – PantoneLIVE	64.39	21.58	294.3
B3	PRB_P	40% - PReflexBlue FWCP – Print	64.39	21.58	277.91
B4	PRB_PL2	40% - PReflexBlue FWCP – PantoneLIVE	67.24	16.80	286.57
B5	PRB_HC2	40% - PReflexBlue FWCP – Hue Corrected	64.39	21.58	294.3

CR	POR021_R_PL	100% – POrange021 – FWCP PantoneLIVE	62.70	93.62	51.98
C1	POR021_PL	50% - POrange021 FWCP – Print	74.66	41.56	37.57
C2	POR021_P	45% - POrange021 FWCP – PantoneLIVE	77.95	38.89	42.80
C3	POR021_PL2	50% - POrange021 FWCP – Print	74.66	41.56	37.57
C4	POR021_P2	45% - POrange021 FWCP – PantoneLIVE	77.95	38.89	42.80
C5	POR021_HC	45% - POrange021 FWCP – Hue Corrected	77.95	38.89	54.32
DR	P4975_R_PL	100% – P4975-FWCP PantoneLIVE	20.10	7.68	24.53
D1	P4975_P_R2	60% - P4975 FWCP – Ink Recipe 2 – Print	53.81	1.37	51.18
D2	P4975_HC_R2	60% - P4975 FWCP – Ink Recipe 2 – Hue Corrected	53.81	1.37	25.07
D3	P4975_HC_R1	60% - P4975 FWCP – Ink Recipe 1 – Hue Corrected	47.1	5.67	26.29
D4	P4975_PL	60% - P4975 FWCP – PantoneLIVE	51.45	2.08	41.68
D5	P4975_P_R1	60% - P4975 FWCP – Ink Recipe 1 – Hue Corrected	55.45	4.00	13.51

Sample preparation

All the samples were printed on an Epson (Epson America, Inc., Long Beach, USA) Stylus Pro 7900 using Esko (Miamisburg, USA) Color Engine Pilot. A custom ink-book was created in Esko Color Engine Pilot. A custom spot color was defined for each of the samples using their respective the L*C*h^o values. The spot colors were proofed on the device using a standard International Color Consortium (ICC) profile – GRACoL 2013. The printed results were measured using a Xrite (Xrite, Grand Rapids, USA) eXact spectrophotometer and Delta E2000 was calculated between the input and the print results. The results with standard ICC profile showed Delta E2000 of magnitude up to 4.5. In order to improve the accuracy of proofed spot colors, the refine ink feature was used in the Esko Color Pilot. The resultant Delta E2000 values between the proofed samples and their respective standards were under 1.21. To prepare the samples for pairwise comparison, two samples were adhered next to each other on a paperboard substrate. The paper white in the proofed samples was adjusted to simulate the white point of the paperboard to avoid background influence. This adjustment was performed in Esko Color Pilot. The color difference between the samples was measured using the Delta E2000 and Delta E1976 metrics. The hue difference between the proofed samples was quantified using hue angle difference (Δh_{ab}) and Delta H (ΔH_{ab}) metrics.

The visual evaluation was conducted under standard lighting conditions (CIE D50) in a light booth. The observers were asked to keep the samples flat in the booth before observing. A training set was also included for untrained observers. The training set included six samples for the color Cyan – 100%, 90%, 80%, 70%, 60% and 50%. This helped the untrained visual observers develop an understanding of differences between solids (100%) and different tint percentages for the same color. The participants were asked to visually judge four sets of samples (P485 – FWCP, POrange021 – FWCP, PReflexBlue – FWCP and P4975 – FWCP) and answer two questions per sample set. The first question was based on pairwise comparison of the five tint samples with each other. The observers were asked to look at one pair of samples at a time and report if they saw a visual difference between the samples. If they reported a difference, they were asked to assign a score to the level of difference on the following scale:
0 – no difference
1 – very low visual difference
2 – low visual difference
3 – medium visual difference
4 – high visual difference
5 – very high difference
The observers were also asked to imagine the two samples as two food product packages kept on retail shelf next to each other. For the sample pairs in which they reported a visual difference, they were asked if the difference was enough to cause a change in their intent of purchase (independent of other influences or biases). This was repeated for all ten pairwise combinations of the five tint samples. For the second question, the observers were instructed to use the solid sample as the reference and asked to rank the five tint samples in order of increasing visual hue difference from the reference sample. This process was conducted for the four sets of samples.

Figure 4.4 shows these comparisons. Pairwise comparison is shown on the left and ranking on the right.

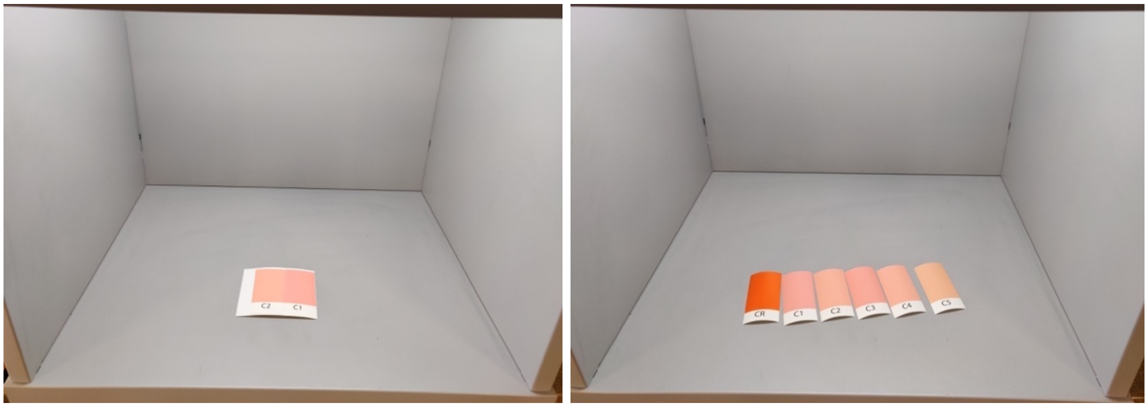


Fig. 4.4. Visual study setup – Pairwise comparison (left) and ranking (right) samples

Thirty observers participated in this study. The mean and median age of the observer group were 32.97 and 29.5 years, respectively (one observer's age was set to zero due to missing field). The mean and median color experience of the observer group was 8.2 and 0.75 years, respectively. The group comprised of equal number of males and females i.e. 15 each. Statistical analysis was conducted in Statistical Analysis System (SAS) and RStudio. The boxplots and histograms of the ranking data were generated in Minitab Express.

Experimental design

The input variables and their respective levels, the output variables and the metrics are summarized in table 4.2. It should be noted that while three unique tint variant samples were used for the colors P485, POrange021, PReflexBlue, five unique samples were used for the color P4975 due to the two ink recipes.

Table 4.2. Summary of experimental design input and output variables

Input Variables	**Levels**	**Output Variables**	**Metrics**
Colors	Four colors: P485 – FWCP POrange021 – FWCP	Visual perceptible difference	Rated difference score – Scale of 0 to 5.

	PReflexBlue – FWCP P4975 – FWCP		Pairs showing mean above 1 had perceptible difference
Ink Recipe	2 ink recipes with different base pigments – Only for P4975-FWCP	Visual difference to cause change of purchase intent	Probability of change of intent to purchase greater than 0.5
Tone Value or tint percentage	1 level per color - SCTV corresponding to the maximum Del H in print (rounded off to nearest multiple of 5): P485 – 60% POrange021 – 45% PReflexBlue – 40% P4975 – 60%	Visual ranking of spot color tint variants	Mean Ranking of samples
Spot Color tint versions	Three versions for P485, PReflexBlue, POrange021: • Print (P) • Digital – PantoneLIVE (PL) • Hue Corrected Print (HC) Five versions for P4975: • Digital - PantoneLIVE (PL) • Print Recipe 1 (P_R1) • Print Recipe 2 (P_R2) • Hue Corrected Print 1 (HC_R1) • Hue Corrected Print 2 (HC_R2)		

The SCTV corresponding to maximum hue shift in print from the previous study were selected for this study. It should be noted that the SCTV values below 15% were not considered as anomalous results were observed at low SCTV values. This was especially true for P4975 due to the low chromaticity of the color.

Results and discussion

Reporting for identical samples

The percentage of people that correctly reported no difference between identical samples was calculated and presented in the figure below. The suffix P, PL, HC denote the print, PantoneLIVE and hue-corrected samples. The samples with suffix P2, PL2, HC2 are the duplicates of their respective samples.

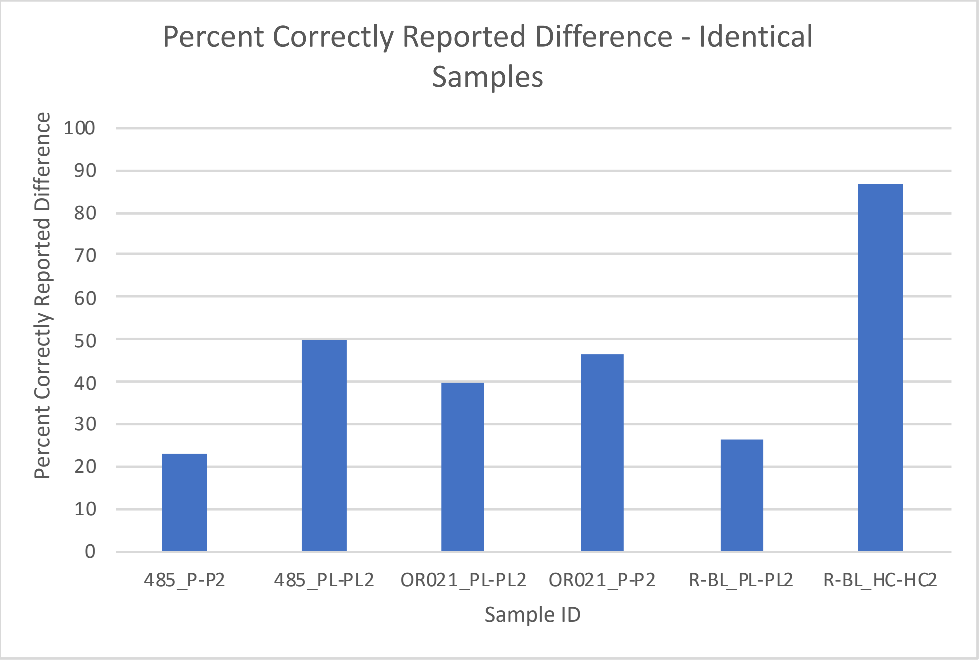


Fig. 4.5. Percentage of people correctly reporting no difference between identical samples

As seen in figure 4.5, less than 50% of the subjects correctly identified identical samples (with the exception of Reflex Blue – HC–HC2 pair). In terms of the number of people reporting a difference, inconsistent results were observed for the sample pairs that had a measured Delta E2000 of less than 1.2. The scatterplot and the low coefficient of determination ($R^2 < 25\%$) from linear regression fit (figure 4.6) supports this inference. For sample pairs with Delta E2000 more than 1.2, more than 90% participants reported a difference between the samples.

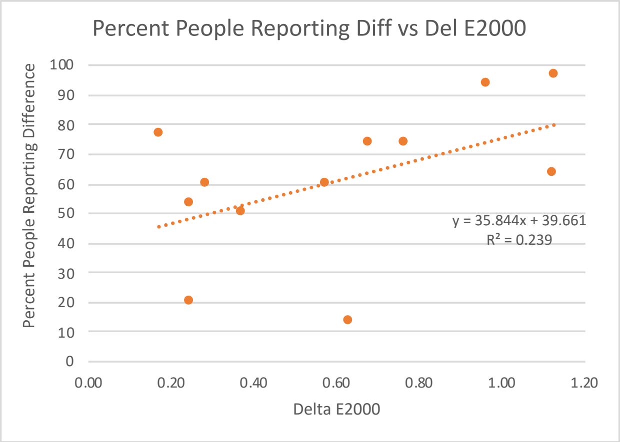


Fig. 4.6. Percentage of people reporting difference between samples versus Delta E2000 between samples

The data collected from the visual analyses were ordinal in nature. Hence, normality could not be assumed, and non-parametric statistical tests were used for hypothesis testing. The rated difference score between the pairwise samples was used to establish if the visual difference was consistently perceptible by the observers or not. Duplicate samples were removed from this statistical analysis to keep the sample size consistent between samples. The color-wise analysis for perceptible and acceptable differences is presented below.

Perceptible difference

The rated difference score data were ordinal with a scale of zero to five, where zero meant no difference and five represented very high visual difference. A sample pair was said to have perceptible difference if the mean rated difference score was greater than 1. The threshold was set to 1 as it was the minimum visual difference score available to the observers on the scale. Du Prel, Röhrig, Hommel, & Blettner (2010) while citing Harms (1998), stated that Wilcoxon signed-rank test can be used to conduct hypothesis testing on ordinal data from paired samples. A signed rank test was conducted using the proc Univariate procedure (in the SAS Statistical analysis package). This procedure tested for the location of mean to be equal to zero. Hence, to prepare the data for statistical hypothesis testing, the entire rated difference score data were transformed by subtracting one from the scores. This transformation meant that while the statistical procedure was testing for mean to be equal to zero, the practical interpretation was whether the mean rated score was greater than one or not.

Null Hypothesis: Mean rated difference score was equal to or lesser 1.

Alternate Hypothesis: Mean rated difference score was greater than 1.

Statistical Hypothesis:

Null: $$\mu_{RD-1} = 0 \qquad \text{Eq. 4.1}$$

Alternate: $$\mu_{RD-1} \neq 0 \qquad \text{Eq. 4.2}$$

Since the signed rank test calculated the p-values for two-tail test ($\mu_{RD-1} = 0$), the one-tail p-value for (upper tail) was obtained by dividing the p-value by 2. In case the test statistic was negative, the p-value for upper tail was obtained by subtracting the one tail p-value from 1 (UCLA: Statistical Consulting Group, n.d.). The significance level (α) was set at 0.05. The p-value for the signed rank test showed the mean to be statistically significantly different from 1.

Table 4.3. Statistical hypothesis testing results – Signed Rank test on rated difference score data

	Location	Variability	Test - Signed Rank	p-value
Sample pair	Mean	Std. Devn.	Test Statistic (S)	Pr >= |S|
P485-PL_P2	0.83	0.87	97.5	<.0001
P485_PL – HC	2.93	0.87	232.5	<.0001
P485_P2 – HC	3.10	0.96	232.5	<.0001
POrange021_PL – P2	1.93	1.01	203	<.0001
POrange021_PL2 – HC	3.47	0.73	232.5	<.0001
POrange021_P2 – HC	2.40	1.04	232.5	<.0001
PReflexBlue – PL – HC	2.83	0.91	232.5	<.0001
PReflexBlue – PL – P	2.37	1.03	217.5	<.0001
PReflexBlue – P – HC2	3.00	0.95	232.5	<.0001
P4975_P_R2 – HC_R2	-0.37	0.56	-38.5	0.9983
P4975_P_R2 – HC_R1	3.20	1.13	231.5	<.0001

P4975_P_R2 – PL	0.90	0.99	98	<.0001
P4975_P_R2 – P_R1	3.20	1.10	231.5	<.0001
P4975_HC_R2 – HC_R1	3.03	1.13	231.5	<.0001
P4975_HC_R2 – PL	0.73	1.05	79	0.0003
P4975_HC_R2 – P_R1	2.87	1.20	230.5	<.0001
P4975_HC_R1 – PL	2.90	1.06	231.5	<.0001
P4975_HC_R1 – P_R1	-0.7	0.79	-137.5	>0.9999
P4975_PL – P_R1	2.33	1.24	201.5	<.0001

As seen in table 4.3, the mean and the test statistics for the pairs P4975_P_R2 – HC_R2 and P4975_HC_R1 – P_R1 were negative. The p-values for these pairs suggested that the rated difference was not statistically significantly greater than 1. Hence, the observers did not report a consistent perceptible visual difference for these sample pairs. It is worth noting that these were the only two samples out of the samples listed in table 4.3, where less than 90% people reported a difference between the samples. The mean and test statistics for all the rest of the tested pairs were positive. Moreover, the p-values were less than 0.05. This indicated that the mean rated difference score was statistically significantly higher than 1 for rest of the tested samples. More than 90%of the subjects reported a difference between these samples. Hence, the observers consistently reported a perceivable difference between these sample pairs.

Acceptable difference

The acceptability of visual difference was determined by the change of intent response from the observers. The Yes/No data were converted to 0(No) and 1(Yes). A binomial hypothesis test was conducted to determine if the mean was statistically significantly different from 0.5. The hypothesis was designed to check if more than 50% of the observers indicated a change in their intent to purchase the product based on the color difference between the samples shown to them in a pair.

Null Hypothesis: Mean change of intent is equal to or less than 0.5

$\mu_{CI} \leq 0.5$Alternate

Statistical hypothesis:

Null: $\mu_{CI} \leq 0.5$ Eq. 4.3

Alternate: $\mu_{CI} > 0.5$ Eq. 4.4

Since the hypothesis test procedure in SAS tested for mean to be significantly different from 0.5, the one-sided test reported significant p-values even for cases where the mean was statistically significantly lower than 0.5. The p-value for such cases was corrected by subtracting it from 1 to get the probability of the upper region (UCLA: Statistical Consulting Group, n.d.).

Table 4.4. Statistical hypothesis testing results – Binomial test on change of intent to purchase

Sample pair	Change_Intent	Frequency	Percent	One-sided Pr >= P
485_PL-P2	1	4	13.33	>0.9999
	0	26	86.67	
P485_PL – HC	1	20	66.67	0.0494
	0	10	33.33	
P485_P2 – HC	1	22	73.33	0.0081
	0	8	26.67	
POrange021_PL – P2	1	17	56.67	0.2923
	0	13	43.33	
POrange021_PL2 – HC	1	26	86.67	<.0001
	0	4	13.33	
POrange021_P2 – HC	1	20	66.67	0.0494
	0	10	33.33	
PReflexBlue – PL – HC	1	20	66.67	0.0494
	0	10	33.33	
PReflexBlue – PL – P	1	17	56.67	0.2923
	0	13	43.33	
PReflexBlue – P – HC2	1	21	70	0.0214
	0	9	30	
P4975_P_R2 – HC_R2	1	1	3.33	>0.9999
	0	29	96.67	
P4975_P_R2 – HC_R1	1	25	83.33	0.0002
	0	5	16.67	

P4975_P_R2 – PL	1	6	20	0.9993
	0	24	80	
P4975_P_R2 – P_R1	1	25	83.33	0.0002
	0	5	16.67	
P4975_HC_R2 – HC_R1	1	23	76.67	0.0026
	0	7	23.33	
P4975_HC_R2 – PL	1	3	10	>0.9999
	0	27	90	
P4975_HC_R2 – P_R1	1	22	73.33	0.0081
	0	8	26.67	
P4975_HC_R1 – PL	1	24	80	0.0007
	0	6	20	
P4975_HC_R1 – P_R1	1	1	3.33	>0.9999
	0	29	96.67	
P4975_PL – P_R1	1	20	66.67	0.0494
	0	10	33.33	

The statistical hypothesis test results (table 4.4) suggested a statistically insignificant probability of at least 50% observers changing their intent of purchase for some of the tested sample pairs. These pairs were 485_PL-P2, POrange021_PL – P2, PReflexBlue – PL – P, P4975_P_R2 – HC_R2, P4975_HC_R2 – PL, and P4975_HC_R1 – P_R1. These have been highlighted in the table. The p-value of less than 0.05 for the rest of the color pairs suggested that there was a statistically significant probability of at least 50% observers changing their intent to purchase the product based on the color difference between the paired samples.

Correlation between visual difference score and acceptability

A logistic regression procedure was run with rated difference score as the predictor variable and the probability of change of intent to purchase as the response variable. The procedure in SAS results in equations 4.5 and 4.6.

$$\ln\frac{P(C)}{1-P(C)} = \beta_0 + \beta_1 * RD \qquad \text{Eq. 4.5}$$

or

$$\ln\frac{P(C)}{1-P(C)} = \beta_0 + \beta_1 * RD \qquad \text{Eq. 4.6}$$

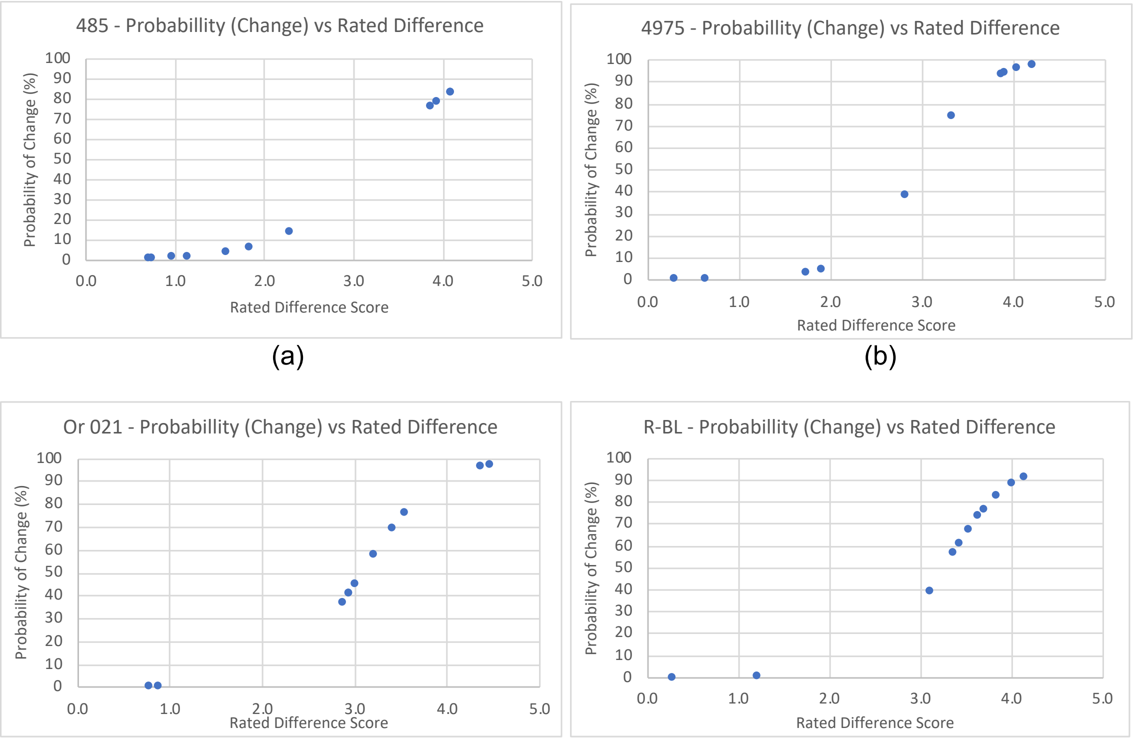
where, P(C) = Probability of change of intent to purchase the product

RD is the rated difference score for a given pair of samples

β_0 is the intercept term from the regression procedure

β_1 is the coefficient of rated difference score (RD) from the regression procedure.

The probability of change was calculated and plotted against the rated difference score. The scatterplots showed a sigmoidal curve shaped correlation between rated difference score and probability of change of intent to purchase. This is shown in figure 4.7. The scatterplots clearly show an increase in the probability of change of purchase intent as the rated difference score increased for the tested sample pairs.



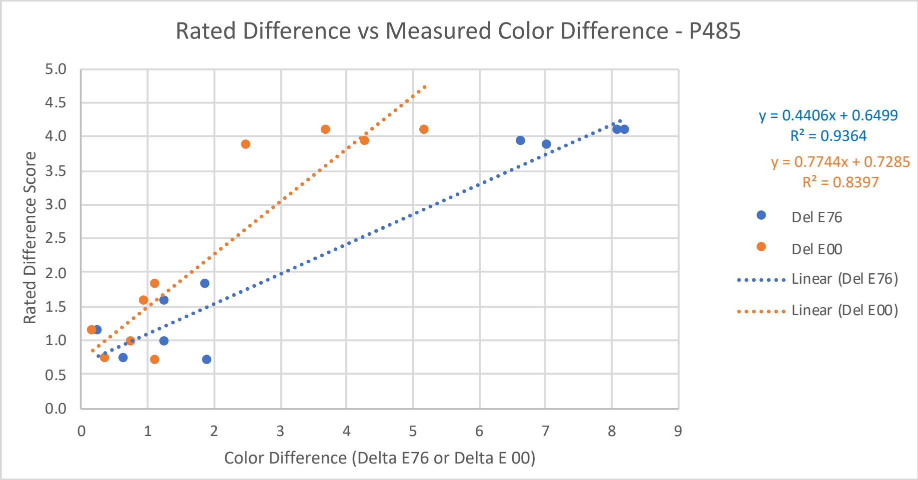
(a) (b)

(c) (d)

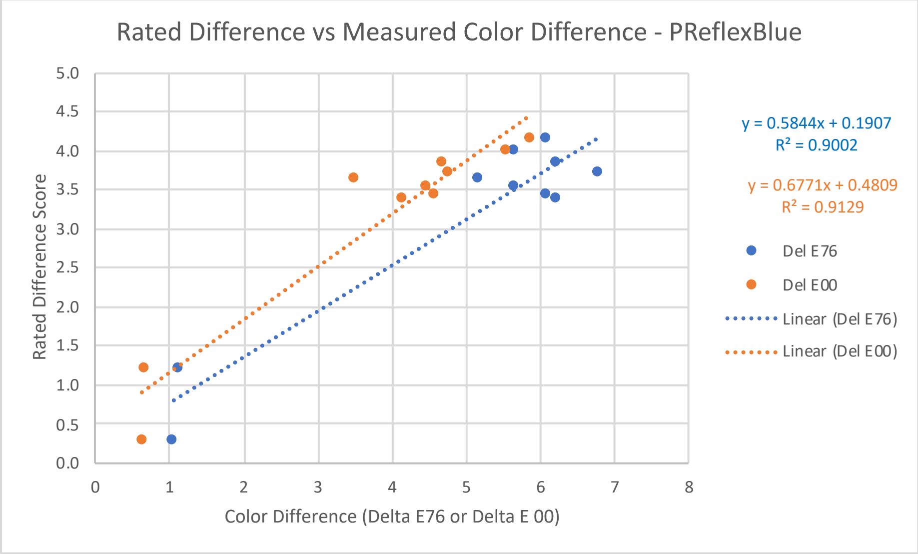
Fig. 4.7. Scatterplots of probability of change of intent to purchase versus rated difference scores

Correlation between visual and instrument-based results

The overall color difference (Delta E2000 and Delta E1976) and the hue difference (hue angle difference, and Delta H) between the samples were measured using a spectrophotometer. These differences were plotted on a scatterplot against the rated difference score reported by the observers. All the samples were included in this analysis and the duplicate samples were not removed in order to preserve the sample size of the original data. This is shown in figure 4.8.



a)



b)

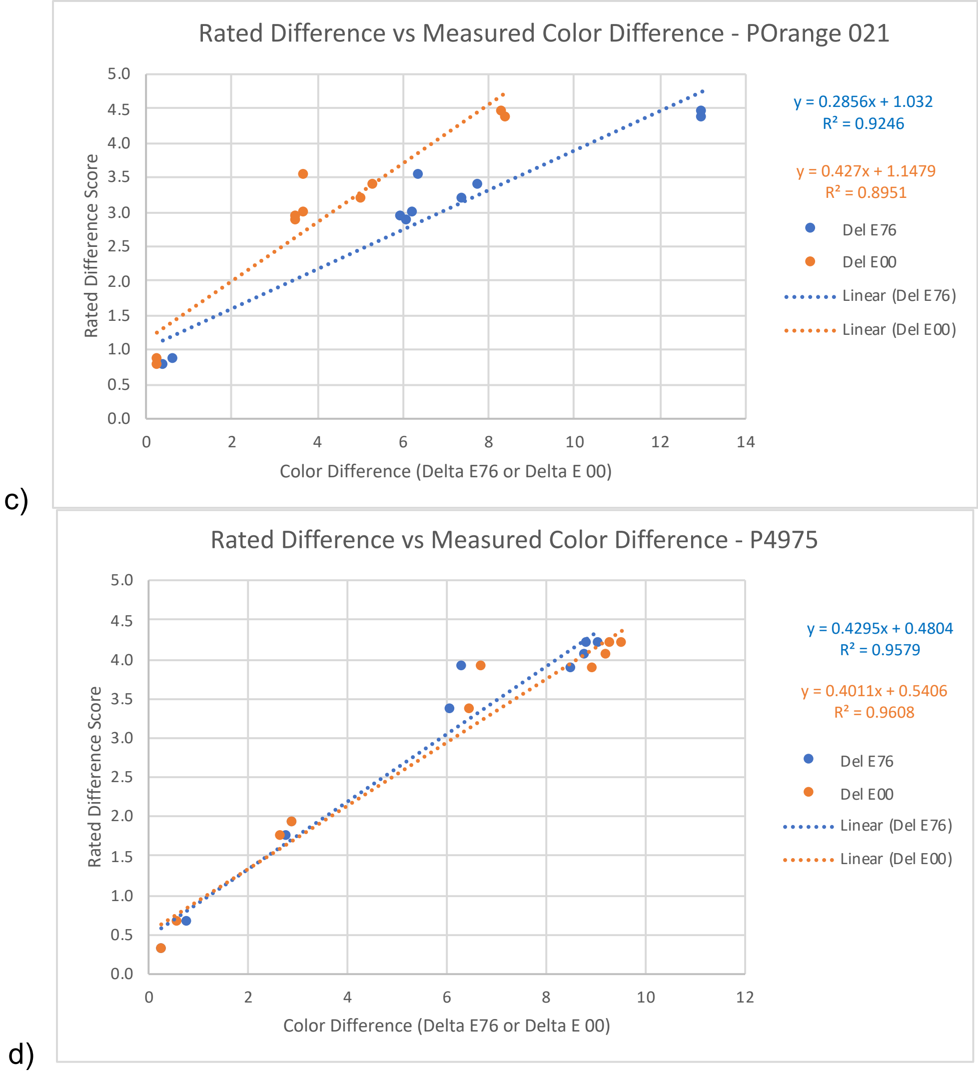
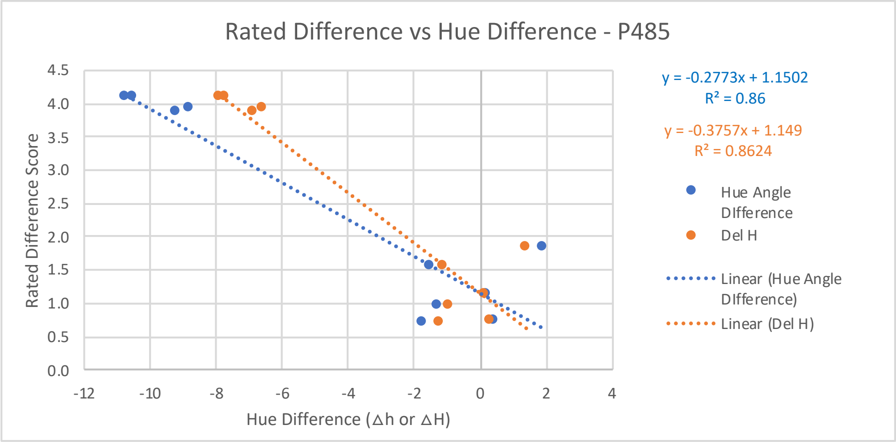
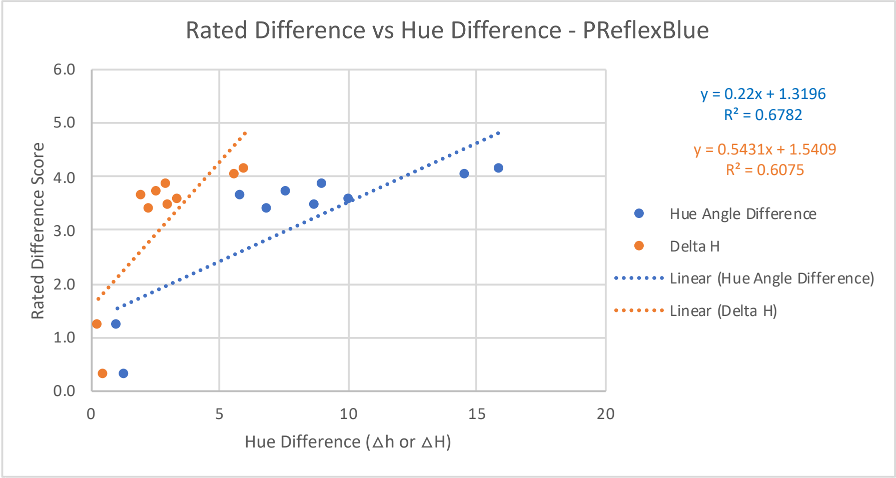


Fig. 4.8. Scatterplots of Rated difference score versus measured color difference – a) P485, b) PReflexBlue c) POrange021 d) P4975. Linear fit equations and coefficients of determination added on plots. Blue represents Delta E1976 data and orange represents Delta E2000 data.

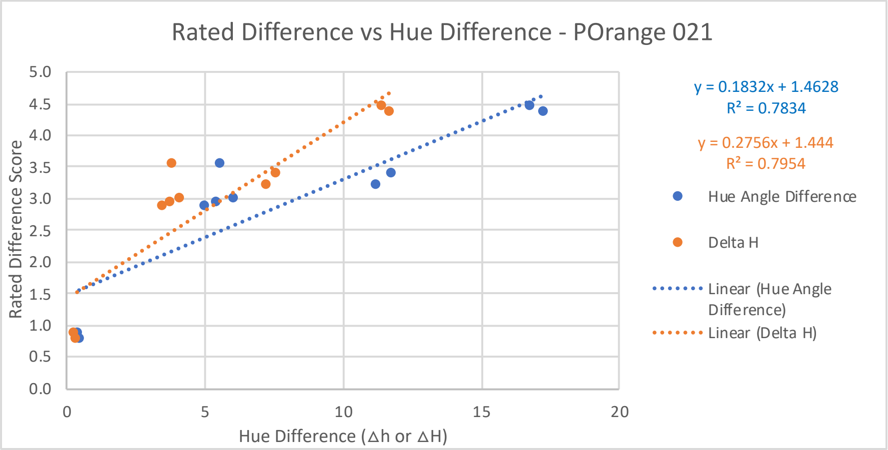
The scatterplots showed a linear correlation between the visually rated difference score and the color difference measured using spectrophotometers. The visually rated difference score increased as the measured color difference increased. The high coefficient of determination (greater than 80% for all cases) suggested a good fit of the data to the linear regression line.


Rated Difference vs Hue Difference - P485
Rated Difference Score
Hue Difference (∆h or ∆H)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-12
-10
-8
-6
-4
-2
0
2
4
y = -0.2773x + 1.1502
R² = 0.86
y = -0.3757x + 1.149
R² = 0.8624
Hue Angle DIfference
Del H
Linear (Hue Angle DIfference)
Linear (Del H)

a)


Rated Difference vs Hue Difference - PReflexBlue
Rated Difference Score
Hue Difference (∆h or ∆H)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
5
10
15
20
y = 0.22x + 1.3196
R² = 0.6782
y = 0.5431x + 1.5409
R² = 0.6075
Hue Angle Difference
Delta H
Linear (Hue Angle Difference)
Linear (Delta H)

b)


Rated Difference vs Hue Difference - POrange 021
Rated Difference Score
Hue Difference (∆h or ∆H)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
y = 0.1832x + 1.4628
R² = 0.7834
y = 0.2756x + 1.444
R² = 0.7954
Hue Angle Difference
Delta H
Linear (Hue Angle Difference)
Linear (Delta H)

c)

d)

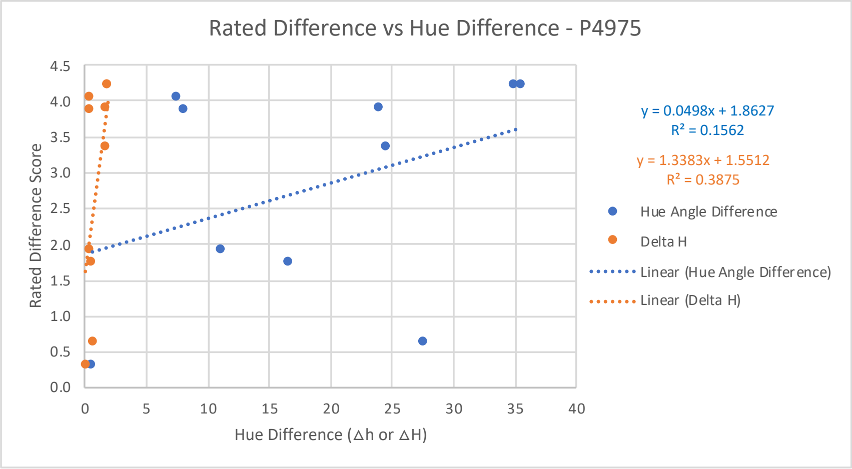


Fig. 4.9. Scatterplots of Rated difference score versus measured hue difference – a) P485, b) PReflexBlue c) POrange021 d) P4975. Linear fit equations and coefficients of determination (R^2) added on plots. Blue represents Delta E1976 data and orange represents Delta E2000 data.

The visually rated difference score was generally observed to increase with hue difference (figure 4.9). The coefficient of determination (R^2) between the visually rated difference score and the hue difference was high (>70%) for P485 and POrange021. The R^2 was above 60% for PReflexBlue while significantly lower for P4975. The low R^2 for P4975 can be attributed to the low chromaticity of the color and its reproduced samples. Limitations in hue angle calculations for transparent object colors at low tristimulus ratios have been reported in the past (McLaren, 1980). CIE/ISO11664-4 (2019) also stated that anomalous hue angles can be obtained if linear functions of tristimulus ratios are used when calculating a*, b* values, especially near the spectrum locus or purple line (CIE/ISO, 2019).

The correlation of visually rated difference score with measured color difference (both Delta E1976 and Delta E2000) showed higher R^2 than with hue difference. This was expected as color difference accounts for lightness and chromaticity differences in addition to the hue difference. The results show that hue angle and hue shift metrics should not be relied upon in case of low chromaticity colors such as P4975.

Ranking study results

The ranking data were collected from the observers in response to the second question. This question asked them to rank the five tint samples closest (rank 1) to farthest (rank 5) in terms of hue appearance from the reference solid sample. The histograms and boxplots for the ranking data were created in MinitabExpress v 1.5.1 software.

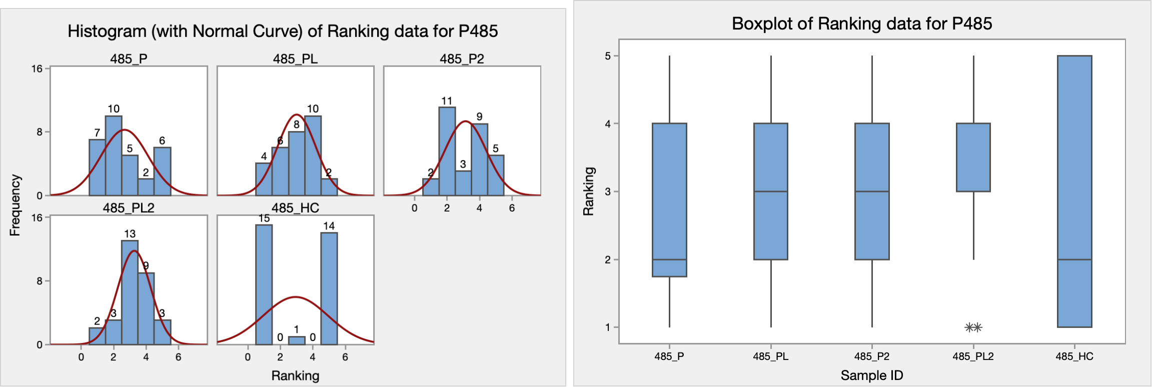


Fig. 4.10. Histograms and boxplots of ranking data for the five samples of P485

Figure 4.10 presents the histogram and boxplots of the ranking data for P485. The histograms for the samples of P485 show spread out distributions for all samples except the hue-corrected sample. The histograms also show which rank was chosen by the greatest number of people for each sample. The distribution for hue-corrected sample was bimodal. An almost equal number of people ranked the hue-corrected first and last. The boxplots show the middle 50% of the data as inter-quartile range (IQR) represented by the boxes. The middle line inside the box represents the median and the asterisks represent outlier observations. The spread, as seen by the height of the boxes, was observed to be highest for the hue-corrected sample.

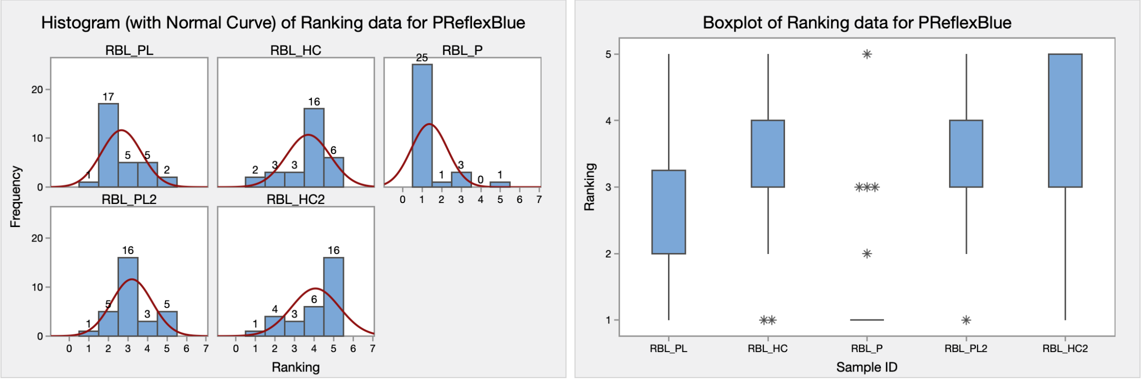


Fig. 4.11. Histograms and boxplots of ranking data for the five samples of PReflexBlue

Figure 4.11 presents the histogram and boxplots of the ranking data for PReflexBlue. The histogram and boxplot directly indicate that a majority of observers chose the print sample as the one closest to the reference sample. The PantoneLIVE sample was most often ranked second, followed by the duplicate PantoneLIVE sample at rank three. The hue-corrected sample and its duplicate were ranked fourth and fifth by more than half of the observers. A clear distinction between the median of samples was seen in the boxplot. The median ranks for PL and PL2 samples were two and three. The HC and HC2 sample median ranks were four and five.

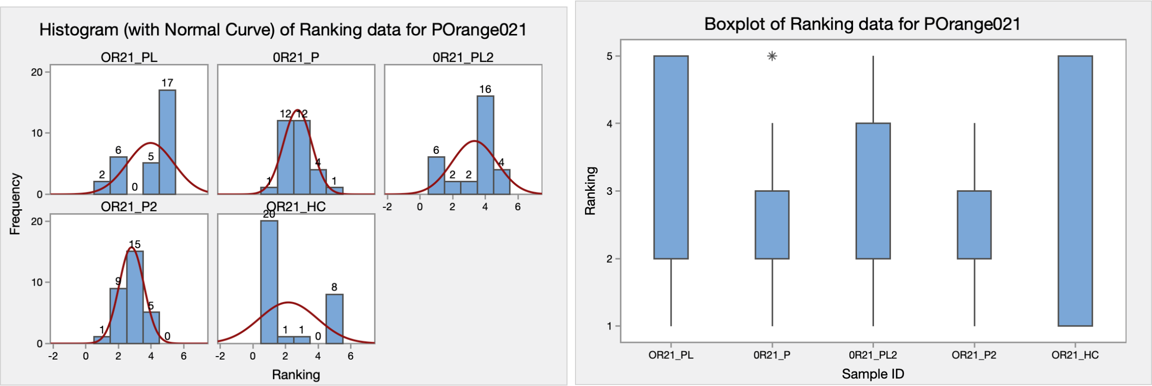


Fig. 4.12. Histograms and boxplots of ranking data for the five samples of POrange021

Figure 4.12 presents the histogram and boxplots of the ranking data for POrange021. The hue corrected sample was ranked first by most of the observers. The PL and PL2 samples were most commonly ranked four and five. The P and P2 samples were ranked second and third by the observers. The boxplots showed the highest spread for the PL and HC samples. The lowest spread was observed for P and P2 samples. The median rank for the HC sample was one. The median ranks for the PL and PL2 samples were four and five. The median rank for P and P2 was three.

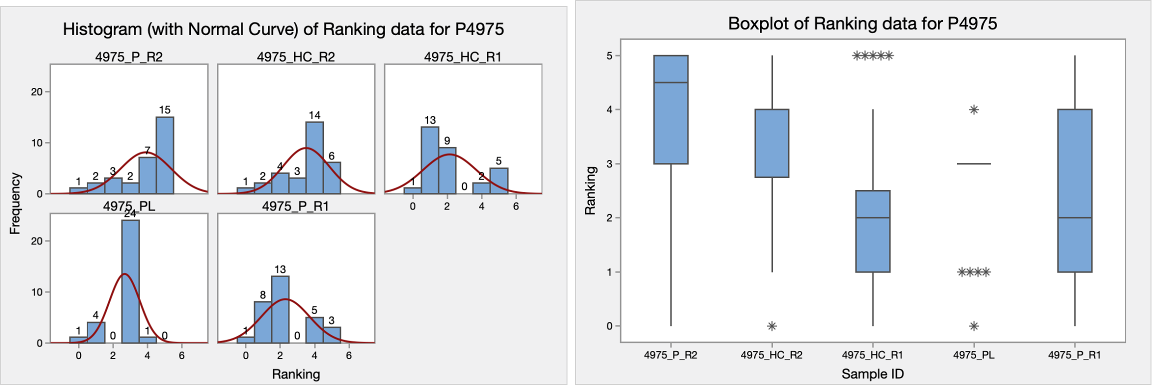


Fig. 4.13. Histograms and boxplots of ranking data for the five samples of P4975

Figure 4.13 presents the histogram and boxplots of the ranking data for P4975. The hue-corrected and print samples for print recipe 1 were most commonly ranked first and second, respectively. The PantoneLIVE sample was ranked third by most of the observers. The print and hue-corrected samples for print recipe 2 were most commonly ranked fourth and fifth. The median ranks for print and hue-corrected samples with print recipe 1 were 4.5 and 4. The IQR spread was negligible for the PL sample while the highest spread was observed for the print sample with ink recipe 1.

In order to determine if the ranking for the five samples of each color was statistically significantly different, a Friedman's rank sum test procedure was used on the data. The confidence level was set at 95% ($\alpha = 0.05$). In cases where Friedman's rank sum test indicated a difference between the samples, a Wilcoxon signed-rank test was used on individual sample pairs as a post-hoc test. Bonferroni correction was also applied, and the adjusted p-value was used to draw inferences.

Hypothesis tested:

Null: The rank for all five samples of a color are not different.

Alternate: The rank for at least one sample is different from the rank of at least one other samples.

Table 4.5. Friedman's rank sum test results

Color	Friedman's Chi-Squared Test Statistic	p-value
P485	2.4533	0.6530
PReflexBlue	53.36	0.0000
POrange021	22.213	0.0002
P4975	29.324	0.0000

The results of the hypothesis test on ranking data is presented in table 4.5. The test results showed that the ranking for the five samples of P485 were not statistically significantly different. The test also showed that the ranking for at least one of the five samples for the colors PReflexBlue, POrange021 and P4975 was statistically significantly different (p-value < 0.05). The Wilcoxon signed-rank test was conducted on individual sample pairs to detect statistically significant differences in ranking of the five samples for PReflexBlue, POrange021 and P4975. The Wilcoxon signed-rank test was not conducted for P485 as the Friedman test did not indicate statistically significant difference between the sample rankings.

Table 4.6. Wilcoxon signed-rank test results on ranking data of PReflexBlue, POrange021, and P4975

Color	Sample Pair	p-value	Color	Sample Pair	p-value	Color	Sample Pair	p-value
PRB	PL-HC	0.2290	POr021	PL-P	0.0266	P4975	P_R2-HC_R2	0.6407
PRB	PL-P	0.0006	POr021	PL-PL2	0.0098	P4975	P_R2-HC_R1	0.0236
PRB	PL-P2	0.0790	POr021	PL-P2	0.0344	P4975	P_R2-PL	0.0014
PRB	PL-HC2	0.0139	POr021	PL-HC	0.0225	P4975	P_R2-P_R1	0.0144
PRB	HC-P	0.0004	POr021	P-PL2	1.8899	P4975	HC_R2-HC_R1	0.0628
PRB	HC-PL2	1.5758	POr021	P-P2	5.214	P4975	HC_R2-PL	0.019
PRB	HC-HC2	0.8554	POr021	P-HC	0.79	P4975	HC_R2-P_R1	0.1804

PRB	P-PL2	0.0002	POr021	PL2-P2	1.9382	P4975	HC_R1-PL	1.378
PRB	P-HC2	0.0001	POr021	PL2-HC	2.453	P4975	HC_R1-P_R1	4.8711
PRB	PL2-HC2	0.5761	POr021	P2-HC	0.3633	P4975	PL-P_R1	2.4653

Table 4.6 presents the results of Wilcoxon signed-rank test with Bonferroni correction on the ranking data of the tested samples. The identical samples have been highlighted in the table. The test showed non-statistically significant difference between identical samples for both PReflexBlue and POrange021 (except the PantoneLIVE identical samples of POrange021). This exception was probably due to majority of people distinctly ranking the two samples fourth and fifth (as can be seen in image 4.12). The ranking for the HC-PL samples of PReflexBlue were not statistically significantly different. The ranking for P-HC samples of POrange021 were not statistically significantly different. This means that the observers did not give statistically distinct rankings to the print and hue-corrected samples of POrange021. The ranking of P-PL and PL-HC samples of POrange021 were observed to be statistically significantly different on at least one occasion. The only samples of P4975 that were statistically significantly different were P_R2-HC_R1, P_R2-PL, P_R2-P_R1, and HC_R2-PL. This suggested that the ranking of print with recipe 1 was statistically significantly different from that of print with recipe 1. Moreover, the ranking of PL sample was found to be statistically significantly different from the ranking of print with recipe 2 and HC with recipe 2. The ranking for rest of the samples of 4975 was not found to be statistically significantly different. This suggested that the observers did not rank the print and hue-corrected samples distinctly differently for either of the print recipes.

Table 4.7. Mean ranking and standard deviation for each unique spot color tint sample

Sample	Mean Rank	Std. Devn.	Sample	Mean Rank	Std. Devn.
P485_P	2.667	1.446	P4975_P_R2	3.900	1.470
P485_PL	3.000	1.174	P4975_HC_R2	3.500	1.333
P485_HC	2.933	1.999	P4975_HC_R1	2.133	1.548
PR-Bl_P	1.367	0.928	P4975_PL	2.667	0.884

PR-Bl_PL	2.667	1.028	P4975_P_R1	2.300	1.393
PR-Bl_HC	3.7	1.119			
POr021_P	2.733	0.868			
POr021_PL	3.333	1.373			
POr021_HC	2.167	1.783			

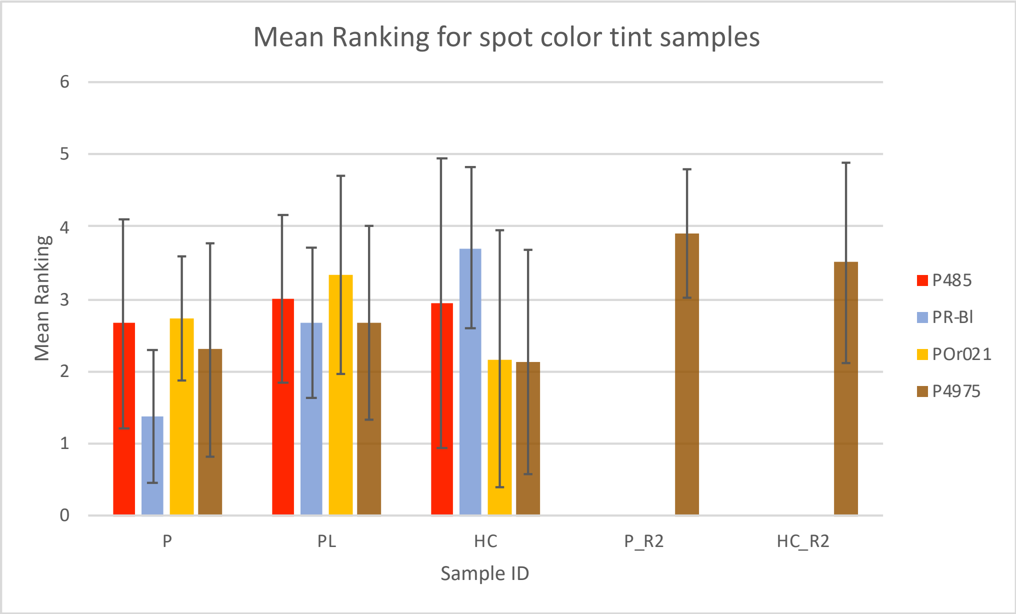


Fig. 4.14. Mean ranking of Print, PantoneLIVE and Hue-Corrected samples

Figure 4.14 shows a visual comparison of mean ranking for print, PantoneLIVE and hue-corrected samples of each color. The mean rank and standard deviation for all the evaluated samples (excluding duplicates) are listed in table 4.7. A lower mean rank suggested that the observers ranked the sample closer to the reference. The lowest mean rank for P485 was observed for the print sample, followed by hue corrected and lastly the PantoneLIVE sample. However, the histogram of ranking data each sample of P485 showed a higher number of people (half the number of observers) ranking the hue-corrected sample as first. It should also be noted that the statistical hypothesis test did not show a statistically significant difference between the samples for P485. This can be seen in the figure 4.14 as the mean rankings are fairly close to each other. The lowest mean ranking for PReflexBlue was recorded for the print sample, followed by PantoneLIVE and hue corrected samples (figure 4.14). Hence, the observers suggested that the printed sample appeared as a more natural tint of the reference solid sample. This inference was in-line with the histogram and box-plot data presented for PReflexBlue (figure 4.11). The lowest mean ranking for the color POrange021 was recorded for the hue-corrected sample, followed by the print and PantoneLIVE samples (figure 4.14). This observation was consistent with the number of people arranging samples in that order and their median ranking score. However, the Wilcoxon signed-rank test procedure did not show a statistically significant difference between the rankings for print and hue corrected samples of POrange021 (table 4.6). The observers also ranked the hue corrected sample (with ink recipe 1) for P4975 closest to the reference sample. The observers ranked the print and hue corrected samples of ink recipe 2 farthest from the reference sample. However, the Wilcoxon signed-rank test suggested that the observers did not rank the print and hue-corrected samples statistically significantly different for either of the print recipes (table 4.6). The print and hue-corrected samples from ink recipe 1 were ranked similar to the PantoneLIVE samples. This was confirmed by the Wilcoxon signed-rank test showing a statistically insignificant difference between these samples (table 4.6).

The data suggested different preferences for different colors. While the observers ranked the hue-corrected samples closer to the reference for the colors POrange021 and P4975, the PReflexBlue print sample was judged closer than the hue-corrected sample. However, the distinction in rankings between the print and hue-corrected tint samples was significant only for PReflexBlue. The difference in personal preference of different people affected the statistical significance of the difference between ranking for different tint samples. However, the number of people ranking one sample over another did show distinct patterns and should be investigated further.

Conclusion

A visual analysis study was conducted to evaluate the hue shifts in spot color tints of four spot colors in flexographic package printing on paperboard. These spot colors were P485, PReflexBlue, POrange021, P4975. The study was designed with three variants of spot color tints for the colors P485, PReflexBlue and POrange021 – print, PantoneLIVE and hue-corrected. The tint samples for P4975 included print and hue-corrected samples from a second ink recipe in addition to these three samples. A visually rated difference score was assigned by the observers to each of the sample pairs to quantify the extent of hue difference between the samples. The study showed consistently perceivable hue differences between all unique color pairs, except the print and hue-corrected samples for recipe 1 and 2 of the color P4975. This suggested that the hue shift in the printed spot color tints were visually perceivable. The detected hue shifts were categorized as acceptable or unacceptable on the basis of change in purchase intent of the observer due to the color difference. The difference between PantoneLIVE and print samples for the colors P485, PReflexBlue and POrange021 was deemed acceptable by the observers. On the other hand, the color differences of the hue corrected sample from the print and PantoneLIVE samples was judged unacceptable and could cause a change in intent to purchase the product for the observers. The visual differences between print and hue-corrected samples, hue-corrected and PantoneLIVE samples, and print and PantoneLIVE samples of P4975 with ink recipe 2 were judged acceptable. Similarly, the difference between the print and hue-corrected samples with ink recipe 1 of P4975 was also judged acceptable. The color difference between all the other sample combinations for P4975 caused a change in purchase intent of the observers. A sigmoidal correlation with high coefficient of determination(R^2) was observed between the rated difference score and the probability of change of purchase intent. The curve suggested that as the visual difference increased, the probability of change of purchase intent increased. The visual results were correlated to the instrument-based results from a previous study for the same colors. A positive sigmoidal correlation with good coefficient of determination(R^2) was observed between color difference and visually rated difference score. The correlation between hue difference and visually rated difference score also showed a positive linear relationship but with a comparatively weaker coefficient of determination(R^2). However, this correlation was very poor for the color P4975, which was attributed to the low chromaticity of this color and associated anomalies in hue angle calculations. The observers were also asked to rank the samples closest to farthest from their respective reference solid samples. The ranking data analysis showed no difference between the ranking for identical samples, except the PL samples of POrange021. The samples of P485 were not ranked statistically significantly different. The print sample for PReflexBlue was ranked first (closest to the reference), followed by PantoneLIVE and hue-corrected samples, respectively. The hue-corrected samples were ranked first for POrange021 and P4975. However, the difference in ranking between hue-corrected samples and the print samples was not statistically significantly different. Similarly, the difference between print and hue-corrected samples was not statistically significant for either of the ink recipes of P4975. The PantoneLIVE sample was not ranked first for any of the samples. Notwithstanding the lack of statistically significant difference, it was observed that the hue-corrected samples were ranked first most frequently for the colors P485, POrange021, and P4975 (with ink recipe 1).

The study showed that there were visually perceivable and potentially unacceptable hue shifts in spot color tints. Although, the visual difference between print and PantoneLIVE samples was consistently recognized by the observers, it was not enough to change their intent to purchase in most of the cases.

Further Study

This study included only the tint samples that showed maximum hue shifts for each color. It would be worth repeating the visual study with more samples across the tonal range. Moreover, based on the findings of this study, a further evaluation of gamut boundary colors with high chromaticity should be conducted. Censoring techniques could be applied to extract more useful information out of the non-parametric data. Once the study is repeated with a larger set of colors, and if a preference trend emerges, steps should be taken towards standardization of spot color tints to match user preference.

References

ASTM. (2016). Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates. *ASTM International*, 1-12

Aurier, P., & de Lanauze, G. S. (2012). Impacts of perceived brand relationship orientation on attitudinal loyalty. *European Journal of Marketing,*

Baribeau, R., & Robertson, A. (2005). Estimation of hue discrimination thresholds using a computer interactive method. *Color Research & Application, 30*(6), 410-415. doi:10.1002/col.20153

Beatty, S. G. (1997). HP goes in for a marketing makeover. *Wall Street Journal,* , 6.

Chan Jean Lee, & Eduardo Andrade. (2010). The effect of emotion on color preferences. *Advances in Consumer Research, 37*, 846. Retrieved from https://search.proquest.com/docview/1808077560

Cheskin, L. (1957). How to predict what people will buy.

CIE International Commission on Illumination. (2019). *ISO/CIE 11664-4:2019 [CIE LEAD] colorimetry — part 4: CIE 1976 l*a*b* colour space.* ().International Organization for Standardization. Retrieved from https://www.iso.org/standard/74166.html

CIE Technical Committee. (2018). Colorimetry. *CIE Pub,* (15.3)

Clement, J. (2007). Visual influence on in-store buying decisions: An eye-track experiment on the visual influence of packaging design. *Journal of Marketing Management, 23*(9-10), 917-928.

Danger, E. P. (1987). *Selecting colour for packaging.* Gower Technical Press Ltd.

Danilova, M. V., & Mollon, J. D. (2016). Superior discrimination for hue than for saturation and an explanation in terms of correlated neural noise. *Proceedings of the Royal Society B: Biological Sciences, 283*(1831), 20160164.

Dantas, M. I., Minim, V. P., Deliza, R., & Puschmann, R. (2004). The effect of packaging on the perception of minimally processed products. *Journal of International Food & Agribusiness Marketing, 16*(2), 71-83.

Davis, W., & Ohno, Y. (2010). Color quality scale. *Optical Engineering, 49*(3), 033602.

DeBerry-Spence, B., Dadzie, K. Q., Ferguson, J. L., & Johnston, W. J. (2008). Country-of-origin effects in service evaluation in emerging markets: Some insights from five west African countries. *Journal of Business & Industrial Marketing,*

Du Prel, J., Röhrig, B., Hommel, G., & Blettner, M. (2010). Choosing statistical tests: Part 12 of a series on evaluation of scientific publications. *Deutsches Ärzteblatt International, 107*(19), 343.

Durmus, D., & Davis, W. (2019). Evaluation of hue shift formulae in cielab and cam02. Paper presented at the *Proceedings of the 29th CIE SESSION,* 888-895.

Garber, L. L., Burke, R. R., & Jones, J. M. (2000). The role of package color in consumer purchase consideration and choice.

Grimes, A., & Doole, I. (1998). Exploring the relationships between colour and international branding: A cross cultural comparison of the UK and taiwan. *Journal of Marketing Management, 14*(7), 799-817.

Grossman, R. P., & Wisenblit, J. Z. (1999). What we know about consumers' color choices. *Journal of Marketing Practice: Applied Marketing Science,* Harms, V. (1998). *Biomathematik, statistik und dokumentation* (7., überarb. Aufl. ed.). Kiel-Mönkeberg: Harms. Retrieved from http://bvbr.bib-bvb.de:8991/F?func=service&doc_library=BVB01&local_base=BVB01&doc_number=008059367&sequence=000002&line_number=0001&func_code=DB_RECORDS&service_type=MEDIA

Heath, R. P. (1997). No title. *The Wonderful World of Color.Marketing Tools, October,*

Hellström, D., & Saghir, M. (2007). Packaging and logistics interactions in retail supply chains. *Packaging Technology and Science: An International Journal, 20*(3), 197-216.

Hine, T. (1996). *The total package*

. New York: Little, Brown and Co.

Holmes, C. B., & Buchanan, J. A. (1984). Color preference as a function of the object described. *Bulletin of the Psychonomic Society, 22*(5), 423-425.

Inman, J. J., Winer, R. S., & Ferraro, R. (2009). The interplay among category characteristics, customer characteristics, and customer activities on in-store decision making. *Journal of Marketing, 73*(5), 19-29.

ISO/TC 130. (2017). *ISO 13655:2017: Graphic technology. spectral measurement and colorimetric computation for graphic arts images.* ().International Organization for Standardization (ISO). Retrieved from https://www.iso.org/standard/65430.html

ISO/TC 130. (2018). *ISO 17972-4:2018. graphic technology — colour data exchange format (CxF/X) — part 4: Spot colour characterisation data (CxF/X-4).* ().International Organization for Standardization. Retrieved from https://www.iso.org/standard/71110.html

ISO/TC 130 Graphic Technology. (2017). *ISO 20654:2017 - graphic technology — measurement and calculation of spot colour tone value.* (). Retrieved from https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/86/68668.html

Jodra, R., Such, A., & Soler, P. (2009). *Representations of spot colors* Google Patents.

Kahneman, D. (1973). *Attention and effort* Citeseer.

Kardes, F. R. (1988). Spontaneous inference processes in advertising: The effects of conclusion omission and involvement on persuasion. *Journal of Consumer Research, 15*(2), 225-233.

Kauppinen-Räisänen, H. (2014). Strategic use of colour in brand packaging. *Packaging Technology and Science, 27*(8), 663-676.

Kauppinen-Räisänen, H., & Luomala, H. T. (2010). Exploring consumers' product-specific colour meanings. *Qualitative Market Research: An International Journal,*

Kauppinen, H. (2005). *Colours as non-verbal signs on packages* Svenska handelshögskolan.

Kauppinen-Räisänen, H. (2011). The impact of salient product cues on aging adults. *Journal of Medical Marketing, 11*(4), 294-302.

Konica Minolta. (n.d.) Understanding standard observers in color measurement. Retrieved from https://sensing.konicaminolta.us/blog/understanding-standard-observers-in-color-measurement/

Labrecque, L. I., & Milne, G. R. (2012). Exciting red and competent blue: The importance of color in marketing. *Journal of the Academy of Marketing Science, 40*(5), 711-727.

Labrecque, L. I., Patrick, V. M., & Milne, G. R. (2013). The marketersâ€™ prismatic palette: A review of color research and future directions. *Psychology & Marketing, 30*(2), 187-202.

Lee, Y., & Lee, J. (2006). The development of an emotion model based on colour combinations. *International Journal of Consumer Studies, 30*(2), 122-136.

Li, C., & Melgosa, M. (2013). A note about the abnormal hue angle change in CIELAB space. *Color Research & Application, 38*(5), 322-327.

Luo, M. R., Rigg, B., & Smith, K. J. (2003). CMC 2002 colour inconstancy index; CMCCON02. *Coloration Technology, 119*(5), 280-285.

Madzharov, A. V., & Block, L. G. (2010). Effects of product unit image on consumption of snack foods. *Journal of Consumer Psychology, 20*(4), 398-409.

MarketsandMarkets (n.d.).Packaging printing market global forecast to 2024 - MarketsandMarkets. Retrieved from https://www.marketsandmarkets.com/Market-Reports/packaging-printing-market-153207109.html

McLaren, K. (1980). CIELAB hue-angle anomalies at low tristimulus ratios. *Color Research & Application, 5*(3), 139-143.

Méndez, J. L., Oubina, J., & Rubio, N. (2011). The relative importance of brand-packaging, price and taste in affecting brand preferences. *British Food Journal,*

Miyazaki, A. D., Grewal, D., & Goodstein, R. C. (2005). The effect of multiple extrinsic cues on quality perceptions: A matter of consistency. *Journal of Consumer Research, 32*(1), 146-153.

Mohebbi, B. (2014). The art of packaging: An investigation into the role of color in packaging, marketing, and branding. *International Journal of Organizational Leadership, 3*, 92-102.

Mouw, T. (2018). Tolerancing part 3: Color space vs. color tolerance. Retrieved from https://www.xrite.com/blog/tolerancing-part-3

O'Hara, L., Gasque, B., Congdon, B., Hall, J., Halford, C., & Hattenberger, E. (2014). *PantoneLIVE library validation study.* ().Xrite Pantone. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=2ahUKEwiH1a2Inq3oAhUineAKHTiLDhEQFjAAegQIBRAB&url=https%3A%2F%2Fwww.pantone.com%2Fimages%2FPantoneLive%2FPantoneLIVE_Library_Validation_Study_Clemson_Final_Version.pdf&usg=AOvVaw01BEL7fvO4uV0F31nbdSsJ

Olson, J. C., & Jacoby, J. (1972). Cue utilization in the quality perception process. *ACR Special Volumes,*

Pantone, X-rite. (2016). *A guide to understanding color.* .X-rite Grand Rapids, MI.

Point of Purchase Advertising Institute. (1995). *The 1995 POPAI consumer buying habits study.* Englewood, NJ:

Prone, M. (1993). Package design has stronger ROI potential than many believe. *Marketing News, 27*(21), 13.

Ren, J., Lin, H., Huang, Q., Liang, Q., & Zheng, G. (2015). Color difference threshold determination for acrylic denture base resins. *Bio-Medical Materials and Engineering, 26 Suppl 1*(s1), S35-S43. doi:10.3233/BME-151287

Rosenfeld, J. (1987). Packaging wraps up sales. *Marketing Communications, 12*(9), 43-48.

Rundh, B. (2005). The multi-faceted dimension of packaging. *British Food Journal,*

Samworth, M. (2017). *Tone predictability of equinox converted spot colors - achieving predictable results of converted spot color tints.* Unpublished report.

Sawatzki, C., Roesch, J., & Specht, A. (2017, Nov 2,). If you work with brand colors, you need to know about CxF. Retrieved from http://www.cgsusa.com/2017/11/02/know-cxf/

Schoormans, J. P., & Robben, H. S. (1997). The effect of new package design on product attention, categorization and evaluation. *Journal of Economic Psychology, 18*(2-3), 271-287.

Séve, R. (1991). New formula for the computation of CIE 1976 hue difference. *Color Research & Application, 16*(3), 217-218.

Shimp, T. A. (1991). Neo-pavlovian conditioning and its implications for consumer theory and research. *Handbook of Consumer Behavior,* , 162-187.

Silayoi, P., & Speece, M. (2007). The importance of packaging attributes: A conjoint analysis approach. *European Journal of Marketing,*

Simms, C., & Trott, P. (2014). Conceptualising the management of packaging within new product development. *European Journal of Marketing,*

Singh, N., & Srivastava, S. K. (2011). Impact of colors on the psychology of marketing—A comprehensive over view. *Management and Labour Studies, 36*(2), 199-209.

Stokes, M., & Brill, M. H. (1992). Efficient computation of ΔH* ab. *Color Research & Application, 17*(6), 410-411.

Stoll, M., Baecke, S., & Kenning, P. (2008). What they see is what they get? an fMRI-study on neural correlates of attractive packaging. *Journal of Consumer Behaviour: An International Research Review, 7*(4-5), 342-359.

Taylor, A. E. (2000). Illumination fundamentals. *Lighting Research Center, Rensselaer Polytechnic Institute,*

UCLA: Statistical Consulting Group. (n.d.). Pvalue.htm. Retrieved from https://stats.idre.ucla.edu/other/mult-pkg/faq/pvalue-htm/

Underwood, R. L., & Ozanne, J. L. (1998). Is your package an effective communicator? A normative framework for increasing the communicative competence of packaging. *Journal of Marketing Communications, 4*(4), 207-220.

Urbany, J. E., Dickson, P. R., & Kalapurakal, R. (1996). Price search in the retail grocery market. *Journal of Marketing, 60*(2), 91-104.

Vartan, C. G., & Rosenfeld, J. (1987). Winning the supermarket war: Packaging as a weapon. *Marketing Communications, 12*(5), 31-36.

Veale, R., & Quester, P. (2009). Do consumer expectations match experience? predicting the influence of price and country of origin on perceptions of product quality. *International Business Review, 18*(2), 134-144.

Venter, K., Van der Merwe, D., De Beer, H., Kempen, E., & Bosman, M. (2011). Consumers' perceptions of food packaging: An exploratory investigation in potchefstroom, south africa. *International Journal of Consumer Studies, 35*(3), 273-281.

Wansink, B., & Huffman, C. (2001). A framework for revitalizing mature brands. *Journal of Brand and Product Management, 10*(4), 228-242.

Weisstein, E. (2020, Jan 02). Point-Line Distance--3-Dimensional. Retrieved Jan 06, 2020, from Wolfram Mathworld: http://mathworld.wolfram.com/Point-LineDistance3-Dimensional.html

Whetzel, N. (2015). CIE standard observers and calculation of CIE X, Y, Z color values - AN-1002b. Retrieved from http://support.hunterlab.com/hc/en-us/articles/203420099-CIE-Standard-Observers-and-calculation-of-CIE-X-Y-Z-color-values-AN-1002b

Wikipedia. (2020). CIE 1931 color space. Retrieved from https://en.wikipedia.org/w/index.php?title=CIE_1931_color_space&oldid=939752612