12-2014

The Effect of Optical Brightening Agent (OBA) in Paper and Illumination Intensity on Perceptibility of Printed Colors

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The Effect of Optical Brightening Agent (OBA) in Paper and Illumination Intensity on Perceptibility of Printed Colors

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A Thesis submitted in partial fulfillment of the requirement
for the degree of Master of Science
in the School of Media Sciences
in the College of Imaging Arts and Sciences
of the Rochester Institute of Technology

December 2014

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The Effect of Optical Brightening Agent (OBA) in Paper and Illumination Intensity on Perceptibility of Printed Colors

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Acknowledgements

I would like to recognize and thank Professor Robert Chung, my primary thesis advisor, for his support and inspiration throughout my research and the writing of this thesis. He inspired my interest in standards and color measurement that helped direct my enthusiasm for this topic. I would also like to express my gratitude to Professor Bruce Myers, my secondary thesis advisor, our meetings may have been short but his advantage experiences in academic and industry gave me a strong guidance.

Thank you to all the faculty and staff of RIT who support and encourage graduate students like myself in their education, interests and research. I would also like to thank the peers I met at RIT including my classmates for all their stimulating lunchtime discussions and joyful lab times.

I would like to thank my girlfriend Yuqing (Grace) He. Thanks to Yuqing (Grace) and her many efforts to this research, congratulations to our fruitful and shining lives in North America. I would also like to express my gratitude to my friends from Wuhan University, without you, I can't imagine such a rich life crossing China to U.S. and Canada.

Finally, I would like to express my gratitude and deeply love to my parents. This would have been impossible without your love and endless support. I appreciate it more than I can say. This is for you.

Love you, China, my home and my dream.

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Abstract

Widely utilized sanctioned color aims for commercial printing are based on paper substrates without optical brightening agents, also known as OBAs. However, in today's market, more and more paper is manufactured with OBAs. This could be problematic for commercial printers as OBAs influence not only paper conformity, but also the accuracy printed colors. This can lead to color mismatch between proofs and the final prints. Recognizing this condition, the objectives of this research were two-fold: first, to verify the perceived color difference between prints due to the presence of OBAs, and second, to study the perceptibility of color differences caused by OBAs in paper substrates, combined with quantitative measurement assessment.

In order to satisfy these objectives, the following research questions were investigated: Does CIEDE 2000(ΔE_{00}) correlate better with visual scaling or ranking for color differences of printed color pairs than CIELABDE (ΔE^*_{ab})? Do different illuminant intensity levels (ISO 3664 P1: 2000lx and P2: 500lx) affect human perceptibility of color differences for color pairs with dark shades?

A psychophysical experiment was carried out for evaluating color differences using printed color patches. In total, 27 pairs of printed color patches derived from the IT8.7/4 Target (1,617 color patches) were prepared using the same colorants printed on paper with and without OBA. Each pair was assessed at two levels of illumination by a panel of thirty-four observers. The visual results were used to investigate the relationship between color difference metrics and visual scaling (ranking) of color differences

induced by OBAs, as well as the relationship between illumination intensity level and visual scaling of color samples with high-density.

The results indicated that: (a) There is better correlation between ΔE_{00} and the visual scaling of OBA-induced color differences than ΔE^{*}_{ab}; and (b) there is no association between different illumination intensities (i.e., ISO: 3664 P1, P2) and visual scaling of color differences in high-density areas.

Chapter 1

Introduction and Statement of the Problem

Printed color is the result of putting ink on paper via the ink transfer mechanism of a printing machine. The modern commercial printing workflow consists of material preparation, color separation, proofing, and printing. All of these steps are aligned to a common set of parameters that uniquely define the intended visual characteristics of the final printed product. In order to maximize efficiency, repeatability, and predictability of the color image reproduction process, a number of ISO standards have been developed to standardize the printing workflow. Many printers are interested in establishing a color-managed workflow supported by standards to which they can verify their proof are predictable and final print products are repeatable.

Background

Modern printing and publishing workflows can be depicted in the form of a block diagram as shown in Figure 1. The process begins with the color conversion of an input file (denoted as Job Data) to a characterized reference printing condition (CRPC). Once converted, the data file is then further processed for proofing (denoted as Data_2). The data file defined in the reference printing may be adjusted for platemaking and printing (denoted as Data_3). If the platemaking and printing are calibrated to standards, and the

inks and paper used conform to these same standards, the resulting print should visually match the proof (Chung, R. & Jensen, S., 2010).

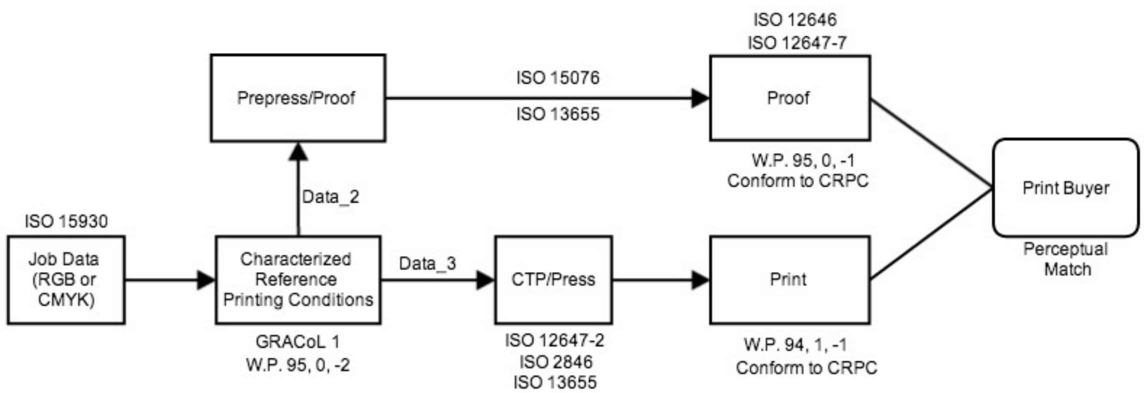


Figure 1: Standard commercial printing and publishing workflow

Printing standards specify a number of characterized reference printing conditions (CRPCs). Each CRPC is the relationship between the CMYK input data and the color as measured on the printed sheet. For example, GRACoL 1 specifies a paper color with the CIELAB coordinates as (95, 0, -2).

Statement of the Problem

In recent years, print buyers have begun to prefer papers in brighter and whiter shades. Paper makers utilize optical brightening agents (OBAs) to make substrates brighter and whiter to satisfy these demands while also lowering their costs, as OBAs are less expensive than traditional brighteners such as titanium dioxide.

OBAs are fluorescent material that absorbs ultraviolet radiation of illuminant wavelengths below the 400 nanometer (nm) region and then re-emits energy in the visible

short wavelength region. This effect makes the paper substrate to appear whiter and brighter, but the paper is also colorimetrically bluer than the white point specified by most commonly used CRPCs. One example representative of this condition is a piece of paper with OBAs produced for CRPC 6 yields a measured CIELAB value of (95, 1, -7), which is much bluer than that of (95, 0, -2). Therefore, the same printing condition on paper with different shades of white will yield different printed colors when comparing both visually and quantitatively.

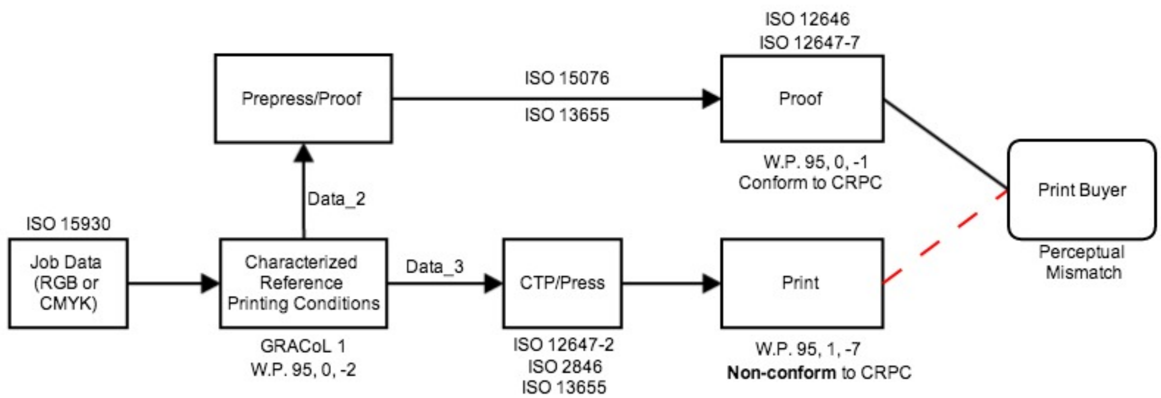


Figure 2: proof-to-print color mismatch caused by the presence of OBA

This condition is problematic for two reasons. First, these non-standard paper substrates cause printing to be out of conformance with ISO specifications. Second, the presence of OBAs in printing substrates may potentially result in color mismatch of proof-to-print. These two problems can be depicted in a modification of the block diagram produced in Figure 1, as shown in figure 2. As illustrated, the presence of OBAs in actual substrates results in a workflow that deviates from the CRPC specifications. Additionally, according to ISO DIS 12647-2 (2012, Section 4.3.2.1), the paper substrates

used for standardized proofing must conform to a fixed white point, which is much different from the white point of OBA-loaded paper for final print. Therefore, paper substrates containing OBAs may also cause problematic proof-to-print color matching.

This represents a potential dilemma of commercial printers: Print buyers prefer paper substrates with OBAs because they are perceptually brighter and whiter. Moreover, they also want repeatable and predictable colors for actual print products. As a matter of fact that standardized color management workflow requires paper without OBAs to achieve predictable colors for actual print products, whereas OBA-loaded paper substrates are what print buyers demand. In such case, commercial printers have problems to meet what their customers' demand.

To address this problem, it would be useful to evaluate OBA effect on printed colors from visual perspective combined with quantitative analysis. This thesis investigates two aspects of OBA-induced color differences: the relationship between visual ranking of OBA-induced color differences and two different DE metrics (ΔE_{00}, ΔE^*_{ab}), and relationship between visual ranking of OBA-induced color differences and two different illumination intensities (ISO 3664 P1, P2).

Reason for Interest in this Study

The researcher's experience in working as a graduate assistant for Professor Robert Chung at the Rochester Institute of Technology (RIT) laid a foundation of studying color perception, color management, and printing process control. The researcher then ventured into the current industry-wide color non-conformity and proof-

to-print mismatches issues caused by OBA papers. The researcher was motivated to investigate (1) if there is a relationship between measured color difference and perceived color difference, and (2) if OBA-induced color difference depends on TAC (total area coverage) and illumination level.

Chapter 2

Theoretical Basis

This research involved psychophysical experiments regarding perceptibility of small color differences caused by the presence of OBA in paper and by visual comparison of prints at two levels of illuminant intensity. Therefore, the theoretical basis for psychophysical studies in similar contexts is discussed in the following sections.

Visual color assessment

According to third edition of *Billmeyer and Saltzman's Principles of Color Technology*, Berns (2000) states:

> *"The first step in visual color assessment is to define the illuminating conditions. The ambient conditions are also strictly controlled to avoid any significant effects on the perception of color and tone,"* (Berns, 78).

In the graphic arts industry, CIE Illuminant D50 is specified by ISO as the reference illumination condition for visual color assessment, and the ambient environment shall be dark (ISO 3664). Berns (2000) then indicates that surround conditions are significant:

> *"The surround is next defined, which refers to light booth's interior walls, and it should be matte and neutral with lightness L^* between 60 and 70. Background refers to the surface upon which samples are placed,*

normally the floor of the booth. If the goal of the visual assessment is to estimate color appearance, the background should be matte and with a middle lightness, that is 50 L^*. Once the booth's background and surround are defined and its sources are selected, the spectral power distributions and illuminances (levels of illumination) must be measured," (Berns, 79).

In order to fulfill the above illuminating, ambient, and surround conditions for visual color assessment, viewing apparatus such as lighting booths are commonly utilized in the graphic arts industry. These lighting booths are manufactured with CIE complied illumination sources (CIE illumination A, CIE D50, and CIE D65, e.g.) and neutral gray matte texture. Apart from the viewing environment, Berns (2000) also proposes the specification for sample size and spacing:

"Larger sizes increase visual precision, so the samples should be at least 2 inches square in consistent, and the samples should have identical sample separation when color differences between two or more specimens are judged," (Berns, 79).

It is also customary to place specimens in edge contact, which means they are arranged with each other on the edge without any separation in between. Furthermore, Berns (2000) emphasizes specimens should be placed on the viewing plane of the light booth and the illumination source should be perpendicular to the center of specimens. When performing visual assessment, observers should keep 6 to 12 inches from the opening of the booth, and at a height where that the observation angle is 45 degrees.

According to *Introduction to Color Imaging Science*, Lee (2005) also indicates:

"One of the most important guidelines in using psychophysical data is to systematically check how physical and psychophysical variables are controlled in the visual measurements that produce the data," (Lee, 326).

Lee (2005) has listed seven major variables, (1) the spectral composition of the stimuli, (2) the spatial layout and modulation of the stimuli (including the target size and the field size), (3) the temporal variation of the stimuli, (4) the luminance level (including achromatic and chromatic adaptation), (5) the noise level, (6) variations between individuals (including age, race, culture, etc.) and (7) the experience and learning effect.

As one or more of these variables changed, visual performance often changes. Therefore, physical and psychophysical variables must be controlled and standard complied in the visual color assessment in order to produce valid data.

Just Noticeable Difference (JND)

Just noticeable difference (JND) is also known as threshold difference or least perceptible difference, it is the initial perceptual difference that can be seen when one of the two originally identical fields of color changes in any given direction, (Kuehni, 2003).

Ernst Heinrich Weber, a 19-century experimental psychologist, began to investigate thresholds of human senses quantitatively, observed that the size of the difference threshold appeared to be lawfully related to initial stimulus magnitude. This relationship, known since as Weber's Law, can be expressed as:

$$\frac{\Delta I}{I} = k, \qquad (1)$$

where

I is the original intensity of simulation,

ΔI is the difference threshold (the jnd),

and k is a constant.

Fechner (1860), a German physicist and mystic, introduced the term 'psychophysics,' and argued that sensation cannot be measured (Elements of psychophysics; Fechner, 1860). He also claimed that all that can be measured are stimuli, and the amount of stimuli that result in a particular sensation or the distinction between two sensations. The smallest difference that results in a noticeable distinction is the threshold difference.

"Fechner saw the just noticeable difference (JND) —expressed in terms of stimulus—to be the unit of sensation, with the magnitude of sensation

being the sum of JNDs that lead from the absolute threshold to a given sensation. Fechner expressed Weber's finding, meanwhile known to him, provided a theoretical rationale (not universally accepted), which permits the amount of sensation to be calculated from the relative amounts of fundamental stimulus and thus achieve a measurement of sensation,"(Kuehni, 65).

Fechner's work contributed to three types of experimental methods applied in psychology, which are (1) the method of limits, (2) the method of constant stimuli, and (3) the method of average error. Each of these methods found champions in succeeding years, and is still employed in the field today. (Kuehni, 65)

Visual stimuli and ranking

Over the century and a half since the beginning of psychophysics several scaling methods for one-dimensional color scaling have been developed (i.e., Ratio Estimation, Magnitude Estimation, Category Scaling, Paired Comparison).

In recent years, a form of interval judgment for the purpose of supra-threshold color scaling has been in wide use. In this method, sample pairs exhibiting small differences are compared against a reference. Observers are asked to rate the perceptual difference of sample pairs based on reference with similar magnitude to those of the sample pairs under estimation. (Kuehni, 118)

In the method of paired comparison, the stimuli are presented in pairs and the observers are required to compare each pair and determine which one is greater or less

than the other in some perceptual attribute. (Lee, 323) In such situations, multidimensional color differences—usually involving hue, chroma, and lightness differences at the same time—are sometimes evaluated as if they were one-dimensional.

In the present research, sample pairs were prepared by arranging printed colors on OBA and non-OBA paper substrates in edge contact and against a neutral gray background. Such sample pairs are the visual stimuli, and visual responses will be ranked in one dimension, i.e., No difference, Just Noticeable Difference (JND), More than JND, and Noticeable difference.

The problem addressed by the researcher is to study how visually ranked small color differences are related to measured color differences. This chapter provides the required theoretical basis to conduct a valid visual ranking experiment. This chapter opens with a discussion of visual color assessment, Just Noticeable Difference and visual ranking methods. After comparing different visual ranking methods, this chapter describes the visual stimuli and ranking method in the present research.

Chapter 3

Literature Review

According to a Printing Industry Center investigation, it's not until recent years that OBA papers are massively used in the printing industry (Chung & Jensen, 2010) and some previous studies have pointed out how OBA affect paper white and printed colors.

Effects of OBA on Paper Whiteness and Printed Colors

Some recent research has been done on studying the effect of OBA on paper whiteness and process colors (Cyan, Magenta, and Yellow), which provided the researcher a solid theoretical frame for the present research.

Effect of OBA on Paper Substrates

According to Lee, Shen, and Chen (2001), fluorescent materials have higher lightness and saturation compared with traditional non-fluorescent materials. (p.1) Optical brightening agents (OBAs) are chemicals adding to papers or other substrate materials to increase the blue light reflectance. From a human visual perception perspective, the increased reflectance of blue light increases the whiteness of the material (Chaikovsky and Garrison, 2012). Therefore, OBAs are commonly added to white fabrics and other white materials to make them appear 'bluer' or 'cleaner' to prevent the yellowish due to age or dirty appears (Datacolor, 2012). Due to the benefits of OBAs, papermakers utilize OBAs to make substrates brighter and whiter to pleasing end

customers and meet the market demands, meanwhile lowering their costs, since adding OBAs is cheaper than traditional bleaching process.

In a spectrophotometric perspective, Paper with OBAs requires ultraviolet radiation of illuminant wavelengths below 400 nm for their excitation. OBAs absorb UV radiation and then re-emit light in the blue region. It brings the peak reflectance wavelength to about 457 nm according to Chung & Tian (2011). As a result, a shift of the CIELAB b^*coordinate towards the blue hue by about 1 to 10 units is caused (ISO 13655:2009, Appendix G).

Figure 3 compares spectral reflectance curves between a paper with OBA (Invercote G) and a paper without OBA (Invercote T). As it illustrated, the peak reflectance wavelength occurs around 440 nm, which indicates an OBA effect. The spectral reflectance curve shows that Invercote G emits more short wavelength energy, which mostly affects ΔZ. The color difference between the two substrates is 6.5 ΔE^*_{ab}, mostly from ΔZ (Chung & Tian, 2011).

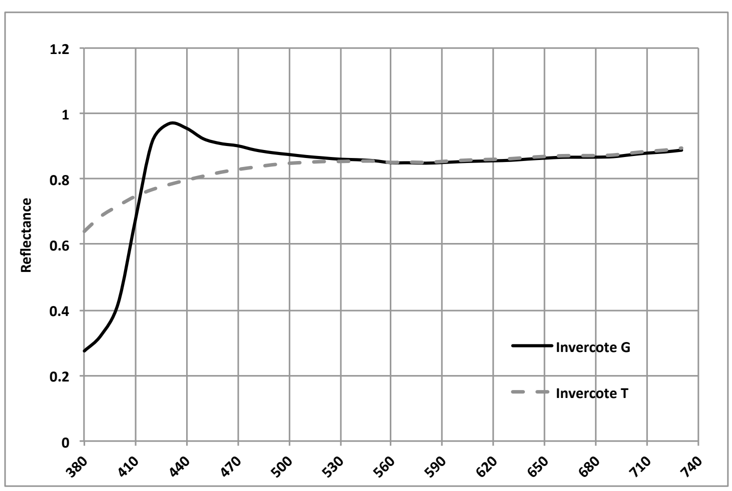


Figure 3: Effects of OBA on paper white. (Figure Based on Chung & Tian, 2011)

Chaikovsky and Garrison (2012) have studied the OBA effect and compared two levels of OBA contained paper samples with non-OBA paper samples under three types of illuminants, which are illuminant A, D50, and D65. The result shows that "the highest reflectance in the visible spectrum of light occurs in the blue part of the spectrum under D65 lighting (light source with highest UV component). The lowest reflectance throughout the spectrum occurs under Illuminant A (light source without UV component)," (Chaikovsky and Garrison, 2012). It is the result of OBAs that increases reflectance in the blue spectrum region under D65 according to Chaikovsky and Garrison's study.

The researcher now has a clear view of how OBAs that affects paper whiteness perceptually in appearance and spectrally inherent at the same time. Another salient factor of OBA effect is on printed colors.

Effect of OBA on Printed Colors

One representation of printing color is manifest in the 1617 CIELAB values from the IT8.7/4 target. Chung and Tian's research shows that there are 16% of printed colors in which ΔE is larger than 4 ΔE^*_{ab}, and in which total ink quantities are less than 85%. This suggests that the effects of OBA impact light ink-covered areas the most (Chung & Tian, 2011).

Chaikovsky and Garrison (2012) also point out that the impact of OBAs decreases to a minimal level with the higher percentage ink coverage on the paper. Furthermore,

Chung and Tian (2011) examined CIE XYZ and CIELAB values of CMY solids and color differences of solid colors on two substrates shown in Table 1. It is apparent that the magenta solid has the largest ΔE (3.51), followed by the yellow solid (2.76), and the cyan solid (1.74). Due to the OBA difference between the two pieces of paper, Δb* is the largest component among ΔL*, Δa*, and Δb* (Chung & Tian, 2011).

Table 1: Comparing process solid colors on OBA and no OBA paper (Reference to Chung & Tian, 2011).

Color	CIEXYZ			CIELAB			Difference			
	X	Y	Z	L^*	a^*	b^*	ΔX	ΔY	ΔZ	ΔE
M	32.5	16.4	13.0	47.4	74.6	1.4	0.55	0.32	1.57	3.51
M_OBA	33.1	16.7	14.6	47.8	74.8	-2.1				
C	14.8	22.5	51.6	54.5	-36.2	-49.4	0.19	0.00	1.18	1.74
C_OBA	15.0	22.5	52.7	54.5	-35.0	-50.7				
Y	68.5	71.7	6.0	87.8	-1.4	95.7	-0.43	-0.24	0.56	2.76
Y_OBA	68.1	71.5	6.5	87.7	-1.9	93.0				
K	1.8	1.9	1.5	14.8	0.2	0.2	0.00	-0.01	0.00	0.18
K_OBA	1.8	1.9	1.5	14.8	0.4	0.1				

The review of OBA effects provides the researcher a thorough understanding of the basic background that is related to the present research, it investigates the relationship between visual ranking and measured difference of OBA-induced color differences. To address a valid research on OBA-induced color differences quantitatively and visually, it

is necessary to review the latest ISO standards on spectral measurements and viewing conditions.

In order to achieve accurate and reliable quantitative assessment of printed colors in graphic arts industry, the International Standard Organization (ISO), established standard procedures, named ISO 13655: 2009, to spectrally measure objects that can reflect, transmit, or self-illuminate (including flat-panel display) (ISO 13655: 2009).

Measuring Color

ISO 13655: 2009 specifies different measurement conditions with the corresponding illuminant requirements and specifies colorimetric computation requirements for such analysis.

Spectral measurement requirements

Measuring instruments play a decisive role in performing spectral measurement of objects. ISO 13655: 2009 standardizes color measurement of objects by restricting spectral measurement procedure ahead of colorimetric computation. Relevant variable here include measurement device verification, measurement range, and measurement conditions. In the first place, all the measurement devices or systems need to be verified before use. The procedure of standardization or adjustment should strictly follow its manufacturer's instructions. Second, the standard specifies wavelength range, interval, and bandwidth. In the wavelength range part, the standard requires data to be measured within the range of 360 nm and 780 nm; the scope of measurement shall include the

range between 400 nm and 700 nm. As to interval and bandwidth, it is stipulated that data should be measured at 10 nm intervals with a spectral response function that is triangular with a 10 nm bandwidth at the half power point. (ISO 13655, 3)

Last but not least, different measurement conditions and illumination requirements (M0, M1, and M2) are also specified in ISO 13655:2009. Measurement condition M0 requires the relative spectral power distribution of the flux incident on the specimen surface to conform to CIE illuminant A, which refers to a distribution temperature of 2856 K correspondingly. In real cases, the relative spectral power distribution of the flux incident on the specimen surface has a tolerable temperature range of 2856K ± 100 K (ISO 13655, 4).

M0 is a legacy specification. As OBA loaded papers are increasingly used in today's commercial printing, the limitation of M0 complied measurement devices is apparent. Widely used measurement devices are equipped an illuminant source that matches illuminant A, it is important to recognize that this is incongruous with the light booth illuminant source in the proofing and pressroom that matched D50 according to ISO 3664 viewing standard. This discrepancy leads to color mismatch in viewing and communicating OBA samples. In response to the issues created by the limitations of the M0 standard, the M1 standard was created by ISO 13655:2009.

Measurement condition M1 requires the spectral power distribution of the light flux incident of the specimen surface for the measurement should match the CIE illuminant D50, it has also defined the UV component is of high importance with respect

to D50, it requires a close match of the relative power in the UV region between 300 nm and 410 nm.

Based on measurement condition M1, currently released spectrophotometers, such as X-Rite i1 Pro 2 and Konica Minolta FD-7 have adopted M1 (CIE Illuminant D50 with defined UV component) as the source in order to address the paper fluorescence effect.

Measurement condition M2 is designed for applications where the UV component of the illuminant needs to be completely eliminated. As such, it includes a UV-blocking filter between the light source and the target. One goal of M2 is to minimize instrument-to-instrument variation. The source is only acceptable when it contains substantial radiation power in the wavelength range that exceeds 400 nm. In order to filter and remove the part that has wavelength lower than 400 nm, a UV-cut filter should be embedded to instrument and then it can suppress the UV content of the source radiation below 400 nm before the radiation impinges on the specimen (ISO 13655, 2009, p. 5). Since some trade-offs exist between a sufficient suppression of residual fluorescent excitation and a reasonable signal-to-noise ratio of the measurement signal, the source for measurement condition M2 is not explicitly specified. ISO 13655 stipulates that the "UV Cut" starts from 420 nm to at least 700 nm.

Colorimetric computation requirements

For reflective samples, once the spectral data measured, the next step is to calculate trsitimulus values. The calculation of tristimulus values shall be based on CIE illuminant D50 and the CIE 1931 standard colorimetric observer (the 2°standard

observer) (ISO 13655, 8). This standard ensures consistency with graphic arts viewing conditions, which is defined in ISO 3664. (ISO3664, 5)

The computation of the tristimulus values X, Y, Z for reflective specimen data shall be as defined by ISO 13655 (p. 8) as follows:

$$X = \sum_{\lambda=360nm}^{780nm} R(\lambda) \times W_X(\lambda) \quad (2)$$

$$Y = \sum_{\lambda=360nm}^{780nm} R(\lambda) \times W_Y(\lambda) \quad (3)$$

$$Z = \sum_{\lambda=360nm}^{780nm} R(\lambda) \times W_Z(\lambda) \quad (4)$$

where

$R(\lambda)$ is the reflectance factor at wavelength λ;

$W_X(\lambda)$ is the weighting factor at wavelength λ for tristimulus value X;

$W_Y(\lambda)$ is the weighting factor at wavelength λ for tristimulus value Y;

$W_Z(\lambda)$ is the weighting factor at wavelength λ for tristimulus value Z;

Spectral weights, $W(\lambda)$, the product of CIE illuminant D50 and 2°standard observer data, shall be used for the calculation of tristimulus values. The spectral weights data shall be referenced to ISO 13655 Table1 (Appendix A).

The present research endeavors to study the relationship between quantitative color differences derived from spectral measurement and colorimetric computation, and perceived color differences based on the visual assessment of color pairs. Having reviewed the spectral measurement and colorimetric computation requirements, the next step is to review procedures of color difference computation.

Color Difference Equations

CIELAB color difference is the Euclidean distance between the two different $L^*a^*b^*$ values representing the two different specimens in the CIELAB color space. The ΔE^*_{ab} formulas as defined by ISO 13655:2009 are as follows:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (5)$$

$$\Delta L^* = L^*_1 - L^*_2 \quad (6)$$

$$\Delta a^* = a^*_1 - a^*_2 \quad (7)$$

$$\Delta b^* = b^*_1 - b^*_2 \quad (8)$$

where

ΔE^*_{ab} is the CIE1976 L*, a*, b* color difference;

ΔL^* is the lightness difference between specimen 1 and specimen 2;

Δa^*, Δb^* are the differences of the CIE 1976 a* and b* co-ordinates, respectively. (ISO13655, 13)

According to ISO 13655, much work on uniform visual color spaces and color difference equations within CIE and related organizations applies to textile evaluation under D65. This work may be extrapolated to apply to printed images viewed under D50. Either manual or instrumental calculation for tristimulus values based on spectral data is an integration of the CIE D50 spectral power distribution function and the CIE 1931 2° standard observer sensitive function. (ISO 13655, 12)

Presently, ISO 13655 recommends ΔE_{00} for the calculation of small color differences. The ΔE_{00} total color difference formula corrects for the non-uniformity of the

CIELAB color space for small color differences under reference conditions. Improvements to the calculation of total color difference for industrial color difference evaluation are made through corrections for the effects of lightness dependence, chroma dependence, hue dependence, and hue-chroma interaction on perceived color difference. The scaling along the a^* axis is modified to correct for a non-uniformity observed with gray colors (ISO 13655 "Annex B"). The resulting recommendation for CIEDE2000 total color difference ΔE_{00} and its calculation is summarized as follows:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \frac{\Delta C'}{K_C S_C}\frac{\Delta H'}{K_H S_H}} \tag{9}$$

where

$\Delta L'$ is the transformed lightness difference between specimens 1 and 2;

$\Delta C'$ is the transformed chroma difference between specimens 1 and 2;

$\Delta H'$ is the transformed hue difference between specimens 1 and 2;

R_T is the rotation function;

K_L, K_C, K_H are the parametric factors for variation in the experimental conditions;

S_L, S_C, S_H are the weighting functions. (ISO13655, 18)

Considering the computational complexity required of the ΔE_{00}, calculation using an Excel spreadsheet with an embedded macro is necessary.

To enable accurate and reliable visual assessments for graphic arts images, light booth standards in proofing and pressroom need to match D50 in terms of the spectral component. Besides, the viewing conditions and surround have to be specified to avoid

variations and misalignments about color appearance of substrates, reproductions, and artwork. Therefore, it would be useful to review the standard viewing conditions implemented in graphic arts industry.

Standard Viewing Conditions

The current ISO 3664 (2009) standard has specified two levels of illumination, a high level for critical evaluation and comparison, and a lower level for appraising the tone scale of an individual image under illumination levels similar to those under which it will be finally viewed.

According to subclause 4.2 of ISO 3664, ISO viewing condition P1—the specified condition for viewing a print—is applicable for a critical comparison between two or more copies of an image. The comparison is usually between either the original or its reproduction or between different copies of a reproduction. The high illumination levels specified permit more critical evaluation of color and tone gradation in higher density areas that may not be perceived under most practical viewing conditions. (ISO3664, 7)

The illuminance of P1 is specified as (2,000 ± 500) lux, and should be (2,000 ± 250) lux at the center of the illuminated viewing surface area. Also, the relative spectral power distribution of the reference illuminant for simultaneous viewing of printed color samples should be CIE illuminant D50. This represents natural daylight, with a correlated color temperature of approximately 5000 K.

ISO 3664 states: “The surround and backing shall be neutral and matte. The surround shall have a luminous reflectance between 10% and 60% with the specific value being selected to be consistent with practical viewing. For many applications, a mid-gray of 20% reflectance is very convenient and is recommended where no other condition is defined,” (ISO 3664, 8).

According to subclause 4.3 of ISO 3664, the specifications are applicable for the appraisal of tone reproduction of individual images, photographic image inspection, or the judgment of prints, which is viewing condition P2. The illuminance of P2 should be (500 ± 125) lux at the center of the illuminated viewing surface area. (It should be noted that the relative spectral power distribution characteristics specified for P2 are exactly the same as those specified for condition P1.) The surround and backing should be neutral and matte, with a luminous reflectance between 10% and 60% (the specific value should be selected for consistency with practical viewing).

Both ISO P1 and P2 viewing conditions need to be implemented in the visual assessments of the present research as it seeks to examine the impact of different illuminant intensity on the perceptibility of color differences between color pairs. (OBA and no OBA printed color arranged in edge contact)

A valid visual scaling or ranking research is deemed as feasible based on ISO 3664 complied viewing environments. Having the standard viewing conditions under control, how to apply experiment utilizing visual scaling is the next to review. The researcher has found recent applications utilizing visual ranking in the following session that related to the present study.

Visual Scaling or Ranking

A study on effect of differences in substrate white point on the acceptability of color matches (Green, Baah, Pointer & Sun, 2012) utilized a six-point scale to rate the size of color difference between reference and sample during the psychophysical experiment, where 1-2 are not perceptible or only barely perceptible, 3-4 are acceptable and 5-6 are unacceptable.

> *"Hardcopy samples were presented in Verivide proof viewing cabinet with D50 simulating illumination at 500 lux against a surround with 20% reflectance, 21 observers with good color vision participated in the psychophysical experiment were asked to rate the size of color difference between reference and sample using the six-point scale, and the perceptibility and acceptability thresholds as the results were determined using the instrumental wrong decisions method,"* (Green, Baah, Pointer & Sun, 2012).

Another recent study on testing uniform color spaces and color-difference formulae using printed samples (Huang, Liu, Cui & Luo, 2012) implemented a gray-scale method to scale the color differences of 446 sample pairs. During the experiment, the sample pair was given in the bottom of the background, and the five gray-scale pairs were presented in the top of the background. They were produced from the same printer on the same substrate. These color difference pairs ranged from 0.2 to 8.0 $\Delta E^{*}_{ab,10}$ units, with a mean of 3.0. Qualified observers with normal color vision were instructed to conduct

visual assessments using the five gray-scale pairs as references. If the color difference of a sample pair was not equal to the color difference of the closet gray scale, observers were encouraged to provide an intermediate step (e,g., 2.6 for a color difference greater than grade 2 but smaller than grade 3).

Habekost (2013) has conducted a research to compare several color differencing equations in corresponding with perceived color differences, both groups of trained and untrained observers in regards to judging color differences were asked to rank color differences of test colors.

> *"The observers viewed the color patches in viewing booth with 5000K lighting. The difference between the standard and the sample patch could be rated into match, slightly different, different, more different and very different. The rankings were translated into numbers from 5 (=match) to 1 (=very different) and a ranking scheme was applied to weight the responses,"* (Habekost 2013, 2)

Habekost (2013) has provided a similar experimental frame with 5 ranking scales for the present study. Having reviewed recent applications involved visual scaling to achieve valid subjective color assessment, the next step is to review the specific statistic method for hypothesis testing.

Two-Way Tables and the Chi-Square Test

A cross-tabulation is a joint frequency distribution of cases based on two or more categorical variables. Displaying a distribution of cases by their values on two or more

variables is known as contingency table analysis and is one of the more commonly used analytic methods in the social sciences.

The joint frequency distribution can be analyzed with the chi-square statistic (χ^2) to determine whether the variables are statistically independent or if they are associated. If a dependency between variables does exist, then other indicators of association, such as Cramer's *V*, gamma, Sommer's *d*, can be used to describe the degree that the values of one variable predict or vary with those of the other variable. (Michael, 2004)

Significant assumptions for the chi-square test include that (1) the sample is not biased, (2) that the data results from independent observations, (3) that row and column variable observations are all mutually exclusive, and (4) that all expected frequencies are fairly large.

The chi-square test is based on a test statistic that measures the divergence of the observed data from the values that would be expected under the null hypothesis of no association and alternative hypothesis claims that some association does exist. This requires the calculation of the expected values based on the data. The expected value for each cell in a two-way table is equal to *(Row total*Column total)/n*, where *n* is the total number of observations included in the table.

Once the expected values have been computed (done automatically in most applicable software packages), the chi-square test statistic is computed as:

$$\chi^2 = \sum \frac{(\text{observed frequency} - \text{expected frequency})^2}{\text{expected frequency}} \qquad (10)$$

Degree of freedom (df) = (R-1)(C-1) where

R represents the number of rows in the two-way table

C represents the number of columns in the two-way table

The chi-square distribution is defined for all positive values. The *P-value* for the chi-square test is $P(\chi^2 \geq X^2)$, the probability of observing a value at least as extreme as the test statistic for a chi-square distribution with $(r-1)(c-1)$ degrees of freedom.

Having reviewed previous studies that implemented visual scaling or ranking for color difference judgments, only observers with normal color vision should be eligible for performing the ranking tasks. Therefore, it is a necessary to screen observers before conducting color ranking or scaling judgments. Based on such experiences, a discussion of color vision screening tests follows.

Color Vision Screening Test

Commonly used color vision evaluation tests include the Ishihara pseudo-isochromatic plates test and the Farnsworth-Munsell 100 Hue test. These tests screen for color vision abnormalities and color-discrimination ability.

In the Ishihara plate test, "a series of plates is designed to provide a test that gives a quick and accurate assessment of color vision deficiency of congenital origin, this is the commonest form of color vision disturbances," (S. Ishihara, 1972).

The Farnsworth-Munsell 100 Hue test offers a simple method for testing color discrimination. It yields data that can be applied to many psychological and industrial problems in color vision. According to the Farnsworth-Munsell 100 Hue Test Instruction,

"The primary uses are, first, to separate persons with normal color vision into classes of superior, average and low color discrimination, and second, to measure the zones of color confusion of color defective persons. Examples of special purposes for which it has been used including testing for type and degree of color defectiveness, and independent control on validity of other color vision tests."

Since the Farnsworth-Munsell 100 Hue test is designed to measure a particular psychophysical aptitude, the test scores cannot be expected to correlate directly with other tests for color vision. The other color vision tests, such as Pseudo-isochromatic plates, color vision lanterns, anomaloscopes and colorimeters, isolate certain factors of color deficiency, but do not measure general color discrimination directly as does the 100 Hue Test.

Considering the need for performing critical color judgment tasks in the present research, the Farnsworth-Munsell 100 Hue test is a more appropriate instrumental test method than the Ishihara plate test. Therefore, FM 100 Hue test was adopted as the screening test in order to obtain useful data regarding visual scaling of color pairs.

In summary, the present literature review begins with an overview of recent studies regarding OBA effect on paper whiteness and printed colors, it then points out measured color difference exist between OBA and Non-OBA paper, and discusses the measurement specifications defined by ISO 13655:2009 as well as viewing standards defined by ISO 3664:2009. It concludes that measurement mode M1 with defined CIE D50 illuminating source is the correct method to measure OBA color samples in graphic arts industry. The review of literature using visual scaling methods investigates different

visual scaling metrology and it provides guidelines for conducting psychophysical experiment in present research.

Previous studies point out OBA-induced color differences depend on the amount of ink coverage. There is neither literature that describes the visual response that OBA causes nor how illumination intensity may affect the visual response. These two directions will be addressed in the following chapters.

Chapter 4

Research Questions

The objective of this research is to investigate two important aspects of OBA-induced color differences: the relationship between visual ranking and measured color differences, and the effect of different illumination intensities on visually ranked or scaled color differences. Two specific research questions were developed from the research objectives.

Research Question 1: Does ΔE_{00} correlate better with visually scaled color differences of sample color pairs than ΔE^*_{ab}?

Research Question 2: Do illumination levels influence human perceptibility for color differences of printed color pairs with dark shades?

Chapter 5

Experimental Method

A psychophysical experimental method was implemented to address the research questions. The experiment included three steps. The first step was to select colors and prepare sample pairs as visual stimuli.

Sample Selection and Preparation

In this research, color pairs were made using the same colorants and printing conditions on two paper substrates: Invercote T (paper substrate without OBA) and Invercote G (OBA substrate). In order to obtain colors that represent various hue, lightness, and chroma values (in other words, to obtain representative colors located at different parts of the color gamut with various measured color differences), there was a need to use a systematic approach to select limited colors from the IT8.7/4 Target, which consists of 1,617 color patches representing various hue, lightness, and chroma values.

Procedure:

1. **Output IT8.7/4 target**

    1.1. The IT8.7/4 targets were output through Kodak Approval imaging system under a known calibrated condition (SWOP3) to the two paper substrates, Invercote T and G.

2. **Measure CIELAB values of the IT8.7/4 targets (T and G)**

   2.1. The IT8.7/4 targets (T and G) were measured by an X-Rite i1 Pro 2 Spectrophotometer at a geometry of 0°: 45° under M1 mode with a D50 illuminating source. CIELAB values were then calculated under CIE illuminant D50 spectral power distribution and CIE 1931 2° standard observer sensitivity function.

   2.2. Compute ΔE between IT8.7/4 T and G samples based on measured CIELAB values (1,617 ΔE measurements). The maximum ΔE value was approximately 8, while the minimum was approximately 0.9.

3. **Select limited colors from all regions of the color gamut**

   3.1. In order to obtain colors representing various lightness, neutral candidates with various L* are necessary.

   3.2. Cyan, Magenta, Yellow, and RGB overprint solids are necessary candidates representing chromatic corners with different hue angles of the color gamut.

   3.3. In the middle of neutral and chromatic corners, a number of moderate-chroma candidates between each solid and neutral and near-neutral candidates between each moderate-chroma and neural are expected to be selected representing various chroma region.

3.4. An Excel spreadsheet was built as the tool to accept CIE L*C*h input, then convert L*C*h into CIE LAB values and compare the input values against the 1,617 dataset to find the closet candidates (CMYK).

3.5. A C^* value was defined and input according to the hue angles of the CMY and RGB solids to select candidates with a specific chroma range. For example, to select moderate-chroma color at the same hue angle as the Cyan solid, input C^* as 30, L^* as 78, and h_{ab} as 228 degrees in the light yellow region of the Excel spreadsheet as shown in Figure 4.

Instructions:
1. Enter L, C, and h (in degrees).
2. The spreadsheet will convert the degree to Radian and ΔE between the sample and all 1,617 colors.
3. Sort 1,617 colors based on Column K (dE00) in acsending order to locate the closest color and its TV.

LAB_L	LAB_C	LAB_h (degree)	
78	30	228	
		3.979350695	<-- Radian
LAB_L	LAB_A	LAB_B	
78	-20.07	-22.29	

SAMPLE_ID	SAMPLE_NAME	CMYK_C	CMYK_M	CMYK_Y	CMYK_K	LAB_L	LAB_A	LAB_B	ΔEab	ΔE00
743	P23	50	0	0	0	74.48	-19.92	-21.47	3.62	2.57
308	G20	40	0	0	0	78.38	-16.22	-16.96	6.59	3.04
317	G29	40	0	0	0	77.79	-16.14	-16.83	6.74	3.11

Figure 4: Select color utilizing CIELCH model from 1,617 CMYK dataset.

3.6. A manual data sort was performed based on the 1,617 ΔE_{00} values from smallest to largest. The color patches at the top of the list were the candidates (the smallest ΔE_{00} values), except the neutral candidates, which should be rendered by K only.

4. Prepare sample pairs

4.1. Color patches were created for each of the selected candidates using Adobe InDesign (see Appendix C). Each color patch was created as a 3.5 in x 3.5 in square, which were then exported as PDFs using the PDF/X-1a: 2001 standard

for generating physical color samples through the Kodak Approval imaging system. The color samples were then transferred through a laminator on the two types of paper substrates (Invercote T and Invercote G) to prepare for making the sample color pairs.

4.2. Each sample color pair was placed in edge contact mount on a matte gray cardboard with a lightness of 62 L^*. Figure 5 shows an example of the appearance of a sample color pair.

Figure 5: Sample pair was placed in edge contact and mount on gray cardboard.

4.3. Instrumental measured CIELAB values and ΔE for each sample pair were generated from an X-Rite i1 Pro 2 Spectrophotometer which utilizes a geometry of 0°: 45° under M1 mode with a D50 illuminating source. CIELAB values were calculated under CIE illuminant D50 spectral power distribution and CIE 1931 2° standard observer sensitivity function.

Conduct Color Vision Screening Test

The FM 100 Hue Test for screening observers with color discrimination deficiency was conducted in the color control lab at the School of Media Sciences of RIT using a GTI GraphicLite viewing booth (D50 and ISO 3664 P1 compliant). The FM 100-Hue Test kit consisted of four wooden cases, a total of ninety-three plastic caps in which the colors were mounted, and score sheets to record observer name, age, gender, email address, test date, and responses.

A total of 35 observers—students and staff from the College of Imaging Arts and Sciences at RIT—took the test. Results were scored by the FM 100 Hue Test software. The test procedure is detailed below.

Prepare the Test:

1. Turn on the GTI GraphicLite viewing booth, select "OPT" setting (D50 illumination), and allow lighting to warm up for at least 30 minutes.
2. Turn off extraneous lighting.
3. Verify the D50 and P1 illuminant condition with the use of the Konica-Minolta FD-7 spectrophotometer (Appendix B).

Procedures:

4. Randomize the caps using the cover of the case.
5. Instruct the observer to arrange the caps according to the two fixed colors at the end of a case by moving the caps by hand without touching the color. No time limit was given, and the test was conducted in a quiet surrounding.

6. Once step 5 was finished, closed the box, flipped over the case, opened it again, and recorded the cap numbers for each case.
7. Steps 4-6 were repeated four times (once for each box).
8. The FM 100-Hue Test Scoring Tool software was used to score the results for each observer.

Conduct the Psychometric Experiment

Visual stimuli, as shown in Figure 6, were used to scale the color differences between the sample pairs. The two anchor pairs used in the experiment were prepared with the same size and material as the samples being used. Anchor Pair A—the reference for ‘no difference’—was made by assembling two same color patches together. Anchor Pair B—the reference for ‘noticeable difference’—was made by assembling the two paper substrates, Invercote T and Invercote G, together. The two anchor pairs were presented for observers to use as a reference when estimating the perceived color differences between sample pair.

Figure 6: Anchor pairs A and B.

During the experiment, the sample pair was shown at the bottom of the background, and the two anchor pairs were presented at the top of the background. This scale of visual assessment was different from a gray-scale method, which is designed to have a range of equal units of visual difference or a range of proportionally increased visual differences. This experiment defined four levels of visual color differences. In addition to 'no difference' and 'noticeable difference,' the levels included 'just noticeable difference' (JND) and 'more than just noticeable difference' (more than JND). Observers had to assign one of the four levels for each sample pair (Appendix D).

Chapter 6

Results and Discussion

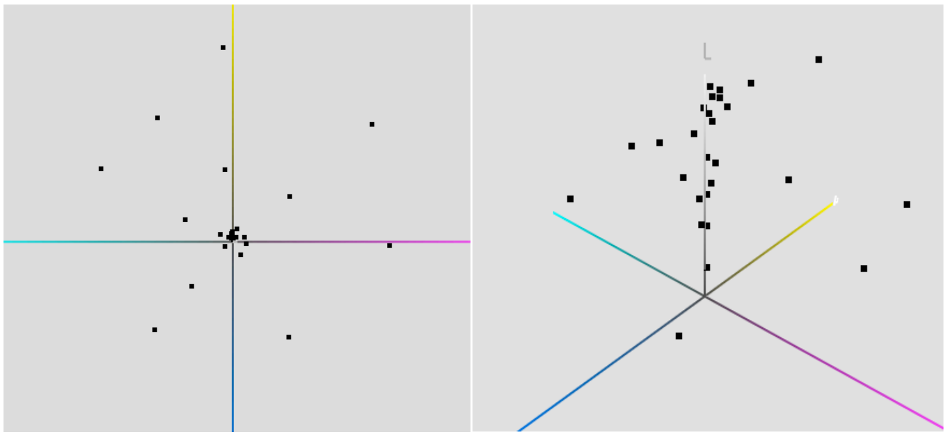
Sample Preparation

Twenty-seven colors were selected from the 1,617 CMYK dataset. Table 2 lists the CMYK tonal values and corresponding ID numbers for the 27 candidates.

Table 2: List of 27 color candidates.

ID	Name	Tonal Values			
		C	M	Y	K
1	N1	0	0	0	0
2	NN1	3	3	3	3
3	N2	0	0	0	15
4	S1	0	3	3	0
5	S2	10	6	6	0
6	S3	7	7	7	7
7	S4	0	5	0	0
8	N3	0	0	0	40
9	NN2	10	0	0	20
10	N4	0	0	0	60
11	NN4	50	40	40	0
12	N5	0	0	0	80
13	NN3	30	30	20	0
14	NN5	20	0	20	60
15	M2	50	0	0	0
16	NN6	20	55	55	0
17	M1	3	3	40	3
18	M4	20	55	55	0
19	M	0	100	0	0
20	C	100	0	0	0
21	R	0	100	100	0
22	G	100	0	100	0
23	B	100	100	0	0
24	Y	0	0	100	0
25	M5	70	20	70	20
26	S5	55	0	100	0
27	N6	40	27	27	100

In order to illustrate that selected candidates are located at different parts of the color gamut representing various hue, chroma, and lightness, ColorThink Pro was utilized to show the distribution of the 27 color centers in CIELAB a^*b^* planes and $L^*a^*b^*$space.



(a) a^*b^* plane (b) $L^*a^*b^*$ space

Figure 7: Distribution of 27 colors in CIELAB (a) a^*b^* plane and (b) $L^*a^*b^*$ space.

The a^*b^* plane in Figure 7 shows that moderate-chroma and near-neutral candidates in between neutral and chromatic corners are nearly in the same hue angel, and candidates in $L^*a^*b^*$ space illustrates various lightness levels, this result meet the selecting criteria of the procedure.

Figure 8 shows the simulation of the 27 color pairs. There was one sample pair made by assembling two Invercote T patches rather than assembling Invercote T patch against Invercote G patch in order to introduce a sample of no difference.[1]

Different from the simulation, real pairs were presented with ID number but without T and G notes.

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[1] Pair 25 was the only pair assembled with two Invercote T samples.

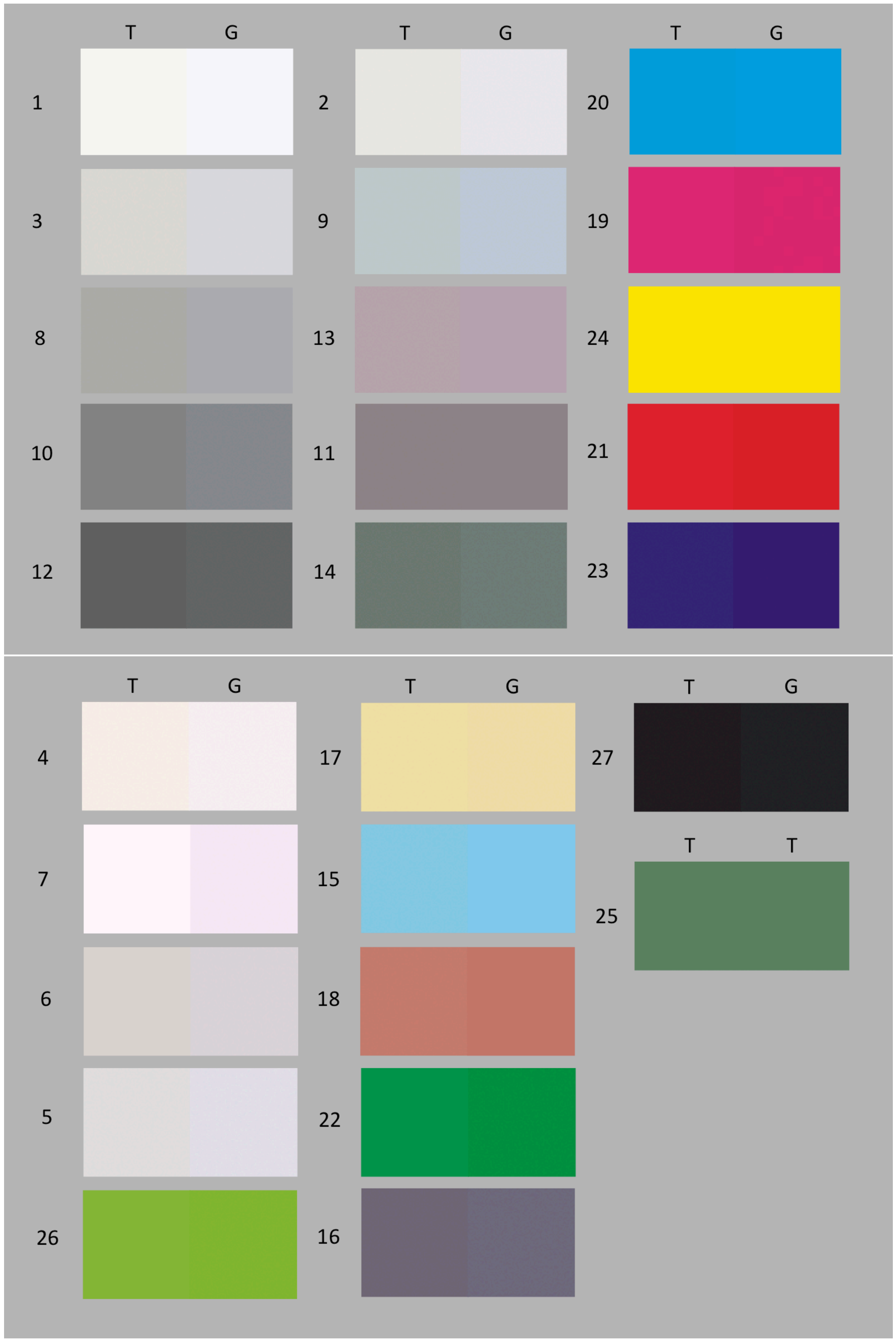
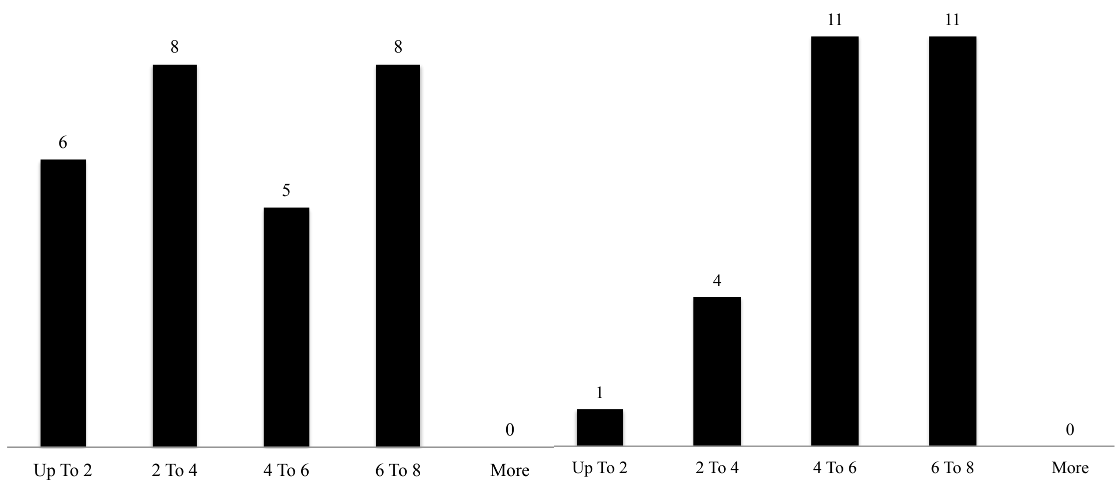


Figure 8: Simulation of 27 color pairs.

The distributions of ΔE_{00} and ΔE^*_{ab} from 0 to 8 at 2 unit intervals for the 27 color pairs are shown in Figure 9. The ΔE_{00} measurements were more evenly distributed than the ΔE^*_{ab} measurements, which infers the non-agreement between the two color difference metrics in evaluating the visually ranked color differences of the 27 color pairs.



(a) ΔE_{00} distribution (b) ΔE^*_{ab} distribution

Figure 9: The distributions of measured (a) ΔE_{00} and (b) ΔE^*_{ab} across 0 to 8 units.

Results of FM 100 Hue Test

Twenty observers had superior color discrimination (FM error score ≤ 20), while fourteen had average color discrimination (FM error score ≤ 100). One observer was color deficient (FM error score > 100). Therefore, 34 of the 35 observers were eligible to participate the psychometric experiment. Figure 10 shows the distribution of the FM 100 Hue test scores for the 34 observers

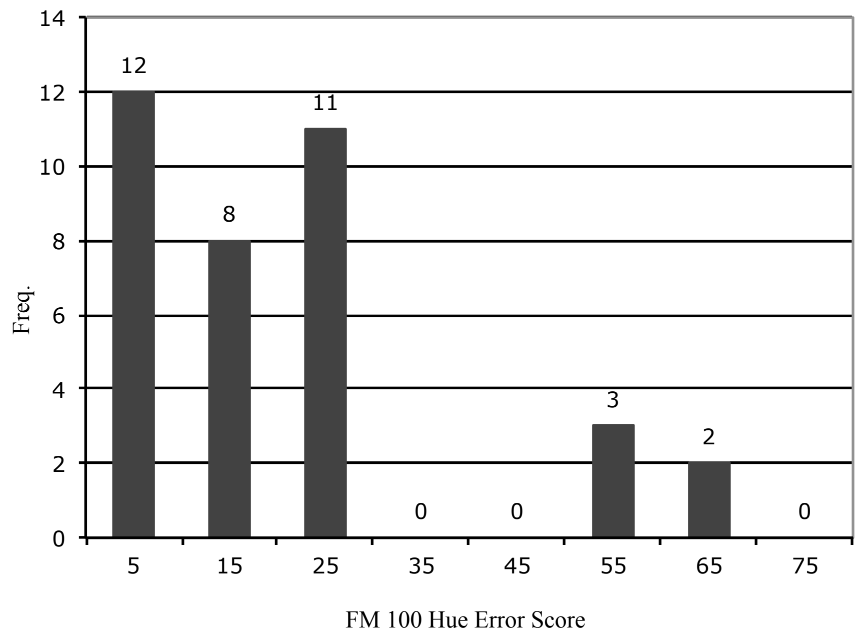


Figure 10: FM 100 Hue Test scores for 34 observers.

The distribution was not a normal distribution. Thirty-one observers had small error scores—indicating good color discrimination ability—although only 20 of these were originally classified as superior color discrimination. On the other hand, three observers fell in another group with error scores greater than 50. This means that their color discrimination ability was not as good as the majority; however, they were still classified as having average color discrimination.

Correlation between ΔE metrics and visual scaling

The visual ranking responses were quantified as follows: "0" for No Difference, "1" for JND, "2" for More than JND, and "3" for Noticeable Difference. The total scores for each pair were then averaged to represent the visual scaling. Both ΔE^*_{ab} and ΔE_{00}

values had already been calculated using spectral measurement after the sample pairs were generated. A linear correlation trend line was used to analyze the relationship between the ΔE metrics and the visual scaling. Figure 11 compares the two linear correlations.

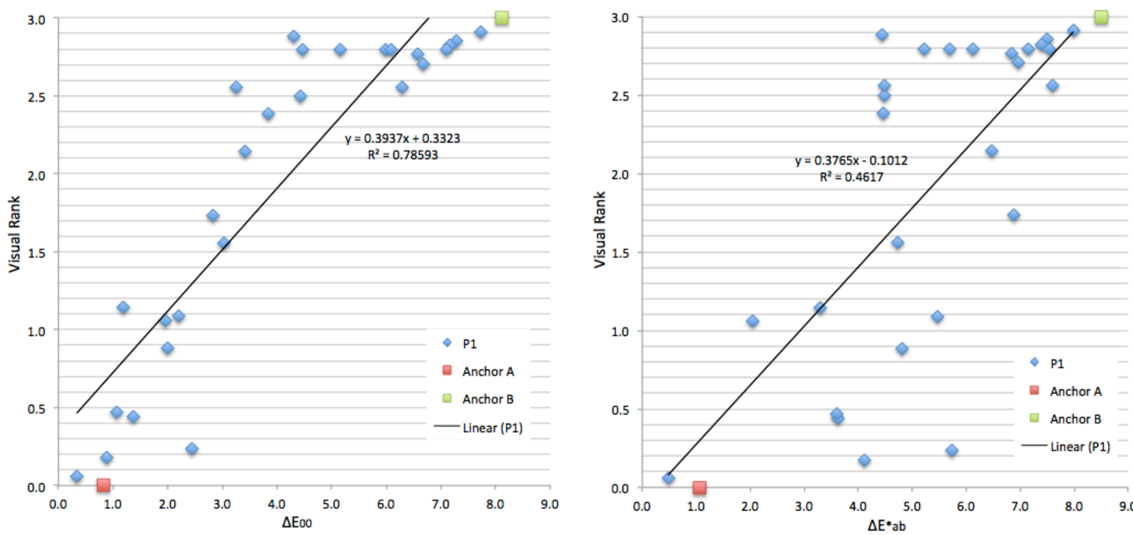


Figure 11: Linear correlation of ΔE_{00} and visual rank, ΔE^{*}_{ab} and visual rank.

With a significant R^2 coefficient of 0.79, the relationship between ΔE_{00} and the visual scaled color differences appear to be highly correlated. The correlation between ΔE^{*}_{ab} and the visual scaled color differences were not as strong, with an R^2 of only 0.46. Based on the above finding, we conclude that ΔE_{00} is a better predictor than ΔE^{*}_{ab} for perceived color differences between color pairs under standard illumination when the present methodology is utilized.

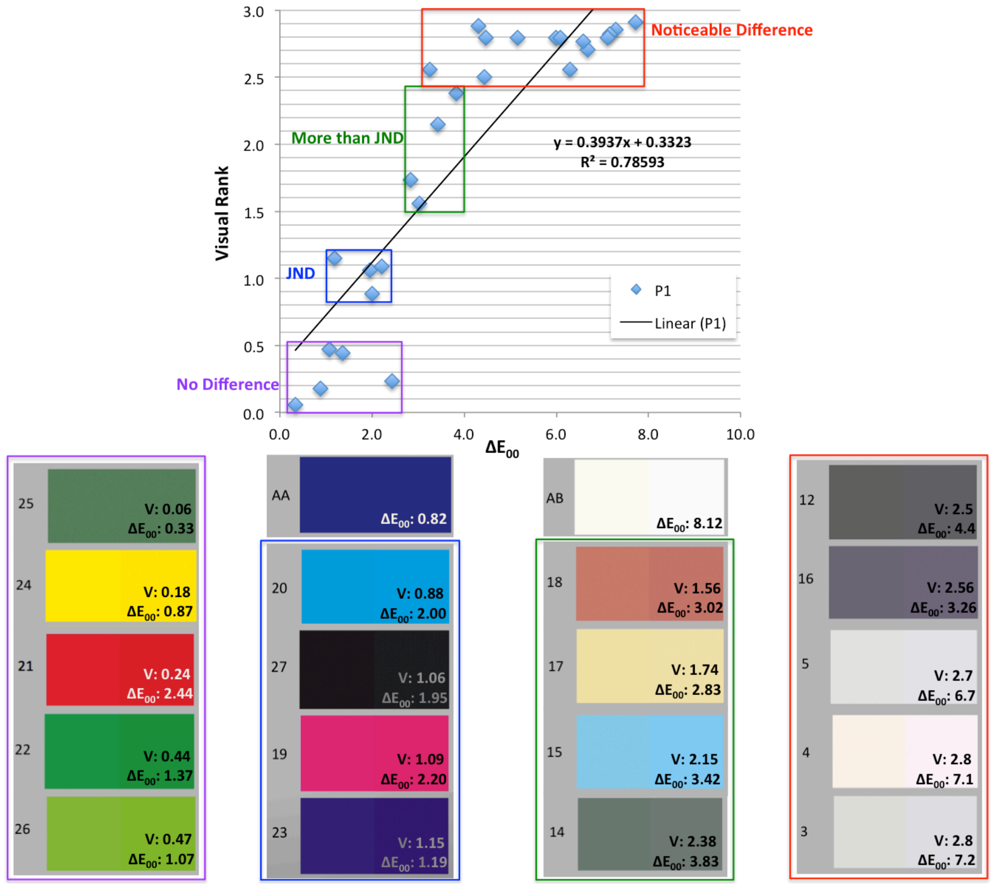


Figure 12: Perceptual uniformity analysis of ΔE_{00}.

As shown in Figure 12, pairs 24 and 25 were color pairs with visual scaling most close to 'No Difference', and corresponding ΔE_{00} of 0.87 and 0.33, respectively. Pairs 19, 20, 23, and 27 were color pairs with visual scaling most close to 'JND', and corresponding ΔE_{00} of 2.2, 2.0, 1.2, and 1.95, respectively. Pairs 18, 17, 15 and 14 were color pairs with visual scaling close to 'More than JND', and corresponding ΔE_{00} of 3.02, 2.83, 3.42, and 3.83, respectively.

Five color pairs with visual scaling close to 'Noticeable Difference' are shown, ranked by their ΔE_{00} values of 7.2, 7.1, 6.7, 3.3, and 4.4. From figure 12, it indicated that

once ΔE_{00} was larger than 4 units, the corresponding visual scaling for color pairs were all close to 'Noticeable Difference'.

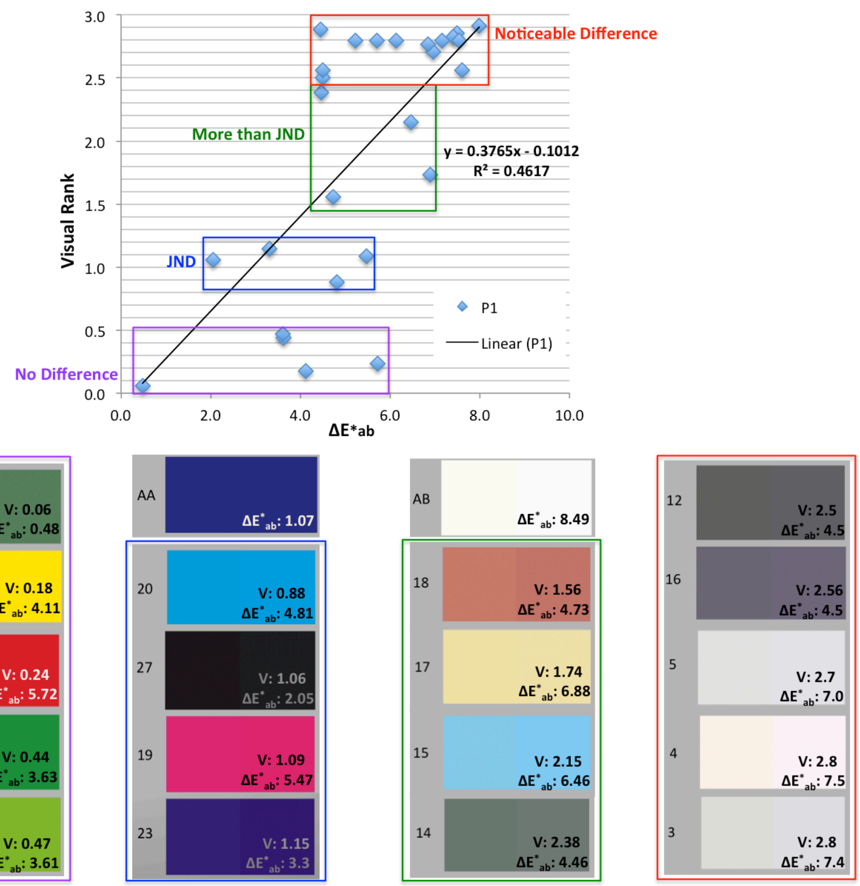


Figure 13: Perceptual uniformity analysis of ΔE^*_{ab}.

As shown in Figure 13, Pairs 24 and 25 were color pairs with visual scaling most close to 'No Difference', and corresponding ΔE^*_{ab} of 4.11 and 0.48, respectively. Pairs 19, 20, 23, and 27 were color pairs with visual scaling most close to 'JND', and corresponding ΔE^*_{ab} of 5.47, 4.81, 3.3, and 2.05, respectively. Pairs 18, 17, 15 and 14

were color pairs with visual scaling close to 'More than JND', and corresponding ΔE^*_{ab} of 4.73, 6.88, 6.46, and 4.46, respectively.

By comparison, ΔE_{00} values in the 'No Difference' region (Figure 12) are closer to each other and much less spread (see the width of purple rectangle) than ΔE^*_{ab} values in the 'No Difference' region (Figure 13). ΔE_{00} values in the 'JND' region (Figure 12) are closer to each other and much less spread (see the width of blue rectangle) than ΔE^*_{ab} values in the 'JND' region (Figure 13). ΔE_{00} values in the 'More than JND' region (Figure 12) are closer to each other and less spread (see the width of green rectangle) than ΔE^*_{ab} values in the 'More than JND' region (Figure 13).

To sum up, for color pairs with visual scaling close to Just Noticeable Difference, ΔE^*_{ab} did not correlate well with the visual scaling. This indicates that ΔE^*_{ab} is not as useful for predicting small-perceived color differences.

On the contrary, for the color pairs with visual scaling close to 'Noticeable Difference', there were 5 representative color pairs with ΔE^*_{ab} of 7.5, 7.4, 7.0, 4,5, and 4.5 (ranked from large to small), which were highly consistent with the ΔE_{00} evaluation. Therefore, the ΔE^*_{ab} and ΔE_{00} metrics had much more agreement in predicting larger differences within the scope as defined by the anchor pairs.

This research indicates that $\Delta E_{00} < 1$ has a corresponding visual issue that roughly equivalent to what is barely perceptual by the human visual system. If ΔE_{00} approached 2 units, the corresponding visual sensation is roughly equivalent to what is just noticeable difference. For ΔE_{00} of approximately 3 units, the corresponding visual difference would be not difficult to notice, while $\Delta E_{00} > 4$ correspond to visual difference. This result

strongly supports ΔE_{00} as a perceptual uniform color difference metric for use in evaluating small color differences under reference conditions.

In addition, the result of this research has also suggested that ΔE_{00} is a better predictor than ΔE^{*}_{ab} for perceived color differences, especially small differences, between printed colors with and without OBA under standard illumination. Therefore, ΔE_{00} is highly suggested when evaluating print color quality under the effect of OBA in today's commercial print.

This research also verified that the effects of OBA were most observable in areas with light ink coverage as stated by Chung and Tian (2011) as well as Chaikovsky and Garrison (2012). All of the color pairs with large visual scaling were light ink coverage colors, and, as the ink coverage of the color pair increased, the corresponding visual difference decreased. However, the color pair with the smallest visual scaling was the yellow solid (pair 24), rather than the darkest tone (pair 27). This is likely due to yellow absorbs blue energy and therefore highly reduces the perceived differences between papers with and without OBA.

This effect was also observed with the red solid (pair 21), which was an outlier for the ΔE_{00} and visual scaling correlation. This pair had a visual scaling of 0.24 and a measured ΔE_{00} of 2.44. This should be a just noticeable difference based on its ΔE_{00} evaluation.

Effect of illumination intensity on visual scaling of color pairs with dark shades

According to ISO 3664, "the high illumination levels specified for viewing condition P1 permit more critical evaluation of color and tone gradation in higher density areas that may not be perceived under most practical viewing conditions (P2)," (ISO 3664, p7 subclause 4.2.1). In order to test the above statement from ISO 3664 (2009), three dark tone pairs—pairs 12, 23, and 27—were selected from the 27 candidate pairs to test the association between different illumination intensities and the visual scaling of color differences.

Two-way tables and the Chi-square test were employed to test the association between different illumination intensities and observers' visual scaling for these three pairs. We expected that visual scaling for the three dark tone pairs vary by different illumination intensities. The null hypothesis H_0 assumes that there is no association between different illumination intensities and the visual scaling of color pairs with dark shades, while the alternative hypothesis H_a claims that some association does exist. The results for each pair are discussed in detail in the following paragraphs.

Chi-square test for pair 12 (C0M0Y0K80, L^*=35)

Figure 14: Pair 12 (C0M0Y0K80, L^* = 35).

Table 3: *Chi-square test of illumination intensity and visual scaling for pair 12.*

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Illumination * Visual	68	98.6%	1	1.4%	69	100.0%

Illumination * Visual Crosstabulation

			Visual			
			No difference	JND	More than JND	Total
Illumination	P1	Count	1	27	6	34
		Expected Count	1.5	27.5	5.0	34.0
		% within Illumination	2.9%	79.4%	17.6%	100.0%
		% within Visual	33.3%	49.1%	60.0%	50.0%
		% of Total	1.5%	39.7%	8.8%	50.0%
	P2	Count	2	28	4	34
		Expected Count	1.5	27.5	5.0	34.0
		% within Illumination	5.9%	82.4%	11.8%	100.0%
		% within Visual	66.7%	50.9%	40.0%	50.0%
		% of Total	2.9%	41.2%	5.9%	50.0%
Total		Count	3	55	10	68
		Expected Count	3.0	55.0	10.0	68.0
		% within Illumination	4.4%	80.9%	14.7%	100.0%
		% within Visual	100.0%	100.0%	100.0%	100.0%
		% of Total	4.4%	80.9%	14.7%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	.752[a]	2	.687
Likelihood Ratio	.761	2	.684
Linear-by-Linear Association	.722	1	.395
N of Valid Cases	68		

a. 2 cells (33.3%) have expected count less than 5. The minimum expected count is 1.50.

Symmetric Measures

		Value	Approx. Sig.
Nominal by Nominal	Phi	.105	.687
	Cramer's V	.105	.687
N of Valid Cases		68	

A chi-square test of independence indicated that different illumination intensities (P1 versus P2) was not associated with the visual scaling of dark tone pair 12 (C0M0Y0K80, L^* = 35), χ^2 (2, N = 68) = 3.215, p = .2 > .05, Cramér's V= .217.

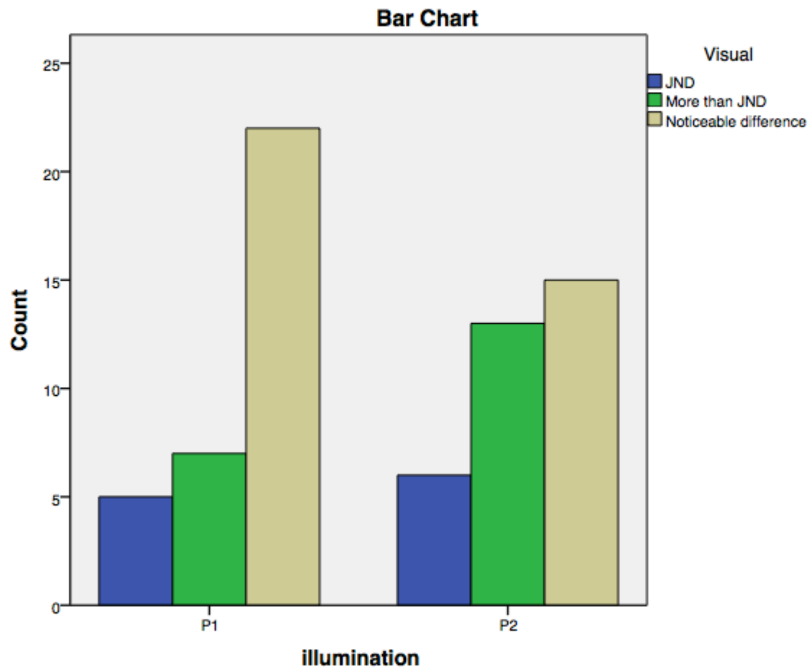


Figure 15: Visual scaling count for P1 and P2 in bar chart of Pair 12.

Although no association between different illumination intensities and the visual scaling for Pair 12 was supported statistically, Figure 15 indicates that observers tend to see more differences for pair 12 under P1 illumination than P2 illumination conditions.

Chi-square test for pair 23 (C100M100Y0K0, L^*=21)

Figure 16: Pair 23 (C100M100Y0K0, L^* = 21).

Table 4: *Chi-square test of illumination intensity and visual scaling for pair 23.*

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Illumination * Visual	68	98.6%	1	1.4%	69	100.0%

Illumination * Visual Crosstabulation

			Visual			Total
			No difference	JND	More than JND	
Illumination	P1	Count	1	27	6	34
		Expected Count	1.5	27.5	5.0	34.0
		% within Illumination	2.9%	79.4%	17.6%	100.0%
		% within Visual	33.3%	49.1%	60.0%	50.0%
		% of Total	1.5%	39.7%	8.8%	50.0%
	P2	Count	2	28	4	34
		Expected Count	1.5	27.5	5.0	34.0
		% within Illumination	5.9%	82.4%	11.8%	100.0%
		% within Visual	66.7%	50.9%	40.0%	50.0%
		% of Total	2.9%	41.2%	5.9%	50.0%
Total		Count	3	55	10	68
		Expected Count	3.0	55.0	10.0	68.0
		% within Illumination	4.4%	80.9%	14.7%	100.0%
		% within Visual	100.0%	100.0%	100.0%	100.0%
		% of Total	4.4%	80.9%	14.7%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	.752[a]	2	.687
Likelihood Ratio	.761	2	.684
Linear-by-Linear Association	.722	1	.395
N of Valid Cases	68		

a. 2 cells (33.3%) have expected count less than 5. The minimum expected count is 1.50.

Symmetric Measures

		Value	Approx. Sig.
Nominal by Nominal	Phi	.105	.687
	Cramer's V	.105	.687
N of Valid Cases		68	

A chi-square test of independence indicated that different illumination intensities (P1 versus P2) was not associated with the visual scaling of dark tone pair 23 (C100M100Y0K0, $L^* = 21$), χ^2 (2, N = 68) = 0.752[2], p = .687 > .05, Cramér's V= .105.

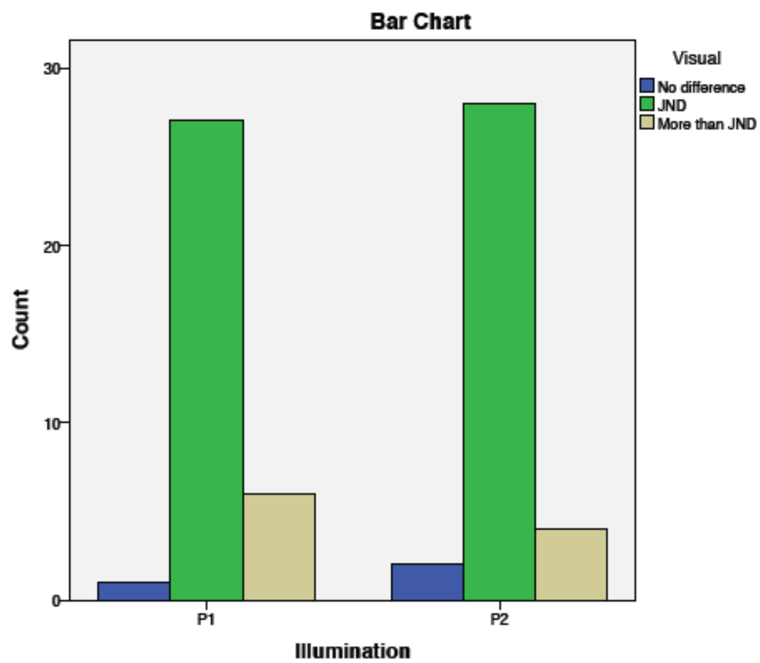


Figure 17: Visual scaling count for P1 and P2 in bar chart of Pair 23.

Although no association between different illumination intensities and the visual scaling of Pair 23 was supported statistically, Figure 17 indicates that observers tend to see more differences for Pair 23 under P1 illumination than P2 illumination conditions.

[2] For these data, two cells (33.3%) have expected cell counts less than five. Cochran (1954) cautions against using Chi-Square in instances where 20% or more of the expected cell counts are less than five, as is the case here. Many researchers respond to this criteria by collapsing the categories, however doing so here would require a different research question. It is also widely recognized that Cochran's edict is very conservative (e.g: Everitt (1977) citing work by Lewontin & Felsenstein (1965)). Therefore the tabular results shown here with less than 34% of the cell frequencies less than five are included in the present analysis.

Chi-square test for Pair 27 (C40M27Y27K100, L^*=13)

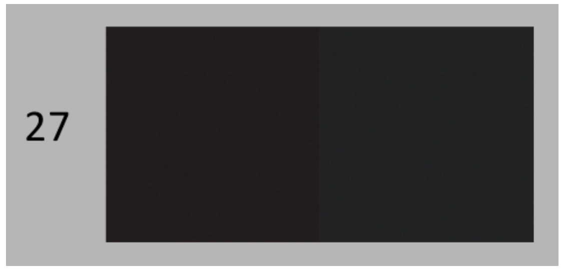


Figure 18: Pair 27 (C40M27Y27K100, L^* = 13).

Table 5: *Chi-square test of illumination intensity and visual scaling for Pair 27*.

Lighting * Visual Crosstabulation

			Visual			Total
			No difference	JND	More than JND	
Lighting	P1	Count	6	20	8	34
		Expected Count	7.0	19.0	8.0	34.0
		% within Lighting	17.6%	58.8%	23.5%	100.0%
		% within Visual	42.9%	52.6%	50.0%	50.0%
		% of Total	8.8%	29.4%	11.8%	50.0%
	P2	Count	8	18	8	34
		Expected Count	7.0	19.0	8.0	34.0
		% within Lighting	23.5%	52.9%	23.5%	100.0%
		% within Visual	57.1%	47.4%	50.0%	50.0%
		% of Total	11.8%	26.5%	11.8%	50.0%
Total		Count	14	38	16	68
		Expected Count	14.0	38.0	16.0	68.0
		% within Lighting	20.6%	55.9%	23.5%	100.0%
		% within Visual	100.0%	100.0%	100.0%	100.0%
		% of Total	20.6%	55.9%	23.5%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	.391[a]	2	.822
Likelihood Ratio	.392	2	.822
Linear-by-Linear Association	.132	1	.717
N of Valid Cases	68		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 7.00.

Symmetric Measures

		Value	Approx. Sig.
Nominal by Nominal	Phi	.076	.822
	Cramer's V	.076	.822
N of Valid Cases		68	

A chi-square test of independence indicated that different illumination intensities (P1 versus P2) was not associated with the visual scaling of dark tone pair 12 (C40M27Y27K100, $L^* = 13$), χ^2 (2, N = 68) = .391, p = .822 > .05, Cramér's V= .076.

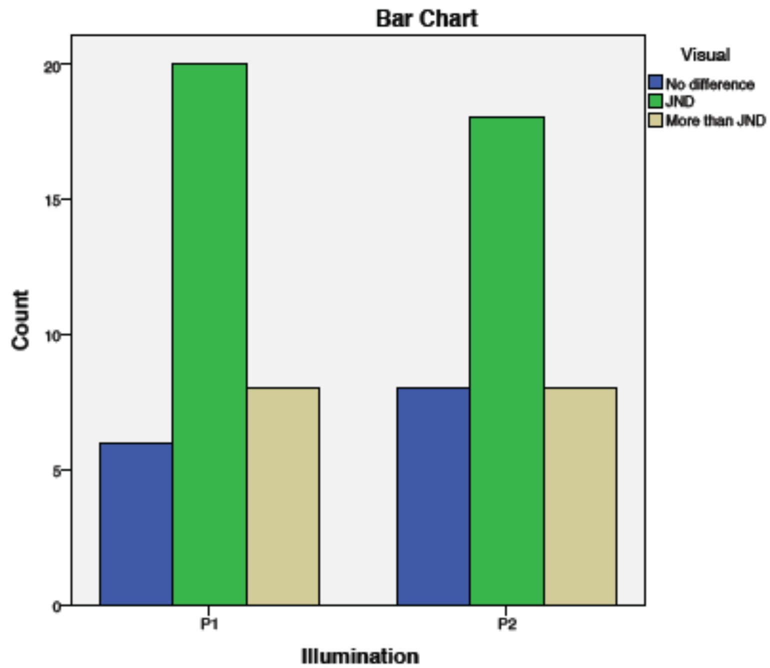


Figure 19: Visual scaling count for P1 and P2 of Pair 27.

Although no association between different illumination intensities and the visual scaling of Pair 27 was supported statistically, Figure 19 indicates frequency distribution for Pair 27 under P1 illumination and P2 illumination conditions.

Chapter 7

Summary and Conclusion

The result from testing the correlation between visual and quantitative assessments of OBA-induced color differences successfully supports that ΔE_{00} is superior to ΔE^*_{ab} as a perceptual uniform color difference metric for use in evaluating small color differences under reference conditions.

Color differencing formulas have been in used for decades, the E^*_{ab} formula that released by CIE in 1976 is still widely used in industry and in research, but this formula has its drawback and a number of other color differencing equations have been issued in order to accommodate how the human eye perceives color differencing in different areas of the color space.

ΔE^*_{94} has been introduced by CIE in 1994 in order to match closer to the color difference perception of the human eye. However, it was discovered a lack of accuracy in the blue-violet region of the color space, which lead to the release of the ΔE_{00} formula in 2000 to address the shortcomings of the ΔE^*_{94}. Apart from CIE, the CMC (Color Measurement Committee of the Society of Dyes and Colorists of Great Britain) is another body that contributed its effort to address the shortcomings of the initial ΔE^*_{ab} formula. It also developed an equation that is based on the L^*C^*h-notion of colors (Clarke, 1984), which is the ΔE_{cmc} formula. The ΔE_{cmc} formula is widely used in the textile industry, and this equation takes the various color sensitivities of the human visual system into consideration, it gives a perceptually uniform evaluation for small color differences in all

regions of the color-wheel, (Habekost, 2013). As ISO has traditionally utilized ΔE^*_{ab} and has more recently turned to ΔE_{00}, the other tolerance methods were not utilized in the present study.

In today's printing industry, more and more paper substrates are highly OBA-loaded, which affects the printing conformity, leads to proof-to-print mismatch and limits the effectiveness of printing standards. In this regard, agreement between the visual and the quantitative assessments of OBA-induced color differences is a significant issue.

ΔE^*_{ab} was found to have limitations correlating OBA-induced small chromatic differences based on the psychophysical experiment in the present research. When compared to ΔE^*_{ab}, ΔE_{00} suggests to be more linearly correlated with visual assessments of OBA-induced color differences. The present research upholds latest ISO standards and specifications to better resolve the printing unconformity and poof-to-print mismatch issues caused by OBA loaded paper substrates.

Limitations and Future Research

The research was limited to color differences induced by OBA-loaded paper, and OBA-induced extra blue energy leads to mainly hue and chroma differences between sample pairs. However, color differences larger than the OBA-induced differences, are outside the scope of this research.

On the other hand, widely utilized ΔE_{cmc} and ΔE_{94} in the industry are not involved in the present research. Further research could involve ΔE_{cmc} and ΔE_{94} into comparison

with ΔE_{00}, and to answer the question whether ΔE_{cmc} and ΔE_{94} will likely perform as well as ΔE_{00} in evaluating OBA-induced small color differences under reference conditions.

Testing the effects of different illumination intensities on visual scaling of color pairs with dark shades was not statistically associated. Therefore, the ISO 3664 (2009) statement, high illumination levels specified for viewing condition P1 permit more critical evaluation of color and tone gradation in higher density areas that may not be perceived under viewing conditions P2, requires further research involving different visual scaling methods, diversified sample pairs, and a larger number of observers to investigate.

Furthermore, one other area of research is to enlarge the visual response from perceptibility to acceptability using pictorial color images.

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Appendix A

ISO 13655 Table 1 Spectral weights, $W(\lambda)$, for illuminant D50 and the 2°observer for calculating tristimulus from data at 10 nm intervals.

Table 6: *ISO 13655 Spectral weights*. *(Reference to ISO 13655 Table 1)*

Wavelength	$W_X(\lambda)$	$W_Y(\lambda)$	$W_Z(\lambda)$
360	0.000	0.000	0.001
370	0.001	0.000	0.005
380	0.003	0.000	0.013
390	0.012	0.000	0.057
400	0.060	0.002	0.285
410	0.234	0.006	1.113
420	0.775	0.023	3.723
430	1.610	0.066	7.862
440	2.453	0.162	12.309
450	2.777	0.313	14.647
460	2.500	0.514	14.346
470	1.717	0.798	11.299
480	0.861	1.239	7.309
490	0.283	1.839	4.128
500	0.040	2.948	2.466
510	0.088	4.632	1.447
520	0.593	6.587	0.736
530	1.590	8.308	0.401
540	2.799	9.197	0.196
550	4.207	9.650	0.085
560	5.657	9.471	0.037
570	7.132	8.902	0.020
580	8.540	8.112	0.015
590	9.255	6.829	0.010
600	9.835	5.838	0.007
610	9.469	4.753	0.004
620	8.009	3.573	0.002
630	5.926	2.443	0.001
640	4.171	1.629	0.000
650	2.609	0.984	0.000
660	1.541	0.570	0.000
670	0.855	0.313	0.000

680	0.434	0.158	0.000
690	0.194	0.070	0.000
700	0.097	0.035	0.000
710	0.050	0.018	0.000
720	0.022	0.008	0.000
730	0.012	0.004	0.000
740	0.006	0.002	0.000
750	0.002	0.001	0.000
760	0.001	0.000	0.000
770	0.001	0.000	0.000
780	0.000	0.000	0.000
Check sums	96,421	99,997	82,524
White point	$X_n = 96{,}422$	$Y_n = 100{,}000$	$Z_n = 82{,}521$
These weighting functions are extracted with permission from Table 1 of ISO 13655: 2009			

Appendix B

The psychometric visual scaling experiments were conducted using a GTI viewing cabinet equipped with a D50 simulator, which adjusts the illuminant intensity. The GTI viewing booth conformed to the ISO 3664 P2 condition when its illumination intensity was set at 40, which had a correlated color temperature of 4781 K and an illuminance of 546 lx. The GTI viewing booth conformed to the ISO 3664 P1 condition when its illumination intensity was set at 80, which had a correlated color temperature of 4927 K and an illuminance of 2039 lx. In addition, the spectral power distribution of the GTI viewing booth conformed to ISO 3664 requirements with a verified Metamerism Index (MI) equal to 0.833 meets grade C (ISO 3664 specifies that grade C shall be < 1.0). The illuminating/viewing geometry was approximately 0°/45° at a viewing distance of about 25 cm.

The GTI booth has an illumination intensity control. By using a Konica Minolta's FD-7 spectro-radiometer, we can verify if the relative color temperature and the illumination intensity level conforms to ISO 3664 P1 (D50 with 2,000 lx) or P2 (D50 with 500 lx) conditions for the required visual experiments.

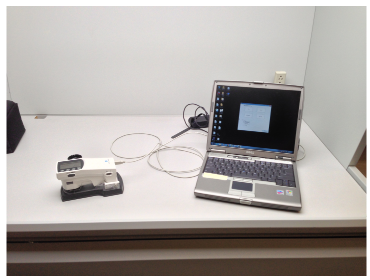

Figure 20: *GTI viewing booth and Konica Minolta's FD-7 spectro-radiometer.*

The Illuminance Adapter is used on the Fd-7 when performing illuminance measurements in the following steps:

1. Remove the target mask and attach the Illuminance Adapter.
2. Point the specimen measuring port toward the illuminant to measure. The angle, distance, and surround are shown in Figure 21.

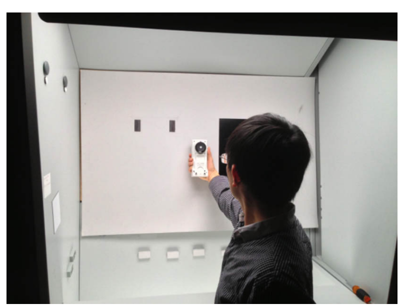

Figure 21: *The angle, distance, and surround when performing illuminance measurements.*

3. Press the measuring button. The measurement value is displayed. The GTI viewing booth conforms to P2 when its luminance is set at 40 (Figure 22).

Figure 22: *Illuminance measurement for P1.*

4. The gti viewing booth conforms to P1 when its luminance is set at 80 (Figure 23).

Figure 23: *Illuminance measurement for P2.*

Appendix C

After the 27 CMYK values were selected from the IT8.7/4 target, the corresponding 27 color patches were created in Adobe InDesign as 3.5 inch squares.

The InDesign file was exported as a PDF with the PDF/X-1a: 2001 preset. The PDF file was used as the input file for the Kodak Approval system to output color samples.

The dimension of the paper was 23*29 inches. There were 4 copies of the color sample output, 2 of which were laminated on Invercote T, while the other 2 were laminated on Invercote G. These were labeled as T1, T2, G1 and G2. Two pairs of T and G were matched to 24 simple color pairs. One pair was used for the psychophysical visual measurements, while the other pair was a backup.

Instrumental color measurement was performed for all color samples before they were cut into individual pairs. For each color sample, it was necessary to measure twice and take the average of the two measurements in order to achieve accurate measurement data.

Appendix D

Instruction for Visual Assessment

Thank you for taking the next 10-15 minutes to go through the visual experiment. The purpose of this visual experiment is to see how you discern and describe small color differences in a color pair.

Please note that this experiment includes two parts, each part followed by same procedure with same stimulus in various sequences, the lighting conditions for the two parts are different and you will get two score sheets (random two of three) for the two parts of the experiment respectively.

There is no wrong or right answer, just your subjective judgment.

Procedures

1) You will be given two sets of Anchor pairs before you are presented with the sample color pairs, which you are asked to evaluate. The perceived color differences of the two Anchor pairs, 'A1' and 'A2' are defined as 'Noticeable difference' and 'No difference'.
2) There are a total of 27 sample color pairs at each part of the test; you will be given one sample color pair at a time.
3) Please compare your perceived color difference to the 'Anchor' pairs and mark your perceived color difference for each sample pair using *Noticeable Difference, More than Just Noticeable Difference, Just Noticeable Difference (JND)* or *No Difference.*

4) After completing the evaluation, the light intensity will be changed and the experiment will be repeated.

Observer _____
Score Sheet (A)
ISO 3664 Lighting Condition (P1, P2)

Given the presence of the 'Anchor' pairs indicating 'Noticeable Difference' and 'No Difference', please place a "√ " mark that describes your visual sensation of the color pairs presented in random order.

Color Pair#	No Difference	Just Noticeable Difference	More than Just Noticeable Difference	Noticeable Difference
6				
27				
9				
16				
19				
20				
17				
11				
25				
18				
24				
2				
13				
22				
15				
1				
3				
23				
21				
14				
7				
8				
10				
4				
26				
5				
12				

Observer _____
Score Sheet (B)
ISO 3664 Lighting Condition (P1, P2)

Given the presence of the 'Anchor' pairs indicating 'Noticeable Difference' and 'No Difference', please place a "√ " mark that describes your visual sensation of the color pairs presented in random order.

Color Pair#	No Difference	Just Noticeable Difference	More than Just Noticeable Difference	Noticeable Difference
3				
4				
16				
2				
27				
6				
18				
15				
22				
17				
19				
1				
14				
24				
25				
13				
23				
5				
11				
10				
7				
9				
8				
21				
12				
20				
26				

Observer _____

Score Sheet (C)

ISO 3664 Lighting Condition (P1, P2)

Given the presence of the 'Anchor' pairs indicating 'Noticeable Difference' and 'No Difference', please place a "√ " mark that describes your visual sensation of the color pairs presented in random order.

Color Pair#	No Difference	Just Noticeable Difference	More than Just Noticeable Difference	Noticeable Difference
15				
17				
14				
6				
16				
22				
20				
25				
9				
5				
24				
23				
26				
8				
4				
12				
3				
10				
27				
18				
19				
21				
13				
1				
7				
2				
11				