An Evaluation of Instrumental Measurement Condition with Fluorescing Substrates and Colorants

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Keywords: Spectrophotometer, Inter-Instrument Agreement, Fluorescence, Accelerated Aging, Measurement Condition, Optical Brightening Agends (OBAs)

When viewing a given reflective object, the perceived color is the result of the spectral reflectance of that object, the spectral power distribution of the illuminant (widely referred to as SPD), and the sensitivity of the observer. Changes to any of these factors can become a source of variation in image reproduction in color critical workflows. Initiatives to control for these in industry include the widespread use of CIE standard observers, and the standardization of the SPD of the illuminant: most commonly D50 as defined by ISO 3644:2009.

While the visible region of the electromagnetic spectrum is generally described as light with wavelengths of approximately 380nm – 760nm, it is important to recognize that a phenomenon known as fluorescence can influence perceived color. Fluorescence occurs when an object absorbs radiation in the Ultra Violet (UV) range of the spectrum (below 380 nm) and re-emits this radiation in the "near UV" visible range (generally, 380-450nm). In commercial color reproduction, fluorescence is realized with the use of Optical Brightening Agents (OBAs) in the manufacture of substrates and colorants. In the case of paper substrates, for example, these OBAs increase the perceived whiteness of a sheet without the more costly and less-environmentally friendly process of bleaching (Vogt & Keif, 2012). Critical to examining OBAs is the recognition that the relative effect is dependent not only on the presence of OBAs in the material, but on the amount of UV radiation present in the illumination source. This represents yet another source of variation in color workflows.

When spectrophotometric instruments are utilized to measure color, the characteristics of the SPD in the respective instrument illuminants needs to be recognized. Historically, CIE Illuminant A, which represents tungsten lighting at 2856 Kelvin has been used in the majority of spectrophotometers (Cheydleur & O'Connor,

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2012). This contrasts with the ISO 3664 specification for visual inspection, which specifies CIE Illuminant D50. As Illuminant D50 includes more spectral power in the UV range when compared to Illuminant A (GTI Technote, 2011), it is recognized that when materials containing OBAs are utilized inconsistencies between instrumental and visual evaluations can occur, even when standardized viewing conditions are strictly enforced.

In response, ISO 13655 further refined the measurement conditions for the illuminants utilized in instrument manufacture. The measurement condition known as M1 mandates a close match to D50, including the UV portion (McDowell, 2006). A 'legacy' condition, known as M0, recognizes the wide population of instrumentation used in the field: Cheydleur and O'Connor state: "M0 is limited in its definition and does not fully define either the measurement illuminant condition or the UV content of the sources. This is because M0 is also meant as a broad definition to included historical instruments of all types that do not fit into any of the other M conditions." As the UV content of measurement condition M0 is not defined, it is generally not recommended for color workflows were OBAs are present in the substrates and colorants. A further delineation of the M1 condition separates such instruments into those where the spectral illumination of the instrument light source matches D50, known as M1 Part One, and those that utilize a compensation method and a controlled amount of UV in the light source, known as M1 Part Two.

The present study analyzes instrumentation commonly used in graphics reproduction workflows using both M0 and M1 measurement conditions. Using five 'legacy' spectrophotometers measuring utilizing the M0 condition, and three spectrophotometers capable of measuring both the M0 and M1, four different paper substrates containing various levels of OBAs are analyzed. To evaluate the effect of solid colorants on the chosen substrates, eight commonly used lithographic printing inks are applied to the substrates using a proofing device with the goal of simulating production ink film thicknesses. These samples are then measured with each instrument and measurement condition. These readings are analyzed to note any differences in the various instruments/measurement conditions.

An additional goal of the study is to evaluate how each instrument/measurement condition reads change in the substrate and substrate/ink combination. Therefore, the samples were subject to accelerated aging in a frequently used fade test which utilized a Xenon-Arc test chamber, and then those same samples were re-measured. It is widely recognized that fade testing not only affects both the color of the ink and paper, but also serves to lessen the effect of the OBAs. As such, it is deemed reasonable by the researcher to employ the fade method in the analysis of change in both color and OBA effect.

Rather than utilize tri-stimulus or colorimetric values to evaluate the chosen instruments, spectral curves were generated and the area under the respective curves were analyzed in the 400 – 460nm region. This region was chosen as this is where the OBA effect would be recognized: Herold (2013) states that the spectral histogram is "…a sure indicator of the presence of OBAs…' (p. 9). Resulting reflectance data are entered into a spreadsheet, and spectral curves are generated. These curves are then fit with trend lines using second order polynomials with the goal of obtaining R2 values over 0.95. In instances where these R2 values were not realized, third order polynomials were utilized to obtain a better curve fit.

The areas under the curves were obtained using Reimann Sum Trapezoidal Rule. To check the validity of this method, ten percent of the resulting equations representing the curves were entered into WolframAlpha™ to calculate the definite integral. When compared to the Reimann Sum Trapezoidal Rule, it was determined that in this case the Trapezoidal Rule represented a reasonable method for comparison.

In instances where the spectral curves both before and after accelerated aging were analyzed, and those curves crossed, WolframAlpha™ was again utilized to determine the point of intersection by setting the curve equations equal to each other. In these cases, the differences in the areas under the respective curves could be better calculated.

Results:

In an examination of measurement condition across all substrates and ink samples before the samples were subjected to accelerated aging, a visual examination of the boxplots as shown in Figure 1 indicates that of the area under the curves for M0 and M1 were similar, and as illustrated in Table 1.

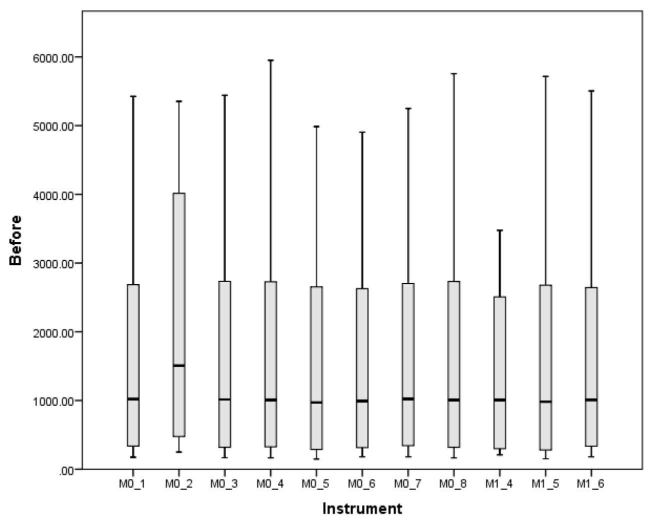

Figure 1. *Boxplot of area under spectral curve 400-460 nm for each sample before accelerated aging, by instrument.*

Instrument	Mean	Range	Standard Deviation
M0_1	1652.6	5251.8	1604.6
M0_2	2127.1	5105.0	1764.4
M0_3	1653.8	5274.4	1622.0
M0_4	1691.9	5784.2	1719.3
M0_5	1560.9	4836.6	1477.3
M0_6	1579.0	4723.4	1498.6
M0_7	1611.8	5070.5	1509.1
M0_8	1636.4	5589.9	1583.8
M1_4	1328.9	3265.8	1127.4
M1_5	1625.0	5563.6	1609.4
M1_6	1618.5	5322.4	1555.0

Table 1. *Area under spectral curve 400-460 nm for each sample before accelerated aging, by instrument.*

Continuing an evaluation of the individual paper substrates only before being subjected to accelerated aging, a further analysis of each instrument measuring each of the four substrates without ink indicates that one M1 instrument yielded noticeably lower values then the other M1 and M0 readings, as illustrated in Figure 2 and Table 2. It is relevant to note that this particular instrument was the sole measurement device that adhered to M1 Part One, whereas the other M1 instruments were reading M1 Part Two. The arithmetic means, range, and standard deviations of the substrate readings are illustrated in Table 2.

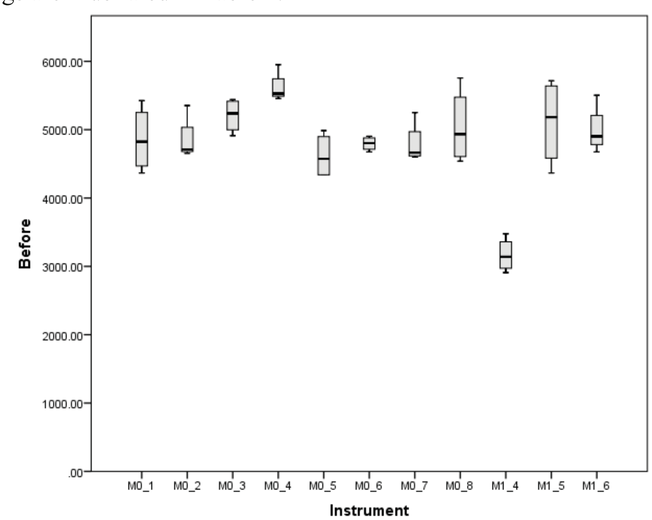

Figure 2. *Boxplot of area under spectral curve 400-460 nm for each substrate only before accelerated aging, by instrument.*

Instrument	Mean	Range	Standard Deviation
M0_1	4860.4	1059.1	480.6
M0_2	4857.4	699.2	332.0
M0_3	5207.8	528.5	252.3
M0_4	5615.9	494.6	225.7
M0_5	4618.39	647.3	331.2
M0_6	4797.0	228.6	103.0
M0_7	4793.9	652.4	306.9
M0_8	5040.8	1215.5	553.8
M1_4	3166.0	566.2	248.7
M1_5	5111.9	1350.5	638.3
M1_6	4995.7	827.5	354.9

Table 2*. Area under spectral curve 400-460 nm for each substrate only before accelerated aging, by instrument.*

Turning to the difference readings, the results from the previously recorded data were compared to the same samples after accelerated aging for each paper and ink sample, and the difference in area under the spectral curves in the 400 – 460 nm region was recorded. The strategy underlying the reporting of such difference readings is twofold. First, when differences in the same sample are measured it affords the ability to examine differences in the same sample: the use of a template for measurement area ensured reading the same spot before and after the accelerated ageing process. Second, ageing not only introduces differences in colorants such as inks in the form of fade, but also diminishes the effect of OBAs: after the accelerated ageing test the samples did not exhibit the same amount of fluorescence when qualitatively viewed under a UV-A illuminant (also known as a "black light").

When all samples are analyzed, distributions of the area under the curves for M0 and M1 were similar, as assessed by visual inspection of Figure 3, and reported in Table 3. These similarities suggest that when used in an absolute manner, the tested spectrophotometers will measure difference nearly the same: measurement condition did not seem to be a factor here in assessing the difference readings of the respective instruments.

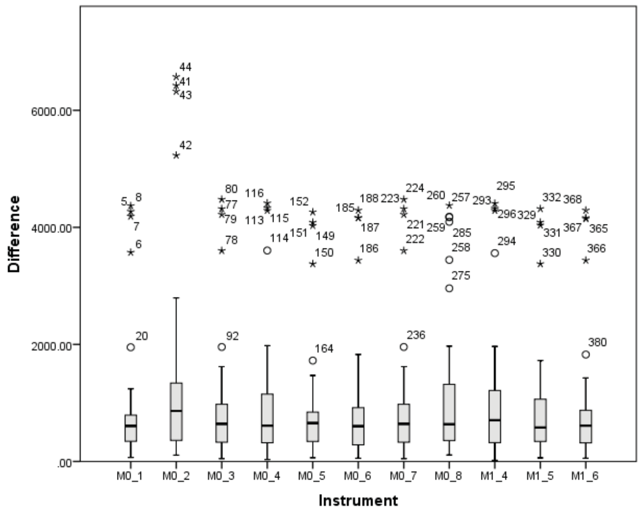

Figure 3. *Boxplot of area under spectral curve 400-460 nm for the difference of each sample before and after accelerated aging, by instrument.*

Instrument	Mean	Range	Standard Deviation
M0_1	965.4	4300.7	1183.7
M0_2	1429.7	6465.4	1803.6
M0_3	1010.1	4428.0	1207.7
M0_4	1027.7	4381.6	1029.8
M0_5	998.3	4198.8	1121.2
M0_6	984.9	4236.0	1161.8
M0_7	1010.1	4428.0	1207.7
M0_8	1174.3	4265.3	1309.6
M1_4	1051.0	4387.7	1199.1
M1_5	983.1	4256.6	1133.0
M1_6	983.2	4236.0	1156.4

Table 3. *Area under spectral curve 400-460 for the difference of each sample before and afteraccelerated aging, by instrument.*

Similarly, analyses were conducted on the difference readings in the individual values obtained when each paper substrate was measured. In these instances, no statistically significant difference was found between the M1 and the M0 instrumentation, consistent with the visual analysis of Figure 4 and Table 4.

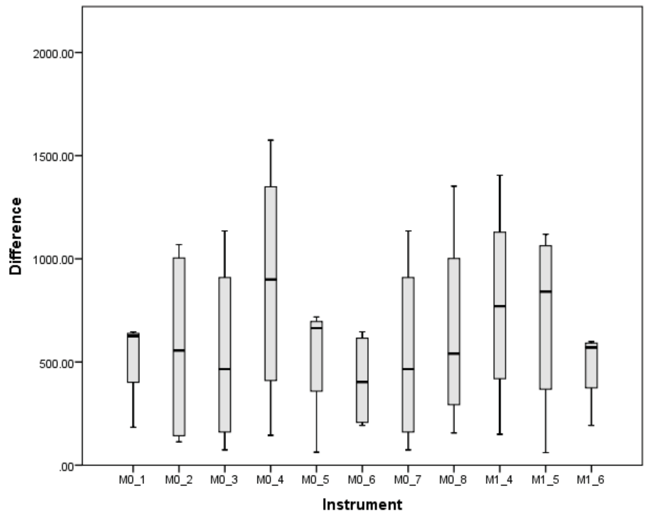

Figure 4. *Boxplot of area under spectral curve 400-460 nm for the difference of each substrate only before and after accelerated aging, by instrument.*

Instrument	Mean	Range	Standard Deviation
M0_1	520.2	461.7	224.6
M0_2	573.3	955.9	500.6
M0_3	543.9	1061.2	475.2
M0_4	879.6	1430.4	612.3
M0_5	527.2	655.5	310.9
M0_6	411.3	453.9	237.3
M0_7	534.9	1061.2	475.2
M0_8	647.3	1195.9	511.5
M1_4	773.9	1254.8	516.7
M1_5	715.6	1058.7	475.5
M1_6	483.1	405.8	194.5

Table 4. *Area under spectral curve 400-460 nm for the difference of each substrate only before and after accelerated aging, by instrument.*

Analysis:

The present study was limited in the number of instruments used to analyze the samples, so the results should be considered preliminary and informational. The analysis here however suggests that it is important to underscore the continued need for diligence when communicating colorimetric values both within and among various instrument types. Practitioners are advised against adopting practices where measurement condition alone is specified when various instruments are utilized throughout a workflow. Rather, measurement condition together with the other metrological variables, as well as colorimetric variables and procedural variables all need to be specified by those that desire to drive variance out of their respective workflows. Technologies exist that automate and succinctly facilitate the communication of such variables: users are encouraged to take advantage of such workflow solutions.

Furthermore, the methodological approach utilized in the present study demonstrates promise: utilizing the area under the spectral curves as a metric for comparison may yield a manner in which to evaluate spectrophotometers without introducing potential measurement variance inherent in more commonly utilized colorimetrics, such as CIE L*a*b*. In addition, using accelerated ageing as a method with which to evaluate differences affords the opportunity to measure essentially the same sample spot before and after, while introducing changes in both color and the fluorescing effects of OBAs.

Finally, is interesting to note there were little notable inequality in the M1 and the M0 instruments in the difference readings of the same samples before and after accelerated ageing. The addition of the effect of decreased fluorescence with fade did not appear to cause increased incongruence between the measurement types in this particular research design.

Conclusion

As M1 instruments increasingly permeate the market, there will likely be more and more instances when they are used side-by-side with legacy M0 instrumentation. The present descriptive research suggests that users remain vigilant about communicating relevant metrology issues. Future researchers may choose to build upon the methods utilized here with the goal of refining the expected variance in color measurement instruments. Further, as instruments capable of measuring M1 become increasingly available, future researchers should examine larger populations of instruments and thereby provide more practical insight for those concerned with inter-instrument agreement issues.

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ISO 13655: 2009 Graphic Technology – Spectral measurement and colorimetric computation to graphic arts images

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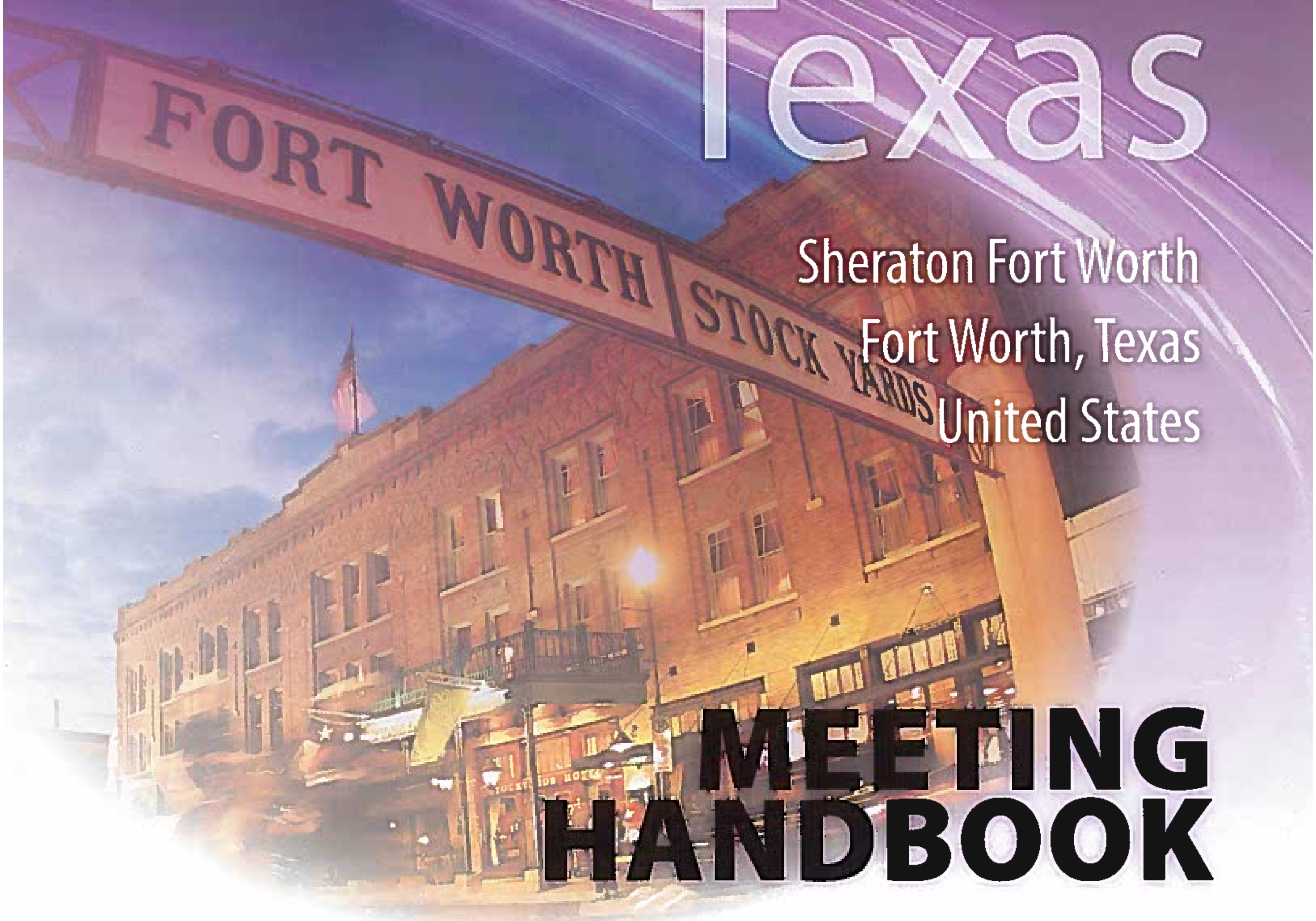

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Optimization Algorithm That Generates the Lowest ΔE_{ab} Values to a Reference Standard Based on Spectral Measurements of Solid inks in Offset Lithography
Søren Tapdrup Jensen, Danish School of Media and Journalism

An Evaluation of Instrumental Measurement Condition with Fluorescing Substrates and Colorants
Bruce Leigh Myers, Ph.D., Rochester Institute of Technology

10:30 a.m.–11:00 a.m.	**Refreshment Break**	**Brushy/Dry Comal Creek**
11:00 a.m.–12:00 p.m.	**Session 2A: Print Analysis**	**Sister Creek**

The Effective Use of Statistics
Ragy Isaac, Goss International Corporation

11:00 a.m.–12:00 p.m.	**Session 2B: Print Processes**	**Grape Creek**

Further Analyses of the Relationship between Midtone Spread and ΔCh
Robert Chung, Rochester Institute of Technology; Pierre Urbain, Alwan Color Expertise Americas, Inc.; Jing Sheng, Packaging Corporation of America

Inkjet Inks with Soy Protein
Zahra M. Khodabakhsh, Alexandra Pekarovicova, and Paul D. Fleming III, Western Michigan University

12:00 p.m.–1:30 p.m.	**Lunch & Annual TAGA Business Meeting**	**Fall/Flat Creek**
1:30 p.m.–3:30 p.m.	**Session 3: Print Processes**	**Fall/Flat Creek**

Innovative Approaches to Make Newspaper Publishing Profitable Again among the English-speaking Countries of the G8
K.K. Puri, Canadian Rotographics Limited

Imaging Technologies for Screen Printing Fine Features in Printed Electronics Applications
Xiaoying Rong, California Polytechnic State University

CMYK vs. KCMY Color Sequence Evaluation
Gary G. Field, California Polytechnic State University

3:30 p.m.–4:00 p.m.	**Refreshment Break**	**Brushy/Dry Comal Creek**
4:00 p.m.–5:30 p.m.	**Session 4: Paper and Color**	**Fall/Flat Creek**

Mechanisms That Determine the Tack Force Experienced by the Paper during Printing
Harrison Gates and Douglas W. Bousfield, University of Maine

Multi-Technology Electronic Printing on Ultra-Smooth PowerCoat Paper
Michael Carlisle, Arjo Wiggins


Stephen C. Lapin
PCT Engineered Systems, LLC


Nir Mosenson
Hewlett Packard


Dr. Bruce Leigh Myers
Rochester Institute of Technology


Alexandra Pekarovicova
Western Michigan University


K.K. Puri
Canadian Rotographics Limited


Xiaoying Rong
California Polytechnic State University


John Seymour
QuadTech, Inc.


Jing Sheng
Rochester Institute of Technology


Anthony Stanton
Carnegie Mellon University


Kirk Szymanski
Ricoh U.S.


Pierre Urbain
Alwan Color Expertise Americas


Chiawei Wu
Rochester Institute of Technology


Dr. Yu-Ju (Mandy) Wu
Appalachian State University

An Evaluation of Instrumental Measurement Condition with Fluorescing Substrates and Colorants

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Introduction

- Perceived Color of Reflective Objects
  - *Result of Spectral Reflectance of Object*
  - *Spectral Power Distribution of Illuminant (SPD)*
  - *Sensitivity of Observer*
- Control of Perceived Color
  - *CIE Standard Observers*
  - *Standardization of SPD*
    - Defined by ISO 3644:2009

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3

Background

- Visible Spectrum ≈ 380 – 700 nm
- Near-UV Range < 380 Can Influence Color
- Fluorescence
  - *Absorb in UV range and re-emit in visible range*
  - *In substrates & colorants fluorescence is result of Optical Brightening Agents (OBAs)*
- Effect Dependent Upon Amount of OBAs Present and UV Component of the Illuminant

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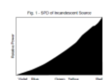
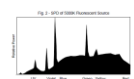
Background

- Instrumentation: Characteristic of SPD Needs to Be Recognized
  - *If Uncontrolled, Inconsistencies in Instrumental and Visual Assessments Can be Realized*
- ISO 13655 Refines Measurement Conditions
  - *M1: Close Match to D50, Including UV Portion*
  - *M0: 'Legacy' Condition, Illuminant A (2,856 K), Lessened UV Component*





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Objective

- Assess the Difference in M0 and M1 Measurement Conditions
  - *Utilize Various M0 and M1 + M0 Instruments*
  - *Utilize Substrates of Varying OBAs*
  - *Utilize Lithographic Colorants*
  - *Measure Both Absolute and Difference*
  - *Refine Methodology for Comparison*

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Methodology

- Instruments:
- Five Legacy Instruments ("M0")
- Three Instruments Capable of Reading Both M1 and M0

	M0	M1
Legacy	5	
M1 + M0	3	3
Total	8	3

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Methodology

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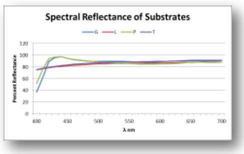
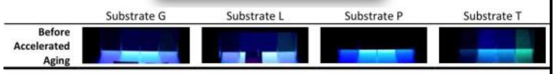
- Substrates: Four Different Papers with Varying Amounts of OBAs





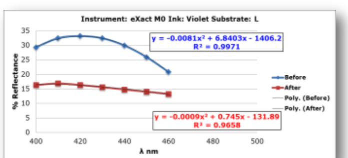
Methodology

- Colorants
  - *Eight Different Lithographic Inks Proofed on Each Substrate at Typical Lithographic Ink Film Thicknesses Using Little Joe Press*
  - *Subjected to Accelerated Aging Process in Q-Sun Xenon Test Chamber (consistent with Lind, Stack & Everett, 2004)*
    - 420nm, 40%RH, Daylight Filter, 198 Hours
  - *Spectral Readings Before and After Accelerated Aging*

	Bio Yellow	Cyan	Magenta	Oxy Yellow	Purple	Rubine	Solid Yellow	Violet
G								
L								
P								
T								

Methodology

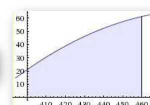
- Analysis Metric
  - *Area Under Spectral Curve in 400 – 460 nm Region*
    - Area where OBA effect most prevalent
    - Curves Generated in Excel
      - Fit with trend lines using second order polynomials: Goal $R^2 > 0.95$
      - Third-order polynomials utilized if $R^2 < 0.95$



Methodology

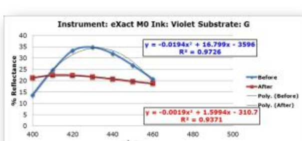
- Areas Under Curves Calculated with Riemann Sums Trapezoidal Method
  - *Validity of Method Tested*
    - Definite Integral Calculated Using WolframAlpha
    - Compared to Trapezoidal Method, Results Reasonably Close

$$\int_{400}^{460} \left(-0.0056\,x^2 + 5.485\,x - 1277\right)\,dx = 2665.8$$



Methodology

- Where the Spectral Curves Before and After Accelerated Aging Crossed
  - *WolframAlpha utilized to determine the point of intersection by setting the curve equations equal to each other*
    - Differences in area under curves calculated accordingly



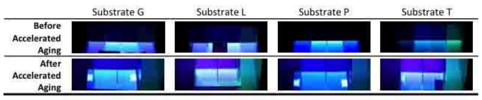
Ink & Substrate Samples

Before Accelerated Aging

After Accelerated Aging

Qualitative Analysis

- GTI SCV
  - *Evaluate OBAs Before and After Accelerated Aging*



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Quantitative Analysis

Before Accelerated Aging Absolute Difference in Area Under Curves 400 – 460nm		
	By	
Substrate + Ink	Measurement Condition	
Substrate only	Measurement Condition	Instrument
After Accelerated Aging Difference Between Area Under Curves 400 – 460nm		
	By	
Substrate + Ink	Measurement Condition	
Substrate only	Measurement Condition	Instrument

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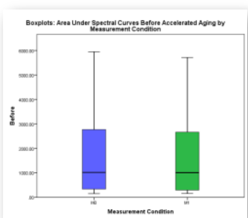
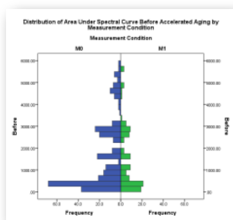
Results: Readings Prior to Accelerated Aging: All Samples by Measurement Condition

- A Mann-Whitney U test was run to examine potential differences in area under the spectral curves in the 400 – 460 nm region between measurement condition M0 and M1. Distributions of the areas under the curves were similar, as assessed by visual inspection. Areas under the respective curves were not significantly different between M0 (*Mdn* = 1018) and M1 (*Mdn* = 1005), *U* = 14,876.5, *z* = -0.67, *p* = 0.5





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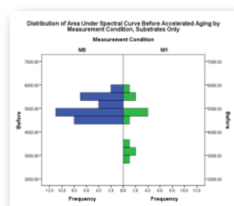
Results: Readings Prior to Accelerated Aging: Substrates Only by Measurement Condition

- Requisite Similar Distributions Not Met: Analysis of Central Tendency and Range Conducted



Measurement Condition	Median	Range
M0	4880	1612
M1	4739	2807

Substrate	Median	Range
G	4811	2088
L	4751	2487
P	5428	3040
T	4692	2211

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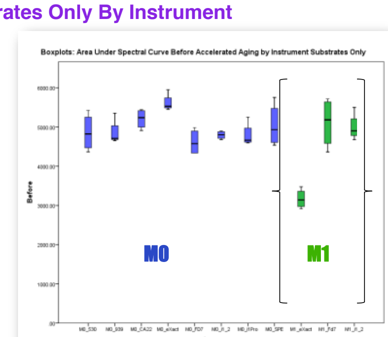
Results: Readings Prior to Accelerated Aging: Substrates Only By Instrument



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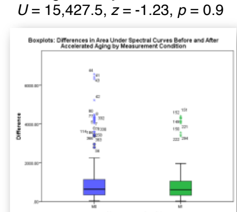
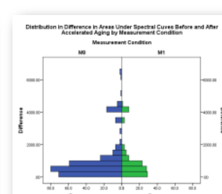
Results: Difference Readings Post Accelerated Aging: All Samples by Measurement Condition

- A Mann-Whitney U test was run to examine differences between area under the spectral curves in the 400 – 460 nm region before and after accelerated aging. Distributions of the areas under the curves were similar, as assessed by visual inspection. Areas under the respective curves were not significantly different between M0 (*Mdn* = 636) and M1 (*Mdn* = 613), *U* = 15,427.5, *z* = -1.23, *p* = 0.9





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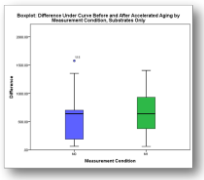
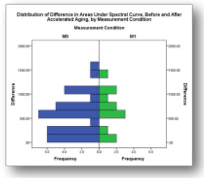
Results: Difference Readings Post Accelerated Aging: Substrates Only by Measurement Condition

- A Mann-Whitney U test was run to examine differences between area under the spectral curves in the 400 – 460 nm region before and after accelerated aging in an evaluation of the substrates alone. Distributions of the areas under the curves were similar, as assessed by visual inspection. Areas under the respective curves were not significantly different between M0 (*Mdn* = 579) and M1 (*Mdn* = 658), $U = 176$, $z = -.422$, $p = 0.69$





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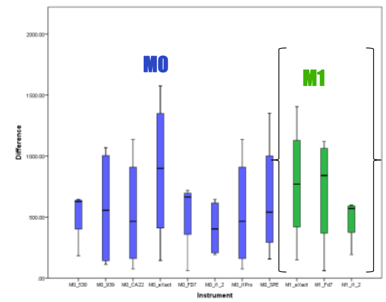
Results: Difference Readings Post Accelerated Aging: Substrates Only By Instrument



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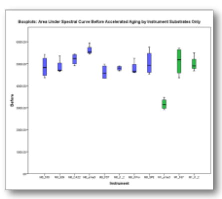
Limitations

- Only three M1 instruments
- Is area under the curve sufficiently sensitive as a metric?



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Discussion

- When Multiple Instruments Utilized in Workflow Diligence is Still Required
  - *Measurement Condition Added to Previously Recognized Instrument-based Variables*
    - Metrological: e.g.: Instrument Geometry, Aperture Size, Model, Measurement Procedure
    - Colorimetric: e.g.: Illuminant, Observer, Tolerancing Method, Parametric Values
  - *Range in M0 Instruments*

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Thank you.

Q/A

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