Does Extended Color Gamut Printing Have a Metamerism Challenge?

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CIE standard illuminants, bbserver color matching functions,
spectral power distribution, retail lighting

Abstract

The use of Metamerism Index (MI) is quite common in the ink industry. It helps us to predict how likely the formulated spot color will still match with the reference under different illuminants and observer angles. Since it is quite certain that most of the printed products will not be viewed by the target audience using standard D50 lighting, MI helps ink manufactures to prevent potential color mismatch due to differences in viewing condition before issue occurs.

Printing with special formulated spot inks could be quite demanding in terms of cost and labor: a custom order needs to be placed between print provider and ink manufacturer, the ink must be delivered and the color verified with drawdowns, and perhaps most significantly, previous spot color inks must be cleaned from the press unit and reloaded before the job. After the job, the leftover spot color ink must be warehoused for future use. Therefore, it makes great sense to replace specially formulated spot color inks with builds of process colors. Since the gamut of the standard process colors does not include many popular spot colors, it is necessary to “extend” the color gamut by adding a few extra “process colors” on top of existing cyan, magenta, yellow, and black to cover more chroma and hue. Most, if not all, Extended Color Gamut (ECG) solutions are based on custom multichannel ICC profiles that use a look-up-table for converting CMYKOVG (or CMYKOV, CMYKOG, CMYKVG, etc.) data to CIE XYZ or CIE L*a*b* back and forth. The ICC profile works quite well if all parties in the workflow agree on a fixed illuminant and observer condition (CIE D50 illuminant and 2-degree observer color matching function).

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Besides flexo, inkjet and digital printing have adopted ECG for a long time, where extra separations are added to standard CMYK, such as light cyan, light magenta, light black, orange, green, violet, etc., and they serve the purpose of proofing efficiently. With the proof approved by the print buyer, it will be utilized during the press run to make sure the real production samples match with color expectation under pressroom D50 view booth.

This study compares a set of reference colors with their ECG simulations and show if metamerism will be a potential problem when the retail store's lighting environment differs from pressroom. This study extends previous work on this topic by including a wider range of illuminants, and by paying close attention to the most popular spot colors.

Introduction

The invention of Extended Color Gamut (ECG) printing has been a controversial subject without a clear definition of what is considered ECG. The earliest sample is a Chinese book called "ShiZhuZhai ShuHua Pu" (Ten Bamboo Studio Collection of Calligraphy and Painting) crated during late Ming Dynasty (1619-1633) using 10-color block printing. For the scale of this study, we are only focusing on ECG printing with half tone so each color intertwines with other process inks to simulate a desired spot color. As of now in 2023, the ECG printing is used to describe a process that utilize Cyan, Magenta, Yellow, Black plus one, two or three other colors. The most popular colors are Orange, Violet, and Green. Other combinations are possible depending on the artwork and special brand colors needed to achieve. ECG is gradually gaining its popularity over the years since it can eliminate the need of specially formulated spot color ink produced by ink manufacturers, and improve press efficiency by eliminating the need for using a dedicated print unit for each spot color ink. This saves wash-up time. Regardless of using formulated spot ink or ECG, metamerism, a phenomenon that occurs when two colors appear to be matching under one illuminant but not when the light condition differs, could happen and lead to color matching failure and customer objection. To prevent metamerism issue, ink manufacturers use Metamerism Index (MI) to determine whether two colors will still match when the illuminant changes. Or during ink correction on press, ink technicians not only check for ΔE but also existing base inks already used in the ink container to prevent "foreign" base inks from being introduced that might cause issues, such as metamerism.

For matching colors, the ECG differ considerably from ink formulation. Instead of mixing base inks (colorants) from chemistry perspective, the ECG relies on overprinting various layers of ink films as color filters, to achieve similar color perception in viewer's brain. Most of the ECG tools available now rely on using multi-channel ICC profile, which has look-up-tables converting colors from source to destination with a Profile Connecting Space (CIE XYZ or CIE L*a*b*), therefore, the spectral data are discarded during ECG color conversion with the implicit assumption that the converted color will be viewed under one set of illuminant and observer function.

A spectrophotometer is an instrument that measures the number of photons that reach its optical sensor after the light is reflected (reflective spectrophotometer) off a sample or transmitted (transmissive spectrophotometer) through a chemical solution. In graphic arts, the reflective spectrophotometer is expected to measure printed sample and display CIE L*a*b* (CIE L*C*h) and ΔE so that color communication among various aspects of the reproduction (brand, design agency, ink manufacture, and print supplier) become streamlined and effective. After measuring a printed sample, the reflectance data captured by the spectrophotometer goes through a series of calculations before transforming to CIE L*a*b*. Below is a chart describing the calculation procedures.

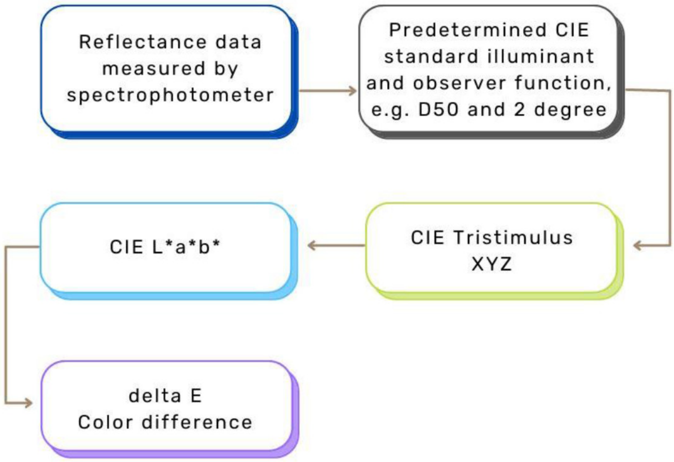

Figure 1. *Flowchart of color calculations*

As shown in Figure 1, before the spectrophotometer displays measurement in CIE L*a*b*, the user must predetermine the standard illuminant and observer function, which have a significant impact on how reflectance data will be calculated. Common spectrophotometers allow the user to choose one of the CIE standard illuminants, including D50, D65, A, F2, F11, etc. and either 2 degrees or 10 degrees as standard observer color matching function. But in the ICC workflow, the prefixed and assumption is color evaluation processes are exclusively under D50 and 2 degrees regardless where the printed samples are displayed for visual perception. The issue here is when the printed samples are displayed at a different lighting environment, for example retail stores use fluorescent light tube or LED, which are notably unique compare to D50 used in pressroom viewing booth, we shall expect printed sample bears changes in color perception.

When two colors that have the same CIE L*a*b* value under an illuminant and observer function, but not the same due to environment change, they are called metameric pair and their spectral reflectance curves intersect at multiple wavelengths. Below is a graph shows two colors that have the same CIE L*a*b* (ΔEab equals 0) under D50 and 2 degrees but apparent difference in spectral curve. If the illuminant changes to F11, the ΔE_{ab} becomes 4.6.

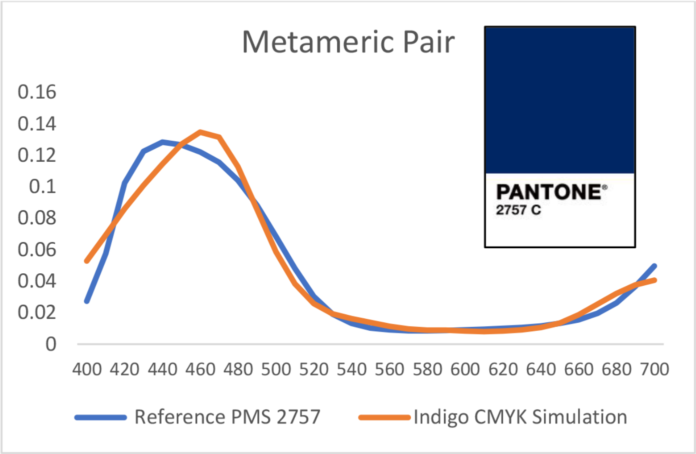

Figure 2. *Metameric pair with divergent spectral curve*

Besides five most common CIE standard illuminants (D65, A, D50, F2, F11), the lighting irradiances at multiple locations of three retail stores (Costco, Lowe's, and Harris Teeter) in South Carolina, USA were measured using a UPRtek MK350 spectrometer.

A valid argument is when the ECG printed samples are displayed in another lighting environment, there may not be a reference color as it was used in the pressroom during production. Thus, there is no easy way to tell if the ECG printed sample has color deviation from the brand color. But, if the ECG printed samples are used as a container or packaging for other parts of product produced by different vendors or print technologies that use custom formulated spot ink (e.g., individually film wrapped chocolate bars packed in a paper folder carton), metamerism should be considered by the brand owner. Or if a print supplier using ECG in production and starting new contracts with brand owners, it becomes crucial to predict how ECG printing match with the existing on-the-shelf products under retail lighting. The result of this study reveals potential metamerism challenges when printing with ECG and considerations needed when ECG as a part of the brand supply chain.

Experiment

Starting with a set of reference colors and their spectral reflectance data, several simulation processes were used to achieve reference colors with the goal of minimum ΔE color difference. After capturing the spectral reflectance data from those simulation samples by a spectrophotometer, it is possible to calculate tristimulus values under different illuminants and observer functions. Tristimulus values were later converted into CIE L*a*b* for metamerism index calculation.

Sample preparation

To understand the metamerism in ECG, this study starts with a database of Pantone reference colors and ECG pairs collected by John Seymour (Seymour, 2020). This database has measured spectral reflectance data of each Pantone colors from Pantone Formulation Guide and Pantone GOE system (discontinued in 2013), characterization data sets from flexographic and digital Indigo 7900 with CMYK and CMYK plus at least one extended color (orange, green, or violet). To narrow down the selection of reference colors for this paper, the researcher filtered the database with the top ten of most popular Pantone colors from a study conducted by Robert Congdon at Clemson University by surveying six prepress facilities in the US. This list omitted several of the most popular colors, such as vivid reds, which are outside of the gamut of ECG. Table 1 shows Pantone reference colors selected for the study and simulation techniques.

Pantone Reference	Approx. Color	Simulation techniques
368 C		GOE System, Flexo ECG, Indigo CMYK Indigo ECG
348 C		
356 C		
130 C		
361 C		
369 C		
144 C		
187 C		
123 C		
2757 C		

Table 1. *Selected Pantone reference colors and their reproduction samples*

Illuminants and Observer functions

Due to the common use of D50 viewing booth in the graphic arts industry, this study uses D50 as the reference illuminant (n1) and other four types of CIE standard illuminants (A, D65, F2, and F11), and two retail lighting as second illuminant (n2) respectively. Figure 3 illustrates the relative spectral power distribution of CIE standard illuminants in this paper. After normalizing the CIE LED-B3 (published in CIE Publication 15, 2018) at wavelength of 600 nm, its spectral power distribution curve (gray dash line) shares decent similarity with that from Costco, Lowe's, and Harris Teeter.

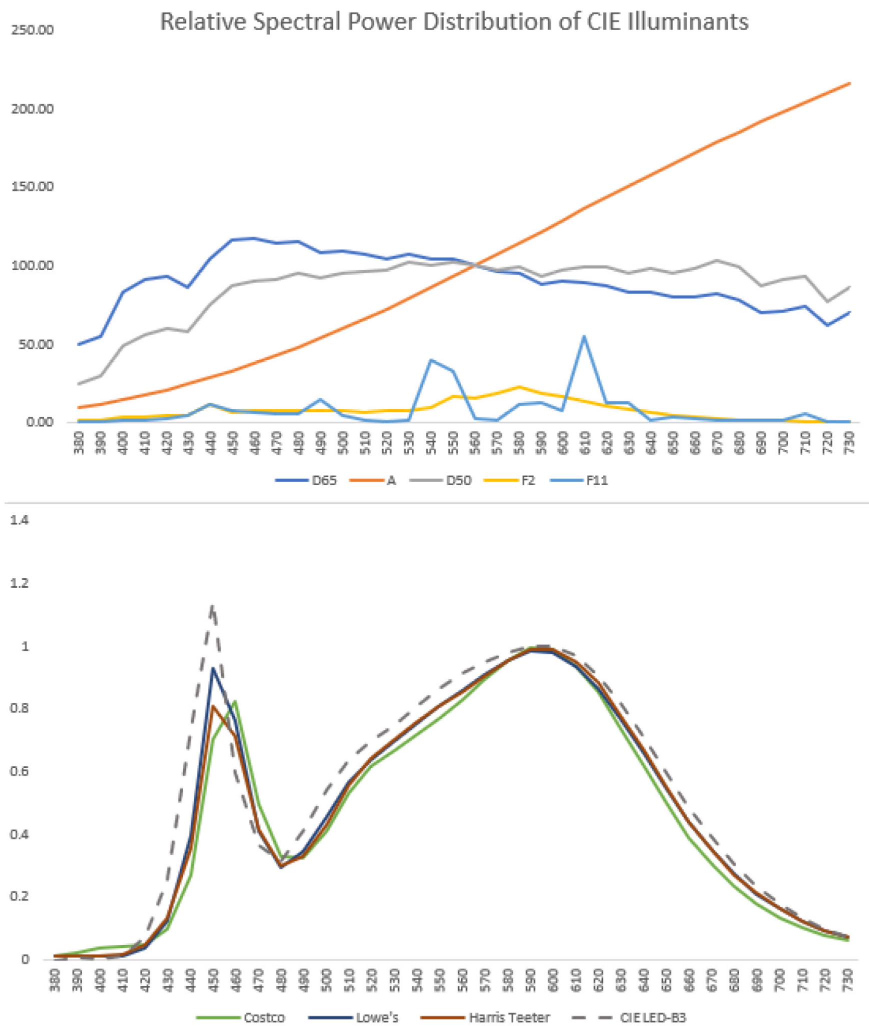

Figure 3. *Relative Spectral Power Distribution of lightings*

Computation of CIE XYZ from Spectral Reflectance

The CIE Standard (CIE, 1986a) recommends the following equations been used for calculating CIE tristimulus values:

$$X = k\sum_{\lambda} R(\lambda)\ S(\lambda)\bar{x}(\lambda)\Delta\lambda \qquad (1)$$

$$Y = k\sum_{\lambda} R(\lambda)\ S(\lambda)\bar{y}(\lambda)\Delta\lambda$$

$$Z = k\sum_{\lambda} R(\lambda)\ S(\lambda)\bar{z}(\lambda)\Delta\lambda$$

With:

$$k = 100 / \sum_{\lambda} S(\lambda) \bar{y}(\lambda) \Delta\lambda$$

Where: R(λ) is the spectral reflectance factor (or spectral radiance factor or spectral reflectance) of the object color

S(λ) is the relative spectral power distribution of the illuminant

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ is the color-matching function of one of the CIE standard observers

k is the normalizing coefficient so the white object Yn = 100 under the Illuminant selected

The standard wavelength range for calculation of XYZ values is from 380 nm to 730 nm with an interval of 10 nm.

Custom Illuminant Calculation

The calculation from CIE XYZ to CIE L*a*b* is well-documented and rather straightforward, while it is necessary to mention the reference white point X_n, Y_n, Z_n for the custom illumination scenarios specified in ASTM E308-08.

The UPRtek MK350 spectrometer measures and exports radiance of a targeted illumination at the interval of 1 nm from 360 to 760 nm. For consistency purpose, measurements were translated to 380 to 730 nm with an interval of 10 nm. After the radiance at each wavelength interval is normalized to 560 nm (method used by CIE), the reference white point X_n, Y_n, and Z_n are calculated shown below:

$$W_x(\lambda) = kS(\lambda)\bar{x}(\lambda)\Delta\lambda \qquad (2)$$

$$W_y(\lambda) = kS(\lambda)\bar{y}(\lambda)\Delta\lambda$$

$$W_z(\lambda) = kS(\lambda)\bar{z}(\lambda)\Delta\lambda$$

$$X_n = \sum_{380}^{730} W_x(\lambda)\Delta\lambda$$

$$Y_n = 100$$

$$Z_n = \sum_{380}^{730} W_z(\lambda)\Delta\lambda$$

Where: W_x, W_y, W_z is the tristimulus weighting factors

Metamerism Index (MI) Calculation

Two specimens having identical tristimulus values for a given reference illuminant and reference observer are metameric if their reflectance values differ within the visible spectrum. The metamerism index calculation is recommended in CIE Publication 15.2 (2004) as described below.

> "It is recommended that for two specimens whose corresponding tristimulus values (X1 = X2, Y1 = Y2, Z1 = Z2,) are identical with respect to a reference illuminant and observer, the metamerism index, M, be set equal to the colour difference ΔE^*_{ab} between the two specimens computed for the test illuminant or for the test observer."

To comply with above recommendation, the spectral reflectance data of all samples tested in this paper were adjusted to exactly match the reference Pantone colors under D50/2. Principal Component Analysis (PCA) was used to identify spectral differences that were probable within each set of spectra. Small amounts of the PCAs were added to actual spectra from the database to achieve a perfect match. Therefore, the color difference ΔE^*_{ab} between the Pantone colors and other samples under test illuminant and test observer is used as calculation of MI.

Results

A set of ten popular Pantone colors were selected and various methods of ECG simulation samples as well as Pantone GOE guide (formulation guide with different ink set and not ECG printing) were accessed based on measured spectral reflectance data. The data transformation from spectral reflectance to CIE L*a*b* were conducted using the same procedure described above. As shown in Figure 4, each selected Pantone color has a dedicated table containing calculated CIE L*a*b* values prepared for the calculation of MI.

	D50/2			D65/2			A/2			F2/2		
	L	a	b	L	a	b	L	a	b	L	a	b
PANTONE Ref	69.74	-46.03	59.02	70.06	-50.55	61.33	67.89	-36.07	50.33	68.04	-33.97	57.56
Flexo EG	69.74	-46.02	59.01	70.04	-49.99	61.50	67.98	-38.15	50.37	69.07	-33.77	59.69
GOE Guide	69.74	-46.02	59.02	70.07	-50.68	61.59	67.88	-35.93	49.95	68.08	-33.82	58.13
Indigo 7900 CMYK	69.74	-46.02	59.01	70.05	-50.23	61.61	67.96	-37.51	49.92	68.89	-33.95	59.47
Indigo 7900 EG	69.74	-46.02	59.01	70.05	-50.23	61.62	67.96	-37.50	49.92	68.89	-33.95	59.47

	F11/2			Costco/2			Lowe's/2			Harris Teeter/2		
	L	a	b	L	a	b	L	a	b	L	a	b
PANTONE Ref	69.66	-42.01	59.02	70.06	-50.55	61.33	67.89	-36.07	50.33	68.04	-33.97	57.56
Flexo EG	69.58	-44.20	59.01	70.04	-49.99	61.50	67.98	-38.15	50.37	69.07	-33.77	59.69
GOE Guide	69.61	-41.69	59.02	70.07	-50.68	61.59	67.88	-35.93	49.95	68.08	-33.82	58.13
Indigo 7900 CMYK	69.85	-44.32	59.01	70.05	-50.23	61.61	67.96	-37.51	49.92	68.89	-33.95	59.47
Indigo 7900 EG	69.85	-44.31	59.01	70.05	-50.23	61.62	67.96	-37.50	49.92	68.89	-33.95	59.47

	D50/10			D65/10			A/10			F2/10		
	L	a	b	L	a	b	L	a	b	L	a	b
PANTONE Ref	68.75	-37.91	60.53	68.81	-41.30	62.04	67.42	-30.92	53.85	67.40	-28.36	59.50
Flexo EG	68.73	-37.47	60.76	68.78	-40.47	62.52	67.49	-32.18	53.98	68.38	-27.73	61.86
GOE Guide	68.79	-38.17	60.94	68.87	-41.73	62.75	67.45	-30.93	53.81	67.47	-28.39	60.48
Indigo 7900 CMYK	68.80	-37.96	61.06	68.87	-41.21	62.93	67.51	-31.98	53.84	68.26	-28.22	61.90
Indigo 7900 EG	68.80	-37.97	61.07	68.87	-41.21	62.94	67.51	-31.97	53.84	68.26	-28.22	61.91

	F11/10			Costco/10			Lowe's/10			Harris Teeter/10		
	L	a	b	L	a	b	L	a	b	L	a	b
PANTONE Ref	68.80	-34.41	63.22	68.22	-33.43	59.55	68.41	-34.60	60.34	68.46	-34.27	59.91
Flexo EG	68.74	-36.31	63.33	68.54	-32.68	59.63	68.69	-33.90	60.85	68.73	-33.57	60.35
GOE Guide	68.78	-34.32	64.05	68.24	-33.25	59.36	68.42	-34.49	60.66	68.47	-34.12	60.13
Indigo 7900 CMYK	69.06	-36.80	63.28	68.44	-32.82	60.77	68.62	-34.07	61.69	68.65	-33.69	61.20
Indigo 7900 EG	69.06	-36.79	63.29	68.44	-32.82	60.77	68.62	-34.07	61.70	68.65	-33.69	61.20

Figure 4. *Calculated CIE L*a*b* under various Illuminants and Observer functions of Pantone 368 C*

With the CIE L*a*b* calculated from the spectral reflectance data and various combination of illuminants and observer matching functions, the MI can be computed for each condition. Based on CIE Publication 15.2, the preferred illuminant for calculating MI is D65. The printing industry, however, has standardized on D50 and 2 degrees, the MI calculation in this study is based on D50 and 2 degrees as the reference illuminant and observer matching function. As shown in Figure 5, the MI result for each Pantone color and various ECG simulation methods are color formatted from white (low MI value) to red (large MI value). To understand the MI distribution of each illuminant and observer matching function across multiple ECG simulations, percentile analysis is plotted to illustrate the data visually.

		D65/2	A/2	F2/2	F11/2	Costco /2	Lowe's/ 2	Harris Teeter/2	D50/10	D65/10	A/10	F2/10	F11/10	Costco/ 10	Lowe's/ 10	Harris Teeter/10
368	Flexo EG	0.59	2.09	2.38	2.21	0.45	0.67	0.60	0.49	0.96	1.27	2.64	1.90	0.81	0.92	0.87
	GOE Guide	0.29	0.40	0.59	0.51	0.53	0.28	0.31	0.50	0.84	0.05	0.99	0.84	0.25	0.34	0.27
	ndigo 7900 CMYK	0.43	1.50	2.10	2.43	1.10	1.17	1.13	0.55	0.90	1.06	2.56	2.40	1.39	1.48	1.43
	Indigo 7900 EG	0.43	1.50	2.10	2.42	1.09	1.17	1.13	0.56	0.90	1.06	2.57	2.40	1.39	1.48	1.44
348	Flexo EG	0.47	2.10	2.49	2.66	0.90	0.73	0.67	0.47	0.88	1.24	2.89	2.47	1.24	1.13	1.08
	GOE Guide	1.30	4.04	2.34	6.23	1.46	1.14	1.23	1.56	2.67	2.10	2.42	4.79	1.12	1.02	0.94
	ndigo 7900 CMYK	0.38	1.64	2.15	3.82	0.57	0.62	0.58	0.51	0.89	1.13	2.54	3.78	0.82	0.89	0.86
	Indigo 7900 EG	0.61	2.80	2.94	5.85	0.49	0.69	0.60	0.51	0.98	1.77	3.29	5.38	1.00	1.07	1.01
356	Flexo EG	0.63	2.04	1.43	4.46	0.96	0.86	0.89	0.70	1.23	1.12	1.01	3.60	0.41	0.34	0.33
	GOE Guide	0.73	2.85	2.46	4.67	0.84	0.98	0.92	0.59	1.11	1.70	2.55	3.96	0.94	1.05	0.98
	ndigo 7900 CMYK	0.57	1.83	0.97	2.43	0.44	0.44	0.48	0.80	1.30	0.88	0.88	1.63	0.39	0.35	0.31
	Indigo 7900 EG	0.33	0.91	0.35	1.01	0.27	0.25	0.28	0.50	0.81	0.40	0.41	0.55	0.18	0.18	0.17
130	Flexo EG	1.63	4.79	5.60	5.82	2.54	2.30	2.38	2.09	3.58	2.55	4.18	6.35	0.93	0.81	0.80
	GOE Guide	0.48	0.88	0.71	0.88	0.45	0.59	0.49	0.83	1.38	0.23	1.31	1.51	0.37	1.04	0.87
	ndigo 7900 CMYK	1.26	3.65	4.74	5.02	2.85	2.54	2.60	1.52	2.67	2.02	3.58	5.10	1.71	1.41	1.45
	Indigo 7900 EG	1.57	4.50	5.51	5.81	3.18	2.81	2.89	1.95	3.39	2.44	4.09	6.04	1.71	1.36	1.42
361	Flexo EG	0.77	2.85	2.88	4.22	0.45	0.64	0.58	0.67	1.27	1.69	3.09	3.60	0.94	0.95	0.89
	GOE Guide	0.31	0.37	0.74	0.51	0.65	0.29	0.34	0.53	0.91	0.09	1.18	1.01	0.40	0.25	0.20
	ndigo 7900 CMYK	0.43	1.47	2.12	2.83	0.92	1.05	1.00	0.67	1.06	1.07	2.66	2.93	1.22	1.36	1.31
	Indigo 7900 EG	0.43	1.48	2.12	2.84	0.93	1.05	1.00	0.66	1.06	1.07	2.66	2.94	1.22	1.36	1.31
369	Flexo EG	0.42	1.46	1.65	1.30	0.32	0.35	0.33	0.35	0.69	0.91	1.86	1.07	0.59	0.58	0.57
	GOE Guide	1.11	3.75	3.50	4.30	0.85	1.09	1.04	1.10	1.99	2.12	3.59	3.46	1.23	1.30	1.23
	ndigo 7900 CMYK	0.35	0.91	1.48	1.19	1.15	1.15	1.11	0.75	1.13	0.64	2.04	1.14	1.49	1.52	1.47
	Indigo 7900 EG	0.38	0.98	1.59	1.23	1.14	1.17	1.13	0.79	1.20	0.69	2.19	1.24	1.48	1.56	1.50
144	Flexo EG	2.67	7.61	9.21	9.06	4.43	3.92	4.06	3.56	6.06	3.94	6.74	10.21	1.79	1.46	1.46
	GOE Guide	0.36	0.62	0.75	0.70	0.46	0.44	0.40	0.63	1.04	0.13	1.11	1.17	0.27	0.68	0.57
	ndigo 7900 CMYK	2.29	6.44	8.06	7.44	4.20	3.72	3.85	3.07	5.22	3.33	5.82	8.29	1.86	1.46	1.52
	Indigo 7900 EG	2.34	6.57	8.19	7.56	4.25	3.77	3.90	3.14	5.33	3.39	5.91	8.44	1.87	1.47	1.52
187	Flexo EG	1.00	2.39	2.50	1.69	2.20	1.32	1.47	1.38	2.42	1.14	2.19	2.38	1.59	0.86	0.92
	GOE Guide	0.10	0.30	0.58	0.43	0.20	0.16	0.16	0.10	0.19	0.19	0.52	0.42	0.11	0.09	0.08
	ndigo 7900 CMYK	0.82	2.05	2.15	2.18	1.35	0.87	0.93	1.16	2.00	0.99	1.70	2.75	0.73	0.76	0.64
	Indigo 7900 EG	0.89	2.24	2.46	2.43	1.52	0.97	1.03	1.25	2.17	1.09	1.93	3.03	0.83	0.81	0.68
123	Flexo EG	0.15	0.35	0.62	1.22	0.34	0.31	0.31	0.33	0.49	0.09	0.43	1.01	0.35	0.27	0.26
	GOE Guide	0.23	0.62	1.36	2.57	0.58	0.55	0.55	0.40	0.63	0.28	0.99	2.22	0.48	0.32	0.33
	ndigo 7900 CMYK	0.10	0.04	0.68	2.11	0.77	0.61	0.63	0.18	0.32	0.10	0.63	2.03	0.71	0.55	0.58
	Indigo 7900 EG	0.20	0.40	0.88	2.15	0.88	0.72	0.75	0.30	0.52	0.23	0.64	1.98	0.71	0.55	0.58
2757	Flexo EG	0.22	1.04	1.28	4.47	0.76	0.66	0.72	0.83	1.01	0.26	0.45	2.93	0.83	0.79	0.70
	GOE Guide	0.32	1.73	1.55	4.24	0.41	0.37	0.41	0.78	0.97	0.71	0.90	2.81	0.73	0.73	0.64
	ndigo 7900 CMYK	0.20	0.35	1.74	4.60	0.87	0.41	0.44	0.09	0.33	0.11	1.49	3.85	0.87	0.44	0.45
	Indigo 7900 EG	0.20	0.35	1.75	4.62	0.87	0.41	0.44	0.08	0.33	0.11	1.49	3.86	0.87	0.44	0.45

Figure 5. *MI value of different illuminants and observer matching functions for selected Pantone colors (Reference illuminant and observer is D50 and 2 degrees)*

The results show that among those CIE defined Standard Illuminants, F11 has the most MI issues across all Pantone colors. This is quite understandable because of the distinctive difference in its illuminant spectral power distribution curve compared to the others. That is, F11 is “spiky”. The MI values of selected Pantone colors are mostly much lower under the lights from Costco, Lowe’s, and Harris Teeter that use LED quite similar to the CIE LED-B3 illuminant. To prevent any outliers due to a specific color or ECG simulation methods, data in Figure 5 was processed by Percentile Analysis to illustrate the MI data distribution under each lighting and observer matching functions. The 90th percentile was chosen to evaluate the majority of ECG specimen under each lighting and observer functions. In Figure 6 and 7, the 90th MI percentile of all ECG simulations and GOE guide were averaged under the same lighting and observer function and callout with arrow pointing indicates its corresponding value on the Y axis. As shown, both lightings and observer functions have some impacts on the MI, while the influence is more significant from different lighting conditions.

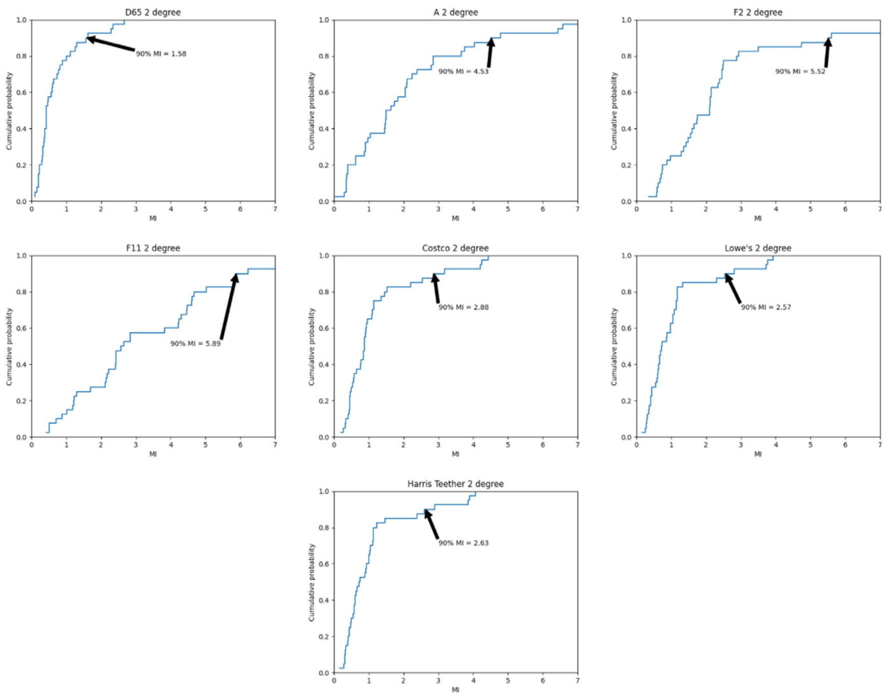

Figure 6. *MI percentile plot of Pantone colors under various lighting and 2 degree observer function*

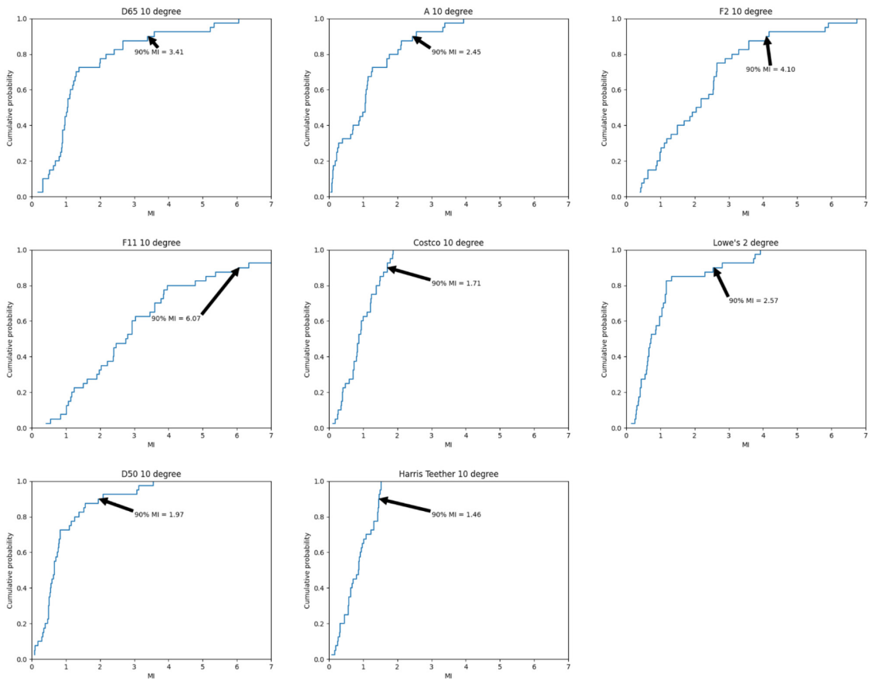

Figure 7. *MI percentile plot of Pantone colors under various lighting and 10 degree observer function*

Conclusion

Among CIE standardized illuminants, F11 has the largest discrepancy with an MI value close to 6 regardless of observer function. Under retail lighting conditions (Costco, Lowe's, and Harris Teeter), the MI values are better than F11, which indicates real life color assessment environment might be more tolerant when ECG printed packages are displayed, as least for the lightings that are similar to CIE LED-B3.

To put the MI value into perspective, Pantone offers a product, Pantone D50 lighting Indicator, that helps user to verify if surrounding lighting condition against D50. This indicator includes a pair of metameric colors with mismatching spectral reflectance behavior, while they are close to visually identical only under D50 lighting. Since this indicator is widely available in the print industry (almost every Pantone Color Guide has it embedded), we will use it as the baseline to compare to calculated MI in this research. By measuring the Pantone D50 Lighting Indicator, the MI of this product is displayed in Figure 8.

MI	
D65/2	1.34
A/2	2.89
F2/2	1.56
F11/2	8.25
D50/10	2.52
D65/10	4.01
A/10	0.90
F2/10	1.18
F11/10	6.02

Figure 8. *Pantone D50 Lighting Indicator and calculated MI*

The MI of Pantone D50 Lighting Indicator is 8.25 and 6.02 under F11 2 degree and 10 degree respectively, which is reasonably close to the 90th percentile of studied ECG simulations under F11 in this research. It can be expected that product printed by ECG with such MI (under F11) will likely be noticed and rejected. But ECG might work fine if the lighting is close to CIE LED-B3. Also, new regulations may be making the issues with spiky fluorescent lights a moot point. Due to the mercury usage in fluorescent lamps, the RoHS (Restriction of the user of Hazardous Substances) directive of 2023 has put a ban on the production of certain fluorescent lamps. EU and States in the US, such as Vermont and California, have already started phasing out the sale of most fluorescent bulbs. It can be expected that the end of fluorescent lamp will come soon. While the regulation does not apply to fluorescent bulbs used in viewing booths until 2025, it is expected that eventually the diminishing economies of scale will make the traditional bulbs less cost efficient. Either way, it is necessary for the ECG printers and brand owners to communicate closely on lighting condition of the final product placement.

As an aside, the standards in the graphic arts currently mandate D50 as the standard illuminant which has traditionally been simulated with fluorescent bulbs. While it is possible to create D50 simulator LED-based viewing booths by using a variety of types of LEDs with selected phosphors, it is worth considering changing the recommendations from D50 to CIE LED-B3. This would be cost-effective for manufacturers of viewing booths. Based on limited sampling of commercial outlets, this may closely approximate real retail environments. As has been shown in this paper, the change in color matching from D50 is minimal. Two samples which match under D50 are likely to match reasonably well under B3. Meanwhile, it would be worthwhile for ECG software vendor to consider calculation based on the spectral reflectance data of reference colors so as to recommend process ink builds based on reduction of metamerism. It may also be beneficial for ECG software to report the MI when an ECG replacement build is given. This might require some fundamental changes when setting up the ECG software, such as importing or measuring each ECG process ink to collect their spectral reflectance data needed during calculation.

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