Brighter is Better? Investigating Spectral Color Prediction of Ink on Optically Brightened Substrate

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Abstract

The effect of fluorescence on the spectral modeling of inks printed on optically brightened substrates was investigated. Color differences were computed between print measurements with ultraviolet included (UVI) and excluded (UVX) instrument setups. Heat-set, CMYK process inks printed at SWOP density on non-optically brightened substrates exhibited color differences less than 1 ΔE^*_{ab}. The same inks printed on optically brightened substrates had color differences greater than 3 ΔE^*_{ab} as a result of fluorescence due to UV component inclusion. A modified spectral Neugebauer printer model was used to model desktop printer ink on optically brightened substrates using both UVI and UVX measurement setups. Results indicate although UVI/UVX model parameters are similar, their output colors are quite different. Printer models using the optically brightened substrates could plug directly into printer models of non-fluorescent substrates.

Introduction

In desktop printing, proofing and commercial printing applications, substrates are available with various brightness levels, white points, gloss levels, opacities, etc. Each of these characteristics effect color reproduction, gamut, dot gain and printed image quality in a different manner. Increased brightness is typically due to the effect of optical brightening agents (OBA) or fluorescent whitening agents (FWA) added to the substrate to boost reflectance in the blue region, negating the intrinsic yellow color of bleached paper. Although the presence of the OBA results in a perceptually brighter substrate, OBA are highly sensitive to ultraviolet radiation and fluoresce strongly in the presence of UV illumination. Figure 1 illustrates differences between UV included (UVI) and UV excluded (UVX) total spectral radiance factor measurements of commercially available offset printing substrates[1] with identical CIE L*. The fluorescent nature of the OBA enhanced substrates present a difficulty for colorimetry.

The influence of fluorescence is disregarded in conventional colorimetry but has been researched extensively. In recent years Emmel, Hersch, et al[2,3,4] have investigated and modeled the relationship of fluorescent inks on non-fluorescent substrates.

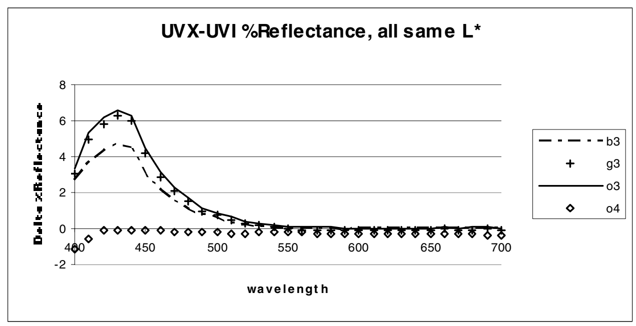

Figure 1. UV included – UV excluded percent spectral reflectance of four offset printing substrates with UVI and UVX L = 93.*

As ICC color managed workflows become more prevalent in the graphic arts, so too do the difficulties encountered by users of color management technology. Despite utilizing proper color management workflow practice, substrate OBA can cause perceived and measured color shifts due to substrate fluorescence when measuring with a UV containing source. Measurements based on ISO 13655/CGATS.5 "Graphic technology – Spectral measurement and colorimetric computation for graphic arts images"[5] (such as those for ICC profiles) specify measurements be made UV included.

Introduction of error due to fluorescence in graphic arts measurements is not limited to how well the instrument light source approximates the UV component of daylight. Figure 2 illustrates the range of reflectance spectra of daylight-fluorescent inks measured with instruments of various correlated-color-temperature (CCT) sources. Substantial differences would be present should profile generation be performed with instruments containing high CCT sources and quality control measurements made with a low CCT instrument. Such a workflow would susceptible to error due to ink and/or substrate fluorescence.

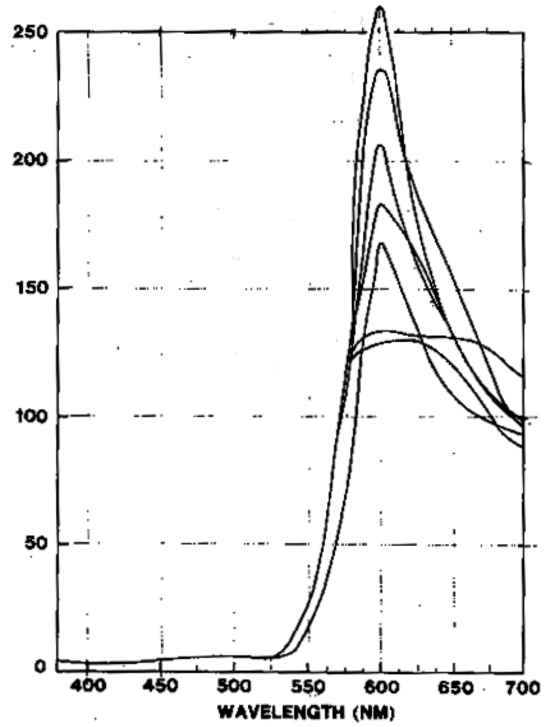

Figure 2. Percent total spectral radiance factor of daylight-fluorescent DayGlo® ArcYellow ink measured on seven commercial instruments containing sources of various CCT.[6]

The causes of error described above can lead users to question their color managed workflow or ICC profiles since color management tools typically do not deal with substrate fluorescence. For these reasons, a CIE Division 8 reportership is currently investigating the influence of fluorescent substrates on color printing accuracy[7]. The ICC Profile Assessment Working Group has identified substrate fluorescence as a possible hang-up for proper ICC color management.

The first motivation behind this research is to investigate heat-set inks printed at SWOP density[8] on substrates with and without optical brightening agents (Part I). A second motivation is to use a conventional printing prediction algorithm to model a halftone printing system using optically brightened substrates (Part II) and investigate the impact of substrate fluorescence on model accuracy. The modeling in Part II was performed using a Yule-Nielsen modified spectral Neugebauer model[9,10,11] where spectral reflectance is defined by equation 1.

$$R(\lambda)=\left[\sum_i F_i R_i(\lambda)^{1/n}\right]^n \tag{1}$$

Where F_i are area coverages of corresponding Neugebauer primaries using the Demichel effective area fraction equations, and n is the Yule-Nielsen n-value.

Part I. Heat-set Inks Printed on Optically Brightened Substrates

Experimental

Heat-set process cyan, magenta, yellow and black inks were printed at SWOP density (1.3 C, 1.4 M, 1.0 Y, 1.6 K) on four substrates: APCO II/II (referred to as APC), Leneta 3NT3 (LEN), Xerox business multipurpose paper (XRX), Epson premium bright white paper (EPS). Substrates APC and LEN are uncoated and do not contain fluorescent OBAs (See Figure 3). APC and LEN are commonly used as commercial printing press substrates. XRX is used in copy machines and desktop printing, advertised with ISO brightness[12] = 86. EPS is an ink jet paper advertised with ISO brightness = 108+. Substrates XRX and EPS are coated and commercially available.

Table I. Measured ISO brightness (percent total radiance factor at 457 nm) of experimental substrates.

	XRX	EPS	LEN	APC
R457	86	113	81	82

The Macbeth Coloreye 7000A integrating sphere spectrocolorimeter was used for all spectral measurements. A black backing was used with a large area view aperture. This instrument has an ultraviolet included (UVI) setting which approximates the ultraviolet component of CIE Illuminant D65. CIELAB coordinates were calculated with D50 illumination and 1931 2° observer (graphic arts standard).

Results

Substrate percent spectral reflectance differences between UVI and UVX measurements are shown in Figure 3. Fluorescence in the presence of UV illumination are substantial for substrate EPS and noticeable in XRX. Little if any fluorescence is present in substrates LEN and APC.

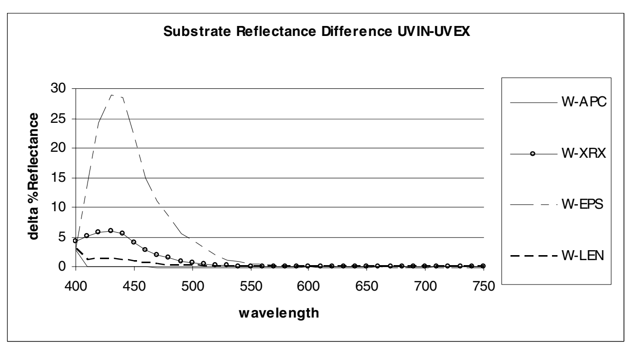

Figure 3. UV included – UV excluded percent spectral reflectance of experimental substrates.

Despite substantial differences present between UVI and UVX measurements of substrates XRX and EPS, spectral reflectance differences between heat-set printed samples are not nearly as significant (Figure 4). This is due to the high ink density limiting the amount of illumination incident on the substrate.

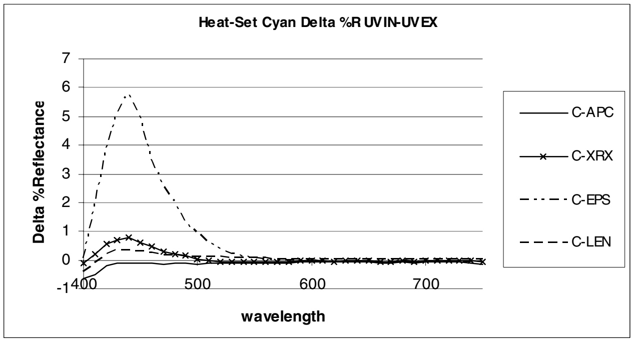

Figure 4. UV included – UV excluded percent spectral reflectance of heat-set cyan on different substrates.

Color differences between UVI and UVX measurements of prints on APC and LEN are less than 0.3 ΔE^*_{ab} (see Table II) and would be imperceptible in an image. Color differences due to fluorescence of prints on XRX could be visible in a side-by-side comparison, but would most likely be acceptable as a press print and undetectable in an image. Color differences of prints on EPS would be visible and most likely detectible in an image.

Table II. UV included – UV excluded color difference components for the four test substrates.

CYAN	ΔL*	Δa*	Δb*	ΔC*	ΔE*ab
APC	-0.10	-0.05	-0.07	0.08	0.13
LEN	0.06	0.09	-0.05	-0.02	0.12
XRX	-0.03	0.34	-0.32	0.13	0.47
EPS	0.25	2.01	-1.88	0.92	2.76
MAGENTA	**ΔL***	**Δa***	**Δb***	**ΔC***	**ΔE*ab**
APC	-0.01	-0.05	-0.05	-0.06	0.08
LEN	-0.01	-0.04	-0.15	-0.07	0.15
XRX	0.02	0.23	-0.39	0.10	0.46
EPS	0.20	0.69	-3.21	-0.34	3.29
YELLOW	**ΔL***	**Δa***	**Δb***	**ΔC***	**ΔE*ab**
APC	0.01	0.01	-0.28	-0.28	0.28
LEN	0.00	0.00	-0.27	-0.27	0.27
XRX	0.02	0.00	-0.34	-0.34	0.35
EPS	0.15	-0.11	-1.82	-1.82	1.83
BLACK	**ΔL***	**Δa***	**Δb***	**ΔC***	**ΔE*ab**
APC	-0.09	0.01	-0.04	-0.03	0.10
LEN	-0.13	0.03	-0.01	0.00	0.14
XRX	0.07	0.05	-0.07	-0.06	0.11
EPS	-0.06	0.51	-1.09	-0.87	1.21

Analysis

Color differences due to UV component inclusion have been calculated for heat-set CMYK inks applied to various substrates at SWOP density. The greatest color differences were measured on substrate EPS which contains fluorescent optical brightening agents. For inks printed on substrates which do not contain fluorescent OBAs, color differences between measurements of different UV component were less than 0.5 ΔE^*_{ab}. Color differences between inks printed on substrate EPS were greater than 1.0 ΔE^*_{ab} for all colors, and greater than 3 ΔE^*_{ab} for magenta. Despite these substrates advertised with various levels of brightness, substrate lightness (L*) was mostly unaffected by UV inclusion. It is shown in Table II that color differences were primarily due to differences in the chromatic component.

Conclusion

The effect of fluorescent optically brightened substrates on printed ink color was examined in a two-part study. In Part I, it was determined that color differences can be present in heat-set inks printed at SWOP density on optically brightened substrates as a result of instrument illumination ultraviolet component inclusion. This difference can be attributed to fluorescence in substrate optical brightening agents. Prints on non-fluorescent substrates had $\Delta E^*_{ab} < 1.0$, between UVI and UVX measurements. Prints on fluorescent substrates had instances of $\Delta E^*_{ab} > 3.0$, between UVI and UVX measurements. Color differences of prints on the OBA containing substrate EPS are large enough to be noticeable in images and can result in incorrect production tolerance failures.

Part II: Spectral Modeling of Halftones on Optically Brightened Substrates

Experimental

Due to the inconvenience and cost associated with obtaining halftoned samples of heat-set inks, this portion of research was performed as a preliminary study on desktop printers. Substrates XRX and EPS were used for this portion. Nine-step CMY ramps were printed on three devices (Hewlett-Packard DeskJet 695C ink jet (referred to as HP), Canon S750 ink jet (CA), Oki Data C7400 laser jet (OK)). The full dynamic range of each printer was used. Ramps were printed from Microsoft Word using each printer's default settings. Measurements were taken similarly as above. Printing from Microsoft Word ensures no color management be applied to the image.

Color differences were initially calculated between the UV excluded and UV included measurements (Table III) of the CMY ramps. Average color differences of CMY ramps were substantially larger than those of the SWOP density CMY solids measured in Part I due to the increased substrate exposure in the halftone measurements. Lighter colors exhibited greater color difference than darker colors

(Figure 5), and greater color differences were measured for prints on substrate EPS than XRX.

In Figures 5 and 6, color differences due to fluorescence of OBAs result are almost entirely due to shifts in the chromatic component; there is very little shift in lightness. This concedes with observations from Table II. The highest lightness colors are shown to be decreasing in chroma. This is due to a blue shift in the yellow ramp, illustrated in Figure 6 below.

Table III. UV included – UV excluded mean and max color differences for each printer and substrate.

	CA		HP		OK	
ramp differences	XRX	EPS	XRX	EPS	XRX	EPS
Mean ΔE*ab	3.30	8.55	1.77	9.00	1.25	7.66
Max ΔE*ab	7.82	12.56	2.87	12.59	2.63	12.14

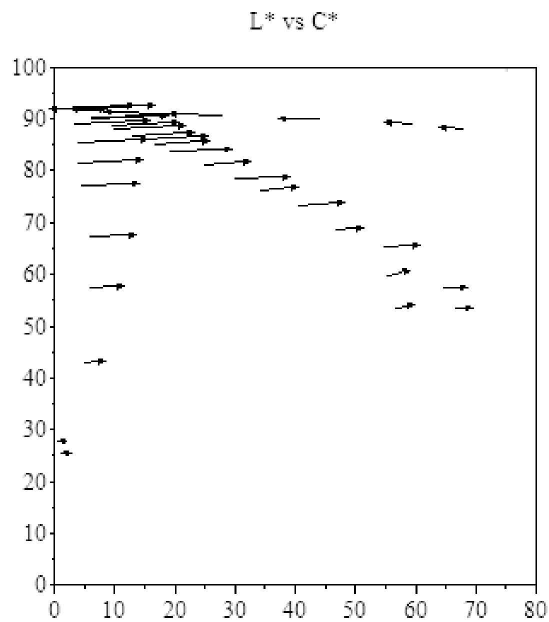

Figure 5. UV excluded to UV included L vs. C* difference vector plots. Data shown for CMYK ramps of device CA, substrate EPS.*

In Figure 6, colors are observed shifting uniformly towards the blue region of color space (lower-right quadrant on the b* vs. a* plane) as a result of substrate fluorescence. The chromatic decrease for the highest L* colors shown in Figure 5 above, is due to a blue shift in the yellow ramp.

To investigate the effects of fluorescent OBA on gamut volume, fifty-six points on the CMY primary cube surface were printed with the OK and CA printers on the EPS and XRX substrates. The volume of the convex hull encompassing the CIELAB coordinates of the approximate gamut was calculated using Qhull[13] convex hull software. This procedure was repeated for complete adaptation to the paper white point; as used in aspects of ICC color management.

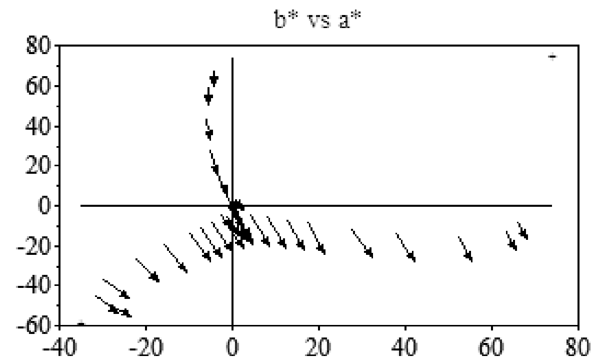

Figure 6. UV excluded to UV included b vs. a* difference vector plots. Data shown for CMYK ramps of device CA, substrate EPS.*

Table IV. Volume of CIELAB gamut-encompassing convex hull calculated with adaptation to source and substrate white point.

	XRX		EPS	
white point	source	substrate	source	substrate
OK UVI vol	2.03E+05	2.55E+05	2.32E+05	2.61E+05
OK UVX vol	2.02E+05	2.56E+05	2.13E+05	2.62E+05
UVI/UVX	101%	100%	109%	100%
CA UVI vol	1.54E+05	1.89E+05	2.17E+05	2.38E+05
CA UVX vol	1.51E+05	1.90E+05	1.98E+05	2.39E+05
UVI/UVX	102%	100%	109%	100%

The volumes associated with gamuts with adaptation to the substrate white point are larger than the volumes representing adaptation to the illuminant D50 white point. This is most likely due to stretching along the achromatic axis when defining adaptation to the substrate white point. For prints on the XRX substrate, volume is shown to increase for both printers when adapting to the substrate, however the ratio of UVI to UVX volume remains approximately constant. On the EPS substrate, the UVI volume is 9% larger than the UVX volume for both printers with adaptation to the source. Despite large color differences for individual colors, the gamut volume does not change as much. This could be partly due to lower color differences at the gamut edges due to high ink density (hence less substrate influence) as well as a uniform shift to the blue region of color space. It is believed the increased EPS gamut is due to a shift in the lighter colors. When adapted to the EPS substrate, CIELAB volumes of both printers remain approximately constant.

It was attempted to model the output of the three printers, on each of the EPS and XRX substrates, and each measurement condition. Each combination was modeled as an independent system, utilizing a Yule-Nielsen modified spectral Neugebauer printer model with a power-law dot gain. For the models to be considered accurate, they should demonstrate the UVI/UVX relationships described above.

Results

A Yule-Nielsen modified spectral Neugebauer printer model with power-law dot gain was employed for prediction of the twelve combinations of printer/substrate/UV inclusion. Using the nonlinear optimization tool *Solver* in Microsoft Excel, Yule-Nielsen *n-value* and effective area power law *dot gain* exponent parameter were optimized for color difference under D50, and separately for spectral error. Optimization for *dot gain* parameter and *n-value* and was performed on the CMY ramps. Model parameters and color differences for characterization data are shown in Table V for the UVX models and Table VI for UVI models.

Table V. Model parameters and colorimetric results on substrate XRX.

XRX	CA		HP		OK	
	UVI	UVX	UVI	UVX	UVI	UVX
dot gain power	0.99	0.99	0.88	0.88	0.70	0.70
n-value	4.66	4.92	3.51	3.58	3.72	3.66
mean ΔE*ab	2.73	2.74	1.83	1.88	4.87	4.96
max ΔE*ab	6.65	6.86	3.41	3.57	12.34	11.94
median ΔE*ab	2.37	2.40	1.94	1.73	3.83	4.41

Table VI. Model parameters and colorimetric results on substrate EPS.

EPS	CA		HP		OK	
	UVI	UVX	UVI	UVX	UVI	UVX
dot gain power	0.94	0.94	0.90	0.89	0.77	0.77
n-value	4.95	5.10	3.41	3.42	3.26	3.50
mean ΔE*ab	4.35	4.20	1.89	1.76	4.47	4.14
max ΔE*ab	10.96	10.48	3.16	3.04	9.59	8.55
median ΔE*ab	3.90	3.68	2.05	1.83	3.35	3.33

Analysis

The colorimetry of three printers output on two substrates was modeled using both UV included and UV excluded measurements. This resulted in twelve printer models, one for each printer/substrate/UV combination. In Tables V and VI, UVI and UVX parameters are quite similar for individual printer/substrate combinations. For printer CA, both UVI and UVX conditions exhibited greater mean, max and median color differences on the EPS substrate than XRX. Conversely, the OK printer exhibited higher model accuracy on EPS than on XRX substrate. Only models of HP/EPS, and HP/XRX, (each for UVI and UVX measurement) have mean colorimetric accuracy close enough to possibly model the actual UVI-to-UVX colorimetric differences exhibited in Table III. Although model parameters and colorimetric accuracy of the other printer/substrate/UV seem reasonable on their own, they will most likely not be able to predict the UVI-to-UVX color differences shown in Table III.

In Tables V and VI, the dot-gain and n-value model parameters are reasonably close for each UVI/UVX combination. Performance of models employing averaged UVI and UVX dot gain power and n-value are shown in Tables VII and VIII. These data indicate UVI measurements could be used in a spectral prediction model generated with UVX data, and predict printer output to a similar color-accuracy level.

Table VII. Mean model parameters and colorimetric results on substrate XRX.

XRX	CA		HP		OK	
	UVI	UVX	UVI	UVX	UVI	UVX
dot gain power	0.99		0.88		0.70	
n-value	4.79		3.54		3.69	
mean ΔE*ab	2.72	2.75	1.83	1.88	4.87	4.95
max ΔE*ab	6.60	6.91	3.45	3.54	12.35	11.92
median ΔE*ab	2.38	2.41	1.91	1.73	3.84	4.41

Table VIII. Mean model parameters and colorimetric results on substrate EPS.

EPS	CA		HP		OK	
	UVI	UVX	UVI	UVX	UVI	UVX
dot gain power	0.94		0.90		0.77	
n-value	5.03		3.41		3.38	
mean ΔE*ab	4.35	4.21	1.92	1.73	4.48	4.14
max ΔE*ab	10.91	10.53	3.46	3.16	10.06	8.81
median ΔE*ab	3.92	3.67	2.04	1.95	3.55	3.26

On average, the color accuracy of EPS UVI models are reasonably close to the EPS UVX models. It is promising that models using UVI EPS were reasonably accurate since the UVI spectral reflectance of the EPS substrate is in excess of 100% in the blue region.

Conclusion

The effect of optically brightened substrates on printed ink color was examined in a two-part study. In Part II, a modified spectral Neugebauer printing model was employed to model various desktop printers and examine the effect of fluorescent OBA containing substrates on printed halftone colorimetry. The output of three printers (two ink jet, one laser jet) were modeled on coated copy paper and coated ink jet paper (containing fluorescent optical brightening agents) using both ultraviolet included (UVI) and ultraviolet excluded (UVX) instrument illumination. This resulted in twelve printer models (one for each printer/substrate/UV combination). Each printer was modeled to reasonable accuracy (less than 5.0 ΔE^*_{ab}); however, the models of the HP printer were the only models to approach the accuracy required to predict the measured differences between UVI and UVX measurements.

It was observed that printer/substrate model parameters and color accuracy were similar independent of UV component inclusion. UVI and UVX printer models were evaluated for color accuracy when using the average model parameters for each printer/substrate combination. Models generated using the average model parameters were within

0.25 ΔE^*_{ab} of models generated specifically for each UV condition. This indicates UVI measurements could directly plug into a model generated with UVX measurements, and perform with reasonable colorimetric accuracy. Once the model parameters for a UVX system have been optimized, those same model parameters could be used to predict output for a UVI system, using the appropriate measurements; a second optimization may not need to be performed. This observation is limited to the accuracy of the model. UVX and UVI models using identical parameters did not exhibit high enough accuracy to predict the difference between UVX and UVI measurements.

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Biography

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