Colorimetric Characterization of Printing Systems Using Targets Compensated for Tonal Value Increase

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Abstract: This research investigated the efficacy of calibrating the output of a flexographic printing press for specified levels of tonal value increase (TVI) prior to the press characterization in order to enhance the accuracy of subsequent profiles. The objective was to determine whether or not the compensation for TVI would result in a more uniform colorimetric sampling of the printing gamut, particularly in regard to the highlights, and whether or not a more uniform sampling would provide profiles that would be more accurate in terms of color reproduction.

The study was conducted on a flexographic press direct printing on corrugated board. Compensation curves were applied to the characterization targets to target 17% midtone TVI and 0% midtone TVI, and characterizations were also conducted with no compensation applied as a control. It was found that while the 17% midtone TVI calibration did result in a more uniform distribution of the colorimetric data than the uncompensated or 0% midtone TVI calibration, the profiles generated from the compensated characterizations did not provide significantly enhanced color reproduction.

Introduction

Colorimetric workflows have provided printers, designers, and prepress professionals with powerful tools for controlling color reproduction throughout the production process. A key element in the success of this workflow is the accuracy of the profiles used to characterize the color rendering abilities of each device. A profile provides the link that enables the color management system (CMS) to translate color between the colorants used by the device and the independent color system (either CIEXYZ or CIELAB) that serves as the profile connection space (PCS) (Sharma, 2004). Profiles are used to maintain specified colors during the

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color conversions inherent in the production process. Profiles document which colors can be produced under specific printing conditions (and conversely, what input is necessary to create a specific color), so that one device can be used to replicate the colors that can be reproduced on another device, provided those colors are within gamut for each device.

For printing systems, the profile is created from colorimetric data captured by printing targets designed to systematically sample the color gamut of the output device, be it a press or proofing system. The printing system can be regarded as all of the ingredients for the job at hand: the substrate, the ink set, the image carrier, and the particulars of the printing process itself, be it flexography, offset lithography, gravure, inkjet, or another printing process. The characterization targets used to create device profiles consist of various tints of cyan, magenta, yellow and black printed as single tints or in combinations to create an array of colors. The printed colors are measured via spectrophotometry and the subsequent colorimetric data is used to create a profile of the device that relates the CMYK input data to the printed colors as specified through an independent color space, either CIEXYZ or CIELAB (Sharma, 2004).

A number of factors affect the color that results from a given input of CMYK. For color reproduction purposes, the main issues that the characterization must address are the tonal value increase (TVI), or dot gain, of the printing system, the individual color ingredients used (the substrate and inks), and the overprint characteristics (Samworth, 2003). Once this data is captured, one can apply the information towards optimizing an image for print and creating separations. A process color reproduction is simply four halftone images superimposed on one another in exact register. To get the most detail from the reproduction, the halftone that constitutes each printer must be optimized to utilize the full range of tones the system is capable of reproducing. Thus, tone reproduction is the first consideration in preparing an image for print (Southworth, 1979). Without a compensation curve, a printed tone scale can have as much as two-thirds to nearly three-quarters of the input data printing above the 50% tone, with a distinct plateau in the shadows. Printing tone scales that have been compensated for TVI results in a more uniform distribution of printed tones. The compensated target provides a more accurate reproduction of the input data (Adams, 1998).

In a colorimetric workflow, the compensation for TVI occurs at the same time as the colorimetric issues of color conversion occur. However, the profile look-up table does not account for individual transforms that occur between the input numbers of the digital file and the resulting color measured on output, and so as long as those transforms are consistent and repeatable, they become part of the printing system. Thus, if one wishes, the profile can easily accommodate a transformation of the input data to adjust for TVI, just as in the case of a photomechanical transfer function. This strategy provides the practical basis for the thesis of this study—obtaining an optimal sampling of the color gamut in the characterization by compensating the colorimetric target for TVI.

Colorimetric characterizations are commonly run without any compensation to the printing system in order to capture the full, unadulterated color rendering capabilities of the printing system. In printing systems where there is a relatively large amount of TVI, the sampling points of the target are clustered in the shadows, with relatively few points sampled in the highlights (Samworth, 2003). However, if the TVI can be addressed by applying compensation at the raster image processor (RIP) for the image carrier, then one has the opportunity to base the characterization on a target that has been optimized for the printing system the same way a traditional halftone is optimized for reproduction through a compensation curve or transform function. The colorimetric sampling can be adjusted so that it is more evenly distributed throughout the color gamut of the printing system.

There has been some debate as to the efficacy of this practice. In a preface to a 2001 IT8.7/4 proposal, David McDowell states that "the CMYK ink values specified are those to used as input to the printing processes; no additional normalization or 'cutback' curves should be applied" (McDowell, 2001). This intention is further documented in CGATS/SC4 N 406, *How to run a good press test for development of a color characterization data set (Draft 2)*, which states, "tone reproduction on separation films and on digitally imaged plates should have a final linear relationship to the original data file" (CGATS/SC4 N 406 draft 2). However, others have proposed alternative approaches to the characterization. The third edition of the Flexographic Image Reproduction Specifications and Tolerances (FIRST) recommends that colorimetric characterization is best performed if the printing system is calibrated for a specific amount of TVI—17% midtone gain, such that the 50% tint prints as a 67% tint (FIRST, 2003). FIRST claims that this amount of TVI will provide the best distribution of colorimetric data from an IT8.7/4 target. At the FFTA's 2003 FIRST conference, it was recommended that TVI compensation be used with ICC profiling for flexography, which typically has relatively high TVI, commonly 25-30% at the midtone. The suggestion was that TVI is a one-dimensional change that can be addressed through a compensation curve, while the colorimetric properties of the inks and their overprints are best addressed through a profile (Samworth, 2003). Using a computer-to-plate (CTP) curve to compensate for TVI results in a printed target with color samples that are more evenly distributed throughout the tonal range of the printing gamut, rather than clustered in the shadows, as happens when the TVI is high.

In 2005, a study was conducted at Clemson University to investigate the efficacy of using cutback targets to produce ICC profiles (O'Hara, 2005).

The study employed an inkjet system, a narrow-web flexographic press and an offset lithography press. Each printing system was calibrated to 17% midtone gain and 0% midtone gain through the application of compensation curves at the RIP, and colorimetric targets for profile generation were printed. For each printing system, an uncompensated target was printed as well. Profiles were made from each of the three calibrations for each printing device, and the profiles were used to make CMYK separations for each printing condition. The evaluation target consisted of color swatches in a digital file in LAB color space that were converted to CMYK by the various profiles. The resulting printed colors were compared to the LAB values specified in the digital file, and CIE ΔE94 values were calculated to evaluate the accuracy of the various profiles. No enhanced benefit was found for profiles created using targets compensated for TVI (O'Hara, 2005).

This current study was undertaken to replicate the efforts of the 2005 study by applying the same experimental technique to another high-gain TVI printing system, a flexographic direct print corrugated press. It was hypothesized that characterization targets that have been calibrated for TVI would be optimized to provide a more uniform sampling of colorimetric data throughout the tonal range and would subsequently provide more accurate color transforms for the printed reproduction of the colors specified in the digital file.

Methodology

The experiment was designed to answer two questions, whether or not the colorimetric data would be more evenly distributed using targets that were compensated for TVI, and whether or not the profiles generated from such targets provided more accurate color reproduction of the LAB values specified in a digital file.

The experiment was designed to specifically investigate the claims of the third edition of FIRST that a printing system that is calibrated to print with 17% midtone dot gain would have a better colorimetric sampling and subsequently improved color reproduction. To test this claim, two experimental treatments were performed along with one control. The first experimental treatment was to calibrate the TVI of the press to have 17% midtone TVI, such that the 50% dot of the digital file would print as a 67% dot. The second experimental treatment was to calibrate the press to a fully compensated condition, such that the 50% dot in the digital file would print as a 50% dot (0% TVI). The control was to apply no compensation for TVI, and allow the 50% dot in the digital file to print at whatever amount of TVI was inherent in the press.

In order to perform the calibration, a test plate was made at Matthews International in Pittsburgh, PA. A series of tone scales were output at various levels of compensation by using Artworks Systems FlexoCal™ imaging software. The FlexoCal™ system involves a series of 12 compensation curves that are stepped in 3% increments from the 50% dot, such that FlexoCal™ A has no compensation (the plate measures 50%), FlexoCal™ B measures 47%, C measures 44%, etc. The initial test run was conducted on unit 3 of the Bobst 160 corrugated press at the Printing and Converting Research Center (PrintCon) at Clemson University. From the calibration run, it was found that the uncompensated condition (FlexoCal™ A) printed with 28% midtone gain (the 50% measured as 78%). It was determined that the colorimetric characterization targets would be compensated using FlexoCal™ E and FlexoCal™ J in order to achieve targets with 17% midtone gain and 0% midtone gain, respectively.

In order to follow the recommended practices of the FIRST methodology, the current draft of the randomized IT8.7/4 was printed to create the profiles. The characterization targets were mounted on the same carrier sheets, which meant that all three characterizations were performed simultaneously, ensuring that the press conditions would be identical for each of the experimental and control treatments. The press run conditions are documented in Table 1, Characterization Press Run.

Table 1. Characterization Press Run

Characterization Run	**pH**	**Viscosity** (#4 DIN)	**Anilox**
Black (station 1)	9.8	24	700 cpi, 2.8 bcm/sq. in, 60˚
Cyan (station 2)	9.8	18	500 cpi, 3.0 bcm/sq. in, 60˚
Magenta (station 3)	9.6	17	500 cpi, 3.0 bcm/sq. in, 60˚
Yellow (station 4)	9.6	21	500 cpi, 3.0 bcm/sq. in, 60˚
Temp. 68˚F, Rel. Humidity 27%			
Press Speed 3600 sheets/hour, driers and sheet cleaner used.			
BCM Inks, 200#E Kemi Art Lite			
Dupont Cyrel TDR analog plates, 100 lpi, Auto Blend Hybrid			

Each characterization included an IT8.7/4, an ink limit target and a set of tone scales for each printer. The tone scales included 10% increments from 0%–100%. The characterization target and the tone scales provided information on the distribution of the sampled colorimetric data. The tone scales were measured for density, CIELAB, CIELCH, and spectral reflectance every 10 nm from 380 nm–730 nm using a GretagMacbeth Spectrolino. The density measurements were performed under Status T conditions, and all measurements were performed using D50 lighting and a 2˚ observer function calibrated to an absolute white. The density measurements were converted to dot area using the Murray-Davies formula, as follows:

$$\text{Dot Area} = \frac{1 - 10^{-D(t)}}{1 - 10^{-D(s)}} x100,$$

where $D_{(t)}$ is the density of the tint,
and $D_{(s)}$ is the density of the solid. (1)

Since the density measurements were taken referenced to an absolute white, the density of the paper was also measured and subsequently subtracted from each measurement prior to dot area calculations. The printed dot area was then plotted against the input dot area of the digital file for each treatment in order to compare the tone reproduction distributions of the various compensations.

After the characterization press run was conducted, press sheets were sent from Clemson to Matthews International in Pittsburgh. There, a GretagMacbeth Spectroscan was used to measure the IT8.7/4 targets and Heidelberg's PrintOpen 5.1 software was used to create the profiles. All measurements were performed with D50/2˚. The profiles were calculated from an average of six randomized IT8.7/4 targets for each of the calibrations. The three profiles were used to convert Photoshop® files consisting of various tint patches of known CIELAB values into separations, and then plates were made using the corresponding TVI compensations. The printed tint patches were subsequently measured and CIE ΔE94 was calculated between the LAB values of the digital file and the printed images.

The first of the three test images was an array of tint patches designed to systematically sample CIELAB color space at various hue angles, saturation and brightness levels. The Color Picker in Adobe Photoshop® was used to create color patches at eight different hue angles: 0˚, 45˚, 90˚, 135˚, 180˚, 225˚, 270˚, and 315˚. Within each hue angle, brightness levels of 100, 75, 50 and 25 were created, and within each level of brightness, saturation levels of 100, 75, 50, 25 and 10 were sampled. In addition, at the brightness level of 100, saturation levels of 15 and 5 were created to provide more data about highlight reproduction, which is an area that would conceivably benefit from the experimental treatments of TVI compensation.

In addition to the array of color swatches, two grayscales were converted from LAB to CMYK via the profiles. The first was a 16-step gray scale created by posterizing a 0-100 L* gradient into 16 levels. The second grayscale posterized an L* 84–100 gradient into 11 levels, in order to provide more data about highlight color reproduction.

The profiles were created with a full-range black (0–100%) and 370% total ink limit. UCR was used for black generation in order to see how each profile could address the CMY color balance for the grayscale reproductions. The profiles were used to convert the color swatches, 16-step grayscale and highlight grayscale from LAB color space to the CMYK color space of each calibration. The plates for each calibration were mounted on the same carrier sheet so that the press conditions for each calibration would be the same.

Once the plates were imaged and mounted, they were sent to PrintCon for the final test run. The test run was performed under the conditions documented in Table 2, Production Run.

Table 2. Production Run

Production Run	**pH**	**Viscosity** (#4 DIN)	**Anilox**
Black (station 1)	9.7	24	700 cpi, 2.8 bcm/sq. in, 60˚
Cyan (station 2)	9.7	17	500 cpi, 3.0 bcm/sq. in, 60˚
Magenta (station 3)	9.7	15	500 cpi, 3.0 bcm/sq. in, 60˚
Yellow (station 4)	9.7	21	500 cpi, 3.0 bcm/sq. in, 60˚
Temp. 77˚F, Rel. Humidity 33%			
Press Speed 3600 sheets/hour, driers and sheet cleaner used.			
BCM Inks, 200#E Kemi Art Lite			
Dupont Cyrel TDR analog plates, 100 lpi, Auto Blend Hybrid			

The printed sheets were measured with a GretagMacbeth Spectrolino, D50/2˚ referenced to an absolute white. The color swatches, 16-step grayscale and highlight grayscale from seven printed sheets were measured and averaged using GretagMacbeth's MeasureTool 5.0.4 software. CIE ΔE94 was used to determine the color match between the LAB values of the digital Photoshop® files and the actual printed values for each calibration.

Results

The first question to be addressed by the research was whether or not the compensation curves provided a more evenly distributed colorimetric sampling of the press color gamut. The first consideration in answering this question was to first examine the tone reproduction curves for each printer under the various TVI calibrations. As an example, the tone reproduction curves for cyan for each calibration are depicted in Figure 1, Cyan Tone Reproduction.

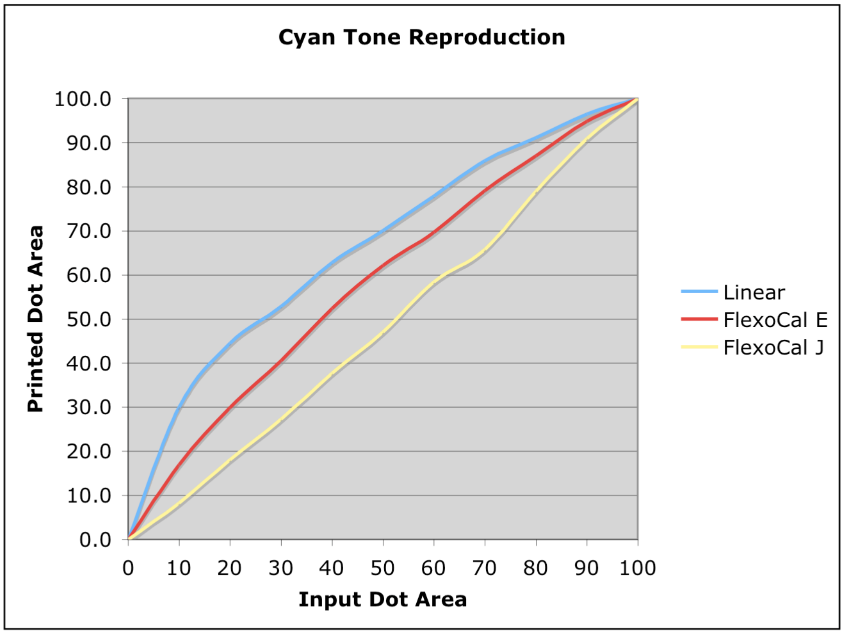

Figure 1. Cyan Tone Reproduction

It should be noted that the press characterization tended to print lighter than the desired levels of TVI for each of the calibrations. The printed dot areas for the 50% tint for each printer and calibration are presented in Table 3, Midtone TVI.

Table 3. Midtone TVI

	Intended	**K**	**C**	**M**	**Y**
Linear Plate	uncalibrated	73	71	76	74
FlexoCal™ E	**67** (17% midtone gain)	64	65	68	60
FlexoCal™ J	**50** (0% midtone gain)	44	49	50	48

To compare the colorimetric distributions for each calibration, the spectral curves of each tint at 10% increments 0%–100% were plotted for the KCMY printers. The resulting graphs were visually compared to examine the uniformity of spectral distributions. The spectral reflectance for the cyan tints for the linear, FlexoCal™ E, and FlexoCal™ J calibrations are shown in Figures 2–4, Cyan Spectral Reflectance. It can be observed that the compensated tint scales are more evenly stepped in terms of absorbing red light than the linear tint scales. This correlates strongly to the tone reproduction curves for each printer.

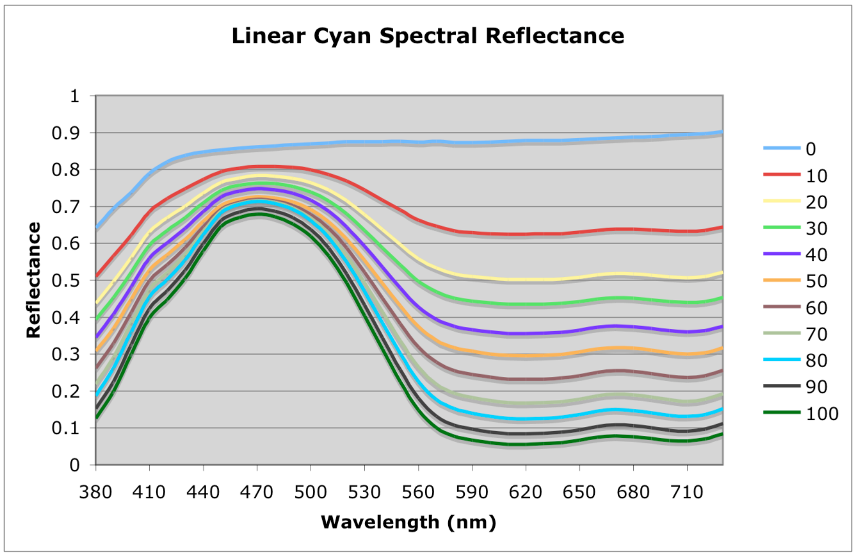

Figure 2. Linear Cyan Spectral Reflectance

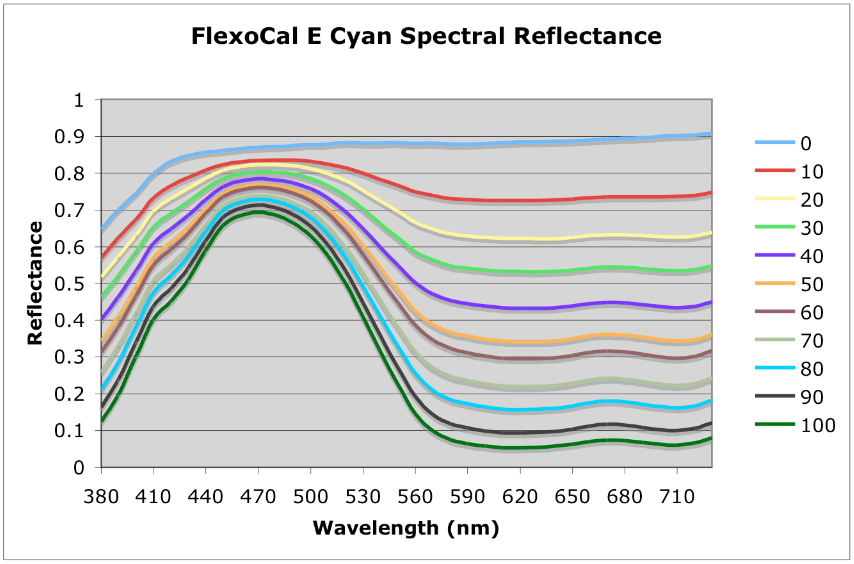

Figure 3. FlexoCal™ E Spectral Reflectance

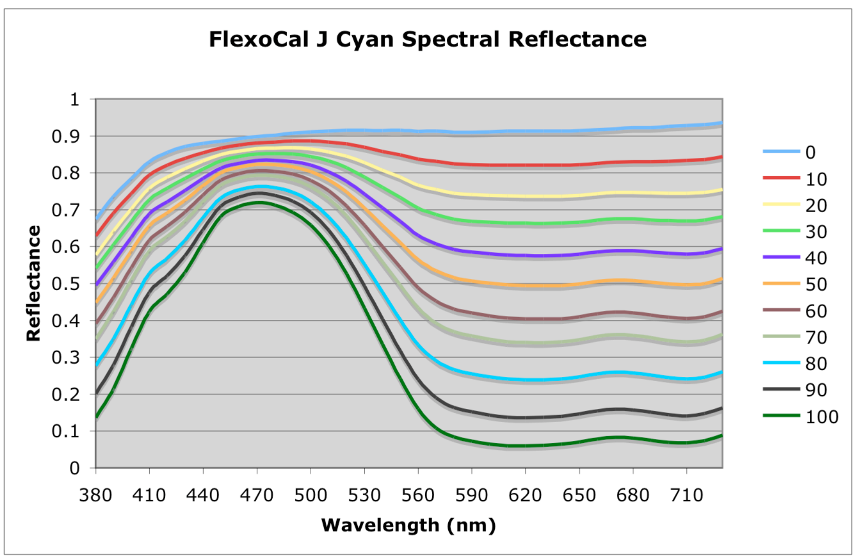

Figure 4. FlexoCal™ J Spectral Reflectance

It is also interesting to compare the distribution of the chroma (C*) for each of the printers. The distribution of chroma for the cyan tint scales is shown in Figure 5, Cyan Chroma. While the linear plate (21% midtone gain) and FlexoCal™ E (14% midtone gain) hold fairly even distributions, FlexoCal™ J (0% midtone gain) has a distinctly depressed curve. At 21% TVI and 14% TVI, the linear and FlexoCal™ E C* midtone gains bracket the "ideal" 17% midtone TVI specified by FIRST within 4% and 3%, respectively.

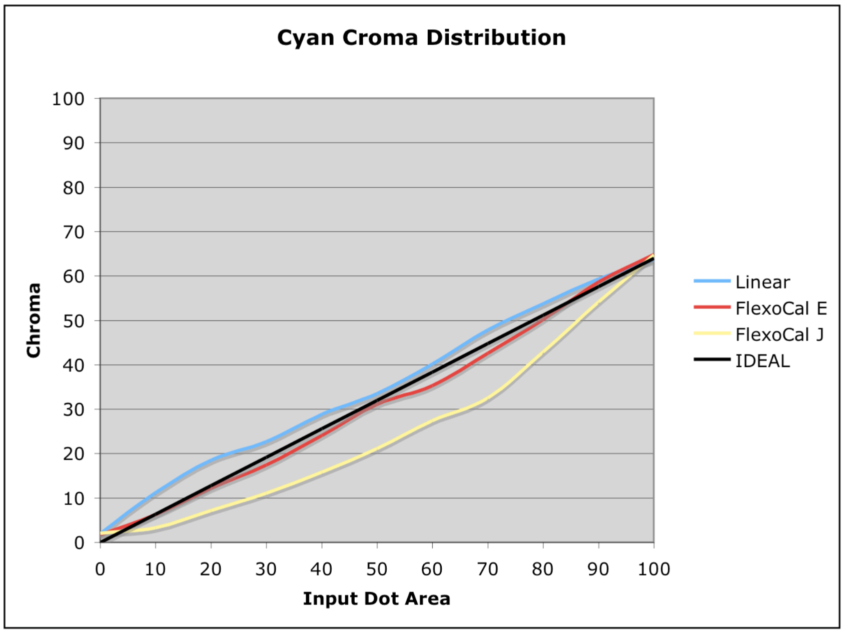

Figure 5. Cyan Chroma Distribution

However, the most illustrative model of the distribution of the sampled colorimetric data from each of the calibrations is to plot each measured point in a three-dimensional model of the CIELAB color space. Figures 6–8 show comparisons between the linear condition and FlexoCal™ E, between the linear condition and FlexoCal™ J, and between FlexoCal™ E and J, respectively. It can be seen that the linear plates, with an average midtone gain of 23.5%, provided colorimetric data weighted towards the shadows, whereas FlexoCal™ E, with an average midtone gain of 14.25%, and FlexoCal™ J, with an average midtone loss of 2.25% have more data in the highlights.

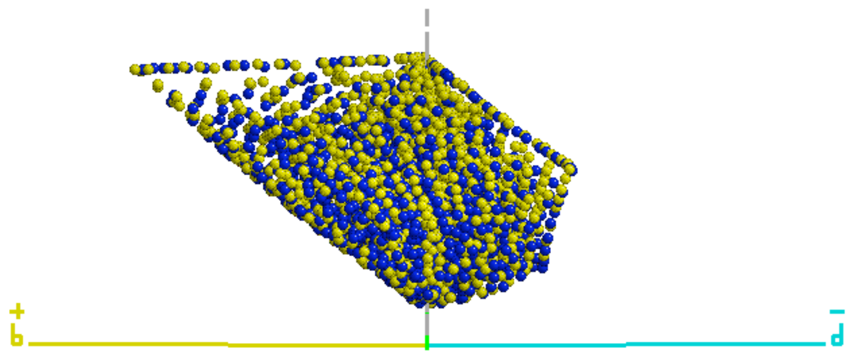

Figure 6. Linear (blue) vs. FlexoCal™ E (yellow) Colorimetric Sampling

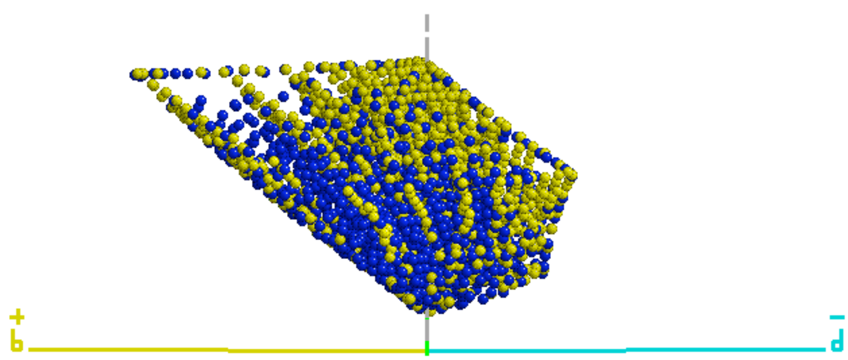

Figure 7. Linear (blue) vs FlexoCal™ J (yellow) Colorimetric Sampling

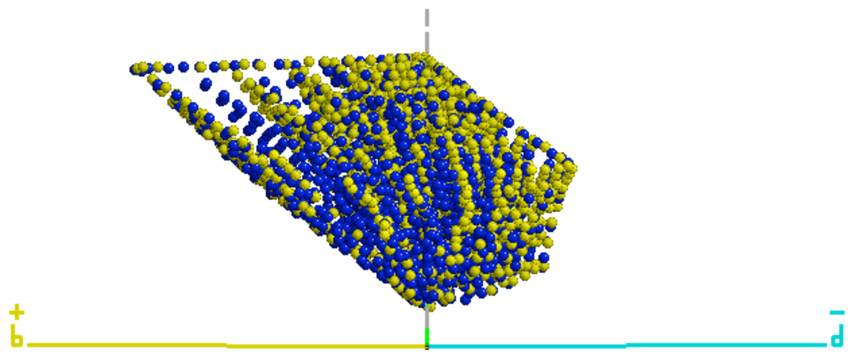

Figure 8. FlexoCal™ E (blue) vs. FlexoCal™ J (yellow)
Colorimetric Sampling

It is also useful to stratify the data in terms of being highlights, midtones, or shadows. For the purpose of comparison, shadows were deemed to be data with a lightness (L^*) value of less than 25, midtones were deemed to be $25 \le L^* \le 75$, and highlights to be $L^* > 75$. Table 3, Sampling Distributions, shows the tonal distribution for each of the TVI calibrations. It is clear that the TVI compensation affects the distribution of colorimetric data.

Table 3. Sampling Distributions

	Linear (Uncompensated)	**FlexoCal™ E** (14% midtone TVI)	**FlexoCal™ J** (-2% Midtone TVI)
$L^* < 25$ (highlights)	118 (7.3%)	214 (13.2%)	406 (25.1%)
$25 \le L^* \le 75$ (midtones)	1321 (81.7%)	1286 (79.5%)	1148 (71.0%)
$75 < L^*$ (shadows)	178 (11.0%)	117 (7.2%)	63 (3.9%)

In order to address the second research question, whether or not the compensated targets would yield more accurate profiles for color reproduction, profiles were created from an average of six randomized IT8.7/4 targets for each of the calibrations. The three profiles were used to convert Photoshop® files consisting of various tint patches of known CIELAB values into separations, and then plates were made using the corresponding TVI compensations. The printed tint patches were subsequently measured and CIE ΔE94 was calculated between the LAB values of the digital file and the printed images. Since the compensation was designed to enhance sampling in the highlights and midtones, the data has been stratified by lightness to examine the impact on those areas of the reproduction as well as consideration of the entire tonal range. The data was stratified based on the L* value of each swatch in the digital file, such that $L^* < 25$ are considered shadows, $25 \leq L^* \leq 75$ are considered midtones, and $L^* > 75$ are considered highlights. The ΔEs for shadows, midtones, highlights, and the combined range of the color swatches were compared for accuracy between each calibration for a given printing system, and a single-factor ANOVA was calculated to determine whether or not a statistically significant difference exists between the accuracies of the various calibrations. Conversions for the 16-step grayscale and highlight grayscale were similarly evaluated.

The results of the color reproduction experiment are tabulated in Table 4, Calibration ΔEs. The lowest ΔE is, of course, the most desirable, and those results are highlighted for each target and strata. Where the difference was statistically significant as determined by a single-factor ANOVA with □ = 0.05, the ΔE value is shaded black.

Table 4. Calibration ΔEs

	Linear (uncom-pensated)	**FlexoCal E** 14.25 % midtone TVI	**FlexoCal J** -2% Midtone TVI
Swatches Shadows	8.8	9.0	7.8
Swatches Midtones	5.6	5.6	6.2
Swatches Highlights	9.4	9.0	10.2
Swatches Overall	7.1	6.9	7.6
16-Step Gray	5.9	6.3	6.1
Highlight Gray	6.6	4.8	7.2

It should be noted that the CIELAB files used to evaluate the accuracy of color transforms contained many colors that were outside the gamut of the corrugated press used in this study. For this reason, the average ΔE numbers were rather high. It was decided to sample the color space based off of hue, saturation and brightness values ranging from 100 to near zero and to allow the profiles to contend with the issues of out-of-gamut colors rather than to design a conversion target specifically for the press. In this way, the same targets could be used to evaluate the characterization technique using different printing processes. No attempt was made to edit the profiles or apply any further color correction.

Discussion

The purpose of this study was to examine the effectiveness of calibrating printing systems for specified amounts of tonal value increase (TVI) prior to conducting press characterizations. It was hypothesized that these procedures would enhance the accuracy of color conversions from CIELAB color space to a CMYK printing system. It was anticipated that a more evenly distributed sampling would provide a benefit, particularly for printing systems with relatively high TVI that tend to place the sampling points of the colorimetric data in the shadows and away from the highlights. It was hypothesized that compensating for TVI prior to printing the characterization would provide more samples in the highlights, thus requiring less interpolation by the CMS in those areas. However, while the results of the experiments support the hypothesis that the colorimetric sampling is more evenly distributed when a compensation for TVI is applied, only one of the test targets supports the hypothesis that the distribution of the sampling data within the device color space provides more accurate color transforms. The highlight grayscale did show a significant difference, as determined by a single-factor ANOVA with an alpha = 0.05. However, the highlight values of the color swatches did not indicate a significant difference, nor did the other targets. The latter results are consistent with the experimental results of the 2005 Clemson study, which found no significant enhancement for ink jet experiments, narrow-web flexography experiments, or offset lithography experiments (O'Hara, 2005).

The authors of this study therefore conclude that there is insufficient evidence to support the assertion that the application of compensation curves to colorimetric characterization targets will lead to improved color reproduction. It appears from the results of this study that given the same gamut boundaries of lightness and chroma, the CMS is powerful enough to overcome the disadvantage of non-uniform sampling to model and provide transforms for the colors within the gamut of the printing system. However, it should be noted that the experiment only evaluated the reproduction of flat tints; other critical issues for color reproduction include the smoothness of tonal transitions and maintaining detail, which were not addressed in this study.

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