The Effects of Coatings on Color Gamuts in Lithography

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Keywords
coating, aqueous, UV coating, hybrid inks, color gamut, Chroma, Delta-E, lithography

Abstract
It has become commonplace today to apply clear coatings on high-quality printed products. In addition to improving scuff resistance and speeding production throughput time, coatings are also known to improve the dynamic range and, therefore, the visual appearance of the prints. This study examined a number of coated samples produced by PIA/GATF to determine if there were measurable increases in color gamuts associated with the addition of clear coatings. The hypothesis that larger color gamuts would result from the addition of coatings was not supported overall. The attribute of Chroma was used to evaluate whether the gamuts were increasing. It was assumed that overall increases in the Chroma values of color patches from the IT-8 Basic Data Set would indicate larger color gamuts overall. Gloss coatings did tend to show slight increases in Chroma but matte-coated samples tended to have reduced Chroma values and some of the conditions had changes in Chroma that were effectively zero. The discrepancies between measured values and perceived increases of colorfulness might be attributable to the difference between the 45/90 illumination geometry of the spectrophotometer and the non-restricted illumination geometry of the human observer. It was found that the color changes due to coating could be accurately predicted by measuring the color differences of an unprinted sample of the substrate with and without coating applied. The differences in L-, a-, and b-values were used to calculate predicted L-, a-, b-values for all of the color patches. Linear regression showed that the predicted and measured L-, a-, b-values typically had correlation coefficients greater than 0.99. Different combinations of coating, ink, and paper yielded best-fitting lines with slightly different slopes and y-intercepts.

Background

This work built on a study of coatings, led by Dr. Mark Bohan, performed at PIA/GATF in the later part of 2004. The PIA/GATF study produced printed samples under 37 different sets of conditions. Throughout this massive undertaking great care was taken to achieve target densities across all the pressruns as well as consistency during the individual runs. Bohan first presented findings at the PIA/GATF Tech Alert Conference in January 2005. The initial analysis had two phases: first, measurements were made to confirm the validity of the samples; then extensive subjective evaluations were made. The findings were that persistent, yet subtle, color differences were observed. The complete findings are presented in a *PIA/GATF Research and Technology Report*.

The current study was undertaken to determine if the application of coatings resulted in a measurable difference in color. Specifically, the hypothesis was advanced that the application of a coating would enlarge the color gamut of a print. This hypothesis was based on the observation that coatings generally increase the apparent dynamic ranges of prints. Theoretically, this is due to the reduction of scattered light across the surface of the print. This effect is most noticeable in the rendering of shadow tones. This improved dynamic range is one of the factors that cause customers to request overprint coatings on their jobs.

To test this hypothesis, colorimetric measurements were made of the samples from the PIA/GATF coating study. The 37 different experimental conditions of the PIA/GATF study are shown in Figure 1. The study compared two different types of paper (gloss coated and matte coated) and two different ink sets (conventional drying oil inks and hybrid UV-curable inks). The conventional inks were examined under two conditions (wet-on-wet applications and wet-on-dry applications). Under each of these conditions a variety of different coatings were applied.

Two different types of coatings (aqueous and UV-curable) were compared. Three different finishes of each coating type (gloss, satin, and matte) were tested. In addition, two different varnishes (gloss and matte) were used to form a basis for comparison. Finally, some of the sheets were laminated with gloss and matte laminates. Not every possible combination was produced. Some combinations, like UV coating on wet conventional inks, are not compatible and, therefore, were not produced. The specific materials that were used in the 2004 PIA/GATF study are listed in Appendix A.

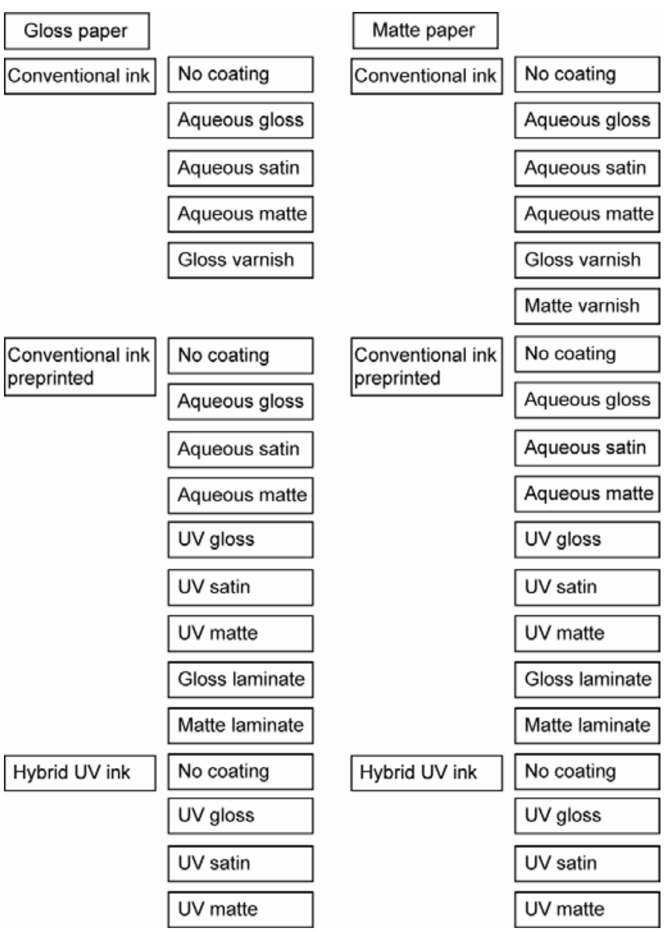


Figure 1. Experimental Combinations Produced in the 2004 PIA/GATF Coating Study

The current study was performed on samples from some (but not all) of these experimental conditions. The samples that were measured and analyzed for the current study were the most frequently used combinations of coatings and inks by the industry.

The test form used for the PIA/GATF study is shown in Figure 2. It is a five color form imaged at 175-lines per inch. The form consists of CMYK with the addition of a reflex blue spot color. The reflex blue element was included because printers have indicated that this color can give rise to specific problems when it is coated. This color was not analyzed in this study, but is included in the PIA/GATF report.

Of the many elements on the test form, the current analysis was based on only two areas of the test form (circled in red in Figure 2). The measured areas include a portion of: the GCA/GATF Digital Proof Comparator for densitometric analysis, and the truncated IT8.7/3 Basic Data Set for colorimetric analysis. The portion of the basic data set included on the test form includes 130 patches, giving a wide sampling of colors dispersed throughout the color space.

Figure 2: Test Form Used for the Study

Press tests were carried out on a Komori L628 sheetfed lithographic press (Figure 3) at the PIA/GATF facility in Sewickley, PA. The coater configuration used on the Komori L628 press is a chambered anilox system. The coating is applied after the printing stations. Using this type of coater, the coat weight is determined primarily by the volume of the anilox roll used. Changes in coating thickness are achieved by altering the viscosity of the coating fluid, and this is commonly achieved by changing the temperature of the coating fluid.

Increases in the temperature will result in a lower fluid viscosity. The volume of the anilox roll in the coater is 12 BCM (billion cubic microns). The coating is pumped to the coating head into an enclosed chamber. This system reduces the level of emissions and can also lead to improved viscosity control.

Figure 3: Press Used for the Study

The prints were all produced to standard density aimpoints determined during pre-trial print runs to evaluate the ink/paper combinations. The aimpoints were chosen to produce a good neutral gray. One issue arose concerning the trapping of the two different types of ink. The trap values obtained with the hybrid ink were lower than the traps from the conventional inks. Therefore, when the densities and tonal reproduction matched, the overprints and grays did not. It was important for the PIA/GATF subjective comparisons that the images should match as closely as possible. To achieve this, the plates for the hybrid ink were curved differently, having a slightly different tonal reproduction for the same target density.

One purpose of the PIA/GATF study was to compare aqueous coatings with UV coatings in both in-line (wet-on-wet) and off-line (wet-on-dry) applications. This necessitated the use of the hybrid UV inks to produce the in-line samples with UV coating because it is not possible to coat conventional inks inline with UV coatings. The hybrid UV ink set was selected as this allows relatively easy transfer on the press between the two ink sets without having to change rollers and blankets, as would have been the case with most UV inks.

In practice, in-line varnishes are often used instead of coatings. To extend the scope of the research, PIA/GATF tested two varnishes with different gloss levels. These varnishes were applied on unit six of the press over the whole of the image area using a solid plate matching the printed areas.

Finally, preprinted dry samples were also laminated with two different laminates (gloss and matte) to serve as another point of reference.

PIA/GATF Printing Procedure

Printed sheets were first produced to the predetermined density specifications using process-color drying oil inks (referred to in this study as *conventional* inks). These were not coated and were allowed to dry over an extended period. Some would be coated during later phases of the study.

A second series of pressruns were then carried out to the same density aimpoints using the same equipment and materials as the first run. These prints were coated inline with each of the three aqueous coatings (gloss, satin, and matte). After each coating was applied, the press was stopped and the print impressions removed from the printing blankets. The dry prints (those produced earlier) were then coated. This ensured that the same coater settings and coating rheology were used to coat wet and dry prints. Two additional pressruns were made using the preprinted samples and applying two types of varnish (gloss and matte).

In the third phase, the prints were produced to the same ink densities using a hybrid UV ink set. These prints were coated inline with the three different UV coatings (gloss, satin, matte). After each coating was applied, the press was stopped and the print impressions removed. The dry prints produced earlier using conventional inks were then coated with the three types of UV coatings.

Finally, some of the dry conventional ink samples were laminated with two different types of laminate (gloss and matte).

Experimental Procedure for the Current Study

The PIA/GATF study provided a wealth of different coating conditions for study. The current study was focused primarily on the in-line aqueous and UV-coated samples on matte- and gloss-coated papers. These conditions were chosen because they represent the most common coating applications used in the production of printed products.

Spectral measurements were made from the PIA/GATF samples using a Gretag SpectroLino XY scanning spectrophotometer. Density measurements were made from some samples using a hand-held X-Rite 500 series spectrodensitometer. In both instances, black backing was used in conformance with standard measurement practices (CGATS.4-2006 and CGATS.5-2003).

Studies of printed materials are always fraught with a myriad of variables that can influence the outcome of the study. The equipment, the materials, the environmental conditions, the press crew will all influence the printed results, sometimes in unpredictable ways. In this study, another factor that must be considered is the age of the printed samples. The samples for this study were produced 15 months before they were measured. During this interval, the samples were stored in a light-tight drawer within the PIA/GATF facility in an area where extremes of heat and humidity were never present. It is assumed that the readings made from these samples will have validity in spite of this limitation.

Spectral measurements of the IT8.7/3 target were made for 35 printing conditions from a single sample chosen from among the available samples for each condition. The analysis based on these data is considered to be *anecdotal* since it relies on single-sample measurements.

For the experimental conditions of central interest, five samples were selected and measured to provide more confidence in the validity of the findings. The average values from the five samples for each of the 130 measured patches were used in the analysis in conformance with the central limit theorem.

Density measurements were made from four printing conditions using single samples selected from the five measured samples as representing the closest to the center of the group. Three measurements were made from each target and the average of the three readings was used in the analysis.

Standard Error of Measurement

To get a reliable estimate for the amount of error that was due to the measuring device and technique, ten measurements were made from the same printed sample (gloss paper, aqueous gloss coating, conventional inks). Standard deviations were calculated for the L, a, and b readings across the 10 samples. These calculations were made for each of the 130 measured patches from the IT8.7/3 target. The average standard deviations, along with the maximum standard deviations found for any of the 130 patches are shown in Table 1.

	L-values	a-values	b-values
Average SD	0.04	0.06	0.07
Max SD	0.15	0.19	0.14
Pearson r	-0.01	0.07	0.19

Table 1. Standard Deviations for 10 Samples and 130 Patches

The variability of these patches gives an estimate for the amount of measurement error to anticipate due to the measuring methods and equipment. Pearson product moment correlation coefficients were calculated to determine if there were relationships between the magnitudes of the values being measured and the amounts of error to expect. No relationships were found, with the correlations being near zero. This was confirmed by the scatterplots (Figure 4) which show the relationships between the standard deviations found for each of the 130 measured patches and the magnitudes of the L-, a-, and b-values for those patches.

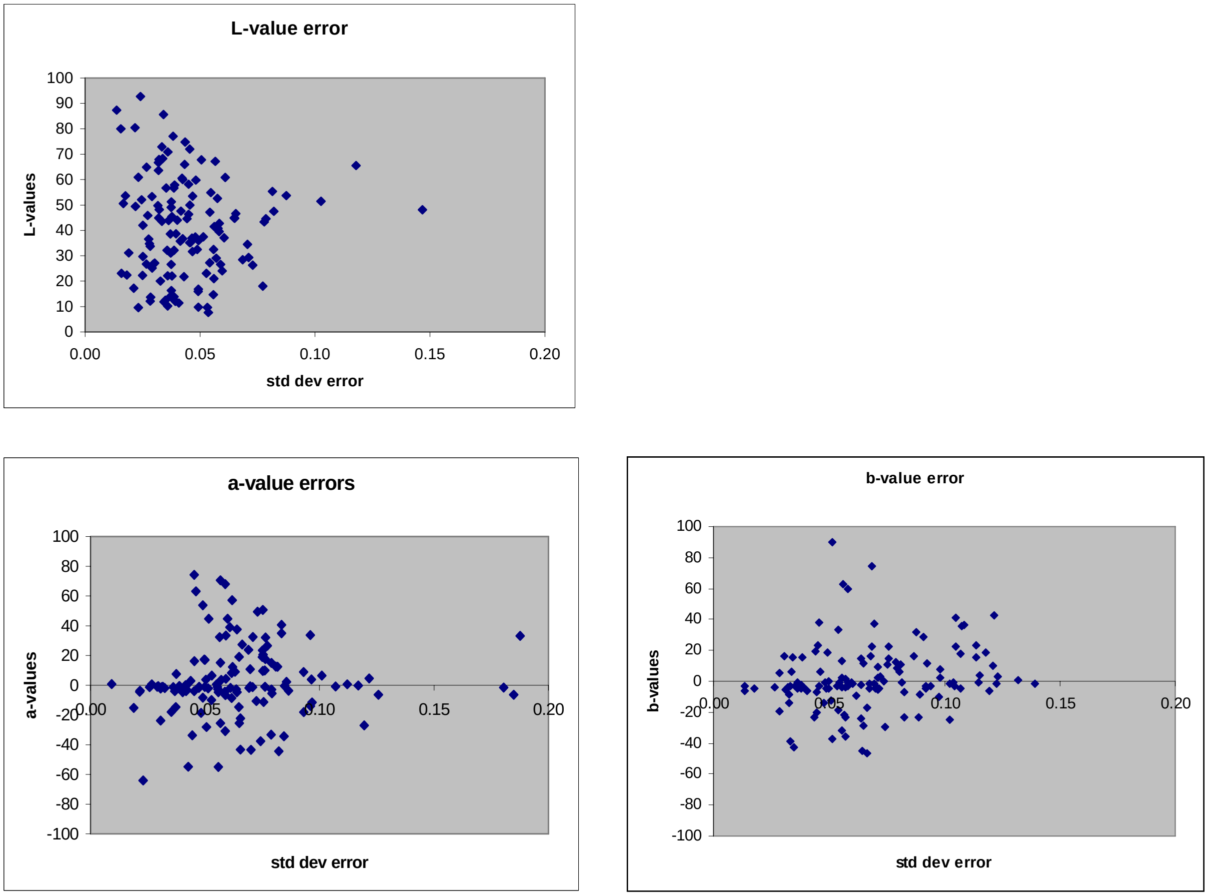


Figure 4. Scatterplots of Standard Deviations vs. L-, a-, b-Values

To obtain an estimate for the amount of measurement error to expect in calculations of Delta-E or Delta-Chroma, these values were calculated for each of the 130 color patches on all ten measured sheets against the average values of the 10 measurements for a given color patch. The average Delta-E and Delta-Chroma values for the 130 patches for each of the ten replicated measurements, together with their overall averages, are shown in Table 2.

reading	avg ΔE	avg ΔC
1	0.130	0.110
2	0.090	0.080
3	0.100	0.080
4	0.080	0.070
5	0.070	0.060
6	0.080	0.070
7	0.100	0.090
8	0.100	0.080
9	0.090	0.070
10	0.090	0.080
Avg	**0.092**	**0.081**

Table 2. Delta-E and Delta-Chroma Averages for 10 Repeated Measures

The data in Table 2 indicate that average measurement errors of slightly less than one-tenth of a Delta-E or Delta-Chroma unit should be anticipated. Larger measured differences, therefore, are due to real differences rather that measurement noise.

Samples of Central Interest

The samples of central interest for this study were 12 experimental conditions forming a 2x2x3 matrix, where the factors were paper (gloss-coated vs. matte-coated), ink/coating (conventional inks with aqueous coatings vs. hybrid inks with UV coatings), and type of coating finish (gloss vs. satin vs. matte). These experimental conditions were chosen because they represent the most commonly used coating combinations in the production of printed materials. The crucial data for this study were obtained by measuring five different samples from each printing condition. On each sample, 130 patches from the IT8.7/3 basic data set were measured. This does not represent the entire basic data set, but rather a truncated version of it. The single ink tone scales (rows "C" through "F" of the Basic Data Set) were omitted from the target to enable it to fit on the test form. The measured data does include solid patches of the single ink film colors. This limitation in the number of measured patches does not adversely influence the findings of this study since the study investigated the relationship between coatings and color gamut. The relative sizes of the color gamuts can be successfully compared with the 130 patches that were measured.

The average values for each measured patch were calculated across the five samples, and this subset was used in the subsequent analysis. To measure the amount of deviation that was present across the five samples from each experimental condition, Delta-E values were calculated between each sample and the average of the five. These values were calculated for each of the 130 measured patches. The average values for the 130 patches were calculated for each sample, and the grand average for the five samples were determined for each experimental condition.

The printing conditions of central interest are shown in Table 3 along with the grand averages of delta E's measured across 130 patches. The entries in the paper column of Table 3 refer either to gloss-coated or matte-coated papers. The coating/finish entries are the type of coating (aqueous or UV) and the finish (gloss, satin, or matte). In some cases, uncoated papers were measured as a basis for comparison. The inks column designates whether the inks were conventional, hybrid UV, or preprint (meaning conventional inks that had been printed and allowed to dry before being coated). The grand averages of the delta-E values indicate that, depending on the experimental condition, the delta-E values could be expected to vary between samples by magnitudes of 0.23 up to 0.76 delta-E units. These values differ from the measurement error found earlier in that the measurement error indicates the amount of variation to be expected from a single measurement while the values in Table 3 indicate the amount of color difference to expect from different samples of a given experimental condition.

The red values in Table 3 were selected experimental conditions from the preprinted samples to determine if they would exhibit different behavior than the wet coated samples. In the case of gloss-coated paper with gloss aqueous coating, the preprinted samples showed higher color variation than the equivalent wet-coated samples. However, in the case of matte-coated paper with matte aqueous coating, the preprinted sample had lower color variation than the equivalent wet-coated samples. Finally, when gloss UV coating was applied to preprinted conventional inks on gloss-coated paper, it exhibited lower color variation than gloss UV coating applied on wet hybrid inks. Since these changes in color variability were inconsistent, it was assumed that there was not a relationship between the coating of dry and wet ink films in terms of color consistency.

paper	coat/finish	inks	avg ΔE
gloss	uncoated	conv	0.35
gloss	aq gloss	conv	0.45
gloss	aq gloss	preprint	0.55
gloss	aq satin	conv	0.30
gloss	aq matte	conv	0.37
gloss	uncoated	hybrid	0.76
gloss	uv gloss	hybrid	0.66
gloss	uv gloss	preprint	0.48
gloss	uv satin	hybrid	0.45
gloss	uv matte	hybrid	0.37
matte	uncoated	conv	0.23
matte	aq gloss	conv	0.30
matte	aq satin	conv	0.39
matte	aq matte	conv	0.47
matte	aq matte	preprint	0.25
matte	uncoated	hybrid	0.74
matte	uv gloss	hybrid	0.44
matte	uv satin	hybrid	0.56
matte	uv matte	hybrid	0.70

Table 3. Samples of Central Interest with Average Delta-E's

To test if the factors of paper or ink/coating were significant in the level of variability found for the five sample measurements, a two-way analysis of variance (ANOVA) was performed. Table 4 shows the results of this analysis.

Source	DF	SS	MS	F	P
paper	1	0.015	0.015	3.11	0.103
inks	1	0.052	0.052	10.73	0.007
Interaction	1	0.005	0.005	1.09	0.317
Error	12	0.057	0.005		
Total	15	0.130			

Table 4. Two-Way ANOVA: Average Delta-E Versus Paper, Inks

The ANOVA showed that the type of inks/coating (conventional/aqueous or hybrid/UV) were a significant source of variability with hybrid inks and UV coatings being associated with higher amounts of variability in color from sheet to sheet. This finding is only relevant to this study and should not be interpreted to indicate a general condition with hybrid ink/UV coating combinations.

Compared to GRACoL

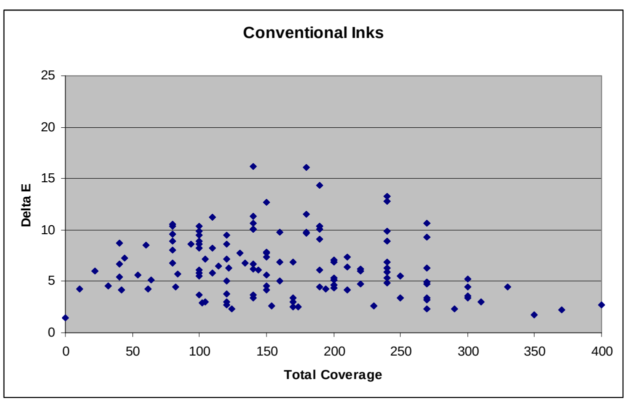
Uncoated and gloss-coated samples with conventional and hybrid inks on gloss coated paper were compared against the GRACoL draft characterization data to judge the closeness of match. Table 5 shows the summary data from Delta-E and Delta-Chroma values between the four chosen experimental conditions and the draft GRACoL characterization data. The data in Table 5 was based on measurements from 130 color patches from the IT8.3/7 Basic Data Set.

Inks	Coating	avg ΔE	max ΔE	min ΔE	avg ΔCh	max ΔCh	min ΔCh
conventional	uncoated	6.69	16.56	1.54	-0.64	7.28	-13.33
conventional	AQ gloss	7.02	17.58	1.34	-0.68	7.52	-13.43
Hybrid UV	uncoated	8.97	23.92	1.42	-2.59	6.31	-19.68
Hybrid UV	UV gloss	10.17	24.59	2.80	-1.94	8.39	-20.43

Table 5. Comparison with GRACoL Draft Characterization Data

The average Delta-E values in Table 5 show substantial color differences between the samples printed for this study and the target values from the GRACoL draft characterization data. Without coatings, the average delta E's across 130 target patches were 6.69 for conventional inks and 8.97 for hybrid UV inks. The addition of gloss coatings in these instances did not improve the match. When the differences in Chroma were examined, it was found that the printed samples on the whole were slightly less colorful than the characterization data as indicated by the negative average delta-Chroma values.

Scatter plots were generated to determine if larger color differences were found with target patches that had higher total dot coverages. The plots, Figure 5, show that no such relationship was found. The correlation coefficients for the two scatter plots are -0.17 for conventional inks and 0.08 for the hybrid UV inks, showing no appreciable relationship in either case.



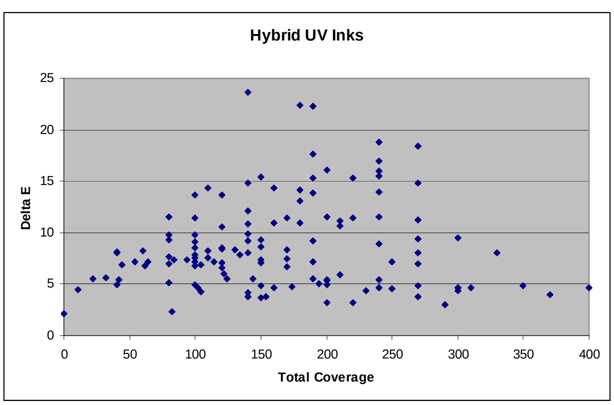


Figure 5. Scatterplots of Average Delta E vs. Total Dot Area Coverage

Since the color differences were so substantial, densitometric analysis was performed to determine how closely the printed samples adhered to the GRACoL guidelines. The results are shown in Table 6. The stated PIA/GATF density aimpoints for the study are also included in Table 6.

solid density		black	cyan	magenta	yellow
GRACoL		**1.70**	**1.30**	**1.40**	**1.05**
Study Aims		**1.75**	**1.32**	**1.49**	**0.99**
no coating	conventional	1.58	1.34	1.50	0.98
gloss coating	conventional	1.69	1.34	1.53	0.98
no coating	hybrid	1.64	1.28	1.42	0.95
uv gloss coating	hybrid	1.69	1.32	1.45	1.01

dot gain		black	cyan	magenta	yellow
GRACoL		**22**	**20**	**20**	**18**
no coating	conventional	19	25	23	21
gloss coating	conventional	20	25	25	23
no coating	hybrid	26	22	25	24
uv gloss coating	hybrid	30	26	29	28

print contrast		black	cyan	magenta	yellow
GRACoL		**40-45**	**35-40**	**35-40**	**30-35**
no coating	conventional	44	32	40	30
gloss coating	conventional	45	30	37	28
no coating	hybrid	35	33	34	25
uv gloss coating	hybrid	30	27	24	21

Table 6. Densitometric Analysis of Samples from Selected Experimental Conditions

The data in Table 6 shows that the printing conditions for this study did not adhere closely to the GRACoL guidelines with the yellow densities being too low and the magenta densities being too high. The dot gains tend to be higher than the GRACoL guidelines and the print contrasts are on the low side. These discrepancies explain the large color differences between the printed samples and the GRACoL draft characterization data. The fact that the printing conditions do not adhere to the GRACoL guidelines does not affect the relationship between the application of coatings and changes in color gamuts, which is of central interest in this study.

An observation that was made from the data in Table 6 was that the dot gain values increased with the addition of overprint coatings. This was true for both ink/coating combinations, but the effect was larger with the hybrid/UV coating combination. This might be due to the diffusion of some of the ink into the coating material, or it might be due to increased optical gain due the addition of a clear layer above the substrate acting as a lens. Since the dot gains increased with the addition of overprint coatings, it follows that the print contrasts would decrease since the two attributes are highly correlated. Again, these changes were more pronounced with the UV coating than with the aqueous coating.

Changes in Color Gamut

Fifteen different coating treatments were compared to their uncoated versions across the 130 patches from the IT8.7/3 target. Each condition was represented by the subset of five samples. The two attributes of Delta-E and Delta-Chroma were considered. Delta-E gives an overall color difference but it does not indicate whether the sample is more or less colorful than the target (the uncoated sheets). Delta-Chroma can result in positive or negative values. Since the values from the uncoated samples were subtracted from the coated sample values, negative values indicate that the coated patches are less saturated than the uncoated patches. Conversely, positive Delta-Chroma values indicate that the coated samples are more saturated (colorful) than the uncoated samples. For the coated samples to have larger color gamuts than the uncoated ones, the overall changes in Chroma would be positive. The data from this analysis is shown in Table 7.

paper	coating	inks	avg ΔE	max ΔE	min ΔE	avg ΔCh	max ΔCh	min ΔCh
gloss	aq gloss	conv	1.65	4.10	0.08	-0.04	2.73	-2.43
gloss	aq satin	conv	1.97	5.55	0.26	-0.83	2.18	-4.37
gloss	Aq matte	conv	2.82	7.23	0.32	-1.96	1.32	-6.45
gloss	aq gloss	preprint	2.82	7.80	0.18	-0.07	4.95	-3.98
gloss	uv gloss	preprint	2.54	5.94	0.65	0.38	3.99	-3.15
gloss	uv gloss	hybrid	2.10	4.89	0.51	0.66	3.95	-0.99
gloss	uv satin	hybrid	2.99	5.90	0.73	-0.22	4.54	-3.68
gloss	uv matte	hybrid	3.88	10.38	0.51	-1.27	3.81	-8.57
matte	aq gloss	conv	2.30	6.79	0.26	0.49	4.38	-2.75
matte	aq satin	conv	2.29	6.40	0.37	-0.12	3.95	-4.65
matte	aq matte	conv	2.79	6.78	0.35	-1.21	2.67	-5.74
matte	aq matte	preprint	5.22	11.88	0.32	-1.47	3.97	-7.87
matte	uv gloss	hybrid	3.64	8.96	1.20	1.04	7.25	-4.71
matte	uv satin	hybrid	2.26	6.09	0.38	0.42	6.08	-1.96
matte	uv matte	hybrid	4.55	9.61	1.13	-1.35	4.22	-7.62

Table 7. Color Differences Between Coated and Uncoated Samples

The data shows color changes in the magnitude a few delta-E units for all of the coating methods, with the matte coated samples showing generally higher color change than the other coatings. These data indicated that the addition of coatings caused real color changes in the printed samples. The magnitudes of the average Delta-E’s are substantially higher than the color changes due to measurement error or sheet-to-sheet variations (see Table 3). This gives confidence to the conclusion that the changes in color were real and not the results of measurement errors or sheet-to-sheet differences.

The Delta-Chroma values in Table 7 were small compared to the Delta-E values. This seemed to indicate that the addition of coatings caused greater change in the lightness of colors than in their saturations, but this conclusion was not justified. The change in Chroma value for a given patch could be either positive or negative, and, when the values for 130 patches were averaged, the positive and negative changes tended to offset each other resulting in lower average values. The changes in lightness (the other component of Delta-E) could also be either positive or negative, but, in practice, most of the changes are negative so that the average values tended to have higher magnitudes.

The majority of the average Delta-Chroma values in Table 7 were negative, indicating overall lower saturation (colorfulness) in the coated samples compared with the uncoated ones. There appeared to be a pattern indicating that the type of coating finish influenced the level of Chroma change where the least amount of Chroma change was associated with gloss coatings and the most Chroma change was found with matte coatings.

The overall finding that the average Delta-Chroma values were negative refuted the hypothesis that measurable increases in color gamuts would result from applying coatings to printed products.

The data in Table 7 represented the average Chroma changes across 130 patches. It was conceivable that the changes in saturated colors were being masked by opposite changes in light and near neutral colors. Since the overall color gamuts are defined by the Chromas of the most saturated colors, the analysis was repeated with a subset of the data representing only the most saturated colors in the data set. A subset of the 37 most saturated colors was assembled for analysis. If the average Delta-Chroma values of this subset were found to be positive, then the color gamuts would be enlarged due the coatings and the hypothesis of the study would be supported. The results of this analysis are shown in Table 8.

paper	coating	inks	avg ΔE	max ΔE	min ΔE	avg ΔCh	max ΔCh	min ΔCh
gloss	aq gloss	conv	1.41	2.72	0.08	-0.22	2.36	-2.43
gloss	aq satin	conv	2.39	5.55	0.63	-1.76	0.85	-4.37
gloss	aq matte	conv	4.41	7.23	1.70	-3.76	-1.05	-6.45
gloss	aq gloss	preprint	3.03	7.80	0.67	0.52	4.95	-2.71
gloss	uv gloss	preprint	2.36	5.24	0.65	0.85	3.19	-1.66
gloss	uv gloss	hybrid	1.45	3.97	0.51	0.53	3.95	-0.78
gloss	uv satin	hybrid	2.49	4.13	0.73	-0.57	3.42	-3.58
gloss	uv matte	hybrid	4.96	9.93	1.78	-3.62	2.33	-8.04
matte	aq gloss	conv	2.23	4.40	0.26	1.17	4.38	-1.17
matte	aq satin	conv	2.82	6.40	0.46	-0.22	3.56	-4.65
matte	aq matte	conv	3.13	6.78	0.35	-2.00	1.75	-5.74
matte	aq matte	preprint	6.16	11.88	1.77	-2.26	2.89	-7.87
matte	uv gloss	hybrid	2.83	8.96	1.45	1.11	7.25	-1.77
matte	uv satin	hybrid	1.79	6.09	0.38	0.47	6.08	-1.96
matte	uv matte	hybrid	4.94	9.30	2.11	-3.08	1.68	-7.62

Table 8. Color Differences Between Coated and Uncoated Samples for Saturated Colors

The data in Table 8 revealed the same trends that were observed for the larger data set. The changes in Delta-E values were modest indicating that the saturated colors did not exhibit substantially more color change than were found for the entire data set.

The Delta-Chroma changes in Table 8 were predominantly negative. These findings further refuted that hypothesis that the application of coatings would increase the color gamuts of printed products. Again, it was noted that matte coatings seemed to cause more loss of color saturation than did gloss coatings.

Factors Influencing Color Changes

To determine which factors were significant in causing overall color changes when coatings were applied, an analysis of variance was performed with average Delta-E as the response variable. This analysis was restricted to the experimental conditions that were of central interest. A three-way ANOVA was used to test the significance of the factors: type of paper (A=gloss or matte), coating finish (B=gloss, satin, or matte), and type of ink/coating (C=conventional/aqueous or hybrid/UV). The results of this analysis are shown in Table 9.

Source	SS	df	MS	F-ratio	F: 0.05	result	p-value
Ai	0.492	1	0.492	2.549	10.128	NS	0.2089
Bj	3.287	2	1.643	8.512	9.552	NS	0.0580
Ck	2.622	1	2.622	13.581	10.128	***	0.0346
ABij	0.846	2	0.423	2.191	9.552	NS	0.2591
ACik	0.026	1	0.026	0.135	10.128	NS	0.7377
BCjk	0.427	2	0.214	1.106	9.552	NS	0.4367
Rijk	0.579	3	0.193				

Table 9. ANOVA Table Delta-E vs. Paper, Ink/Coating, Coating Finish

The ANOVA in Table 9 showed that the type of ink/coating was significant at an alpha level of 0.05. Hybrid inks with UV coatings were associated with greater overall color changes than conventional inks with aqueous coatings. The type of coating finish (gloss, satin, matte), although not significant at an alpha of 0.05, had a 94% probability of significance, with matte coatings associated with the highest amounts of color change, satin coatings had medium amounts of color change, while gloss coatings showed the least amounts of color change.

To determine if the same factors were significant in causing changes in Chroma as those found to cause changes in Delta-E, the analysis was repeated using Delta-Chroma as the response variable. The factors again were: type of paper (A=gloss or matte), coating finish (B=gloss, satin, or matte), and type of ink/coating (C=conventional/aqueous or hybrid/UV). The results of this analysis are presented in Table 10.

Source	SS	df	MS	F-ratio	F: 0.05	result	p-value
Ai	0.723	1	0.723	3.743	10.128	NS	0.1485
Bj	8.099	2	4.050	20.975	9.552	***	0.0172
Ck	0.719	1	0.719	3.722	10.128	NS	0.1493
ABij	0.060	2	0.030	0.157	9.552	NS	0.8613
ACik	0.091	1	0.091	0.469	10.128	NS	0.5426
BCjk	0.073	2	0.036	0.189	9.552	NS	0.8369
Rijk	0.579	3	0.193				
total	8.280	11					

Table10. ANOVA Table Delta-Chroma vs. Paper, Ink/Coating, Coating Finish

The results in Table 10 (Delta-Chroma ANOVA) showed an interesting difference from those in Table 9 (Delta-E ANOVA). The factor of ink/coating (conventional/aqueous vs. hybrid/UV) was significant in causing overall color changes (Delta-E), but it was not close to significance in causing changes in Chroma. This implied that the influences of ink/coating combinations were most pronounced in changing the lightnesses, rather than the Chromas, of sample patches. The basis for this conclusion was that Delta E values are combinations of changes in lightness and changes in Chroma. To confirm this situation, differences of lightness (Delta-L) and differences of Chroma (Delta-Chroma) between uncoated and coated samples were calculated for each of the 130 patches from the IT-8 target. The Delta-L and Delta-Chroma values were averaged in two ways. First, the absolute values of the Delta-L and Delta-Chroma values were averaged to obtain average changes in the magnitudes of the attributes. Then straight averages were taken to determine whether the changes over all 130 patches were positive or negative. The results are shown in Table 11.

paper	coating	inks	abs ΔL	abs ΔCh	ΔL	ΔCh
gloss	aq gloss	conv	0.97	0.81	-0.89	-0.04
gloss	aq satin	conv	0.87	1.26	0.18	-0.83
gloss	aq matte	conv	1.34	2.07	1.24	-1.96
matte	aq gloss	conv	1.07	1.05	-0.92	0.49
matte	aq satin	conv	1.04	1.16	-0.82	-0.12
matte	aq matte	conv	1.12	1.88	1.02	-1.21
		average	**1.07**	**1.37**	**-0.03**	**-0.61**
gloss	uv gloss	hybrid	1.66	0.77	-1.65	0.66
gloss	uv satin	hybrid	1.62	1.31	-1.54	-0.22
gloss	uv matte	hybrid	2.48	2.40	1.80	-0.94
matte	uv gloss	hybrid	2.26	1.66	-2.25	1.04
matte	uv satin	hybrid	1.62	0.97	-1.57	0.42
matte	uv matte	hybrid	2.95	2.19	1.95	-1.35
		average	**2.10**	**1.55**	**-0.54**	**-0.07**
	Ratio: hybrd/UV vs. conv/aq		**1.97**	**1.13**		

Table 11. Delta-L and Delta-Chroma Ratios

The data in Table 11 reinforced the finding that the hybrid/UV combination had a disproportionately strong influence on the lightness of colors compared with the conventional/aqueous samples. The average lightness change on the hybrid/UV samples across all types of coating finish, both types of paper, and all 130 measured patches was 2.10 L-units, as opposed to an average magnitude of 1.07 with the conventional/aqueous samples. Furthermore, the average magnitude of Chroma changes were 1.55 units for hybrid/UV samples and 1.37 for conventional/aqueous samples. Ratios of the average change magnitudes of hybrid/UV samples compared to conventional/aqueous samples were calculated for both lightness and Chroma. These values of 1.97 for lightness and 1.13 for Chroma showed that the hybrid/UV samples exhibited relatively more change in the lightness of colors than in the Chroma of colors than did their conventional/aqueous counterparts.

The data in Table 11 further revealed that the conventional/aqueous combinations resulted in larger changes in Chroma than in lightness. However, the hybrid/UV combinations resulted in larger lightness changes than Chroma changes. These differences indicated that the UV coatings used in this study were less optically clear than the aqueous coatings and caused an overall decrease in the lightnesses of the printed colors.

For most of the experimental conditions that were measured, the changes in lightness and Chroma were negative, indicating slight losses of both lightness and saturation with the addition of any coating.

To determine if this observation was valid for the changes in Chroma (related to color gamut), the data were analyzed to determine if the mean values Delta-Chroma were statistically different from zero. To achieve this, one-sample t-tests were applied to each of the experimental conditions of central interest to test the hypothesis that the mean

Delta-Chroma values were equal to zero. Ninety-five percent confidence intervals were calculated around the means, and the probabilities that the means were equal to zero were also calculated. The results are shown in Table 12.

paper	coating	inks	mean	stan dev	95% conf interval		prob of 0
gloss	aq gloss	conv	-0.04	0.99	-0.207	0.137	0.69
gloss	aq satin	conv	-0.83	1.30	-1.056	-0.604	0.00
gloss	aq matte	conv	-1.96	1.80	-2.275	-1.651	0.00
matte	aq gloss	conv	0.49	1.28	0.268	0.712	0.00
matte	aq satin	conv	-0.12	1.57	-0.390	0.155	0.40
matte	aq matte	conv	-1.21	1.91	-1.538	-0.876	0.00
gloss	uv gloss	hybrid	0.66	0.85	0.511	0.806	0.00
gloss	uv satin	hybrid	-0.22	1.68	-0.515	0.069	0.13
gloss	uv matte	hybrid	-0.94	2.99	-1.461	-0.042	0.00
matte	uv gloss	hybrid	1.04	1.77	0.735	1.349	0.00
matte	uv satin	hybrid	0.42	1.40	0.182	0.668	0.00
matte	uv matte	hybrid	-1.35	2.54	-1.796	-0.913	0.00

Table 12. Confidence Intervals for Delta Chroma Means

The data in Table 12 showed that (with 95% confidence) the average changes in Chroma were negative under the some experimental conditions. This indicated that the color gamuts were slightly smaller when coatings were applied. The experimental conditions were the gamuts were smaller were the following:

- gloss-coated paper – conventional inks/aqueous coating – satin finish
- gloss-coated paper – conventional inks/aqueous coating – matte finish
- matte-coated paper – conventional inks/aqueous coating – matte finish
- gloss-coated paper – hybrid inks/UV coating – matte finish
- matte-coated paper – hybrid inks/UV coating – matte finish

However, under the following conditions the average changes in Chroma were positive indicating slightly larger color gamuts:

- matte-coated paper – conventional inks/aqueous coating – gloss finish
- gloss-coated paper – hybrid inks/UV coating – gloss finish
- matte-coated paper – hybrid inks/UV coating – gloss finish
- matte-coated paper – hybrid inks/UV coating – satin finish

Finally, for the following treatments the average changes in Chroma did not significantly differ from zero:

- gloss-coated paper – conventional inks/aqueous coating – gloss finish
- matte-coated paper – conventional inks/aqueous coating – satin finish
- gloss-coated paper – hybrid inks/UV coating – satin finish

Overall, these results were mixed. Some treatments showed positive changes in Chroma while others showed negative changes or unchanged conditions. In all cases, the magnitudes of the changes were small indicating that there were very little, if any, differences in the color gamuts of the coated vs. uncoated printed samples.

A clear pattern in the findings listed above was that matte-finish coatings were associated with smaller color gamuts and gloss-finish coatings were associated with larger color gamuts. This was assumed to be due to the optical effects of surface scattered light in the case of the matte coatings, and the absence of that dilution effect with gloss coatings.

Predictability of Color Changes Due to Coatings

Most of the experimental treatments that were examined in this study were found to exhibit color changes when coatings were applied. These changes were small, but were found to be real. It would be useful if the color changes (either negative or positive) were predictable. This would allow applications of color management to modify press profiles to accommodate different coating systems.

To calculate predicted color values for the coating applications, the L-, a-, and b-values of the zero coverage (unprinted substrate) patch in the IT-8 target were measured with and without coatings. Figure 6 shows the 3D scatterplots of the bare paper patch with various coating treatments for each type of paper.

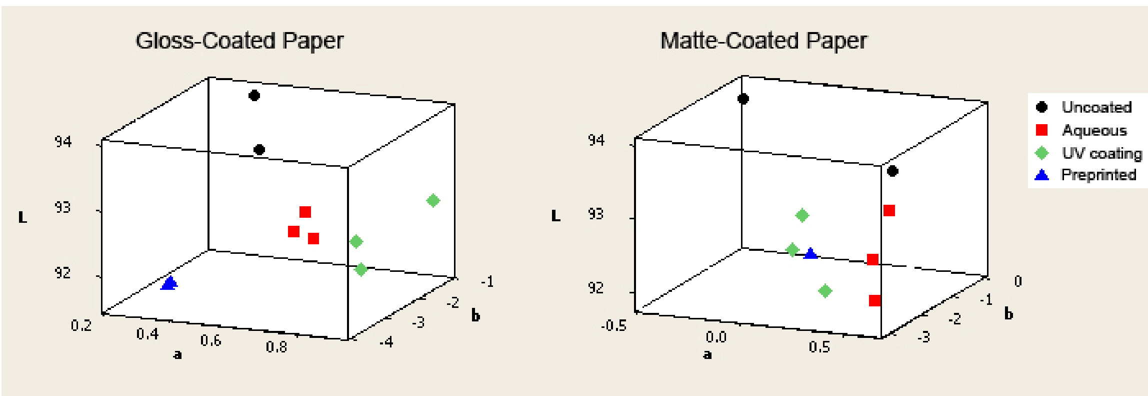


Figure 6. Coatings on Unprinted Paper

The scatterplots in Figure 6 show the uncoated substrates as black dots, the aqueous coating as red squares, the UV coatings as green diamonds, and all coatings on preprinted conventional inks as blue triangles. For each coating treatment, the differences in L-, a-, and b-values were calculated for the unprinted substrate with and without coating. These differences were used as correction factors and were added to the L-, a-, and b-values of the 130 printed patches from the IT-8 target on the uncoated samples. The resulting values were used as predicted values for the coating applications from which the correction values were taken. This technique resulted in very highly correlated relationships between the actual and predicted values. Figure 7 shows the relationships for the L-, a-, and b-values for gloss-coated paper, conventional inks/aqueous coating, gloss finish (the most commonly used coating combination). The r-squared values for these linear relationships indicated that 99.8 percent of the variation in the L-values of the coated sample colors were predicted from the target L-values. The percentages of predicted variations for the a- and b-values were each 99.9.

The predictions for L-, a-, and b-values for all of the experimental conditions examined in this study yielded highly correlated results. The r-squared values for the L, a, and b predictions for all of the experimental conditions examined in this study are presented in Table 13. The lowest r-squared value of all the linear regressions was 98.9, indicating that there were good fits with the linear models for all of the coating combinations studied.

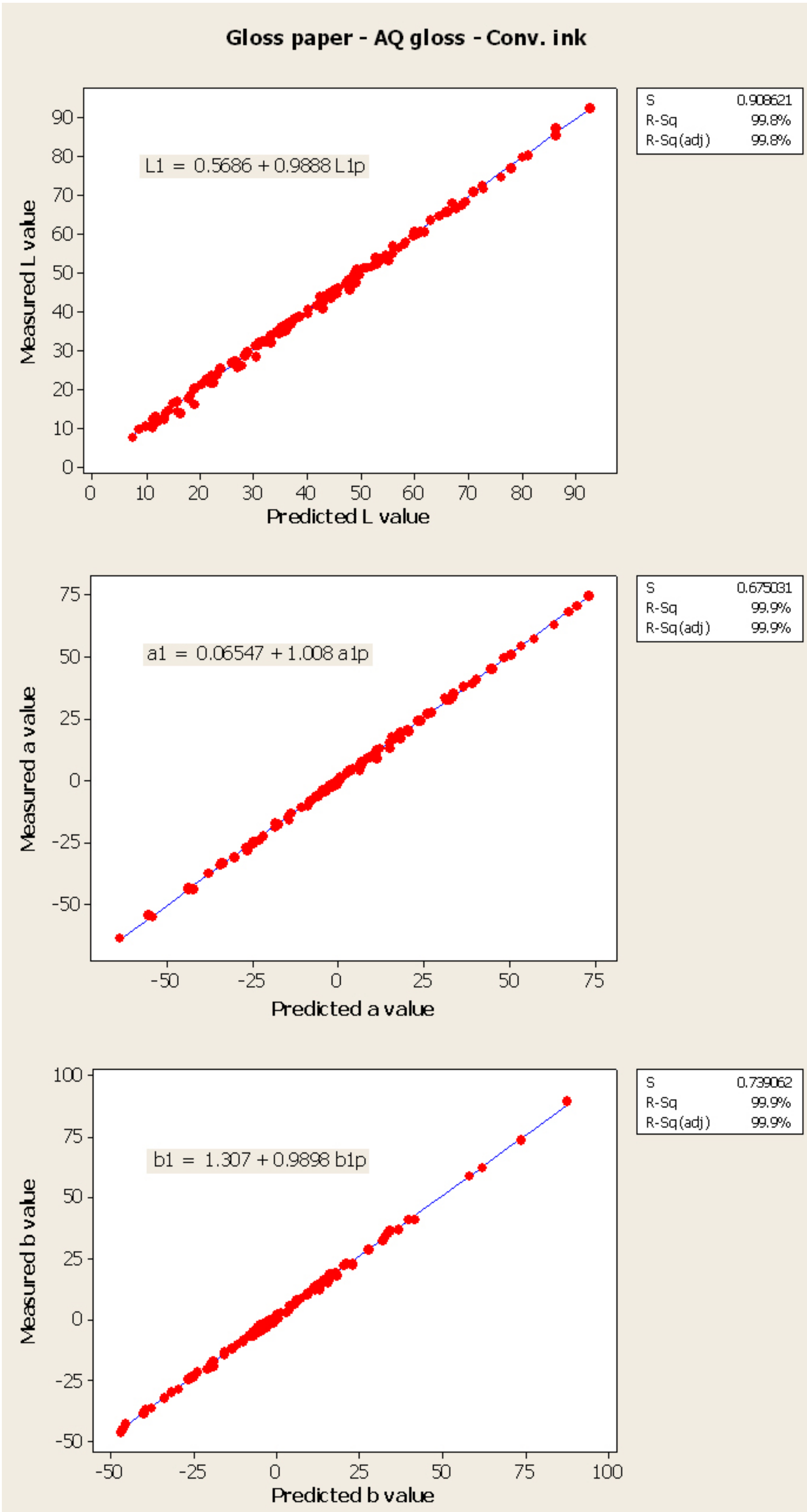


Figure 7. Linear Regressions for L- a-, and b-Values Between Predicted and Actual

Gloss-Coated Paper

Ink	Coating	Finish	L r^2	a r^2	b r^2
conv	AQ	gloss	99.8	99.9	99.9
conv	AQ	satin	99.8	99.9	99.7
conv	AQ	matte	99.9	99.8	99.8
hybrid	UV	gloss	99.7	99.9	99.9
hybrid	UV	satin	99.4	99.7	99.7
hybrid	UV	matte	99.5	99.2	98.9

Matte-Coated Paper

Ink	Coating	Finish	L r^2	a r^2	b r^2
conv	AQ	gloss	99.6	99.8	99.8
conv	AQ	satin	99.7	99.6	99.5
conv	AQ	matte	99.8	99.6	99.7
hybrid	UV	gloss	99.2	99.6	99.3
hybrid	UV	satin	99.6	99.8	99.8
hybrid	UV	matte	99.2	99.3	99.0

Table 13. R-Squared Values for L, a, b Predictions

Although the r-squared values were all high, there were slight differences in the slopes and y-intercepts of the best-fitting regression lines for the different experimental conditions and for the different coordinates being predicted. Table 14 shows the slopes and y-intercepts for all of the experimental conditions examined in this study.

			L-value		a-value		b-value	
Paper	Coating	Ink	y-int.	Slope	y-int.	Slope	y-int.	Slope
Gloss	Gloss	Conv	-0.424	0.989	0.309	1.008	0.636	0.990
Gloss	Satin	Conv	1.476	0.969	0.214	0.980	0.755	0.959
Gloss	Matte	Conv	2.874	0.961	0.697	0.941	0.801	0.915
Gloss	Gloss	Hybrid	-0.991	0.984	-0.023	1.024	-0.325	1.013
Gloss	Satin	Hybrid	-0.425	0.973	-1.650	1.003	-0.257	0.992
Gloss	Matte	Hybrid	6.899	0.877	-0.308	0.975	-0.462	0.920
Matte	Gloss	Conv	-1.132	1.005	-1.276	1.018	-0.183	1.036
Matte	Satin	Conv	-0.380	0.989	-0.868	1.004	-0.442	0.996
Matte	Matte	Conv	1.542	0.988	-1.502	0.961	-0.176	0.959
Matte	Gloss	Hybrid	-0.508	0.958	-1.255	1.032	-1.085	1.039
Matte	Satin	Hybrid	0.448	0.951	-0.466	1.028	0.364	1.016
Matte	Matte	Hybrid	7.477	0.867	-1.614	0.959	-0.552	0.939

Table 14. Slope and Y-Intercept Values for Linear Equations to Predict Color Changes from Uncoated Colors

To make predictions for the L-, a-, and b-values for a color with coating, the values from Table 14 can be inserted into a linear model of the form:

Predicted coordinate = (**slope** x measured coordinate) + **y-intercept**

IT-8 targets could be measured on different paper and ink combinations and correction factors could be stored to make predictions for selected coating applications.

Conclusion

The hypothesis that was advanced at the outset of the study was that the applications of coatings in lithography would result in larger color gamuts. The hypothesis was tested by examining the changes in the Chroma values of 130 patches from the IT-8 Basic Data Set.

Overall, the hypothesis was not supported by this study. Although, some of the experimental conditions yielded samples that did exhibit small amounts of increase in Chroma values compared to uncoated prints, others exhibited no growth or negative growth. The gloss-coated samples were most likely to show increases; while the matte-coated samples were most likely to show decreases.

It was found that the changes in color for coated samples could be accurately predicted from the color changes observed when the coatings were applied to unprinted substrate. The differences in the L-, a-, and b-values between coated and uncoated substrates were used to predict the color changes that would result when the coatings were applied to printed substrates. In production applications, this could be used to predict color changes to anticipate if various coating applications were selected.

Acknowledgement

The authors wish to thank Ms. Sara Walsh of PIA/GATF for making many of the spectrophotometric measurements for this study.

Appendix A: Equipment and Materials Used in the Study

Blankets	Kinyo 7620
Fountain solution	Prisco
Plates	Presstek Anthem
Screening	175 lpi
Anilox coater volume	12 BCM

Paper	Meadwestvaco Sterling Ultra Gloss Text Meadwestvaco Sterling Ultra Matte Text
Conventional ink	INX OSF Vision Plus
Hybrid ink	INX VersaCure Hybrid
UV gloss coating	Craig Adhesives
UV matte coating	Craig Adhesives
UV satin coating	Craig Adhesives
Aqueous gloss coating	Nicoat
Aqueous matte coating	Nicoat
Aqueous satin coating	Nicoat
Varnish	Braden Sutphin Crystal Clear Braden Sutphin Magnum Flat O/P
Lamination	Protect-all