The relative accuracy and effectiveness of automated ink optimization software

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Keywords: Gray component replacement, ink, ink consumption, ink optimization, ink reduction, color matching, color difference

Abstract

This study was conducted to test the effectiveness of ink optimization software programs in use today. Ink optimization programs implement gray component replacement to reduce the amount of ink required to print color images. Ideally, this is performed without altering the color appearance of the output.

Nine different vendors (ten total programs) were compared in this study to determine how much ink reduction was being achieved and how much color difference was associated with the use of the ink reduction programs. Printing Industries of America (PIA) supplied digital files of selected test images to the participants, who returned digital files processed through their own ink optimization programs. All output files were prepared for the U.S. Web Coated (SWOP) v.2 destination color space. Kodak Approval proofs were made from all of the vendor-supplied output files and compared with a control proof made by PIA with no ink optimization applied.

One participant submitted files that did not have ink optimization applied. The remaining nine ink optimization programs all resulted in substantial ink reduction of 15%–26% less than the ink coverage of the control file to which no ink optimization was applied.

The results with respect to color differences associated with the applications of the ink optimization programs were mixed. The files from five of the vendors were found to provide commercially acceptable color matches, while the files from the other four vendors did not.

Purpose of the Study

With the advent of digital image processing in the early 1980s, it became feasible to perform ink reduction in terms of total coverage by evaluating the CMYK values of each pixel in the image, selectively reducing its *gray component*, and boosting the black by the amount necessary to match the color that the unaltered pixel would have produced. The gray component of a pixel refers to the cyan, magenta, and yellow portion of the total CMYK values that form a balanced gray and therefore do not add to the hue of the pixel, but serve to desaturate the color. The theory behind gray component replacement (GCR) is that black ink can be substituted for the appropriate amount of CMY inks to desaturate colors with less total coverage, therefore resulting in net ink savings.

The process has been known by other names, including *complementary color reduction, achromatic synthesis, polychromatic colour removal, and integrated color removal,* but the term *gray component replacement* is the most commonly used descriptor of the process.

The potential advantages to using gray component replacement include the following:

- Savings based on reduced use of expensive process color inks in exchange for the slightly increased use of less expensive black ink.
- Greater color stability on press because less of the total color appearance is dependent on the balance of CMY inks.
- Fewer printing problems like setoff, back trapping, and ink show-through.
- Better drying characteristics due to the reduced total amount of ink on the sheet.

However, several complicating factors make the implementation of GRC difficult enough that, after more than two decades of continuous developments, the process is only now gaining traction in the marketplace. The purpose of this study was to evaluate the leading software products available today and compare how accurate their color matches were for a sample of colors. Further, the study compared the estimated ink savings that would be realized from the use of these software products.

Background

As photomechanical color separation was developed in the early 20th century, the process of undercolor removal (UCR) was found to improve the printability and shadow detail of color images. During the exposure of the CMY color separation negatives, a photographic mask was placed in the image path that reduced the amount of cyan, magenta, and yellow that would print in shadow areas.

UCR was a forerunner to today’s GCR, but it was practiced only on neutral shadows and provided only modest savings in the use of CMY inks. The purpose of undercolor removal was to avoid press problems associated with printing too much total ink coverage in image shadows. The theoretical limit of ink coverage for a four-color system is 400%, but it was impractical to apply that much ink to a sheet of paper with the major printing processes of the time including offset lithography, the dominant printing process of the 20th century.

Because applying too much ink would lead to drying problems, setoff, show-through, back trapping, and softening of shadow detail, different industry segments and individual printers have set limits on the acceptable total ink coverage for shadow tones. The magazine industry, for example, through the SWOP Committee has established total dot area coverage limits of 300% (for #5 paper) and 310% (for #3 paper) for any pixel in an image. Similarly, the newspaper industry, through the Specifications for Non-heat Advertising Production (SNAP), limits total coverage to 260%. Commercial printers produce a more diverse range of products than do publication printers. They limit total ink coverage differently for different substrates and products. Those who adhere to the GRACoL specifications are limited to 340% total area coverage for #1 and #2 coated papers.

The gray component of a color was described by Yule (1940, 1967) as a better basis for assigning density in the black printer than was the earlier practice of *ortholuminous* assignment, in which the black printer was a record of the overall darkness of a color. He pointed out (1967) that color scanners eased the process of constructing black printers based on gray components.

Tobias (1954) proposed a color correction process based on an extreme application of what later came to be known as gray component replacement. Tobias pointed out that:

> It is evident that in a three color printing ink system, such as magenta, yellow, and cyan, all proportions of the printing inks taken two at a time, e.g., magenta and yellow, yellow and cyan, and magenta and cyan, define the entire chromaticity gamut of the system. The addition of the third ink to a binary mixture causes graying but does not alter the chromaticity gamut available from the binary mixtures. (p. 86)

The Tobias color correction process would use only two primary colors to create the chromaticity and black ink to add the needed graying component. This process was never commercially developed.

In the 1980s, papers about gray component replacement were published with increasing frequency as electronic imaging became more sophisticated. Saleh (1984) describes a system that followed the Tobias model of making colors with only two process inks plus black. He referred to the process as *achromatic synthesis*. Saleh pointed out that the colorimetric impurities of printing inks led to the unintentional reduction of some *wanted* colors when *unwanted* colors were removed.

Jung (1984) stressed that gray component replacement (which he referred to as *complementary color reduction*) could be partially implemented on a 0–10 scale according to the needs of the customer. The calculation of ink reductions was based on measurements from a printed test target in addition to colorimetric principles. It soon became common practice to implement gray component replacement in a measured way taking out some, but not all, of the gray component of a color image. Also, when the implementation of gray component replacement resulted in total ink coverage that was insufficient to produce a rich black, a different program, undercolor addition, was implemented to reintroduce cyan, magenta, and yellow inks in the neutral shadows to correct this condition.

Johnson (1984) explained that gray component replacement (which he referred to as *polychromatic colour removal*) was simply an extended version of undercolor removal. He outlined four steps by which the process could be successfully implemented: removing the gray component, replacing it with black, correcting the color values, and adding the black that is common to four-color reproduction. He presented equations for correcting for the unwanted absorptions of process inks and for the additivity failure of replacement by black ink.

Fisch (1988) did a comparative test between three scanner manufacturers applying different levels of gray component replacement to a photographic test image. He found significant differences between the results of the three systems, which varied for different levels of application.

Gray component replacement became common enough during the 1980s to be considered as a parameter for inclusion in industry-wide print specifications, like SWOP, PIRA, and FOGRA. Johnson (1988) argued against the standardization of gray component replacement because it was not a basic control parameter. Gray component replacement could not be specified as a single number. Instead, the optimal implementation of gray component replacement was highly dependent on gray balance, which, in turn, was dependent on a variety of factors already included in print specification (platemaking, substrate, print sequence, density, and tone rendition). Added to this complexity were the complications of the fractional implementation of gray component replacement where less than 100% was used. Johnson concluded that the inclusion of gray component replacement in print specifications as an informative appendix would be useful, but it was impractical and undesirable to include it in the specifications themselves.

During the 1990s gray component replacement was mentioned in several research studies, but typically not as the principle subject. The concept had become widely endorsed by the industry, and the work to refine the needed algorithms took place in proprietary research. During this period, gray component replacement was more commonly found in trade literature where the concept was presented to a wider graphic arts audience.

Whiteman (1996) presented a detailed method for implementing gray component replacement into color reproductions. This work made it clear that the application of gray component replacement had not yet become automatic and still required a level of skill to successfully implement.

Enoksson and Bjurstedt (2006) studied the literature about gray component replacement and undercolor removal. They found that distinctions between the two terms are not clearly expressed in modern digital imaging environments. They advocated combining the two terms into a single compensation for black (CB) function.

Since the 1980s, the graphic media industry has evolved to embrace an all-digital workflow that has become highly decentralized. An aspect of this decentralization is that software has been developed to perform many of the functions that were previously done by skilled craftspeople. Color management, for example, has been developed to achieve consistent color appearance across dissimilar media. Similarly, ink optimization software is available from a number of vendors to implement gray component replacement, undercolor removal, and undercolor addition into image files. The term *ink optimization* expresses the environmental and economical value of reducing the consumption of ink. As Enoksson and Bjurstedt pointed out, it is most sensible to consider the ink reduction functions in neutral and saturated colors together in the digital workflow environment.

Description of the Study

This study was designed to test the ink optimization software products that are currently available. Vendors were asked to voluntarily participate in the study with the understanding that the publicly released results would be coded to protect the identities of vendors, but each vendor would be supplied with their code number to enable them to track their own results. Nine vendors agreed to participate in the study. There were ten entries because Agfa entered two different software solutions. For ease of analysis, the Agfa entries were treated as two different vendors. Information about all the vendors is given in Appendix A.

The two research questions that this study sought to answer were:

1. Do the ink optimization programs included in this study reduce the amount of ink needed to print a series of test images, and to what extent does each program reduce ink usage?
2. Do the ink optimization programs cause unacceptable color shifts in the reproduction of test files compared to control files made through the default Photoshop workflow?

Differences between the software vendors were evaluated with respect to the research questions to determine if there were significant differences in the performances of the products being tested. Further, the vendors were ranked in relation to ink savings and color matching.

Participants in the study were supplied with digital files of selected pictorial and synthetic images. Two sets of files were supplied (both included the same images) to each vendor:

- One in RGB color using Adobe 1998 as the working color space.
- One converted to CMYK color using U.S. Web Coated (SWOP) v.2 as the destination color space.

The images were all labeled as either RGB or CMYK so they could be easily distinguished during analysis.

The test images that were used during the analysis included nine individual photographic images, a composite image of the nine pictures, a subjective evaluation test image, and an X-Rite Color Checker Chart. Three of these are shown in the figures that follow. Figure 1 shows the composite image that was used for the ink consumption analysis. The nine individual images were larger files of each of the photographs included in the composite.

Figure 1. Composite pictorial image used for measuring ink consumption

The photographs in the composite image shown in Figure 1 were chosen to represent a wide variety of challenging reproduction subjects. The composite image has high ink coverage and therefore offers ample opportunity for significant ink reduction.

Figure 2 shows the composite image that was used for subjective color-matching evaluations.

Figure 2. Subjective evaluation test image

The composite image in Figure 2 was smaller and less distracting than the larger composite image used for ink consumption analysis, yet it offered ample areas for critical evaluation of color matching and image quality. As explained later, the judges were given specific areas to focus on when making their evaluations.

The X-Rite Color Checker Chart (Figure 3) was used for the measured color difference analysis in this study.

Figure 3. X-Rite Color Checker Chart used to measure color differences

The X-Rite Color Checker Chart (formerly the MacBeth Color Checker) consists of 24 color patches that represent a variety of colors critical for reproduction. This target was chosen for measured color differences because it was reproduced at a size where reliable color measurements could be made. Furthermore, it contains a reasonable sampling of the color space while requiring a manageable number of measurements.

The participants in the study were asked to apply the optimum ink reduction settings to both the RGB and the CMYK files. In the first case, the software is converting from the RGB color space to the CMYK color space, while in the second case the software is modifying the CMYK files within that color space. These two scenarios are referred to throughout this report as two distinct workflows.

Assumptions and Limitations of the Study

This study was designed to compare the performances of competing software packages for reducing ink consumption while maintaining color matching in high-volume print production environments. Due to practical considerations, no printing was performed for this study. Instead, Kodak Approval proofs were used as the output representing the application of the software programs. All the proofs were made by GATF from the files supplied by the participating vendors. All color measurements were made from the proofs. It was, therefore, assumed that the proofs were consistent for all vendors and that the proofs were acceptable predictors of the U.S. Web Coated (SWOP) v.2 printing condition for which they were calibrated.

The color difference analysis was based on single color measurements for each patch. Some measurements were redone to confirm accuracy when the original measurements resulted in particularly high color differences. For this analysis, it was considered to make multiple readings for sub-sampling purposes, but, by the time this was planned the proofs had aged sufficiently that it was felt that the multiple readings might be less accurate than the single readings that were taken when the samples were newly made.

This study was conducted with the cooperation of vendors of ink optimization software who were each responsible for their own file submissions based on a series of test files supplied by GATF. There was no central control over the settings or the application of the different software programs. One software vendor (vendor #3) submitted files that were improperly made, resulting in greater ink consumption rather than less. The vendor was unable to submit new files, so, although their results are carried through the analysis, they are not comparable to the results of the other vendors.

The calculations of ink consumption are based on ink coverage data taken from the digital files. Although these ink coverages are strong indicators of the volume of ink that would be used on a printing press, they are not perfect indicators due to press conditions such as ink film thickness, dot gain, ink trapping, and paper absorptivity. Therefore, the ink consumption findings should be interpreted as approximate.

The default Photoshop conversion of the RGB files to the CMYK U.S. Web Coated (SWOP) v.2 destination color space automatically provides some ink optimization to comply with the maximum total area coverage limit set by the SWOP specifications. The CMYK control files were made through this default conversion, and these were the files against which the vendor-supplied files were compared. Therefore, ink reductions found in this study are in addition to the ink reductions already inherent in the control RGB–CMYK.

Findings Regarding Ink Savings

The analysis of ink consumption was based on the ink coverage calculated for all of the digital files that were prepared for output. Serendipity Black Magic software was used to determine the CMYK coverage in each of the output files.

The ink coverage was calculated for each of the nine individual photographic images, for the composite of all nine photos, for the X-Rite color checker image, and for the subjective evaluation image. The ink coverage data for all the images used in this study is shown in Appendix B.

The ink coverage values of the control images were the same for both workflows because the RGB data needed to be converted to CMYK before ink coverage values could be computed. The vendor data was all in CMYK color space and a comparison was made between the ink coverage values generated from the supplied RGB and CMYK files. The average differences in ink coverage between the two workflows are shown in Table 1.

Vendor	Black	Cyan	Magenta	Yellow
V1	2.6%	1.2%	6.2%	5.6%
V2	-3.6%	-3.5%	-0.8%	-0.5%
V3	-2.0%	6.2%	10.9%	8.5%
V4	0.2%	-3.0%	0.7%	0.7%
V5	2.7%	-2.1%	0.2%	1.8%
V6	-0.4%	-1.0%	2.6%	4.9%
V7	0.2%	-1.1%	2.0%	3.3%
V8	-2.8%	3.9%	6.7%	7.6%
V9	-8.2%	9.8%	9.5%	9.7%
V10	1.7%	-2.4%	1.1%	0.3%

Table 1. Average differences in ink coverage between the RGB–CMYK and the CMYK–CMYK workflows (“V” designates vendor number)

The values in Table 1 were calculated by subtracting the coverage of the CMYK–CMYK workflow from those of the RGB–CMYK workflow. Therefore, positive values indicate lower ink coverage with the CMYK–CMYK conversions than for the RGB–CMYK workflow. Conversely, negative values mean higher coverage with the CMYK–CMYK files.

There is a distinct difference between vendors in uniformity of results between the two workflows. Analyzing the results of vendor #9, for example, shows that this vendor made much more significant ink reductions in the RGB–CMYK workflow than in the CMYK–CMYK workflow even though the images for each workflow were the same. The same could be said to varying degrees about vendors #8, #3, and #1. This data was plotted in graphical format as seen in Figure 4.

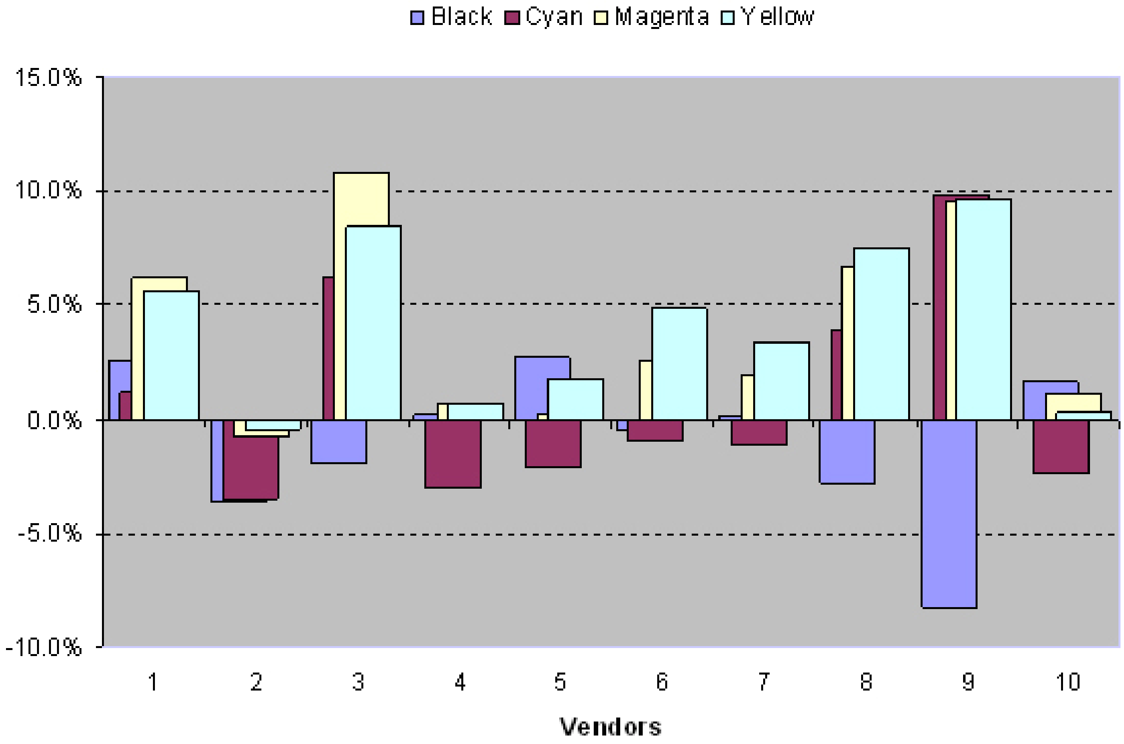


Figure 4. Differences in average ink coverages between two workflows

Figure 4 shows that vendor #1 had higher coverage for all four inks in the RGB–CMYK workflow. This indicates that there was more ink overall for the RGB–CMYK workflow and not simply a difference in the application of ink optimization, which would have resulted in black coverage being lower in concert with higher coverages of the CMY inks.

The comparison of the average ink coverages between the two workflows showed that the two workflows needed to be analyzed separately. The differences in ink coverage between the two workflows for each of the 12 original images used in this analysis were calculated for each vendor. To simplify the labeling of the graphs, the images were numbered from 1 through 12 in correspondence to the table in Appendix B. The differences in ink coverage between the control files and the optimized results for each of the process inks, participating vendors, individual images, and workflows are shown in Appendix C.

Examination of the 20 graphs shown in Appendix C led to the following observations:

- Vendor #2 showed relatively consistent ink reduction results across the two workflows and for all of the images with one striking exception. The high-key picture (#4) was rendered in the CMYK–CMYK workflow with black ink coverage increasing from 11% to 72% and also showing increases for magenta and yellow. This was an isolated case, and the high-key picture showed no unusual results with any of the other vendors.
- Vendor #3 did not make ink reductions with either workflow. Indeed, ink coverage was increased for the RGB–CMYK images and was the same as the control files for the CMYK–CMYK workflow.
- Vendor #3 made virtually no changes to the ink coverages of any of the CMYK images with the exception of the X-Rite Color Checker image. This, however, is the image from which color differences were measured in a later part of the analysis, making those calculations not indicative of the performance of vendor #3 for the CMYK–CMYK workflow.
- The outdoor image (#6) had smaller ink coverage changes than the other images for most of the vendors and for both workflows. This might be because this image is dominated by saturated secondary colors and, therefore, offered less gray component to be replaced.

The average changes (compared to the control images) in ink coverage across the twelve images for each vendor, process color, and workflow are shown in Table 2. This table also contains the total coverage changes for the four ink colors and the rank order of the vendors in terms of amounts of ink reduction.

The combined rank in Table 2 (far right column) is the rank order of the vendors for ink reduction when both workflows are considered together. The ranks of vendors are fairly consistent between the individual workflows and their combined ranking, with a few exceptions. The most noteworthy exception is vendor #8, who provided the most ink savings with the CMYK–CMYK workflow but ranked only fifth for the RGB–CMYK workflow, resulting in a combined ranking of fourth.

Excluding the results of vendor #3, who provided no ink reduction, the ink reductions from the other vendors ranged from 20% to 55% for the RGB–CMYK workflow and from 36% to 51% for the CMYK–CMYK workflow. The totals in Table 2 are the cumulative amount of dot area reduction for all four process inks; they are **not** calculated as a percentage of the total ink printed for the job, which is calculated later for the composite image in Table 6. Still, it is clear that the vendors who participated in this study are significantly reducing the amount of ink used to reproduce color images.

			RGB–CMYK				Comb
Vendor	**Black**	**Cyan**	**Magenta**	**Yellow**	**Total**	**Rank**	**Rank**
V1	18%	-19%	-11%	-12%	**-25%**	**8**	**8**
V2	20%	-32%	-23%	-20%	**-55%**	**1**	**1**
V3	-1%	5%	10%	8%	**23%**	**10**	**10**
V4	17%	-25%	-18%	-16%	**-43%**	**3**	**5**
V5	12%	-17%	-14%	-14%	**-33%**	**6**	**7**
V6	19%	-23%	-17%	-10%	**-32%**	**7**	**6**
V7	12%	-18%	-17%	-19%	**-42%**	**4**	**3**
V8	16%	-22%	-16%	-13%	**-36%**	**5**	**4**
V9	8%	-12%	-9%	-7%	**-20%**	**9**	**9**
V10	21%	-27%	-21%	-20%	**-47%**	**2**	**2**

			CMYK–CMYK			
Vendor	**Black**	**Cyan**	**Magenta**	**Yellow**	**Total**	**Rank**
V1	15%	-21%	-17%	-17%	**-40%**	**7**
V2	24%	-29%	-22%	-20%	**-46%**	**3**
V3	1%	-1%	-1%	0%	**-1%**	**10**
V4	17%	-22%	-19%	-17%	**-41%**	**5**
V5	10%	-15%	-14%	-16%	**-36%**	**9**
V6	19%	-22%	-20%	-15%	**-38%**	**8**
V7	12%	-17%	-19%	-22%	**-46%**	**4**
V8	19%	-26%	-23%	-21%	**-51%**	**1**
V9	16%	-22%	-18%	-17%	**-41%**	**6**
V10	20%	-25%	-22%	-21%	**-48%**	**2**

Table 2. Changes in ink coverage for each vendor (“V” designates vendor number)

Further analysis was performed to examine the ratio of ink reductions between the four process colors. The cyan, magenta, and yellow ink reductions were totaled for each of the vendors and each photographic image. These sums were then divided by the amount of black ink that was added for each picture to obtain a ratio to express the relationship of three-color to black ink. The consistency of this ratio from image to image was measured with a coefficient of variation for each vendor. The vendors were then ranked from lowest variation to highest. All of these ratios are shown in Appendix D, and the summary statistics are given in Table 3.

					Vendors					
RGB	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
mean	**2.23**	**3.40**	**11.53**	**3.24**	**3.43**	**2.73**	**4.03**	**3.25**	**4.15**	**2.94**
std dev	**0.52**	**1.04**	**23.08**	**0.94**	**1.47**	**0.83**	**1.81**	**7.20**	**11.02**	**0.72**
variation	**0.24**	**0.31**	**2.00**	**0.29**	**0.43**	**0.31**	**0.45**	**2.21**	**2.65**	**0.25**
rank	**1**	**5**	**8**	**3**	**6**	**4**	**7**	**9**	**10**	**2**
CMYK										
mean	**3.24**	**2.93**	**10.07**	**3.19**	**4.21**	**2.83**	**4.36**	**3.44**	**3.32**	**3.15**
std dev	**0.88**	**1.07**	**7.91**	**0.78**	**2.25**	**0.61**	**1.89**	**0.90**	**0.67**	**0.72**
variation	**0.27**	**0.36**	**0.79**	**0.24**	**0.53**	**0.22**	**0.43**	**0.26**	**0.20**	**0.23**
rank	**6**	**7**	**10**	**4**	**9**	**2**	**8**	**5**	**1**	**3**

Table 3. Statistics from the ratio of ink reductions by vendor and workflow

The means in Table 3 are the average ratios of the changes in CMY dot areas to the changes in black ink dot areas for the 12 test images used in this study. The averages show substantial differences between vendors and between workflows with respect to the amount of colored inks removed versus the amount of black ink added to compensate for that removal. The coefficients of variation in Table 3 are indicators of how much difference was found between the ratios for each of the various test images. Some variation in these values was expected because the compensation of black ink for color inks is dependent on a host of factors, including substrate, tonal rendition, ink trapping, additivity failure, and the colorimetric impurities of the process inks.

The mean values in Table 3 show that vendor #3 had mean ratios that were clearly out of synch with the rest of the vendors. Also, vendors #8 and #9 had high coefficients of variation compared to the other vendors for the RGB–CMYK workflow meaning that these two vendors had large differences in their CMY-to-black ratios for different photographic images. Both the mean ratios and the coefficients of variation for the CMYK—CMYK workflow were more uniform between vendors than they were for the RGB—CMYK workflow.

The rankings of CMY-to-black ink ratios for different images did not correlate strongly with the vendor ranks for total ink savings (Table 2). The Spearman correlation coefficients were 0.37 and 0.32 for the RGB–CMYK and the CMYK–CMYK workflows, respectively.

To examine the influences of the individual photographs on the ratios of the reduction in CMY inks versus the addition in black ink, the CMY-to-black ratios for each vendor and each picture were computed. These were placed in rank order such that images that resulted in higher CMY-to-black ratios were ranked higher. Spearman correlation coefficients were calculated for each vendor combination, as shown in Table 4.

The correlation coefficients in Table 4 show some clear patterns. Most obvious is that the results from vendor #3 are negatively correlated with all the other vendors for the RGB–CMYK workflow. Although the results for vendor #3 look much better for the CMYK–CMYK workflow, they should also be disregarded since there were virtually no ink coverage changes with this vendor and workflow combination (see Appendix C). The correlations between vendor #8 and the other participants were extremely low for the RGB–CMYK workflow. However, vendor #8 performed much better in relation to the other companies in the CMYK–CMYK workflow. Overall for both workflows, the high incidence of correlation coefficients above 0.80 is evidence that there was broad agreement in the data about the ranking of the images in terms of the CMY-to-black ratios.

		Vendors								
	RGB	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
Vendors	**V1**	0.79	-0.55	0.82	0.84	0.88	0.69	0.39	0.85	0.71
	V2		-0.37	0.99	0.93	0.90	0.97	0.16	0.92	0.97
	V3			-0.40	-0.45	-0.57	-0.29	-0.24	-0.31	-0.34
	V4				0.95	0.92	0.95	0.23	0.91	0.94
	V5					0.97	0.87	0.24	0.87	0.89
	V6						0.84	0.30	0.84	0.87
	V7							0.17	0.88	0.94
	V8								0.18	0.01
	V9									0.85
	CMYK									
Vendors	**V1**	0.86	0.80	0.83	0.90	0.89	0.94	0.86	0.92	0.88
	V2		0.73	0.96	0.90	0.94	0.92	1.00	0.97	0.99
	V3			0.63	0.88	0.86	0.73	0.73	0.74	0.74
	V4				0.80	0.86	0.88	0.96	0.96	0.97
	V5					0.93	0.90	0.90	0.87	0.90
	V6						0.87	0.94	0.94	0.94
	V7							0.92	0.91	0.90
	V8								0.97	0.99
	V9									0.99

Table 4. Spearman correlation matrix between vendors for rankings of images in terms of changes to CMY-to-black ratios when ink optimization was applied

To determine which vendors had the highest overall correlations with the other vendors for each of the workflows, average correlations and rank orders were calculated as shown in Table 5.

	RGB		**CMYK**	
Vendors	**Avg Corr**	**Rank**	**Avg Corr**	**Rank**
V1	0.60	8	0.88	8
V2	0.69	2	0.92	2
V3	-0.39	10	0.76	10
V4	0.70	1	0.87	9
V5	0.68	3	0.89	6
V6	0.66	6	0.91	5
V7	0.67	4	0.89	7
V8	0.25	9	0.92	2
V9	0.67	5	0.92	4
V10	0.65	7	0.92	1

Table 5. Average correlations of vendors to other vendors in relation to the ranking of images in term of the ratio of changes of CMY-to-black ink coverage

The correlations of vendors to each other were higher for the CMYK–CMYK workflow than for the RGB–CMYK workflow. This was expected because the RGB–CMYK workflow required conversion from one color space to another, while the CMYK–CMYK only required the optimization of image files within the CMYK color space. Vendor #2 ranked very highly in both workflows. Several vendors, notably #4, #8, and #10, had very different ranks in the two workflows.

In order to estimate the amount of ink savings that the ink optimization programs in this study were providing, the coverages of the composite image were examined. This image was chosen because it contains nine different photographic images that represent common image types found in production. This composite image mimics a press form with high ink coverage and thus presents a best-case example of ink savings. Table 6 shows the ink coverages for this image in the control file and the vendor-optimized files.

	Composite Image Ink Coverage				**Total**	**Ratio**
	Black	**Cyan**	**Magenta**	**Yellow**		
Control	**37%**	**49%**	**50%**	**60%**	**196%**	
RGB						
V1	55%	28%	40%	49%	171%	87%
V2	57%	17%	29%	41%	144%	74%
V3	36%	53%	61%	69%	220%	112%
V4	54%	24%	33%	45%	155%	79%
V5	49%	31%	37%	46%	164%	84%
V6	56%	26%	35%	51%	166%	85%
V7	49%	30%	34%	42%	155%	79%
V8	54%	27%	38%	51%	170%	87%
V9	44%	37%	43%	55%	179%	91%
V10	58%	21%	30%	40%	149%	76%
CMYK						
V1	53%	27%	33%	43%	155%	79%
V2	58%	20%	27%	39%	144%	73%
V3	38%	48%	49%	60%	194%	99%
V4	53%	27%	32%	44%	157%	80%
V5	46%	34%	36%	45%	162%	83%
V6	56%	27%	31%	45%	159%	81%
V7	49%	32%	32%	38%	150%	77%
V8	55%	24%	29%	41%	148%	76%
V9	53%	28%	32%	45%	157%	80%
V10	56%	24%	29%	41%	150%	77%

Table 6. Ink coverages for composite image from control file and optimized vendor files

The ratios in the last column of Table 6 are derived by dividing the total coverage of the vendor-optimized files by the total coverage of the original file. The vendors (excluding vendor #3) show a range of ink coverages that are from 73%—91% of the coverage that would occur with no ink optimization applied. The mean of these coverages is 80%, indicating that the use of ink optimization on this image would have resulted in a savings of 20% in terms of the volume of ink required for the image. The cost savings would be greater than the volume savings because more black ink would be printed in place of cyan, magenta, and yellow inks, and black ink is less expensive than the other process color inks.

Because this study did not involve a pressrun, the ink savings were not confirmed in practice. Some studies (Jung, 1984) found that press operators tend to run at higher ink film thicknesses when gray component replacement is incorporated into the images.

Regardless of the exact amount of ink savings, it is clear that the ink optimization programs in this study are providing significant reductions in the volume of ink needed to print color images. However, this savings only has value if the color renditions of the images are not significantly altered.

Subjective Evaluations

Kodak Spectrum proofs were made of the subjective test image for visual evaluation, the composite image of the nine individual photographs, and the X-Rite Color Checker Chart. Proofs were made for both workflows and for each of the ten vendors, showing the results of the image files with the vendor's optimal ink reduction settings. Additionally, a control proof was made showing the default output of the images to the U.S. Web Coated (SWOP) v.2 printing condition.

Seven judges were asked to rate the color matches of the vendor samples for each workflow to the control proof. The judges were employees of PIA/GATF and were familiar with graphic arts processes. Of the seven individuals, five were experienced color evaluators with extensive experience in the graphic arts. The judges were asked to evaluate the color matches for each of the two workflows (RGB–CMYK and CMYK–CMYK). The judgments were made from the subjective evaluation test image in five specific areas representing a range of challenges for color reproduction. Judges were also asked to give each vendor an overall score for the accuracy of color match. The ratings were made on an arbitrary scale from 0 to 5, with 5 being an ideal color match, 3 a commercially acceptable color match, and 0 a very poor color match. Figure 5 shows the image that was used for the subjective evaluations and the five specified areas that were individually rated.

Figure 5. Subjective evaluation test image with five areas for individual evaluation

To test the level of agreement between the judges, a composite ranking of the evaluations of the seven judges was made for the ten vendors across all of the evaluation spots in the subjective evaluation test image and across both workflows. Similar rankings of the ten vendors were calculated for each individual judge. Spearman coefficients of rank correlations were calculated between each of the judges and the group as a whole. These values are shown in Table 7.

Judge	**1**	**2**	**3**	**4**	**5**	**6**	**7**
r_s	0.75	0.91	0.96	0.83	0.55	0.90	0.90

Table 7. Spearman correlation of rank coefficients for the seven judges

The Spearman correlations, which averaged 0.83, indicate an overall strong level of agreement among the judges with respect to the rank order of the vendors. Judge #5 stands out as having the lowest correlation with the rankings of the group. Interestingly, this judge was one of the more experienced color evaluators. Overall, the judges showed sufficient cohesion in their evaluations to provide a valid measure of color matching.

All the scores of the individual judges for both workflows and all 10 vendors are shown in Appendix E. The average subjective scores of the seven judges for each of the ten vendors were calculated for both workflows. The summary data from these calculations is shown in Table 8.

		Vendors									
		V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
RGB–CMYK	Average	3.6	3.5	3.6	3.7	2.5	3.5	2.9	3.1	2.3	2.7
	Max	4.4	4.0	4.0	4.0	2.9	4.0	3.7	3.9	2.9	3.1
	Min	3.0	3.0	3.0	3.3	1.4	3.1	2.3	2.1	1.7	2.3
	Rank	2	4	3	1	9	5	7	6	10	8
CMYK–CMYK	Average	3.1	3.2	4.3	3.6	2.6	3.6	2.7	3.6	3.5	3.3
	Max	3.6	3.9	4.6	4.1	3.0	3.9	3.3	4.3	3.9	3.9
	Min	2.9	2.7	4.0	3.1	2.1	3.1	2.1	2.7	3.1	2.9
	Rank	8	7	1	2	10	2	9	4	5	6
Combined	Difference	0.5	0.3	-0.7	0.1	-0.1	-0.1	0.1	-0.5	-1.1	-0.6
	Average	3.4	3.4	3.9	3.7	2.5	3.6	2.8	3.3	2.9	3.0
	Rank	**4**	**4**	**1**	**2**	**10**	**3**	**9**	**6**	**8**	**7**

Table 8. Average subjective scores (using a 1 to 5 scale, with 1 being a poor color match with the control proof and 5 being an ideal match)

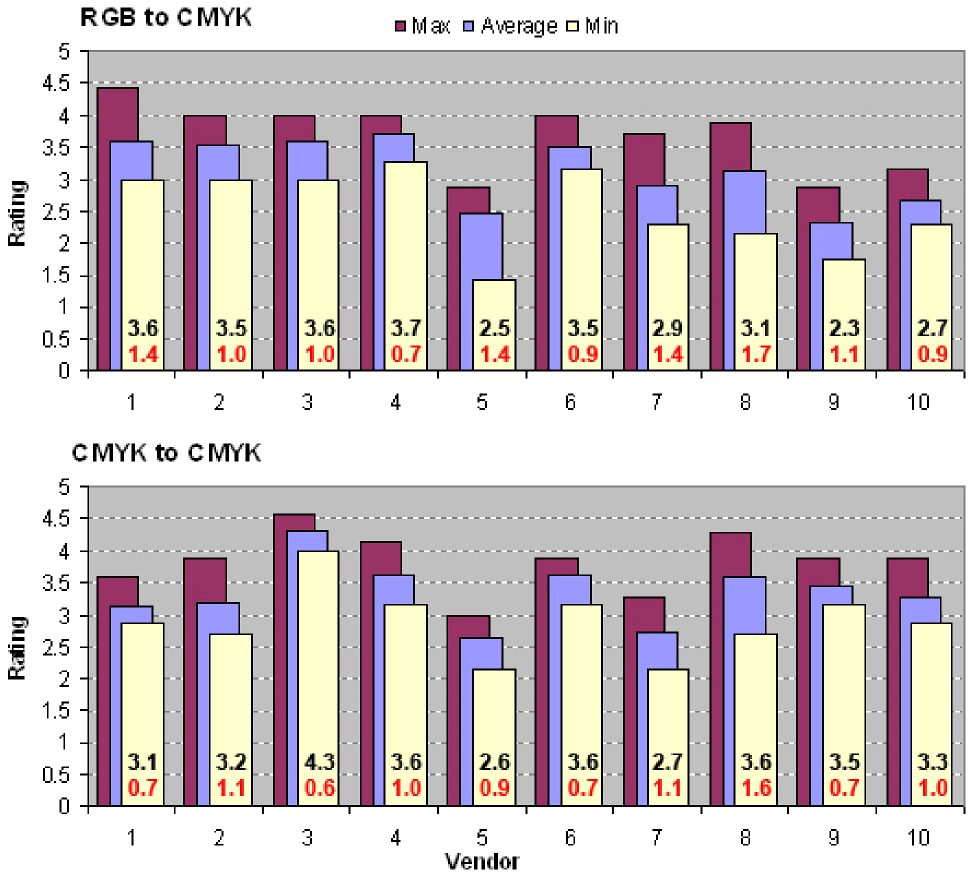
The data in Table 8 led to the following observations:

- Vendor #3 was ranked highest for color matching in the CMYK–CMYK workflow, but this result is not valid since vendor #3 applied no changes to the CMYK file.
- Vendors #4 and #6 (in that order) followed by vendors #1 and #2 (tied for third) were the top choices overall for matching colors when ink optimization software was applied.

- The top two ranking vendors (#4 and #6) were very uniform in their color matching scores between the two workflows.
- Vendors #9, #7, and #5 (in that order) were judged to be the least successful at maintaining color appearance when their ink optimization programs were applied. Of these, the results for vendor #9 showed the largest difference between the scores from the two workflows.

The overall average color matching score for the CMYK–CMYK workflow was about 0.21 points higher than for the RGB–CMYK workflow. Of the 10 vendors, 6 were given higher scores for the CMYK–CMYK workflow, while the other four received higher scores for the RGB–CMYK workflow. The average difference between the scores for a single vendor was 0.43. Vendors #4, #5, #6, and #7 were the most consistent between the two workflows, having differences of only about 0.1 between the subjective scores of the two workflows. Vendors #9 and #3 stand out as having substantially different scores for the two workflows.

Figure 6 shows the maximum, average, and minimum scores for each of the vendors and for both workflows in graphical form to clarify the relationships between vendors in terms of their subjective scores. The black numbers in the graph indicate the numerical averages for each vendor, and the red numbers are the differences between the picture areas with the highest average rating and those with the lowest average rating.


RGB to CMYK

CMYK to CMYK

Figure 6. Average subjective scores for all target locations

Although the judges did not find that any of the samples showed perfect matches, most of the results were considered to be acceptable (as indicated by the average subjective ratings being higher than three) in most instances. In the RGB–CMYK workflow, vendors #5, #7, and #9 were judged not to provide commercially acceptable color matches overall. In the CMYK–CMYK workflow, vendors #5 and #7 were found to produce non-acceptable color matches. Again, the high rating of vendor #3 in the CMYK–CMYK workflow was not valid because this vendor made no changes to the supplied CMYK file.

The red numbers in Figure 6 indicate the range of average scores for different target locations on the image. In the RGB–CMYK workflow, the average range for vendors was 1.16 subjective units, while it was 0.94 for the CMYK–CMYK workflow. In both workflows, the results for vendor #8 showed the largest differences of the group. This indicates that color matching for that vendor is more dependent on the specific colors being matched than for other vendors. A Spearman correlation was calculated to determine if vendors tended to finish in the same rank order for the two workflows. The results (0.33) indicate a weak relationship between the ranks of vendors between the two workflows.

Analysis was done to compare the ratings for different target areas in the picture. Selected statistics from the analysis are shown in Table 9.

		Target Area				
		1	**2**	**3**	**4**	**5**
RGB	Mean	3.10	2.87	3.60	3.29	2.89
	Standard Deviation	0.88	0.43	0.64	0.46	0.57
	Coefficient of Variation	0.28	0.15	0.18	0.14	0.20
CMYK	Mean	3.50	3.01	3.71	3.29	3.24
	Standard Deviation	0.68	0.41	0.53	0.44	0.66
	Coefficient of Variation	0.19	0.14	0.14	0.13	0.20

Table 9. Statistics from subjective evaluations of individual target areas

Table 9 shows that, for both workflows, the lowest subjective scores were given to target area #2 (shadow area with a dark blue towel), and the second lowest scores were given for target area #5 (portrait of a young girl). These findings are not surprising. Target area #2 is near the outer limit of the color gamut—an area that is often problematic for matching. Target area #5 is dominated by flesh tones, which are always critically scrutinized by human observers.

The coefficients of variation show that areas #1 and #5 had the highest variation in the scores awarded to the 10 vendors for both workflows. Target area #1 contains highly saturated colors that are close to the outer limits of the color gamut. The high variation in the scores for different vendors in this area suggests that the reproduction of saturated colors was an important distinguishing characteristic between the vendors participating in this study. Target area #5, as mentioned, contains flesh tones. The results suggest that the reproduction of these colors was a distinguishing factor in evaluating the success of color matching for the different ink optimization programs.

It is interesting that target area #2 received low subjective scores for color match, but it had low variation in terms of the scores of the different vendors. This indicates that this target area was challenging for all of the vendors. This might be due to the significant texture the target area contains, combined with the highly saturated and dark blue tones.

Figure 7 shows a graphic illustration of the maximum, average, and minimum subjective scores given for each target area in the evaluation image.

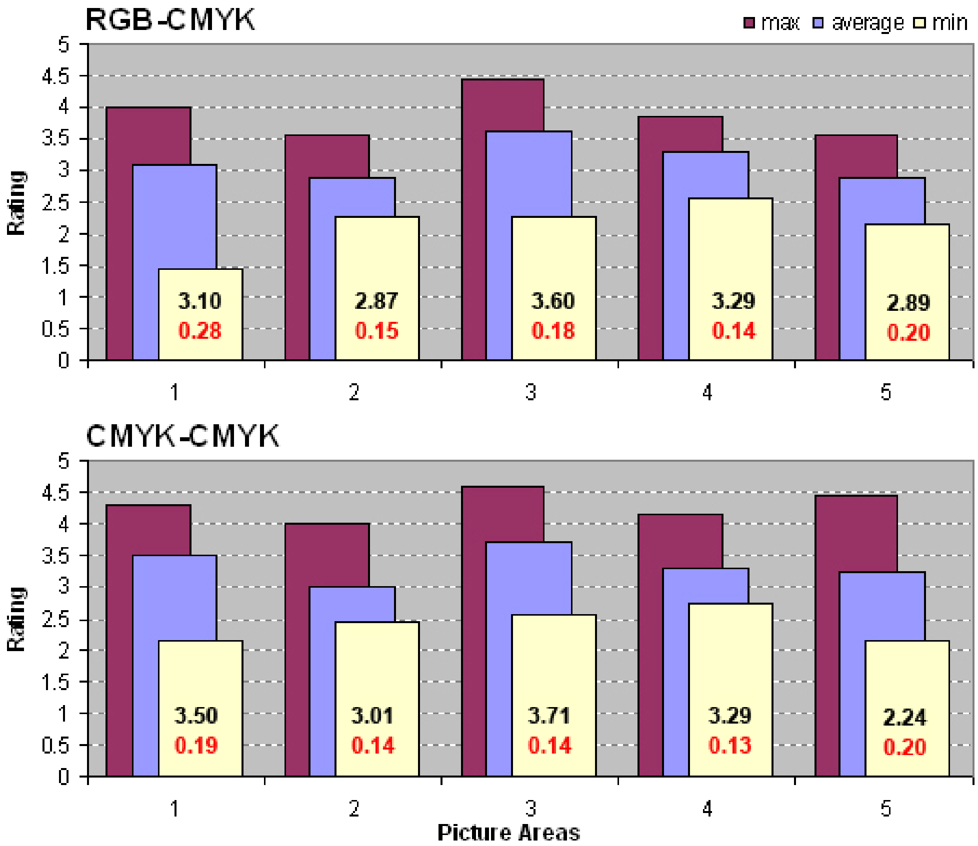


Figure 7. Maximum, average, and minimum subjective ratings by picture area

In Figure 7, the top (black) numbers in the graph show the mean subjective scores across the 10 vendors for each target area in the picture. The bottom numbers (red) are the coefficients of variation for each of the target areas. These values are indicators of the amount of variation in the subjective scores awarded to the 10 vendors for each target area. In this instance, making judgments from the range of subjective scores (difference between the maximum and minimum values) is deceiving because one vendor received very low scores. Picture areas #1 and #5 received the most varied scores across vendors. Area #1 was dominated by saturated secondary colors and area #5, as previously noted, contained flesh tones. For this study, these subjects were most influential in differentiating among the color reproductions of the vendors.

The subjective evaluations showed clear preferences among the judges with respect to the color matching of the vendor samples, but it was of interest to test whether measured color differences corresponded with the subjective choices.

Color Difference Measurements

The measurement of color differences is an area of active research and development in the graphic arts. Since 1976, Delta-E (ΔEab) has been used as a measurement of color differences that relates to the perceived differences of a standard observer. The ΔEab value is the vector distance between two points plotted in the CIELAB color space. However, it has been found that ΔEab does not accurately model color differences in all parts of the color space because it treats differences of lightness, hue, and chroma equally, while the human observer does not respond to changes in these three parameters equally. These inaccuracies can be equated to the fact that the LAB color space is not truly perceptually uniform.

Work is taking place along two avenues to obtain more accurate color difference calculations. One approach is to transform the CIELAB colorspace to make it more perceptually uniform. Roesler, Chairman of the Industrial Tolerances Working Group of the German Society of Color Science and Application, reports that the DIN 99 standard for calculating color differences relies on non-linear modifications of the coordinates of the CIELAB color space. The resulting color space is more perceptually uniform, making it possible to use vector distances to calculate color differences.

The second approach, which has taken place in a number of stages since the mid-1980s, has been to introduce correction factors into the ΔEab equation to improve the correlation between calculated and perceived color differences. The first of these, ΔEcmc , was defined by Clark, McDonald, and Rigg (1984) from work initiated by the UK Colour Matching Committee of the Society of Dyers and Colourists in 1984. This equation includes weighting factors for lightness and chroma that are typically set at 2:1 or 1:1 for graphic arts applications. Although this equation was developed for textiles, it has been found to yield improved color difference values for some printing applications (Habekost, 2008).

In 1995, the CIE adopted the ΔE94 color difference equation from work done on a study of automotive paints by Berns, Alman, Reniff, Snyder, and Balonen-Rosen (1991). This equation includes weighting factors for lightness, chroma, and hue designed to improve acceptability tolerances for industrial applications. Acceptability tolerances for graphic arts are not well established, although Johnson and Green (2006) have addressed the subject and published some initial recommendations. The ΔE94 color difference equation has been found in several studies to yield improved color difference values compared to the ΔEab for graphic arts applications.

Another color difference formula emerged in 2001 from the work of Luo, Cui, and Rigg (2001) that introduced a hue-chroma interaction term. This equation was accepted by the CIE and was released as ΔE2000. Johnson and Green (2006) found this equation, as well as ΔE94, yielded improved color difference values compared to ΔEab for graphic arts applications.

For the current study of ink optimization software, the most relevant color difference research has been done by Habekost and Rohlf (2008) and by Habekost (2008). Both studies found that ΔEcmc and ΔE2000 were better measures of perceived color differences than ΔEab; however, the studies had conflicting results as to which of the two was better. Habekost and Rohlf found that ΔE2000 corresponded slightly better to perceived differences that did ΔEcmc. Habekost, in the second study, found that ΔEcmc was a slightly better measure than ΔE2000. In both studies each of the equations was evaluated with the weighting factors set at unity.

For the current study, it was decided to make color difference calculations by ΔEab, ΔEcmc, and ΔE2000 and compare the strength of their correlations with the subjective evaluations to choose which measure to incorporate into the analysis.

Colorimetric measurements were made from the 24 patches of the X-Rite Color Checker for each of the two workflows (RGB–CMYK and CMYK–CMYK). CIELAB values were extracted from these measurements for use in calculations of color differences. The physical samples were Kodak Approval proofs made from files supplied by the participating ink optimization software vendors. Separate sets of vendor proofs were made for each of the two workflows. They were compared to a single control proof made from the CMYK file that represented the default Photoshop RGB to CMYK conversion.

Color differences (ΔEab, ΔEcmc, and ΔE2000) were calculated for all of the Color Checker patches between each of the vendor samples and the control sample for both workflows. The three different measures were compared with the results of the visual evaluations in two ways: coefficients of variation and rank-order correlations.

The coefficients of variation were calculated for each color difference formula and for the judges’ subjective evaluations for each vendor. Data from both workflows were combined for this analysis. For the color difference formulae, the coefficients of variations were calculated from the color differences for all 24 measured patches from both workflows. For the subjective evaluations, the coefficients of variation were calculated from the average responses of the seven judges for each of the five targeted picture areas. This resulted in 10 average subjective color matching scores across the two workflows. Line plots of these data are shown in Figure 8.

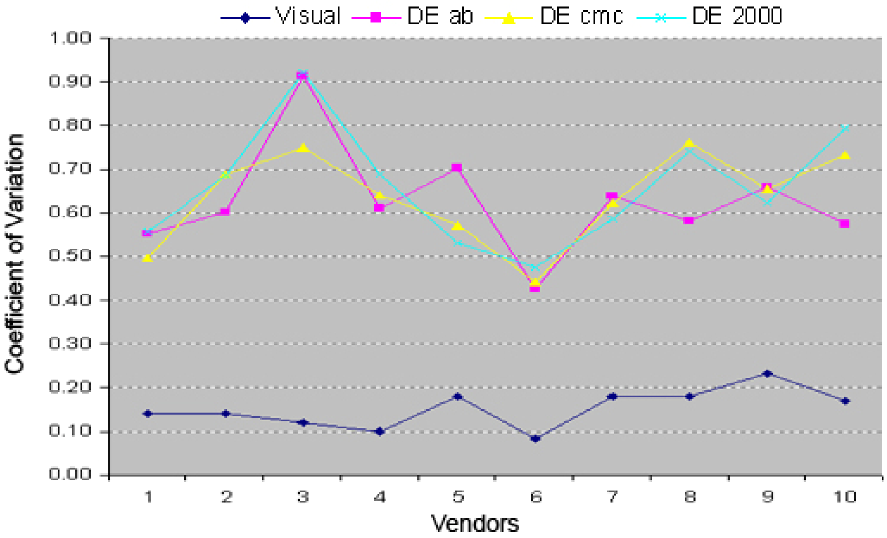


Figure 8. Coefficients of variation for color difference values and subjective evaluations

To test if any of the three color difference formulae was more closely related to the visual evaluations in terms of the coefficients of variations for the different vendors, Pearson product-moment correlation coefficients were calculated. The results were 0.17 for ΔEab, 0.34 for ΔEcmc, and -0.02 for ΔE2000. This showed that very weak, if any, relationships existed between the variations exhibited by any of the color difference formulae and those found in the subjective evaluations. Still, the correlation for ΔEcmc (0.34) was stronger than the correlations for the other two color difference calculations.

The lack of a clear relationship in Figure 8 was expected because the subjective evaluations were made from different colors than were the measured color differences. Also, the subjective scale of 1–5 was very imprecise compared to the measured values.

The second means by which the performances of the three color difference formulae were tested was by examining the Spearman rank-order correlations between each formula and the visual evaluations. Again, the data from the two workflows was combined. The average subjective scores given by the seven judges across the five target areas and the two workflows were calculated. The ten vendors were then put in rank order according to these combined scores. Since high subjective scores were desirable, a higher ranking means better color matching for a given vendor.

For all three color difference formulae, the calculated color differences were averaged for all of the 24 measured patches and for both workflows. These average values were put in rank order. In this instance, lower color difference averages indicated better color matching, so lower rank order scores are better. The rank order data is shown below in Table 10.

	Vendors									
	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
Visual	4	5	1	2	10	3	9	6	8	7
ΔEab	5	8	9	10	1	6	2	7	3	4
ΔEcmc	7	8	10	9	1	6	2	4	3	5
ΔE2000	8	9	10	7	1	5	2	4	3	6

Table 10. Rank orders of vendors in terms of average color differences ("V" designates vendor numbers)

Spearman rank-order correlation coefficients were calculated between the visual results and those from each color difference formula. The results were -0.89 for ΔEab, -0.94 for ΔEcmc, and -0.83 for ΔE2000. In this instance, there are very strong correlations between the subjective rankings of the vendors and the rankings found with each of the color difference formulae. The correlations are all negative because a high ranking in subjective terms indicated a low average color difference. Of the three color difference equations used, ΔEcmc again showed the strongest relationship to the subjective data. Therefore, ΔEcmc was selected as the best color difference formula to use for this analysis. These findings support the findings of Habekost (2008).

All the ΔEcmc color differences between the control proof and the vendor proofs for both workflows are shown in Appendix F. The maximum, average, and minimum color differences among the 24 Color Checker patches are shown in Figure 9 for each workflow and each vendor, along with their coefficients of variation.

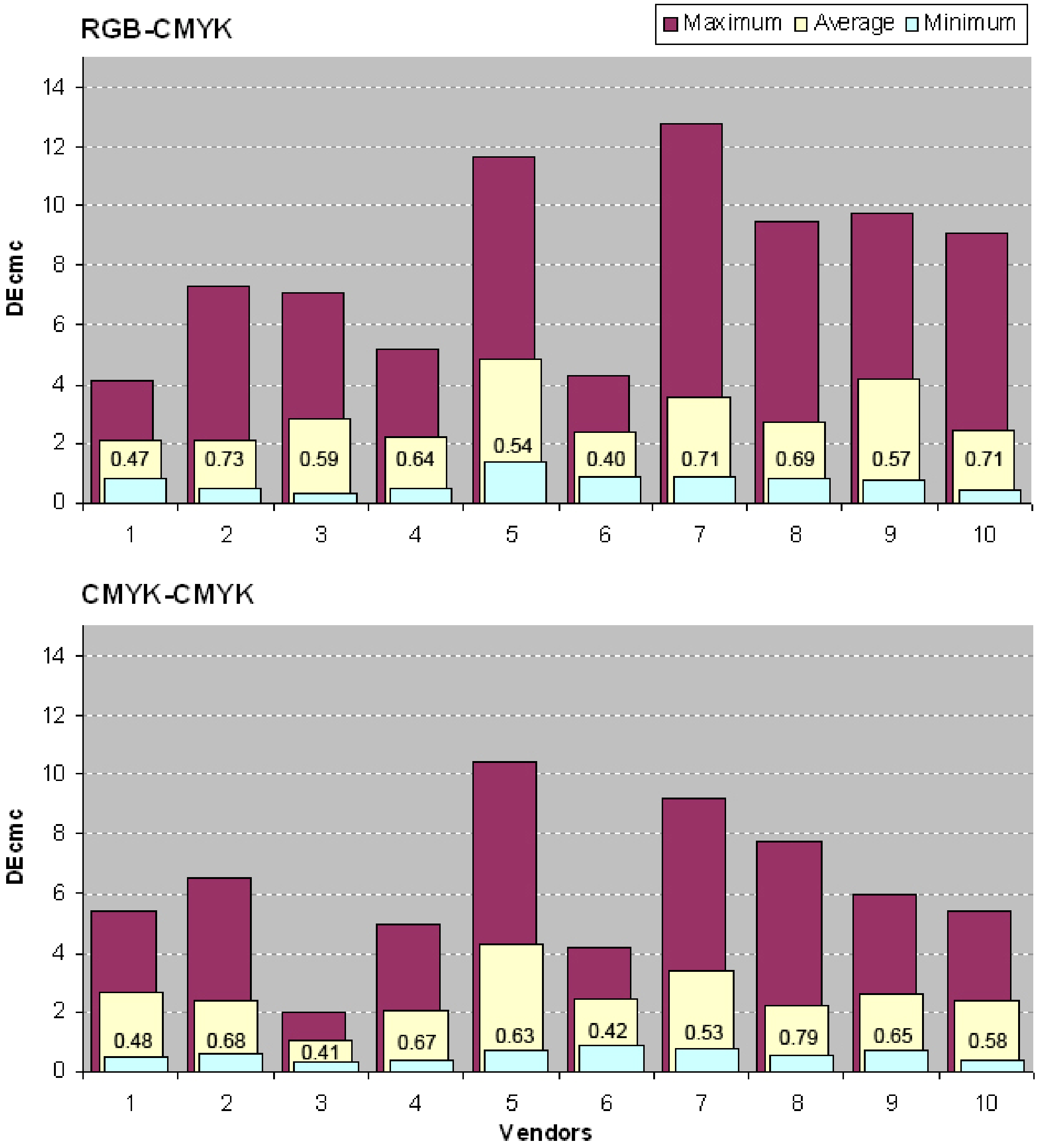


Figure 9. Maximum, average, and minimum ΔEcmc color differences between the control and ink-optimized prints with the coefficients of variation across the 24 measured colors

Examination of Figure 9 led to the following observations:

- The maximum color differences for the RGB–CMYK workflow were larger than those found with the CMYK–CMYK.
- Vendor #6 showed the most uniformity between the two workflows.

- The color matching of vendor #3 for the CMYK–CMYK workflow was the best and most consistent across different colors; however, this result is not valid because vendor #3 made no changes to the ink coverages of the original CMYK file.

The coefficients of variation (black values in the graph) reveal some interesting characteristics of the data shown in Figure 9. These values are indications of the variability shown by each vendor/workflow combination among the color differences found for the 24 measured patches. For example, the results from vendors #7 and #8 in the CMYK–CMYK workflow reveal that the maximum color difference for vendor #7 was higher than for vendor #8. Vendor #7 also had a higher average color difference and a larger range of measured color differences than did vendor #8. However, vendor #7 had a lower coefficient of variation than did vendor #8, showing that the color differences for vendor #7 were more tightly clustered around the mean than for vendor #8. A similar relationship was found between vendors #4 and #5 for the CMYK–CMYK workflow.

This prompted an examination of the skewness and kurtosis of the color difference data for each of the vendors. The skewness is a measure of the symmetry of a distribution, with zero indicating a normal distribution. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values, while negative skewness indicates the opposite. The kurtosis value is a measure of the extent to which the data is clustered around the mean. The normal distribution has a kurtosis of zero. Positive kurtosis values indicate distributions that are more tightly clustered than the normal distribution, and negative kurtosis indicates distributions in which the values are more spread out than in the normal distribution. The mean, standard deviation, coefficient of variation, skewness, and kurtosis values for all of the ΔEcmc color differences for each of the vendors and each workflow are shown in Table 11.

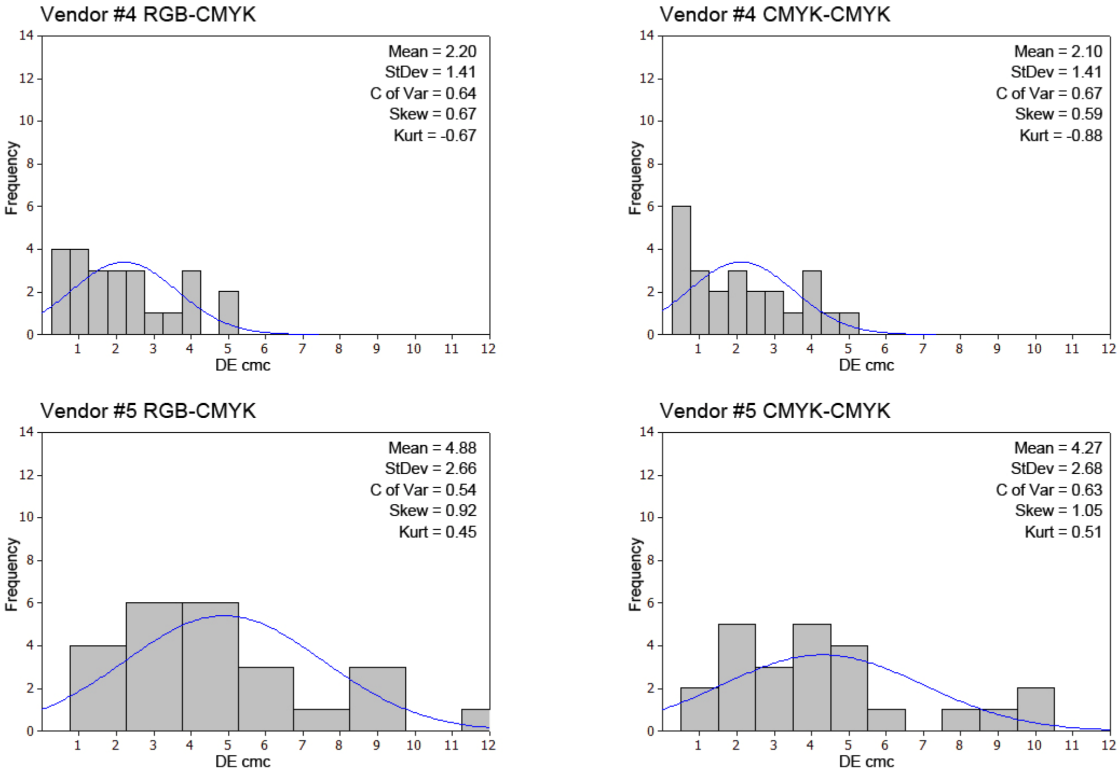
	Vendors									
RGB-CMYK	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
Mean	2.11	2.16	2.86	2.20	4.88	2.36	3.56	2.73	4.15	2.43
Std. Deviation	0.99	1.57	1.68	1.41	2.66	0.95	2.52	1.89	2.35	1.73
Coef. of Variation	0.47	0.73	0.59	0.64	0.54	0.40	0.71	0.69	0.57	0.71
Skewness	0.47	1.64	0.72	0.67	0.92	0.71	2.43	2.19	0.67	2.53
Kurtosis	-0.72	3.49	0.50	-0.67	0.45	-0.58	7.32	6.31	0.02	9.04
CMYK-CMYK	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
Mean	2.68	2.36	1.10	2.10	4.27	2.41	3.36	2.21	2.60	2.38
Std. Deviation	1.29	1.60	0.45	1.41	2.68	1.01	1.78	1.75	1.68	1.38
Coef. of Variation	0.48	0.67	0.41	0.67	0.63	0.42	0.53	0.79	0.65	0.58
Skewness	0.38	0.90	0.31	0.59	1.05	0.41	1.48	1.52	0.81	0.50
Kurtosis	-0.46	0.36	-0.36	-0.88	0.51	-0.88	3.80	2.91	-0.22	-0.47

Table 11. Statistics by vendor and workflow for ΔEcmc color differences

All of the skewness values in Table 11 are positive. This was expected for this data because zero color difference forms a limit on the lower side of the mean, while there is no limit to the color differences on the upper side of the mean. The color difference data for some vendors is more asymmetrical than others; for example, vendors #7, #8, and #10 in the RGB–CMYK workflow have relatively high skewness values. This indicates that there were certain colors for these vendors that showed unusually high color differences, while most of the color differences were closer to the mean. Indeed, the kurtosis values for these three vendors showed that their color difference values were more tightly clustered around the mean than the other vendors or than the normal distribution.

The kurtosis values overall showed a wide range of results. To test whether these values were indicators of subjective acceptability, correlation coefficients were calculated with the subjective ratings of the vendors. The Pearson coefficients were -0.34 for the RGB–CMYK workflow and -0.40 for the CMYK–CMYK workflow. Although the relationship was weak, it was interesting that it was negative, meaning that more tightly clustered data was associated with lower subjective scores. Rank-order correlations gave similar results.

Histograms with superimposed normal curves and summary statistics of the distributions of DEcmc color differences for all the vendors and both workflows are shown in Appendix G. These graphs show a wide disparity of color difference distributions between the vendors and between the two workflows. To illustrate this, the histograms from the vendors with the lowest mean color differences (vendor #4) and the highest mean color differences (vendor #5) are shown in Figure 10.


Vendor #4 RGB-CMYK

Vendor #4 CMYK-CMYK

Vendor #5 RGB-CMYK

Vendor #5 CMYK-CMYK

Figure 10. ΔEcmc color difference distributions for vendors #4 and #5

The histograms in Figure 10 do not fit the normal distribution very well. It appeared that the mean color differences had the strongest relationship with the subjective color evaluations. This relationship was tested. The graphs in Figure 11 show the results of a linear regression analysis of these two variables.

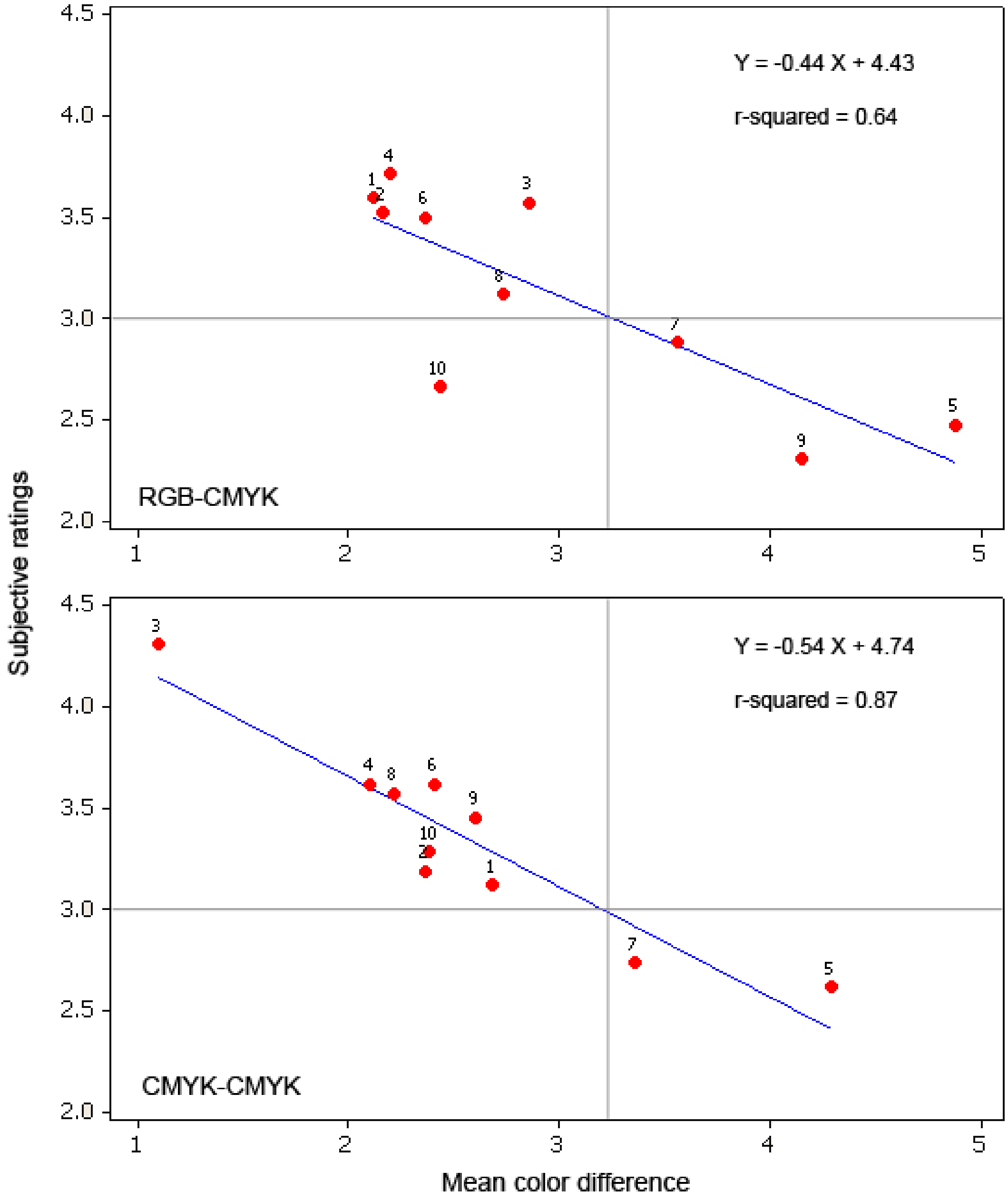


Figure 11. Linear regression for subjective ratings and mean ΔEcmc color differences

The mean measured color differences were found to correlate reasonably well with the subjective ratings of the vendors. The relationship was stronger for the CMYK–CMYK workflow with an r-squared value of 0.87, as opposed to an r-squared of 0.64 for the RGB–CMYK samples. The best-fit linear equations in the upper right portions of the graphs in Figure 11 were very similar for the two workflows, indicating that the relationships are essentially the same; that is, they differed in strength but not in form.

The horizontal lines at subjective ratings of 3 show the cutoff the judges were given for commercially acceptable color matches. The vertical lines at mean color differences of 3.23 were determined empirically as the average of the x-coordinates of the intersection points of the two regression lines with the commercially acceptable color limit. The x-coordinates were 3.22 for the RGB—CMYK workflow and 3.25 for the CMYK—CMYK workflow.

The mean color difference limit of 3.24 for commercially acceptable color matching was reasonable based on Johnson and Green (2006), who considered 3.0 ΔE2000 units to be a reasonable acceptability limit for graphic arts. Habekost (2008) found that ΔEcmc tolerances were slightly higher than equivalent ΔE2000 tolerances, but a commercially acceptable tolerance recommendation was not given. Therefore, the value of 3.23 ΔEcmc was a accepted as a reasonable limit to use for this study.

The only data point in Figure 11 that was unacceptable according to subjective evaluation but acceptable according to mean color difference was for vendor #10 in the RGB–CMYK workflow. When the data for vendor #10 was examined, it was found that the visual ratings were particularly low for the target areas #2 and #5. Area #2 was a dark section with a textured blue towel and deep shadows, and #5 was a woman's face. The measured color differences from the Color Checker patches labeled dark skin tones, black, blue sky, and cyan were all higher than the mean color difference for this vendor. These colors were related to the subject areas that were judged to be poor color matches.

This incident demonstrates a weakness in basing color acceptability on measured color differences. People typically evaluate images in terms of areas of interest, which leads to a non-uniform weighting of the importance of certain colors. The areas of interest will differ for different observers and different images, making it difficult to incorporate the weighting into an objective color measurement scheme. Indeed, Habekost found different pass/fail tolerances for each color that he considered. The issue is further complicated because human observers will attach different levels of importance to the same color depending on the context in which it is found.

In summary, the color differences found through subjective judging and objective measurement were in close agreement. In the RGB–CMYK workflow, six of the vendors (#1, #2, #3, #4, #6, and #8) produced acceptable color matches by both measures; three vendors (#5, #7, and #9) did not provide color matches that were commercially acceptable; and one case (#10) was ambiguous, passing the objective measure but failing the subjective evaluation. In the CMYK–CMYK workflow, eight vendors (#1, #2, #3, #4, #6, #8, #9, and #10) produced acceptable color matches by both measures, and two vendors (#5 and #7) failed to produce commercially acceptable color matches.

The rankings of the vendors for color matching are shown in Table 12.

Rank	Visual		Measured		Combined		Overall
	RGB	CMYK	RGB	CMYK	RGB	CMYK	
1	V4	V3	V1	V3	V1	V3	V4
2	V1	V6	V2	V4	V4	V4	V3
3	V3	V4	V4	V8	V2	V8	V2
4	V2	V8	V6	V2	V6	V6	V6
5	V6	V9	V10	V10	V3	V2	V1
6	V8	V10	V8	V6	V8	V10	V8
7	V7	V2	V3	V9	V10	V9	V10
8	V10	V1	V7	V1	V7	V1	V9
9	V5	V7	V9	V7	V9	V7	V7
10	V9	V5	V5	V5	V5	V5	V5

Table 12. Rankings of vendors for color matching (“V” designates vendor number)

The rankings in Table 12 are all in the order of best (low ranks) to worst (high ranks). The rankings for vendor #3 are highlighted because their files did not provide any ink optimization in the RGB–CMYK workflow, and their CMYK–CMYK files made no changes to the original CMYK ink coverages. The highlighted cells at the bottom of the table show the vendors whose color matching was found to be unacceptable by commercial standards. The rankings of the two evaluations of color matching (visual and measured) are shown separately for both workflows on the left side of the table. On the right, the visual and measured results are combined for each workflow. The last column shows the ranking of the vendors when the two workflows and the two color evaluation methods are all combined.

Conclusions

To determine which vendors were providing both ink savings and acceptable color matches, the data from the ink reduction analysis and the color matching analysis were combined in Table 13.

Rank	Overall Color	Ink Reduction			Ink Savings
		RGB	CMYK	Overall	
1	V4	V2	V8	V2	25.9%
2	V3	V10	V10	V10	24.5%
3	V2	V4	V2	V7	22.6%
4	V6	V7	V7	V8	22.4%
5	V1	V8	V4	V4	21.6%
6	V8	V5	V9	V6	17.9%
7	V10	V6	V1	V5	17.7%
8	V9	V1	V6	V1	16.6%
9	V7	V3	V5	V9	15.6%
10	V5	V9	V3	V3	none

Table 13. Overall color matching ranks combined with ranks from ink reduction analysis (“V” designates vendor number)

Table 13 shows the ranking for overall color matching of the vendors in the second column. The highlighted cells show vendors that did not provide commercially acceptable color matching. The subcolumns in the center of the table under the heading Ink Reduction show the rankings of the vendors for each of the two workflows, as well as a ranking that combined the two workflows. Again, the shaded cells show the vendors that did not provide acceptable color matches. The last column shows the percentage of ink that was saved by each of the vendors across all twelve image files used for this study. The vendor who failed to implement ink optimization for this study is listed as having none for ink savings. In fact, the files submitted by this vendor increased the total coverage of ink when compared to the control file.

The research questions that prompted this study were:

1. Do the ink optimization programs included in this study reduce the amount of ink needed to print a series of test images, and to what extent do the participants reduce ink usage?
2. Does the application of the ink optimization programs cause unacceptable color shifts in the reproduction of the test files compared to printing the files with no ink optimization applied?

The answer to the first question was clearly *yes* for nine of the participants of this study. The entry of vendor #3 was the exception. It was believed that their ink optimization program was not properly applied to the test files, and it was unknown how well their program would have performed otherwise. The amount of ink savings varied from 15% to 26% of the total ink required for control file. (The specific levels of ink savings for each of the vendors in this study were shown in Table 6.)

The answer to the second research question was *yes* for five of the vendors and *no* for four of the vendors. The acceptability of color matching was determined through subjective evaluations and also through measured color differences. The two methods of evaluation showed strong agreement. (The vendors were ranked in their color matching accuracy in Table 12.)

In conclusion, vendors #1, #2, #4, #6 and #8 were all found to provide a combination of substantial ink savings together with commercially acceptable color matches in the context of this study.

Acknowledgment

The authors wish to thank the vendors who participated in the study. We also wish to thank the following individuals, who served as judges for the subjective color matching portion of this study: Hallie Barcalow, Lindsay Ferrari, Joe Marin, Eric Neumann, Greg Radencic, and Joe Suffoletto.

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Appendix A

Participants in the study

Company	Software	Implementation	Market	Platform
Adobe www.adobe.com	Photoshop (GCR)	Photoshop	General	Win, Mac
Agfa www.agfa.com	Arkitex Intelliune Arkitex OptiInk (CMYK)	Stand-alone	News, Pub	Win, Mac
Agfa www.agfa.com	ApogeeX Inksave	Option (for :ApogeeX RIP)	News, Pub, Com	Win
Alwan Color Expertise www.alwancolor.com	CMYK Optimizer	Stand-alone, OEM integration (via JDF)	News, Pub, Com	Mac
Binuscan www.binuscan.com	IPM Workflow Server PDF Server	Stand-alone	News, Pub, Com	Win
CGS www.cgs-oris.com	ORIS Ink Saver	Option (for ORIS ColorTuner)	News, Pub, Com	Win
FineEye Color Solutions www.fineeyecolor.com	ICEmaker (RGB) ICEsaver (CMYK)	Photoshop Plug-in (1) Acrobat Plug-in (2)	Pub, Com	Mac
Fujifilm www.fujifilmcfit.com	C-Fit Image Intelligence	Stand-alone	Pub, Com	Win
GMG www.gmgcolor.com	ColorServer InkOptimizer (CMYK)	Stand-alone	Pub, Com	Win
IQ Colour, LLC www.iqcolour.com	IQ Colour	Photoshop Plug-in, Stand-alone	News, Pub, Com	Win, Mac
Newscolor www.newscolor.com	Vesper		News	Win
OneVision www.onevision.com	INKSAVE Speedflow	Plug-in for Asura workflow	News	Win
Rampage www.rampage.com	INKdrop	Option (for Rampage RIP)	Pub, Com	Win
TGLC www.tglc.com	PerfX Color Server	Stand-alone	News, Pub, Com	Win, Mac

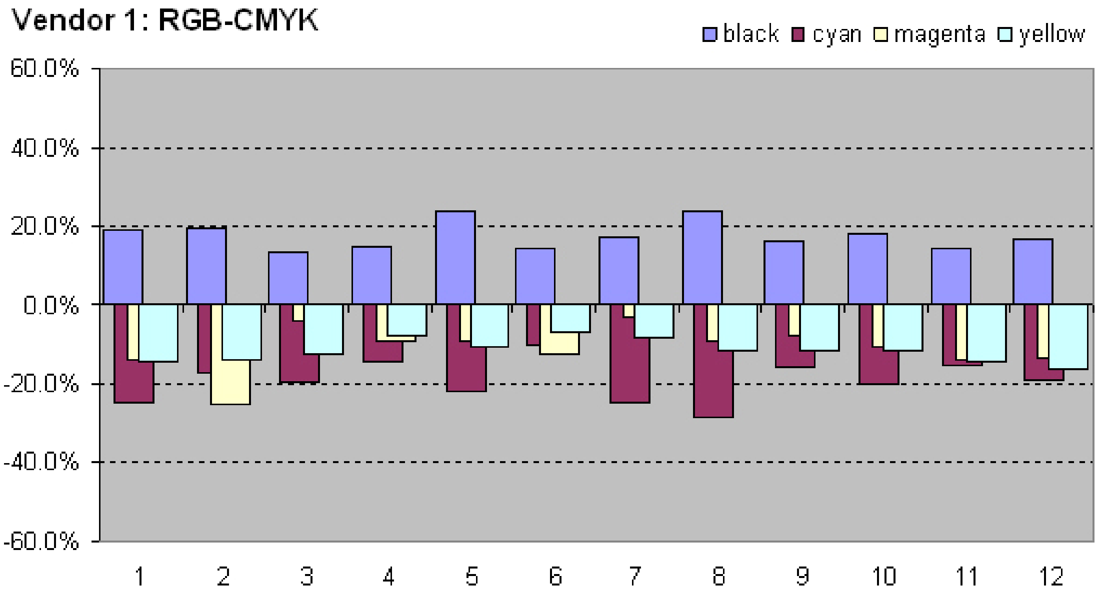
Appendix B

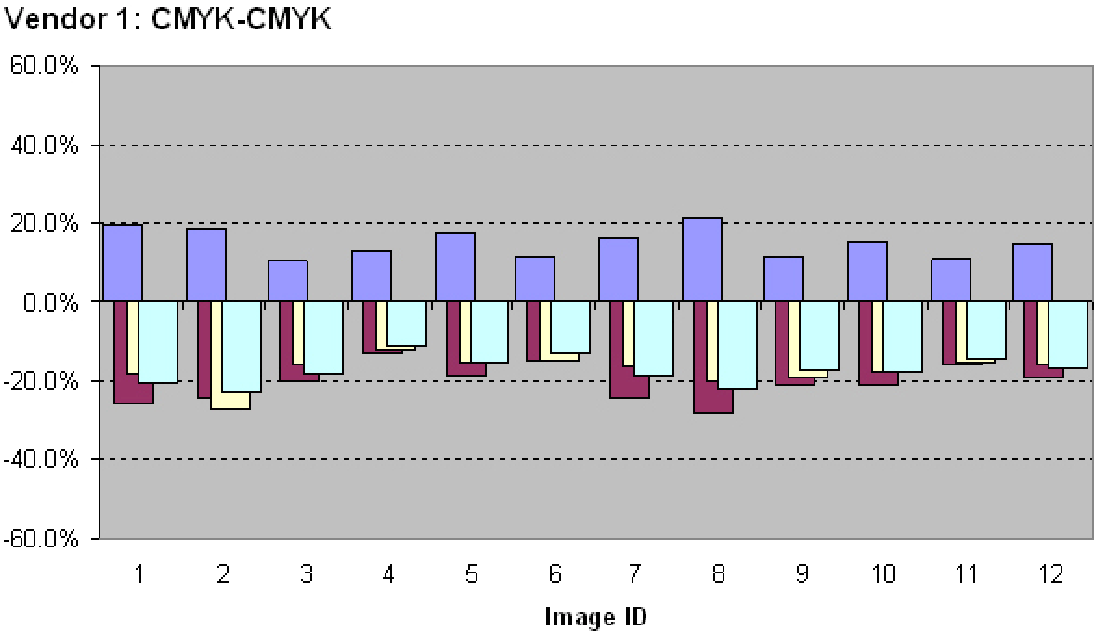
Area coverage values for all of the photographic images used in this study

ID	Photo	Black	Cyan	Magenta	Yellow	Total
1	kitchen	30.6%	38.5%	58.7%	77.2%	205.0%
2	flowers	44.4%	68.2%	50.9%	83.6%	247.1%
3	low key	58.2%	44.7%	62.3%	66.2%	231.4%
4	high key	11.0%	36.1%	25.8%	34.6%	107.5%
5	group	21.4%	45.5%	49.7%	47.5%	164.1%
6	outdoor	24.1%	52.3%	34.1%	44.1%	154.6%
7	portrait	43.0%	42.0%	59.5%	63.0%	207.5%
8	fruits	36.8%	44.1%	57.8%	71.2%	209.9%
9	neutrals	62.5%	64.6%	52.9%	54.9%	234.9%
10	composite	36.9%	48.5%	50.2%	60.3%	195.9%
11	color checker	39.1%	57.6%	55.4%	56.9%	209.0%
12	subjective	29.3%	43.8%	50.7%	50.8%	174.6%

Appendix C

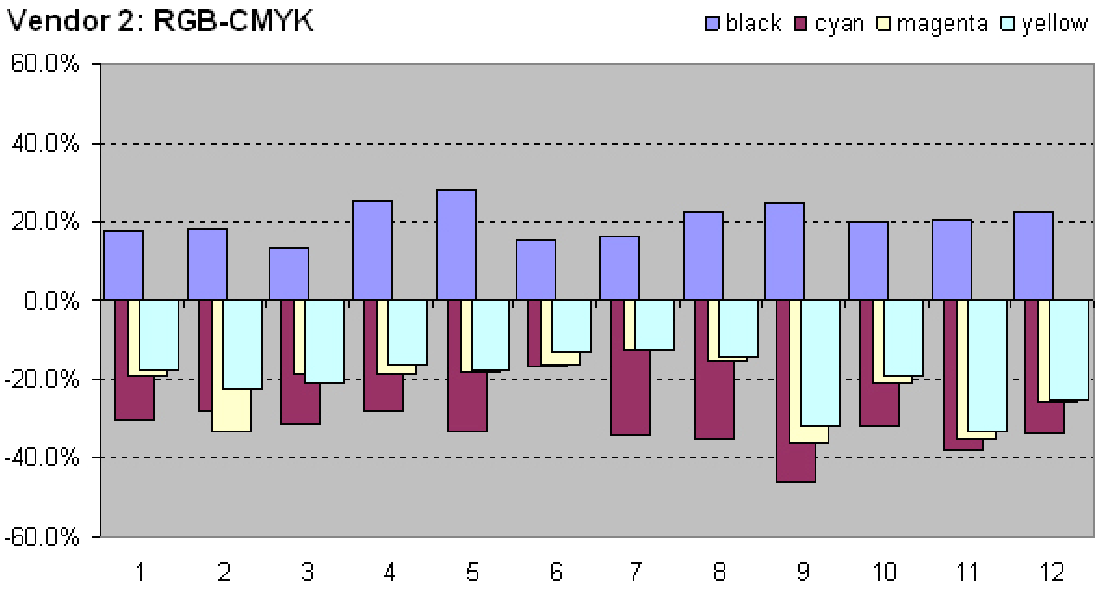
Ink coverage differences from original file by vendor and photographic image

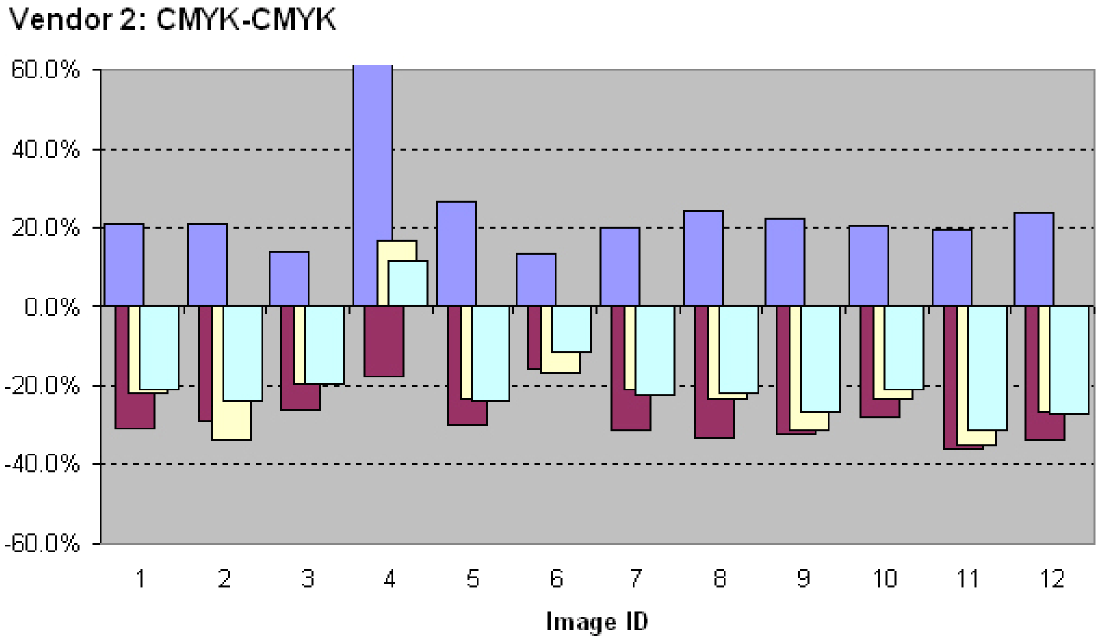




Appendix C (continued)

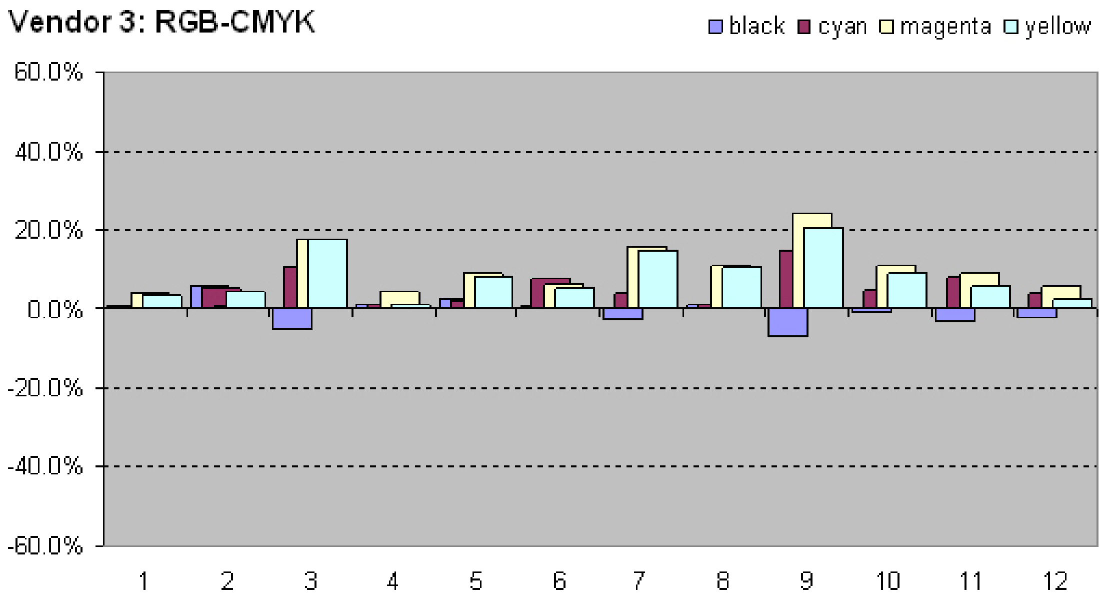
Ink coverage differences from original file by vendor and photographic image

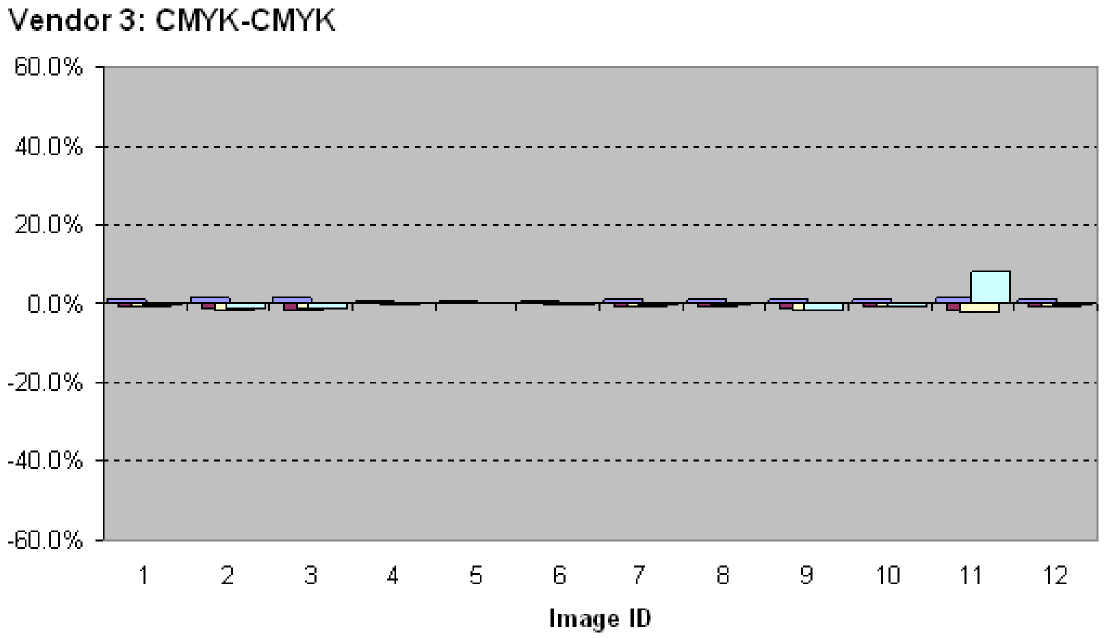




Appendix C (continued)

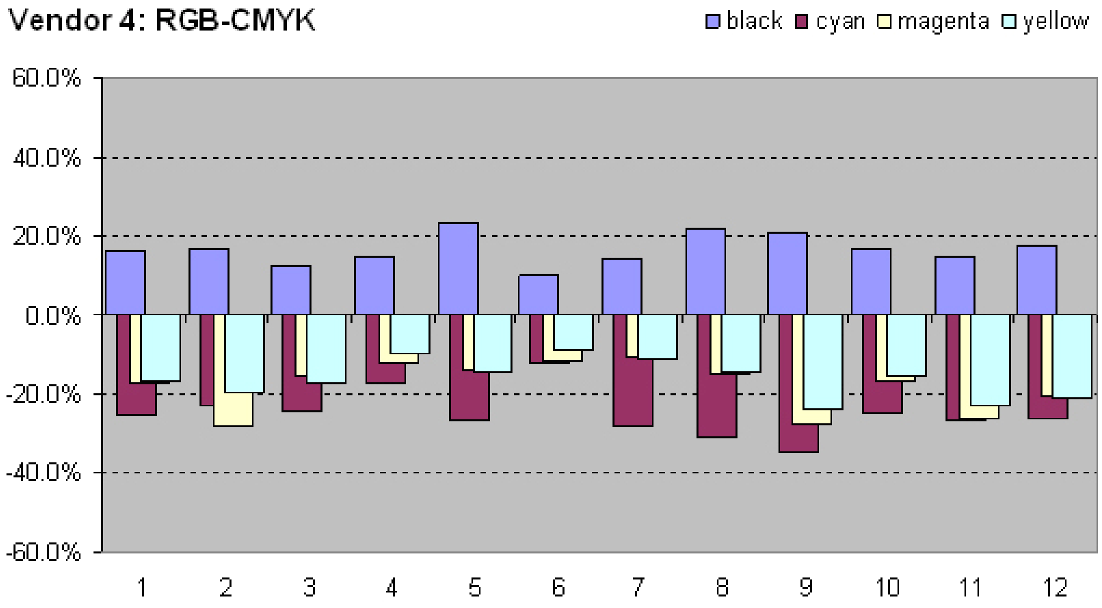
Ink coverage differences from original file by vendor and photographic image

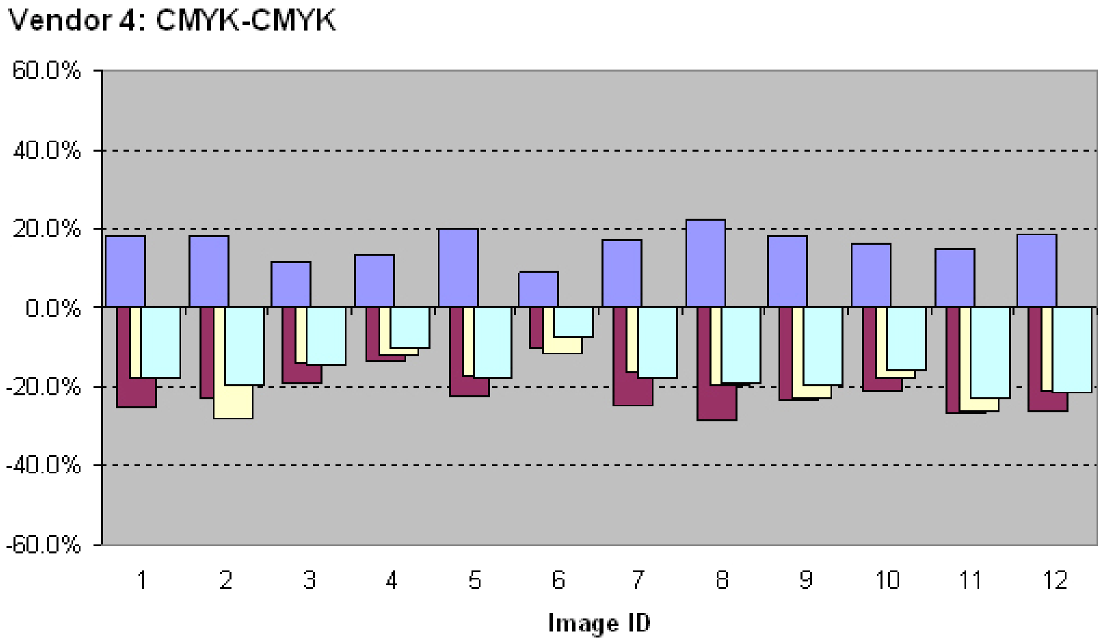




Appendix C (continued)

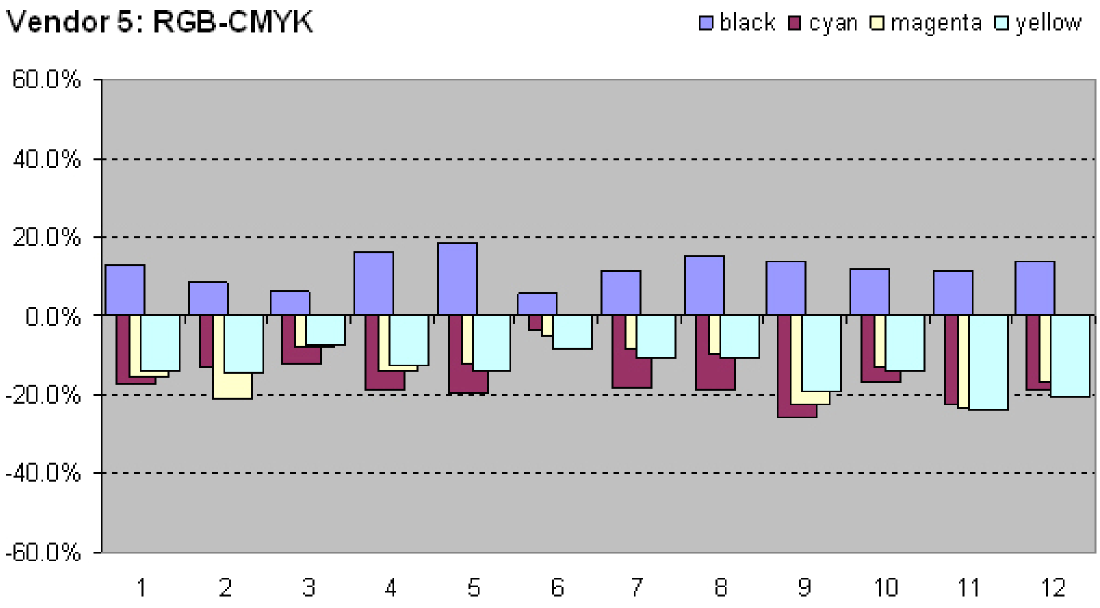
Ink coverage differences from original file by vendor and photographic image

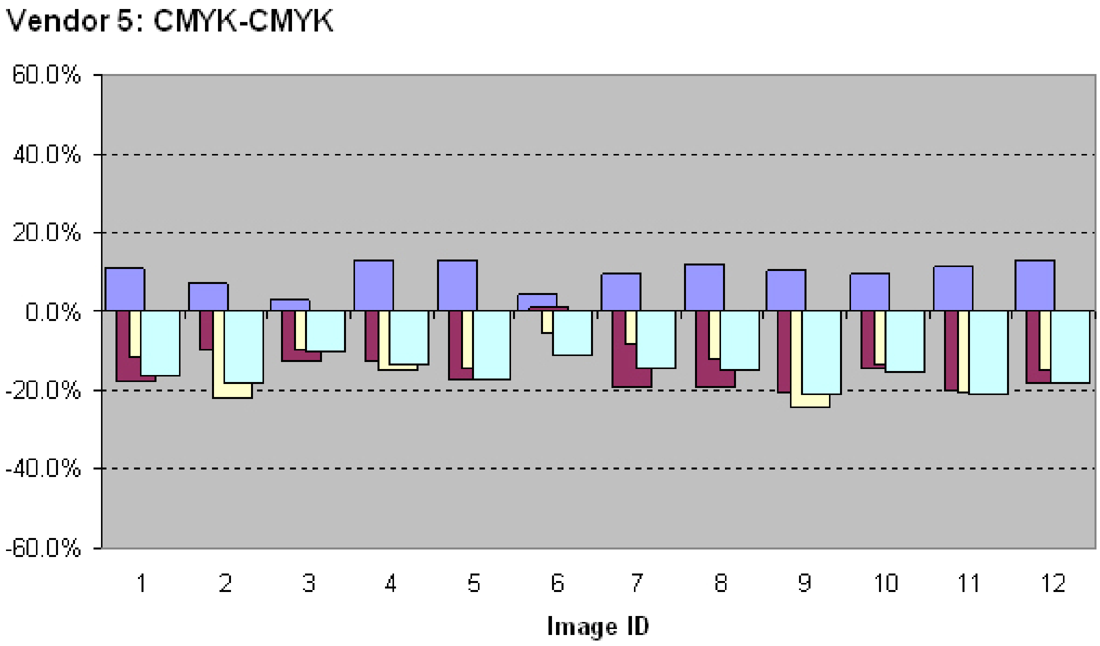




Appendix C (continued)

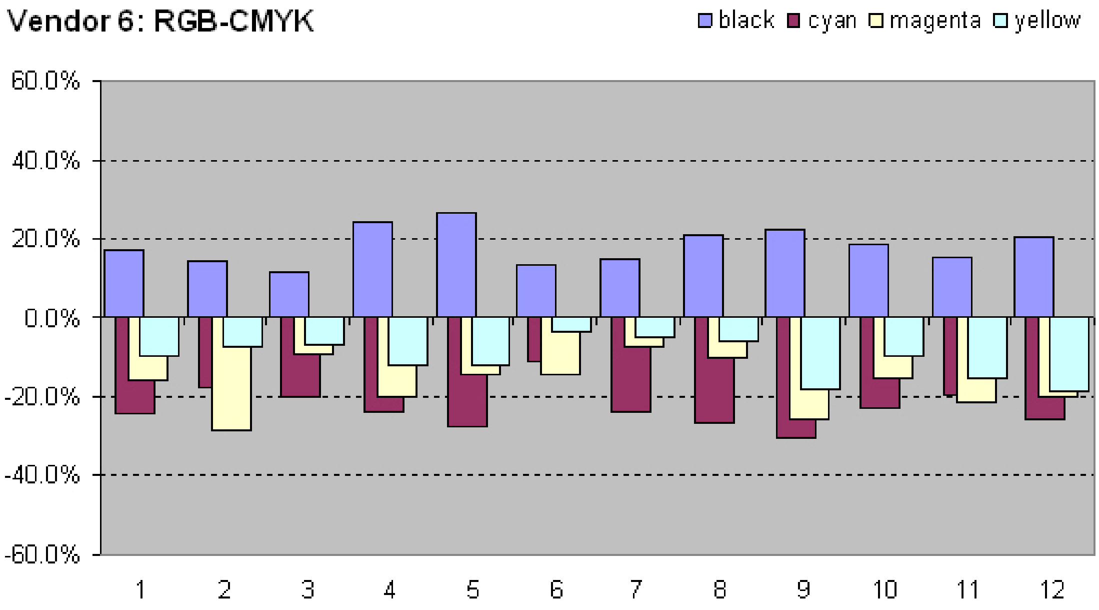
Ink coverage differences from original file by vendor and photographic image

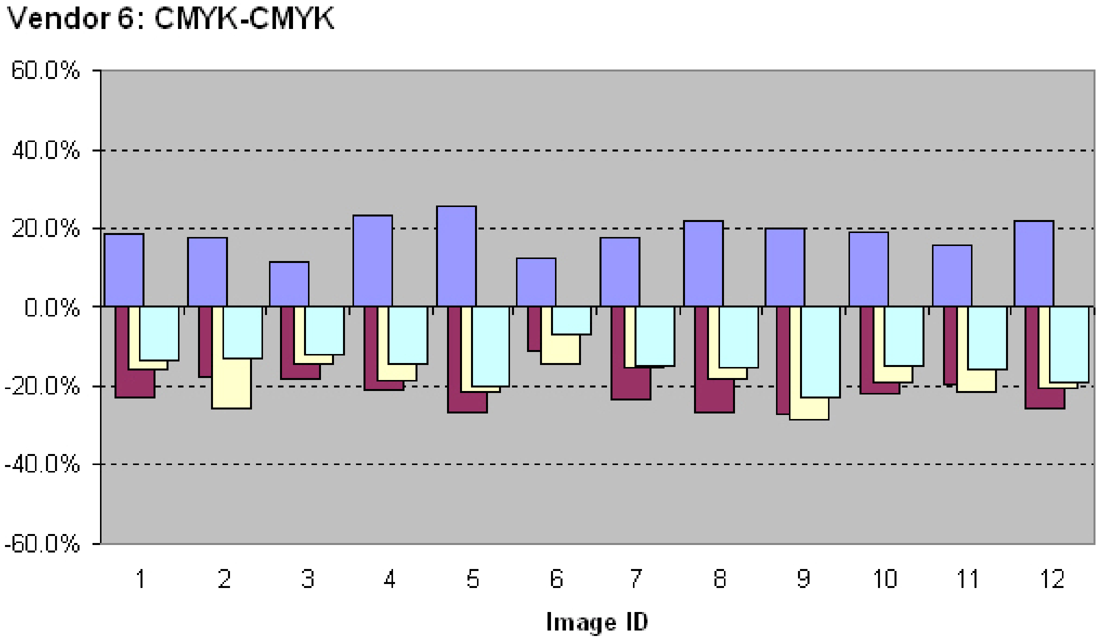




Appendix C (continued)

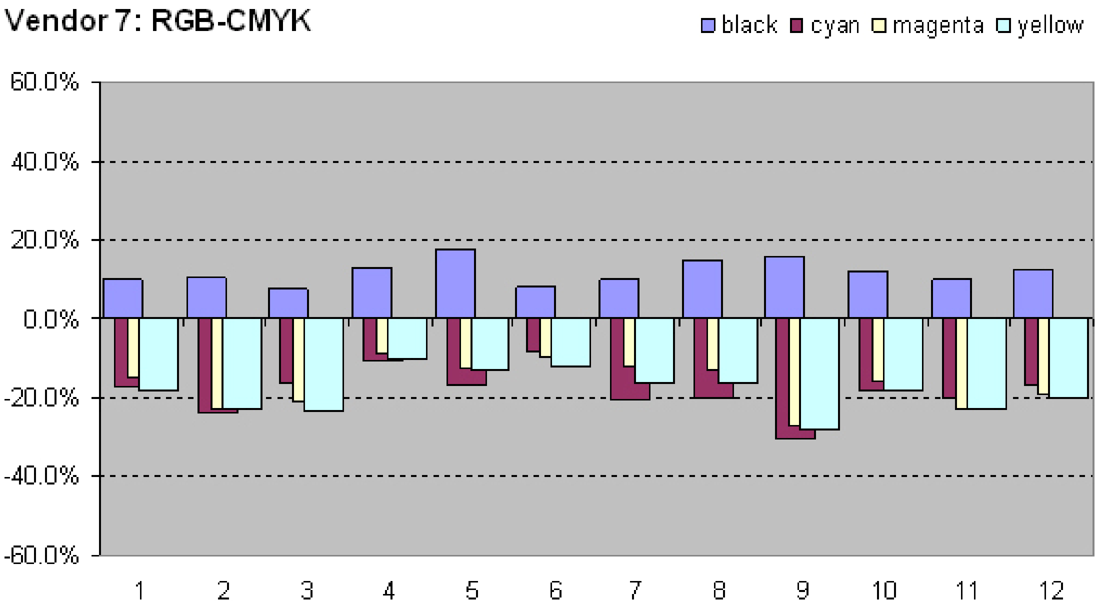
Ink coverage differences from original file by vendor and photographic image

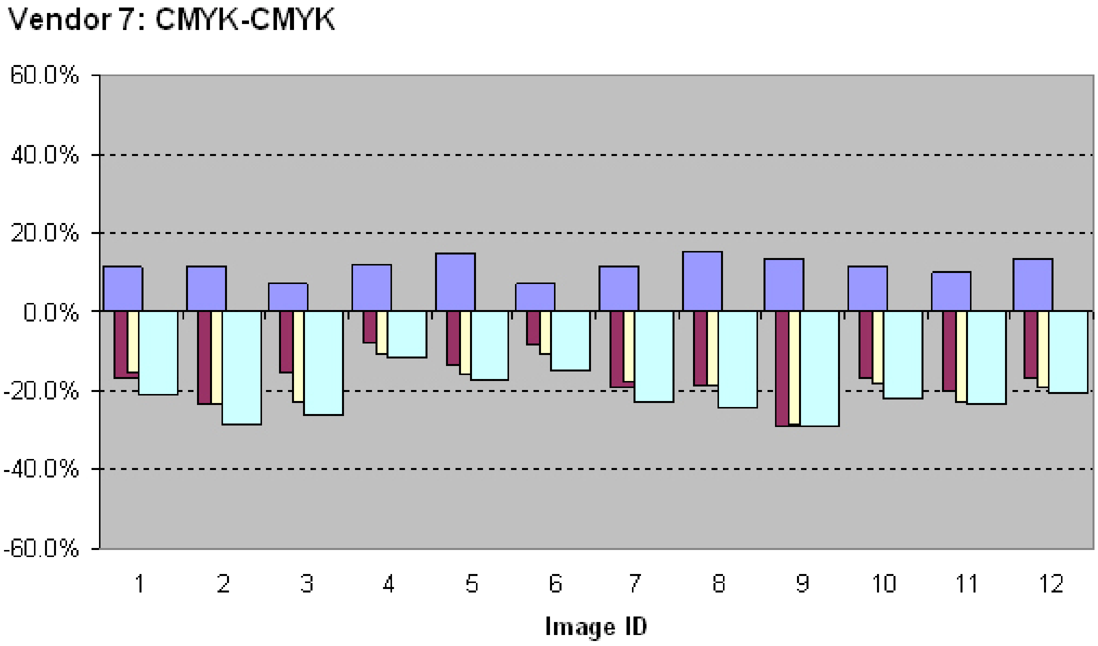




Appendix C (continued)

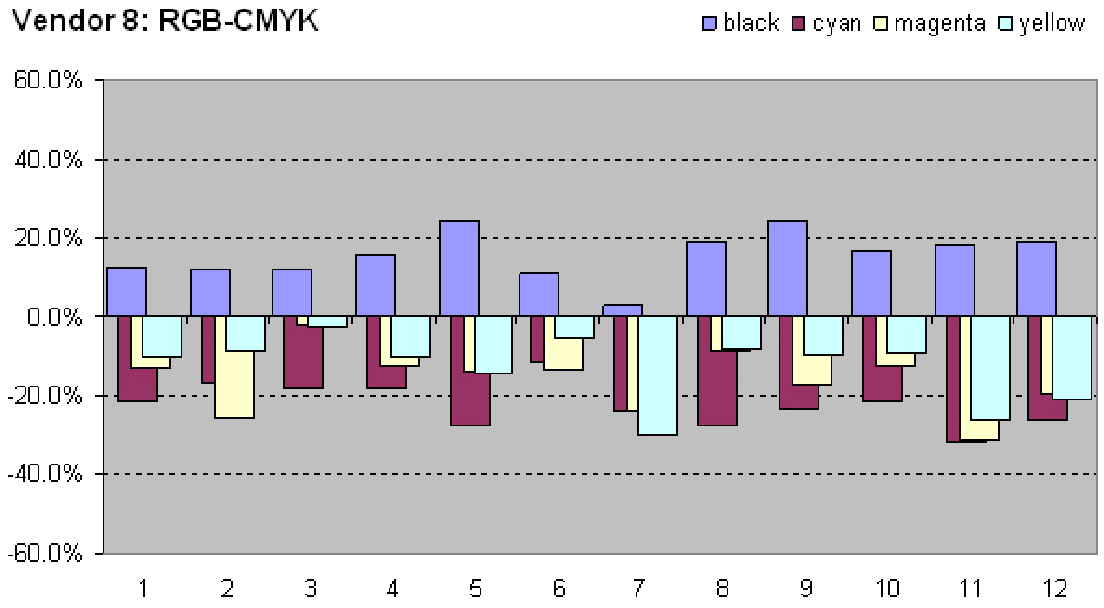
Ink coverage differences from original file by vendor and photographic image

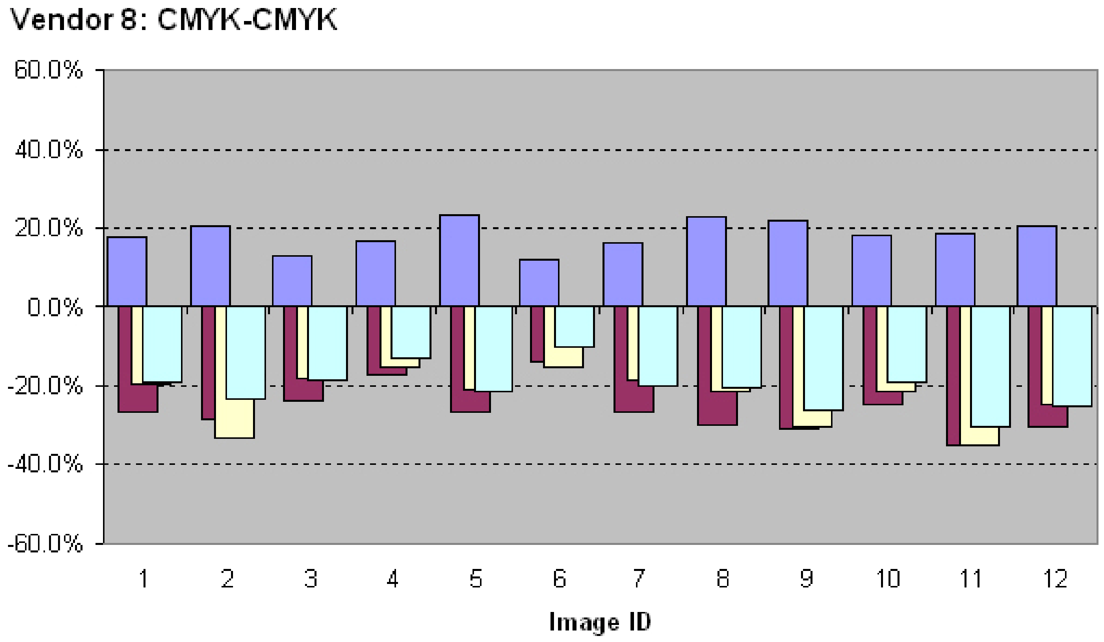




Appendix C (continued)

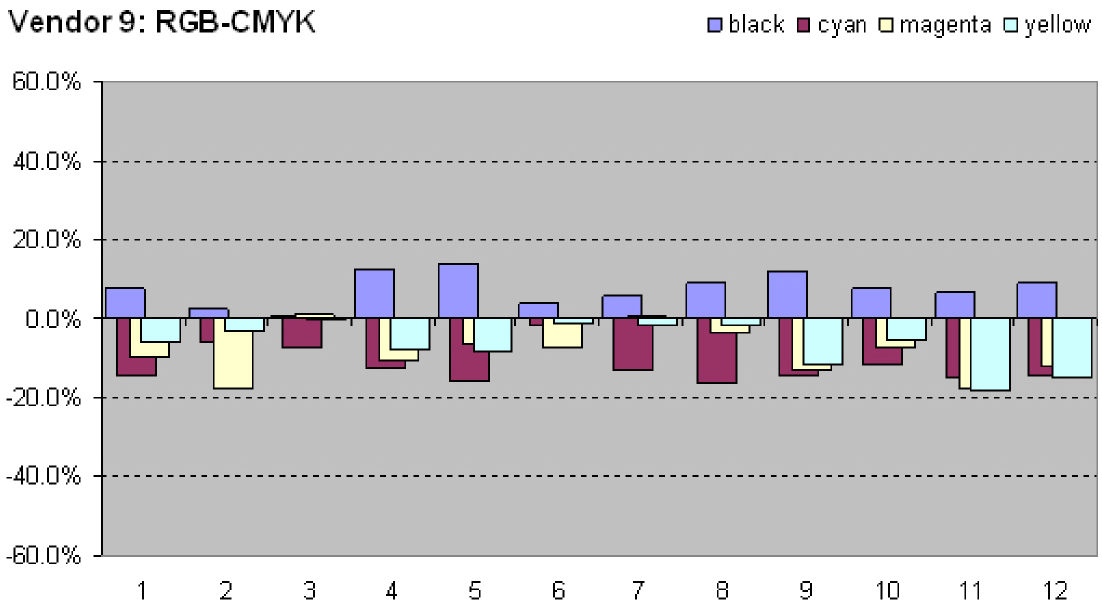
Ink coverage differences from original file by vendor and photographic image

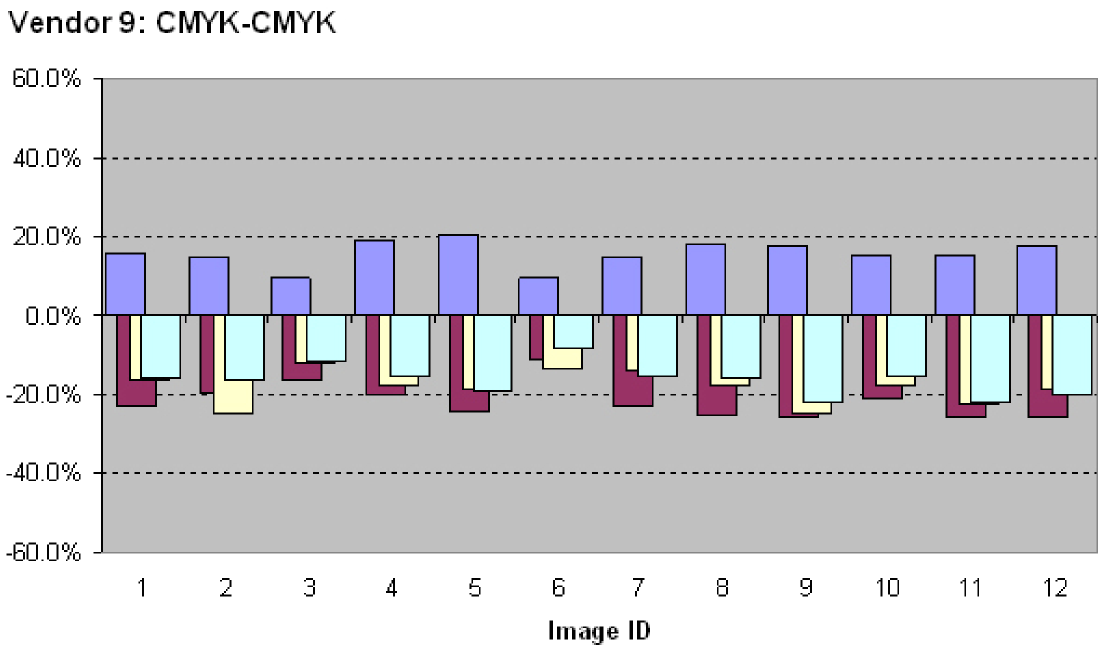




Appendix C (continued)

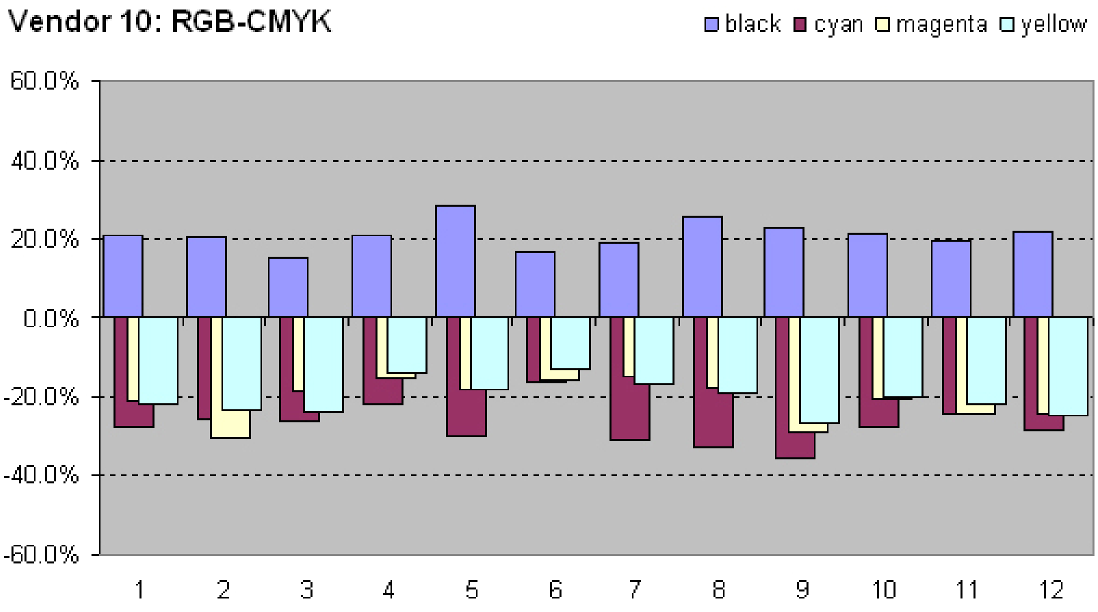
Ink coverage differences from original file by vendor and photographic image

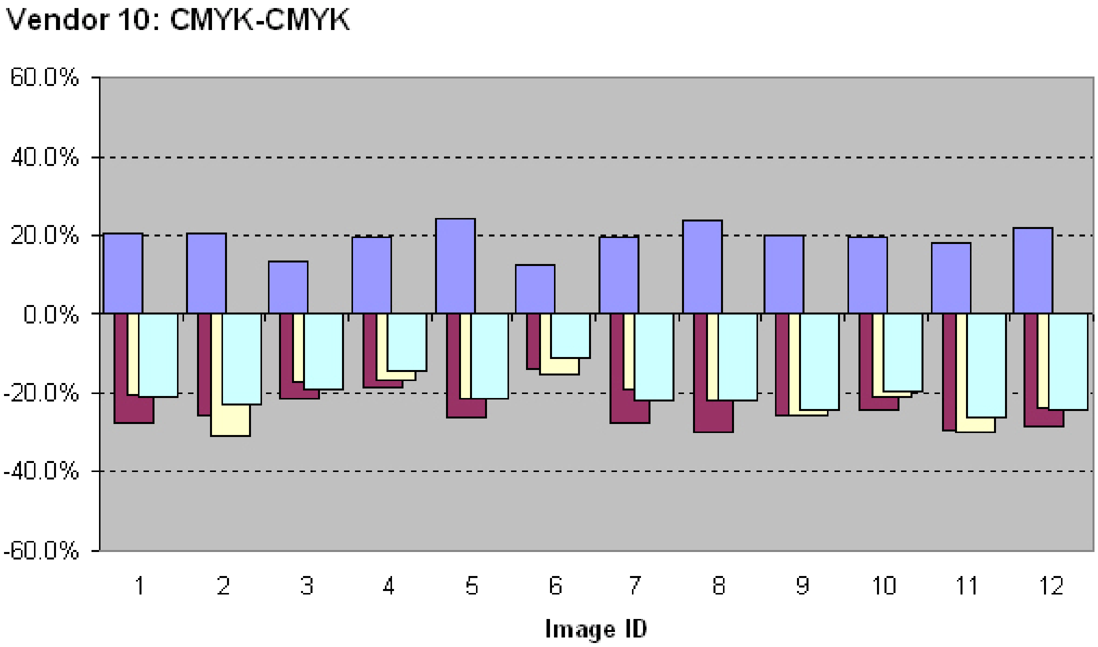




Appendix C (continued)

Ink coverage differences from original file by vendor and photographic image





Appendix D

Ratios of ink coverage changes: changes in dot area of cyan plus magenta plus yellow divided by changes in black ink dot area for each picture and vendor together with summary statistics

	Vendors									
RGB	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
composite	2.35	3.55	27.22	3.40	3.56	2.57	4.40	2.56	3.28	3.20
kitchen	2.23	2.81	64.50	2.71	2.78	2.82	3.27	3.39	4.96	2.49
flowers	3.15	3.92	7.69	3.85	6.35	4.94	5.51	5.42	22.13	3.15
low key	2.42	5.03	9.38	4.30	3.97	2.76	7.44	1.75	38.67	4.15
high key	1.65	2.18	16.67	1.99	2.25	1.95	1.65	2.08	1.91	2.03
group	1.86	2.55	6.96	2.47	2.60	2.10	2.47	2.40	2.38	2.41
outdoor	1.79	2.33	71.75	2.49	1.81	2.36	2.56	2.77	4.56	2.09
portrait	1.92	3.47	14.15	3.20	2.85	2.17	4.68	27.59	2.57	3.07
fruits	1.66	2.32	35.40	2.11	1.99	2.14	2.42	2.14	3.63	2.21
neutrals	2.07	4.49	8.84	4.00	4.65	3.24	5.20	1.99	3.06	3.90
color checker	2.94	5.09	6.86	4.98	5.81	3.51	6.68	4.78	7.52	3.52
subjective	2.93	3.76	4.71	3.87	4.00	3.09	4.43	3.49	4.56	3.54
mean	**2.23**	**3.40**	**11.53**	**3.24**	**3.43**	**2.73**	**4.03**	**3.25**	**4.15**	**2.94**
std dev	**0.52**	**1.04**	**23.08**	**0.94**	**1.47**	**0.83**	**1.81**	**7.20**	**11.02**	**0.72**
variation	**0.24**	**0.31**	**2.00**	**0.29**	**0.43**	**0.31**	**0.45**	**2.21**	**2.65**	**0.25**
rank	**1**	**5**	**8**	**3**	**6**	**4**	**7**	**9**	**10**	**2**
CMYK										
composite	3.62	3.50	2.70	3.33	4.72	2.94	4.89	3.58	3.49	3.34
kitchen	2.39	2.64	18.09	2.43	2.99	2.32	3.07	2.68	2.63	2.45
flowers	3.29	3.44	21.44	3.47	6.55	3.56	4.25	3.46	4.01	3.24
low key	4.85	4.38	4.00	3.80	10.03	3.48	8.71	4.34	3.88	3.98
high key	2.11	0.90	23.00	1.99	2.47	1.96	1.83	2.18	2.35	2.12
group	2.92	3.00	4.33	2.96	3.87	2.72	3.24	3.05	3.19	2.91
outdoor	2.77	2.58	17.33	2.81	1.88	2.28	3.49	2.48	2.76	2.43
portrait	3.39	3.58	4.80	3.24	4.05	2.83	4.85	3.74	3.29	3.28
fruits	2.65	2.66	14.60	2.40	2.77	2.12	3.14	2.58	2.49	2.53
neutrals	4.84	3.95	3.60	3.52	6.13	3.77	6.14	3.93	3.93	3.70
color checker	4.03	5.14	8.63	4.94	5.41	3.49	6.73	5.34	4.44	4.55
subjective	3.44	3.67	2.30	3.66	3.98	3.01	4.24	3.87	3.65	3.53
mean	**3.24**	**2.93**	**10.07**	**3.19**	**4.21**	**2.83**	**4.36**	**3.44**	**3.32**	**3.15**
std dev	**0.88**	**1.07**	**7.91**	**0.78**	**2.25**	**0.61**	**1.89**	**0.90**	**0.67**	**0.72**
variation	**0.27**	**0.36**	**0.79**	**0.24**	**0.53**	**0.22**	**0.43**	**0.26**	**0.20**	**0.23**
rank	**6**	**7**	**10**	**4**	**9**	**2**	**8**	**5**	**1**	**3**

Appendix E

Subjective judgments

							Vendors					
Judge	**Workflow**	**Location**	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
1	**RGB**	**1**	4	3	5	3	2	3	3	3	2	3
		2	2	2	4	3	3	3	3	3	4	2
		3	4	4	4	3	3	4	3	4	2	3
		4	3	4	4	4	4	4	3	4	3	3
		5	4	4	3	4	3	4	3	3	2	2
		Overall	**3**	**4**	**3**	**4**	**3**	**4**	**3**	**3**	**2**	**3**
	CMYK	**1**	2	4	4	4	2	3	3	4	3	4
		2	2	2	4	2	4	2	2	2	3	2
		3	3	3	4	4	3	3	3	3	3	3
		4	3	3	4	3	3	4	2	4	3	3
		5	3	2	4	4	3	4	2	4	4	3
		Overall	**3**	**3**	**4**	**3**	**3**	**3**	**3**	**4**	**3**	**3**
2	**RGB**	**1**	4	3	5	5	1	5	4	3	2	3
		2	3	3	2	3	1	2	1	2	3	2
		3	5	4	4	4	2	3	4	4	4	3
		4	5	4	3	4	2	4	3	3	4	3
		5	3	4	2	4	2	4	2	2	3	4
		Overall	**4**	**3**	**2**	**4**	**2**	**4**	**2**	**3**	**2**	**4**
	CMYK	**1**	2	4	5	4	1	3	2	5	4	4
		2	3	3	5	3	2	3	1	2	3	3
		3	4	4	5	4	2	4	3	4	5	4
		4	4	3	4	4	3	4	3	3	3	4
		5	4	3	5	3	3	5	1	4	5	3
		Overall	**3**	**3**	**5**	**3**	**2**	**4**	**2**	**4**	**4**	**4**
3	**RGB**	**1**	3	3	3	4	2	5	4	4	2	3
		2	3	3	5	4	2	3	2	3	3	3
		3	5	5	4	4	2	5	4	4	3	3
		4	5	5	4	5	2	4	3	4	3	3
		5	3	3	4	4	2	3	2	3	3	3
		Overall	**4**	**4**	**4**	**4**	**2**	**3**	**2**	**3**	**3**	**3**
	CMYK	**1**	3	4	5	4	2	4	3	4	3	3
		2	3	2	4	3	2	3	2	2	2	2
		3	3	3	5	4	2	4	3	3	3	4
		4	3	3	5	4	2	4	4	3	3	3
		5	3	2	5	2	2	3	3	2	2	2
		Overall	**3**	**3**	**5**	**4**	**2**	**4**	**2**	**3**	**2**	**3**
4	**RGB**	**1**	3	3	3	3	2	3	3	3	2	3
		2	3	3	3	3	2	3	3	3	2	3
		3	4	4	5	4	3	4	4	4	3	4
		4	3	4	3	3	3	3	3	4	3	3
		5	3	3	3	3	3	3	3	2	3	3
		Overall	**3**	**3**	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
	CMYK	**1**	3	3	4	4	2	3	3	4	3	3
		2	3	3	4	3	3	3	3	3	3	3
		3	4	4	5	4	3	4	4	4	4	4
		4	3	3	5	4	4	3	3	4	3	3
		5	3	3	5	3	3	3	2	3	4	3
		Overall	**3**	**3**	**5**	**4**	**3**	**3**	**3**	**4**	**4**	**3**

Appendix E (continued)

Subjective judgments

			Vendors									
Judge	**Workflow**	**Location**	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
5	**RGB**	**1**	2	3	3	4	1	2	3	3	2	4
		2	3	3	3	2	3	4	2	3	3	2
		3	4	2	2	3	3	4	3	3	2	3
		4	3	2	2	2	2	2	2	2	2	2
		5	3	4	2	2	2	2	2	1	2	1
		Overall	**3**	**3**	**2**	**2**	**2**	**3**	**2**	**3**	**2**	**3**
	CMYK	**1**	2	4	3	3	2	4	2	4	3	3
		2	2	3	3	3	4	3	2	3	3	3
		3	3	4	4	4	3	4	2	4	4	4
		4	2	2	2	2	2	2	2	3	3	3
		5	3	2	3	2	3	4	2	3	3	3
		Overall	**2**	**3**	**3**	**3**	**3**	**4**	**2**	**3**	**3**	**3**
6	**RGB**	**1**	4	4	4	4	1	3	3	3	1	2
		2	3	3	3	3	2	3	3	3	1	2
		3	4	4	4	4	2	3	3	3	1	2
		4	2	3	4	4	2	3	3	3	1	1
		5	2	2	2	3	3	3	2	1	1	1
		Overall	**3**	**4**	**4**	**4**	**2**	**3**	**3**	**3**	**1**	**2**
	CMYK	**1**	3	3	4	4	2	4	3	4	3	3
		2	3	3	4	4	2	4	3	3	3	3
		3	3	3	4	4	2	4	3	4	3	3
		4	3	3	4	4	2	3	2	4	3	3
		5	3	3	4	3	2	3	2	3	3	2
		Overall	**3**	**3**	**4**	**4**	**2**	**4**	**3**	**4**	**3**	**3**
7	**RGB**	**1**	5	4	5	5	1	4	3	4	1	2
		2	4	4	5	5	4	4	2	4	3	2
		3	5	5	4	5	5	5	5	5	1	4
		4	5	4	5	5	4	4	4	4	4	3
		5	5	5	5	5	5	5	3	3	2	2
		Overall	**5**	**4**	**5**	**5**	**4**	**4**	**3**	**3**	**1**	**2**
	CMYK	**1**	5	5	5	5	4	5	5	5	5	4
		2	4	4	4	4	4	4	4	4	5	4
		3	5	5	5	5	3	4	5	4	5	5
		4	4	3	5	5	3	4	4	4	4	4
		5	4	4	5	5	3	5	3	5	5	5
		Overall	**4**	**4**	**5**	**4**	**3**	**4**	**4**	**4**	**5**	**4**

Appendix F

ΔEcmc color differences

RGB-CMYK	Vendors									
	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
Dark Skin	3.10	2.36	2.73	3.82	4.31	3.16	12.76	3.53	4.96	4.16
Light Skin	2.29	1.23	2.40	2.21	3.05	1.92	2.35	2.00	2.58	2.69
Blue Sky	3.63	3.53	2.27	3.51	3.55	4.24	3.15	4.60	4.26	3.89
Foliage	2.27	3.13	1.92	2.54	6.32	1.96	3.26	2.96	5.21	3.11
Blue Flower	2.19	0.87	1.06	0.88	1.40	2.65	1.92	2.40	3.06	2.09
Bluish Green	0.99	0.49	4.84	1.23	2.78	1.45	0.91	0.89	2.94	1.14
Orange	1.36	1.36	1.59	1.28	5.85	1.97	2.17	1.27	2.62	1.65
Purplish Blue	0.95	1.09	1.51	1.21	1.36	1.76	4.53	1.66	3.11	0.43
Moderate red	1.67	1.19	1.65	1.79	3.90	2.28	2.20	1.73	3.51	1.74
Purple	1.95	3.15	2.65	4.05	9.61	3.96	4.77	3.49	7.50	2.11
yellow green	2.08	2.10	2.95	0.60	6.83	2.36	2.72	1.98	1.08	2.40
Orange Yellow	1.16	1.45	1.55	0.50	6.59	1.40	2.87	0.87	2.37	1.59
Blue	2.21	1.27	3.55	1.57	8.34	1.75	8.00	1.79	4.89	1.54
Green	2.98	2.97	7.08	2.38	11.65	3.16	3.21	2.98	3.39	2.56
Red	1.56	1.31	1.51	2.02	5.17	1.47	2.45	1.66	2.68	1.77
yellow	1.13	0.68	0.32	0.72	3.12	1.76	2.60	1.45	0.75	1.22
Magenta	0.88	1.13	0.28	0.84	3.88	1.94	1.83	0.84	6.20	0.52
Cyan	3.97	3.91	4.58	5.14	8.56	3.04	4.78	5.46	8.24	3.64
White	0.84	0.68	3.64	0.66	2.03	0.91	1.14	1.84	1.08	1.16
Neutral 8	1.09	1.08	4.27	1.29	2.22	1.64	1.81	2.20	1.76	1.25
Neutral 6.5	4.10	1.76	5.99	4.19	4.70	1.54	5.39	4.69	6.29	2.47
Neutral 5	2.82	3.89	3.20	2.80	3.36	3.90	2.82	2.88	5.63	3.13
Neutral 3.5	2.86	3.92	3.22	2.73	3.48	4.02	2.68	2.86	5.72	3.06
Black	2.67	7.27	3.78	4.80	5.04	2.50	5.19	9.48	9.80	9.07
Maximum	4.10	7.27	7.08	5.14	11.65	4.24	12.76	9.48	9.80	9.07
Average	2.11	2.16	2.86	2.20	4.88	2.36	3.56	2.73	4.15	2.43
Minimum	0.84	0.49	0.28	0.50	1.36	0.91	0.91	0.84	0.75	0.43
Std. Deviation	0.99	1.57	1.68	1.41	2.66	0.95	2.52	1.89	2.35	1.73
Coef. of Variation	0.47	0.73	0.59	0.64	0.54	0.40	0.71	0.69	0.57	0.71

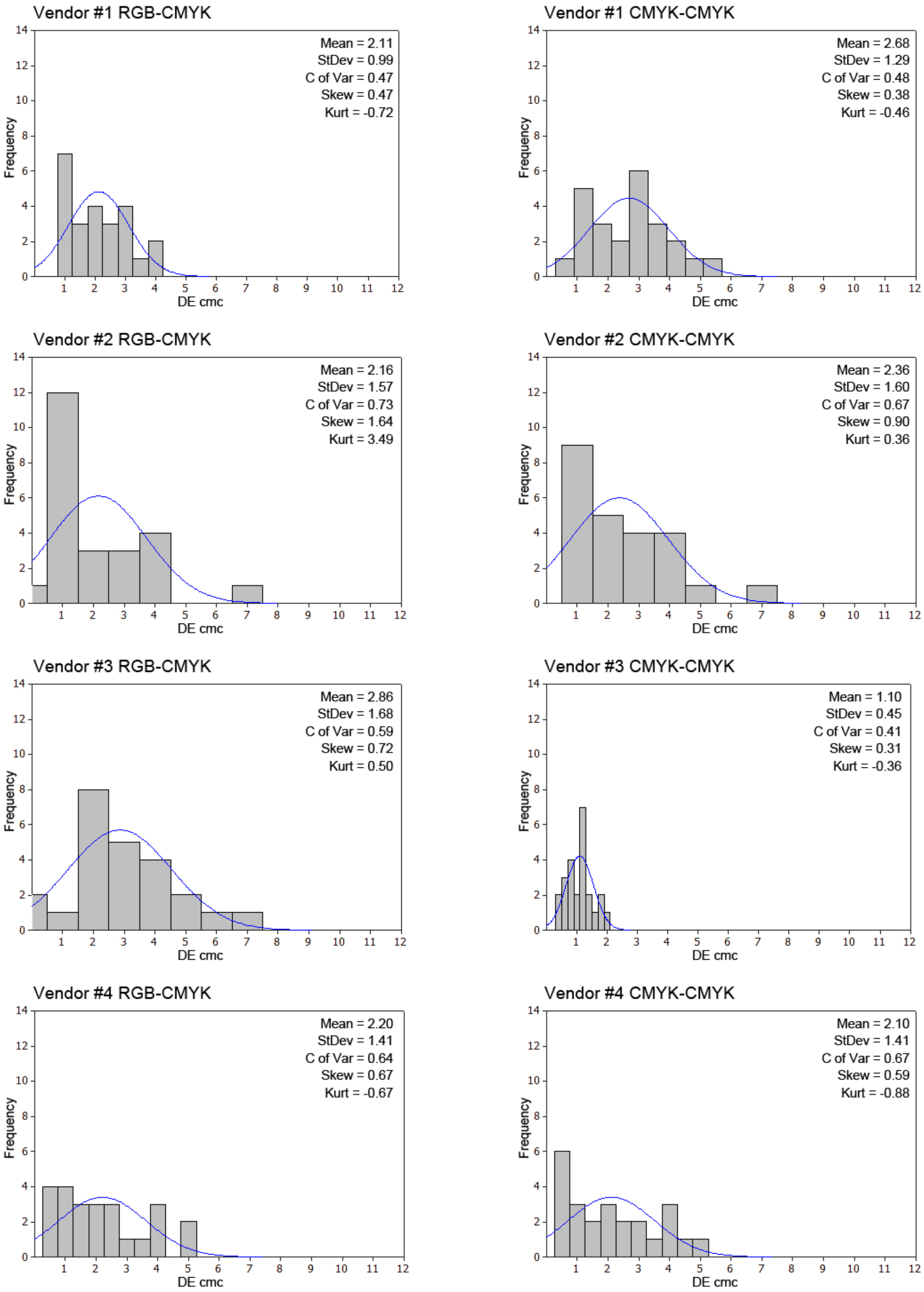
Appendix F (continued)

ΔEcmc color differences

CMYK-CMYK	**Vendors**									
	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**
Dark Skin	3.35	3.42	1.46	3.80	3.32	3.08	3.86	3.73	3.00	3.78
Light Skin	2.34	2.10	1.21	2.00	2.09	1.78	2.36	1.07	2.72	2.79
Blue Sky	5.06	4.37	1.28	3.43	4.27	4.05	3.24	4.65	5.99	4.93
Foliage	3.57	2.89	1.11	2.43	4.64	1.94	3.36	3.04	3.50	3.16
Blue Flower	3.02	2.94	0.53	0.71	1.55	2.82	1.97	2.39	2.47	2.64
Bluish Green	1.25	1.42	0.82	0.96	10.20	1.36	0.77	1.07	0.88	1.22
Orange	1.64	0.74	0.78	0.92	3.97	1.76	2.09	1.00	1.16	0.97
Purplish Blue	1.37	0.87	0.89	1.22	1.48	2.13	4.79	0.90	0.87	0.89
Moderate red	2.01	1.59	1.29	1.41	0.70	2.05	2.30	1.36	1.83	2.01
Purple	5.38	4.87	1.52	3.80	10.43	3.98	4.95	4.00	5.99	4.15
yellow green	2.74	2.00	0.90	0.68	6.09	2.48	4.14	0.77	1.99	2.33
Orange Yellow	1.34	0.80	0.32	0.38	4.57	1.11	3.01	0.57	0.93	0.98
Blue	2.89	1.08	1.06	1.94	7.87	3.19	9.19	0.55	1.08	1.16
Green	3.63	2.76	1.16	2.34	5.13	2.81	3.76	2.32	3.18	3.00
Red	2.17	1.62	1.15	1.77	3.39	1.17	2.36	1.55	2.17	2.08
yellow	1.86	0.94	0.44	0.58	2.76	0.89	3.36	0.66	0.91	1.01
Magenta	1.08	0.56	0.77	0.60	1.51	2.02	1.92	0.64	0.70	0.60
Cyan	4.34	4.36	1.34	4.51	8.66	3.50	4.68	4.06	5.89	4.02
White	0.47	0.63	0.62	0.61	1.84	1.18	1.34	0.78	0.92	0.37
Neutral 8	1.41	0.77	0.62	1.43	2.25	2.08	1.38	1.45	1.57	1.54
Neutral 6.5	4.29	2.32	1.29	4.18	5.02	1.96	5.10	2.42	3.74	2.52
Neutral 5	3.15	3.57	1.89	2.84	3.74	4.09	2.71	3.31	3.99	2.86
Neutral 3.5	3.25	3.57	1.83	2.96	3.62	4.16	2.67	3.07	4.03	2.79
Black	2.73	6.55	2.03	4.99	3.79	2.28	5.36	7.75	2.98	5.38
Maximum	5.38	6.55	2.03	4.99	10.43	4.16	9.19	7.75	5.99	5.38
Average	2.68	2.36	1.10	2.10	4.29	2.41	3.36	2.21	2.60	2.38
Minimum	0.47	0.56	0.32	0.38	0.70	0.89	0.77	0.55	0.70	0.37
Std. Deviation	1.29	1.60	0.45	1.41	2.68	1.01	1.78	1.75	1.68	1.38
Coef. of Variation	0.48	0.68	0.41	0.67	0.63	0.42	0.53	0.79	0.65	0.58

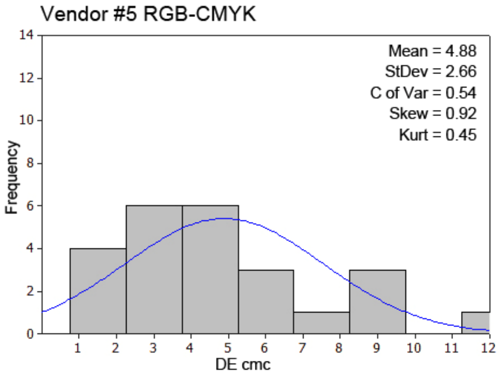
Appendix G

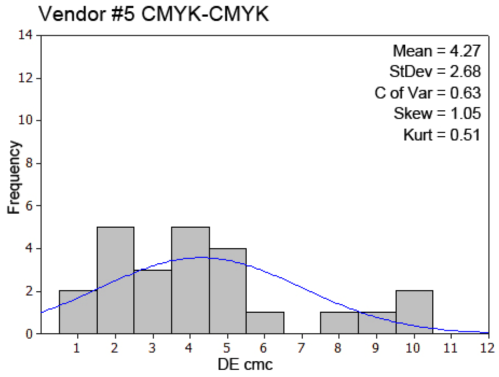
Histograms of ΔEcmc color differences for 24 measured patches

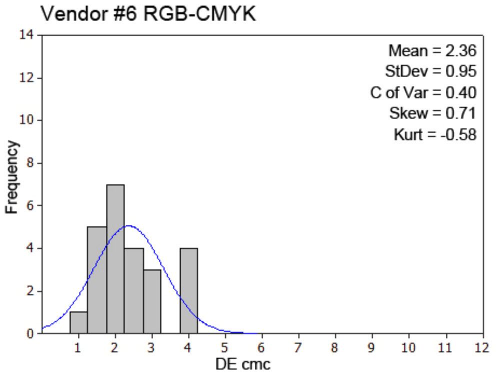


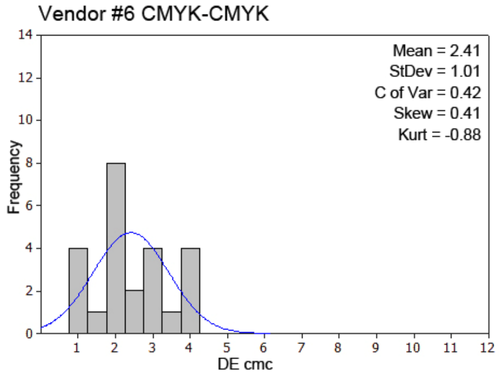
Appendix G (continued)

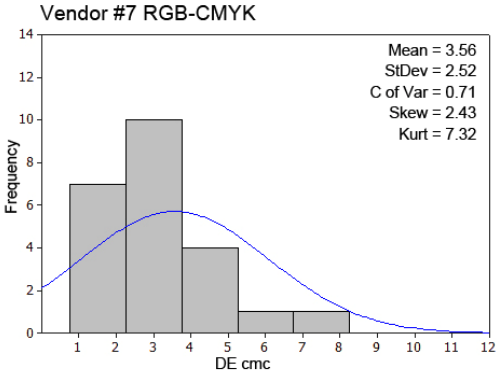
Histograms of ΔEcmc color differences for 24 measured patches

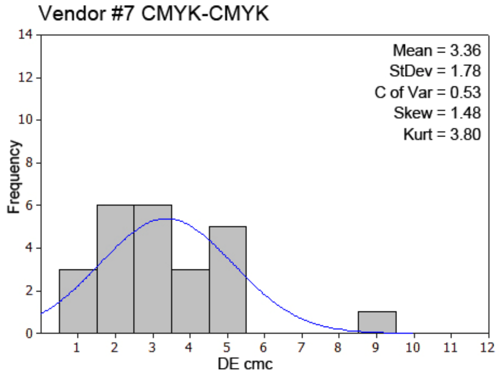


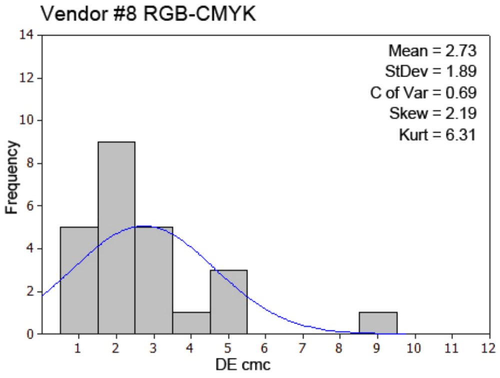


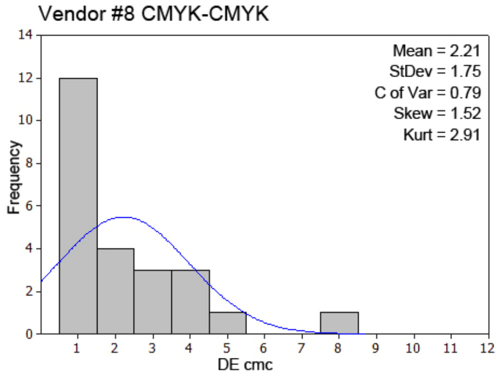






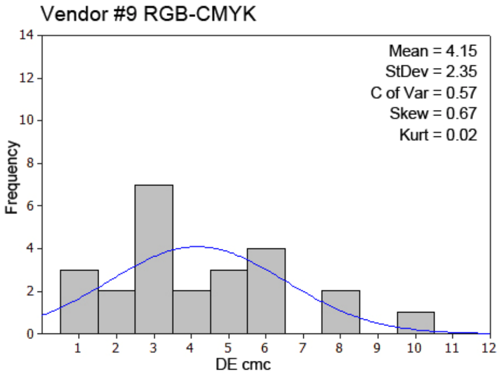




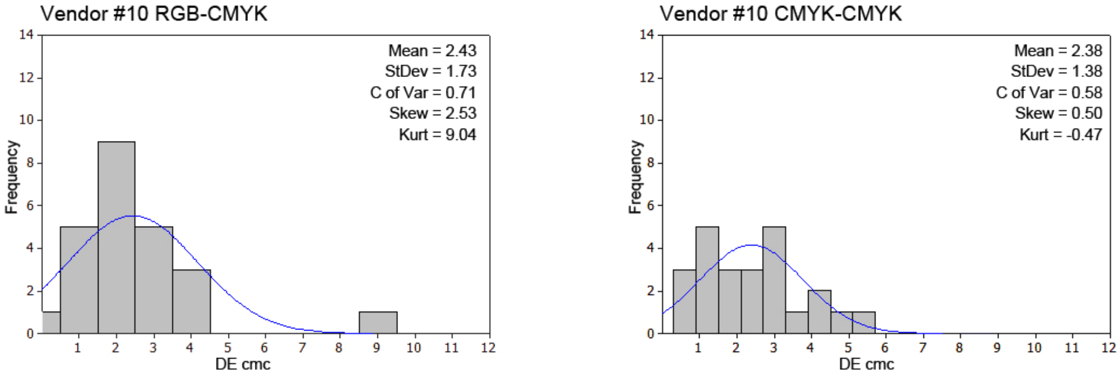


Appendix G (continued)

Histograms of ΔEcmc color differences for 24 measured patches


Vendor #9 RGB-CMYK

Vendor #9 CMYK-CMYK


Vendor #10 RGB-CMYK

Vendor #10 CMYK-CMYK