Influences of Rendering Intents on Reproduced Colors Using Color-Managed Graphic Workflows

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Abstract
This study is an extension of work done by Bohan and Radencic at PIA/GATF and presented at the Color Management Conference in Phoenix, Arizona in December 2006. The current study was a partial replication of the earlier work, which had uncovered some concerns about the validity of the samples. In the current study, a test file consisting of two ISO targets (one color chart and one natural image) was distributed to four color management software vendors, who were asked to prepare five files for output to the SWOP reference printing conditions. The five files represented applications of each of the four available rendering intents plus a file that applied no color management.

This study found that the application of color management had a pronounced measurable effect on reproduced colors with all of the rendering intents. Furthermore, there were substantial differences between the rendering intents and between the software products. Interactions were found between the rendering intents, the software products, and the specific colors being reproduced.

Several anomalies were found with varying degrees of consequence, from idiosyncratic characteristics of particular software products to substantial flaws in reproduced work.

Background

The graphic communications industry has been in a state of disruptive change for more than three decades as electronic and digital processes have replaced photomechanical methods. Every phase of the traditional graphic workflow from photography, editing, image assembly, proofing, platemaking, printing, binding, and finishing, through addressing and labeling has felt the impact of this change. The overarching management functions of estimating, scheduling, procurement, process control, and job tracking have undergone similar transformations utilizing the new tools provided by the digital age. By the mid-1990s, an entirely digital workflow was feasible for high-volume graphic production. The last pieces needed for the completion of this digital loop were digital photography and devices for the laser imaging of aluminum printing plates. Today, it is not uncommon to encounter graphic reproduction companies that utilize entirely digital workflows.

New digital printing techniques, principally inkjet and electrophotography, stand out among the recent technological developments in that they offer new hard-copy production options that have distinct advantages over traditional printing methods. They are environmentally friendly, produce little or no waste, and can image variable data to provide personalized graphic products. Inkjet has the further advantages of being extremely versatile in terms of image size, substrates, and the variety of inks and other fluids that can be applied. To date, however, no digital printing process has been developed that rivals the quality and low cost of traditional methods for run lengths over 1000.

Another noteworthy development of the digital age has been the proliferation of electronic publishing across the World Wide Web and via CD-ROMs and DVDs. Today, it is common to utilize a variety of media to communicate with the desired audience. Often the same digital assets (images) are used in several output modes with the expectation that the quality and appearance of the images will be consistent between all of the different media used. Achieving this goal is the purview of color management.

Color management was coined as a term with the formation of the International Color Consortium (ICC) in 1993. This consortium of eight member companies was formed to provide interchange standards for color files between different computer systems and software products. The goal of color management is to provide consistent color appearance across all stages of reproduction and output devices.

Today, the ICC lists 69 member companies, associations, and universities, and the latest version of the ICC specification (v4) has been approved as an International Standard, ISO 15076. There is widespread support for color management among today's software and hardware vendors. Most graphics programs recognize ICC profiles attached to image files, and operating systems come with default color management modules to be used in the absence of other color management software.

In spite of this substantial support, the results of color management implementation in output devices are mixed. One challenging area is the difficulty of gamut mapping an image into a color space that differs from the display space where the customer expectations were set. Frequently, an image is moving from a larger color space to a smaller one, and the out-of-gamut colors have to be compressed to fit the destination space. The best way to achieve the necessary compression is dependent on the rendering intent of the customer.

ICC Rendering Intents

The ICC has identified four different rendering intents: absolute colorimetric, media-relative colorimetric (which can be done with or without black point compensation), perceptual, and saturation. The first two intents operate directly on the measured colorimetric data (though possibly with corrections for chromatic adaptation). With the second two rendering intents, the colorimetric values are manipulated as needed to achieve desired outputs and to compensate for differences in device color spaces.

The absolute colorimetric and media-relative colorimetric intents are used for transformations from one color space to another where the relationships between colors are not altered to achieve perceptual goals. In absolute colorimetric rendering, all media-relative color values are calculated relative to an ideal white diffuser or transmission source under D50 illumination. Thus, the original and reproduction color values are both normalized to the same white point and should be equal for all in-gamut colors.

The media-relative colorimetric intent includes transformations of colors to adjust for the different white points of various color spaces. In this intent, the data is normalized relative to the media white point. This maintains highlight detail and keeps the medium white, even if the original and reproduction media differ in color. Although relationships between colors are maintained, there is an overall shift in colors when the media-relative colorimetric intent is applied. In general, the two colorimetric rendering intents are most effective when the reproduction color spaces are similar to the original color spaces.

The perceptual rendering intent allows for a preferential (proprietary to software vendors) adjustment of color values, in concert with an image state transition, to achieve a “most pleasing” rendition of an image. Image states (e.g., scene-referred, original-referred, and output-referred) have different potentials of color and tone encoding values. Since there are no defined goals for color transformations, there is no “right” solution for applying this intent other than that the results are considered to be pleasing to most observers. The perceptual intent is most appropriate for natural images such as photographs where the “best rendition” is desired in any output medium.

The saturation rendering intent is similarly vague in its requirements. This intent tries to maintain a high degree of colorfulness in the rendered images. Again, the exact means by which colors are modified is not specified, but is left to the discretion of the software vendors. The relationships between colors in the image are not maintained, and out-of-gamut colors are typically mapped near the borders of the destination color space resulting in rich, colorful images. This intent is useful for applications like business graphics, where the impact of the graphic is more important than the colorimetric accuracy.

Description of the Study

The purpose of this study was to determine whether the four rendering intents available in a color-managed workflow would produce the desired effects in the finished reproduction. The software products from four different vendors (Global Graphics, Heidelberg, Helios, and Kodak) were compared to determine how uniform the results would be from different vendors. Output files were prepared by the participating software vendors from the supplied test file. Each participant was asked to supply five files representing the application of each of the four ICC rendering intents and one with no color management applied. (Heidelberg supplied an extra file showing the condition of media-relative colorimetric intent with and without black point compensation. In most instances, both files are included in the findings. However, when direct comparisons were made with other vendors, the file without black point compensation was examined since that is the condition that is assumed for the other software vendors.)

The testing utilized a test form (Figure 1) that contained a field of measurable color patches plus a photographic image containing a broad range of colors, fine details, and subtle lighting effects. Both of these target elements are from the ISO 12640-2 standard containing color image data. The color chart is synthetic image S6, which contains 293 color patches representing primary, secondary, and tertiary colors. The photographic image of threads is natural image N7, a still life containing a sampling of rich, saturated colors suitable for evaluating the limits of color gamuts.

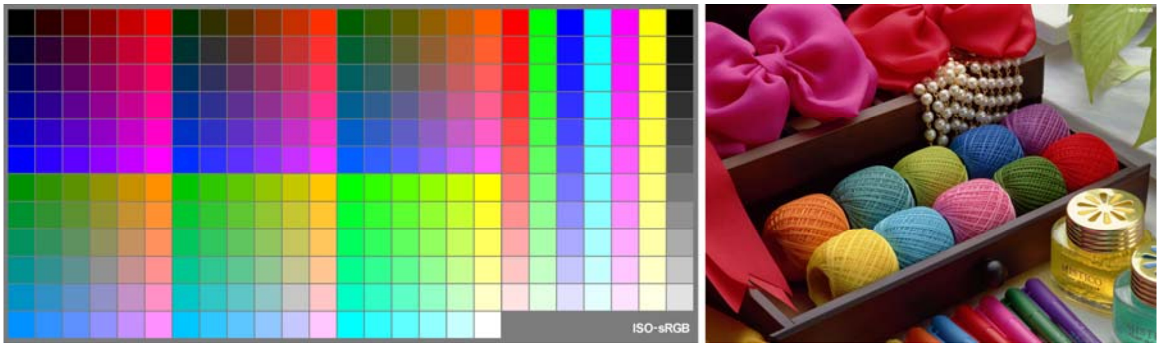


Figure 1. Test image from ISO 12640-2 used in study.

The ISO test images are encoded in sRGB, a standard RGB working space that is referenced to a D65 white point. The software vendors were instructed to prepare printing files targeted at the PhotoShop U.S. Web Coated (SWOP) v2 output profile, which is based on ANSI/CGATS TR001-1995, *Graphic Technology—Color Characterization—Data for Type 1 Printing.*

The software vendors created 600-dpi TIFF composite files for each of the rendering intents and posted them to the PIA/GATF FTP site for downloading. The downloaded files were placed into printing forms using Adobe InDesign. Two forms were required to accommodate all the vendor-supplied files. Color control bars were also placed on the printing forms for use in process control.

The forms were imaged on a Kodak Spectrum proofing system using SWOP-certified DuPont WaterProof transfer materials. The composite proofs were transferred to #1 coated sheets of paper. Analysis of the color control bars on the two proofs confirmed that they were properly exposed and had nearly identical color densities and dot gains. For this study, the proofs were treated as the final output and the files were not printed on press.

The proofs were cut apart and read with a Gretag Eye-One spectrophotometer equipped with an auxiliary scanning table. Each of the samples was measured twice with several weeks between measurements.

Since the output substrate was not representative of SWOP paper, it was determined not to solicit subjective judgments about the perceptual or saturation rendering intents. Instead, the analysis focused on the measured color values and the compression of out-of-gamut colors.

Color Differences

The calculation of color difference is an evolving science. The 1976 CIE ΔE values are commonly used as indicators of perceptually based color differences. However, it has been shown that the CIELAB color space is not truly perceptually uniform. This has led to the development of a succession of color difference calculations that show improved correlation with perceived differences. These include: ΔE_{CMC}, ΔE_{94}, and ΔE_{2000}. In this paper, we use ΔE_{2000} as the primary measure of color differences. There are some concerns about the accuracy of ΔE_{2000} for large color differences, especially with colors of very different hues (Sharma, et al.), but in this study these concerns were not found to apply.

The ΔE_{2000} formula that was used for this study is shown in Appendix A. In general, the ΔE_{2000} formula yields smaller numerical values than the traditional ΔE calculation, but the numbers are more indicative of the number of just-noticeable steps that separate two colors. There are some findings of the study where both values are given to allow readers to judge the magnitude of ΔE_{2000} values in relation to the more familiar ΔE values.

Measurement Error

The technician who made the measurements observed that the instrument scratched the surface of the print, making her suspicious that large measurement errors would be found. In order to estimate the amount of variation that was attributable to the measuring device, a single sample was selected and measured 10 times.

The target contains 293 color patches, and the standard deviations of the measurements of the L, a, and b values for each patch were calculated across the 10 measures. The average values of the 293 standard deviations for L, a, and b were 0.36, 0.16, and 0.14 respectively. Thus, the variation in lightness measurements was about twice as large as the variations in red-green or yellow-blue measurements.

To examine the measurement error in terms of perceptual color difference, average L, a, and b values were calculated for each of the color patches based on the 10 sample readings. Delta-E calculations were made for each sample and for each color patch between the sample and the average values. The averages of the 293 ΔE values are shown in Table 1.

Measure	ΔE2000	ΔE	ΔL	Δa	Δb
1	0.07	0.14	-0.01	0.01	-0.03
2	0.29	0.35	0.29	0.01	0.02
3	0.31	0.37	0.32	0.01	0.02
4	0.79	0.95	-0.80	-0.03	-0.03
5	0.17	0.22	-0.17	-0.01	-0.01
6	0.06	0.10	-0.05	-0.01	0.01
7	0.08	0.11	-0.06	-0.01	0.00
8	0.34	0.42	0.34	0.01	0.02
9	0.34	0.43	0.33	0.02	0.02
10	0.19	0.22	-0.19	-0.01	-0.02
Average	**0.26**	**0.33**	**0.00**	**0.00**	**0.00**

Table 1. Average color differences for repeated measures.

Most of the repeated measurements showed ΔE_{2000} variation of less than one-third unit as an average across 293 samples. Measurement #4 was an exception, yielding average ΔE_{2000} value of 0.79, more than two times higher than any of the other measurement samples, but still below the threshold of perceptual difference. The calculated standard error of measurement was 0.05 ΔE_{2000} units. Therefore, it was concluded that the measuring instrument added only a small amount of variability to the findings in this study.

Second Measurements

The measurement of samples was repeated during the course of this study so that findings would not be based on single measurements. The analysis was carried out on the average of the two readings. Due to the constraints of scheduling, the second readings were made several weeks after the first readings were completed. In the intervening time, the samples were stored in a dry, cool, lightfast environment.

To evaluate the consistency between the two sets of readings, color differences between reading 1 and 2 were calculated for each of the target patches and each of the samples. The average color differences between the two readings for the 293 readings and the maximum color differences found for any of the 293 patches are shown in Table 2.

		no CM	Abs	Perc	Rel	Rel BPC	Sat
Global	Avg ΔE2000	0.67	0.50	0.67	0.72		0.91
	Max ΔE	1.48	1.17	1.37	1.31		1.74
Heidelberg	Avg ΔE2000	0.72	3.83	1.42	1.56	0.62	0.92
	Max ΔE	1.35	6.41	2.24	2.13	1.40	2.74
Helios	Avg ΔE2000	0.45	0.98	0.38	0.55		0.44
	Max ΔE	0.91	1.63	1.06	1.04		2.36
Kodak	Avg ΔE2000	0.40	0.31	0.39	1.42		0.70
	Max ΔE	1.17	0.74	1.17	2.21		1.47

Table 2. Average and maximum ΔE_{2000} differences between two readings.

The average color differences were generally less than 1 with the notable exception of the Heidelberg sample showing the absolute rendering intent where the average color difference was 3.83 and the maximum color difference was 6.41. Findings involving this sample were suspect due to the substantial differences between the two measurements. This is noted where appropriate in the findings.

No Color Management Applied

The software vendors were asked to supply files that were made without the application of color management to assess the overall amount of color difference that would result from using color management. The average color differences across all the patches in the S6 color field are shown in Table 3. For the ΔL, Δa, and Δb values, positive numbers indicate that, overall, the values with color management were higher than those without color management, and negative numbers indicate the opposite.

		ΔE2000	ΔE	ΔL	Δa	Δb
Global	Absolute	10.35	17.92	2.88	-3.38	-2.40
	Perceptual	10.22	17.54	3.52	-3.00	-4.00
	Relative	8.16	15.19	-0.66	-0.56	3.47
	Saturation	10.15	17.31	1.05	-3.14	-4.49
Heidelberg	Absolute	13.31	20.95	7.65	-3.40	-2.13
	Perceptual	7.84	14.02	-0.11	-0.65	1.50
	Relative	8.53	15.25	0.15	-1.57	2.43
	Saturation	8.12	14.58	-0.75	-0.81	2.07
Helios	Absolute	9.95	20.08	-0.42	-1.58	-1.21
	Perceptual	9.11	17.01	-3.32	1.23	2.97
	Relative	9.68	18.30	-4.11	1.05	4.69
	Saturation	9.37	17.89	-4.30	1.07	4.03
Kodak	Absolute	9.52	18.02	-4.57	0.79	3.36
	Perceptual	9.68	18.40	-3.98	0.98	4.97
	Relative	9.55	16.93	-4.80	0.85	1.52
	Saturation	9.97	18.43	-5.68	1.09	3.93

Table 3. Average differences from samples with no color management applied.

The results from each of the participating software vendors showed substantial color differences between rendering intents with the application of color management. The results from Heidelberg showed substantially more color change when the absolute colorimetric rendering intent was used than the other rendering intents. The results from Helios and Kodak showed decreases in the lightness values and increases in the a and b values. The results from Global and Heidelberg showed consistent decreases in the a values and mixed results with the L and b values.

This data indicates that the application of color management is strongly influencing the colors of reproductions and that there are differences between software vendors in how the colors are altered.

White Point Analysis

The ISO S6 color field contains a patch that is pure white. The reproductions of the white point were examined separately because the two types of colorimetric rendering intent have different requirements for the reproduction of white. Absolute color rendering reproduces the original white point without adjusting it to match the destination white point, and relative colorimetric rendering adjusts all the color values to the reference white of the reproduction. The CIELAB values of the reproduced white patches are shown in Table 4.

		L	a	b
	SWOP	**88.66**	**-0.33**	**3.64**
no CM	**Global**	94.91	1.12	-1.99
	Heidelberg	94.69	1.14	-2.01
	Helios	94.62	1.23	-2.18
	Kodak	94.84	1.21	-2.05
Abs	**Global**	92.30	-1.67	-5.77
	Heidelberg	97.84	1.30	-1.80
	Helios	95.47	1.21	-2.07
	Kodak	94.87	1.16	-2.09
Perc	**Global**	91.42	-1.62	-6.62
	Heidelberg	95.11	1.30	-1.76
	Helios	94.98	1.23	-2.05
	Kodak	94.38	1.33	-1.93
Rel	**Global**	95.19	1.16	-2.11
	Heidelberg	95.09	1.16	-2.04
	Helios	95.04	1.18	-2.08
	Kodak	95.80	1.32	-1.77
Sat	**Global**	80.26	-0.10	-14.61
	Heidelberg	94.99	1.17	-2.08
	Helios	94.73	1.16	-2.00
	Kodak	94.92	1.17	-2.04

Table 4. CIELAB values of reproduced white patches.

It is not valid to compare the relative colorimetric white patches against the SWOP targets because the output was not made on paper appropriate for SWOP. However, the data in Table 4 shows that the there was very little difference for most software vendors between the white point renditions for absolute and relative colorimetric rendering intents. The relative colorimetric white (referenced to D50) was expected to have less blue than the absolute white point (referenced to D65), but the data do not reflect this.

An obvious discrepancy was found in the white point rendering from the Global Graphics software. The white patch for the relative colorimetric intent is in agreement with the other software vendors, but the white patches from the other three rendering intents are far too blue and, in the case of the saturation rendering intent, too dark as well. Figure 2 shows a three-dimensional graph of the white point CIELAB values for the absolute colorimetric rendering intent. Graphs for the other conditions are shown in Appendix B.

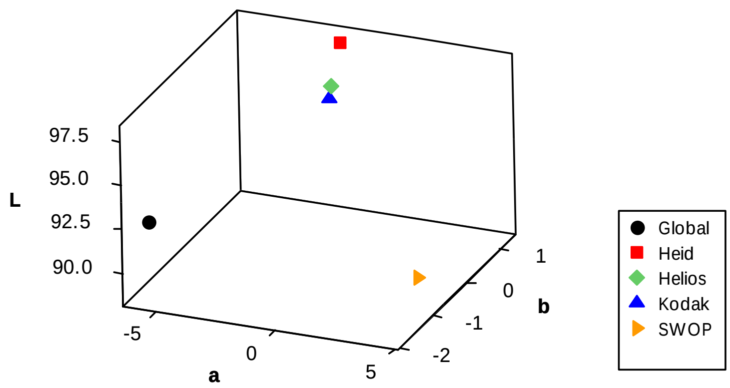


Figure 2. White point reproductions for absolute colorimetric rendering.

To check whether this anomaly was restricted to the white patch, the lightest seven pastel patches from the ISO S6 color field were selected. Examination of the CIELAB data revealed that the results from Heidelberg, Helios, and Kodak were tightly clustered and that the Global values were distinctly different for three of the rendering intents. A sample 3D plot for the measured CIELAB values from the pastel red color patch (S11 on the chart) is shown in Figure 3.

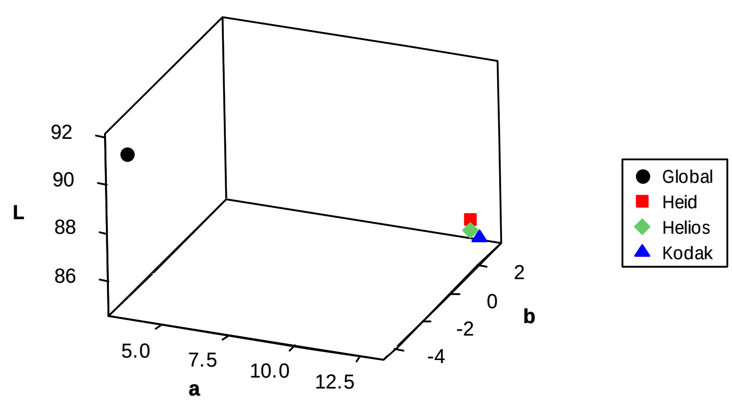


Figure 3. CIELAB values for pastel red color patch and perceptual rendering intent.

The color differences exemplified by Figure 3 were easily seen when examining the reproductions. To quantify these color differences, the average CIELAB values from Heidelberg, Helios, and Kodak were calculated for the selected pastel color patches and ΔE_{2000} color differences were calculated between the Global CIELAB values and the averages of the other software vendors. The results are shown in Table 5.

	no CM	Absolute	Perceptual	Relative	Saturation
White	0.20	5.84	5.83	0.20	15.21
Red	0.06	3.68	9.34	0.56	12.80
Green	0.38	4.98	12.52	0.21	15.12
Blue	0.07	2.45	7.15	0.32	10.78
Cyan	0.09	2.81	1.50	0.05	6.70
Magenta	0.06	3.27	7.02	0.54	13.67
Yellow	0.13	5.42	14.05	0.57	16.81
Gray	2.18	2.15	9.20	0.32	7.44

Table 5. Color differences (ΔE_{2000}) for selected pastel colors between Global Graphics and averages of other software vendors.

The data in Table 5 shows that the discrepancies found with the white patch were true for pastel colors as well. The results from Global Graphics were in close agreement with those from other vendors for the relative colorimetric rendering intent and also for the samples where no color management was applied. However, the Global results were very different from the other vendors for the saturation, perceptual, and absolute colorimetric rendering intents. Examination of the CIELAB values showed the same pattern of deviations as found with white. The b values for the Global samples were far higher negative values than for the other software vendors. These were primarily responsible for the large color differences. The saturation rendering intent had the largest color differences because, as with the white patch, the L values were substantially lower than the average in addition to large b value discrepancies.

Analysis of the Absolute and Relative Colorimetric Intents

The materials that accompany the ISO 12640-2 image data include a file listing both the RGB and XYZ (tristimulus) values of the patches in the color field used for this study. The RGB values are referenced to the sRGB color space, which is based on D65 illumination, and the XYZ values are referenced to an ideal display system also using a D65 white point. However, the SWOP reference printing conditions (the output target for this study) is a color space based on CMYK colorants under D50 illumination. This type of conversion is challenging, but it is representative of the daily workflow of the printing industry. It should be noted that achieving exact colorimetric matches is not the typical goal of these conversions.

All the measurements made for this study were made with a D50 white point. The ISO tristimulus values were the targets for exact colorimetric matches; therefore, it was necessary to apply corrections for chromatic adaptation to these values to obtain target tristimulus values referenced to D50 illumination.

The XYZ scaling technique was used where each X-, Y-, and Z-value is multiplied by the ratio of the appropriate D50 white point values (X=96.42, Y=100.00, Z=82.51) divided by the D65 white point values (X= 95.04, Y=100.00, Z=108.88). Appendix C contains a subset of these calculations for the primary and secondary tone scales (columns 19 through 25) of the S6 target.

CIELAB values were computed from the D50 XYZ values using the equations shown in Appendix D. The calculated CIELAB values for the primary and secondary tone scales (columns 19 through 25) of the S6 target are shown in Appendix E.

To check the CIELAB values, the ISO TIFF file of the S6 color field was opened in PhotoShop. With the image in RGB color mode, the cursor was hovered over a large random sample of patches while the information window displayed the RGB values of the patches. The RGB values in the ISO data file were found to be correct in every instance. The image mode was then switched to Lab color, and the L, a, and b values of the patches from columns 19 through 25 were recorded. Color differences were calculated between the PhotoShop values and the values calculated from the XYZ data. The average ΔE_{2000} difference for the 77 patches was 1.16, and the average ΔE difference was 3.69. These differences were most pronounced in the blue tone scale. The discrepancies can be explained by two factors: rounding errors because the LAB values in PhotoShop were rounded to the nearest whole number, while the calculated LAB values were carried to several decimal points, and PhotoShop uses the Bradford scaling method (rather than XYZ scaling) to correct for chromatic adaptation of the reference whites yielding slightly different results.

Annex E of the ISO 12640-2 standard contains a data table giving average L, a, and b values for columns 19 through 25 of the S6 target. These measurements were made from hard-copy output, but the output profile is not specified in the standard. Color differences were measured between the calculated target values and the ISO data set. Color difference calculations yielded an average ΔE_{2000} value of 15.02 (average ΔE=25.25), indicating that the ISO hard-copy output did not match the calculated CIELAB values. These large color differences were probably influenced by the gamut mapping that was done during the ISO output process.

Color differences were calculated for each of the samples that were made to the absolute and the relative colorimetric rendering intents. Table 6 contains the average ΔE_{2000} color differences between the measured samples and the calculated target values for each of the two colorimetric rendering intents. The data in Table 6 is further divided to show the color differences for the subset of the target that includes the tone scales (rows 19–25 of the data field) and the average differences for the individual color scales (each of the last 7 columns of the target). Finally, average color differences were calculated for a subset of the tone scales colors consisting of 35 of the lightest colors that are clearly within the SWOP gamut. The in-gamut colors were expected to be reproduced more accurately than the tone scale subset overall because out-of-gamut mapping was not required for the in-gamut colors.

	Absolute Colorimetric				Relative Colorimetric			
	Global	Heidelberg	Helios	Kodak	Global	Heidelberg	Helios	Kodak
Overall	**10.49**	**10.63**	**10.30**	**10.20**	**9.38**	**10.33**	**9.34**	**8.97**
Subset	**12.36**	**12.15**	**11.95**	**13.06**	**11.26**	**12.57**	**11.42**	**11.01**
In-gamut	**9.38**	**8.69**	**8.90**	**10.17**	**7.84**	**7.89**	**8.00**	**7.51**
Reds	8.92	8.28	8.72	7.50	7.25	7.31	7.38	6.80
Greens	19.58	16.70	19.15	20.87	18.69	17.77	18.90	18.58
Blues	14.22	21.34	13.79	9.66	8.13	17.10	8.33	7.94
Cyans	18.92	15.87	18.22	19.24	16..83	18.34	17.06	16.29
Magentas	7.97	6.56	7.30	17.57	13.78	13.03	14.02	13.73
Yellows	10.90	8.84	10.33	10.54	9.53	9.26	9.62	9.25
Grays	5.35	7.01	5.57	5.30	3.98	4.48	3.93	3.86

Table 6. Average color differences (ΔE_{2000}) from calculated values for colorimetric rendering intents.

The overall magnitudes of color differences were similar for all the software vendors, but they were slightly lower for the relative colorimetric results. This is not surprising because the calculated values were adjusted for the differences between the sRGB and SWOP white points, and the relative colorimetric intent calls for adjustments for the different media whites. This is supported by the marked improvement in rendering the gray tone scale with the relative colorimetric intent. The average color differences were consistently higher for the subset of the data (tone scales) than for the color field as a whole. There were interesting differences in the magnitudes of the average ΔE_{2000} values for specific tone scales. For example, the reproduction of greens and cyans showed high color differences for all the vendors. Interestingly, in the absolute colorimetric results, the Kodak samples showed high amounts of color differences in the magenta tones and low amounts in the blue tones compared to the other vendors, but these differences were not found in the relative colorimetric results.

The subset of color differences associated with in-gamut colors in Table 6 were lower than the differences for the tone scales overall. The colors in this subset did not require out-of-gamut colors to be mapped into a more restricted color space and therefore would be expected to have lower color differences. Again, the results for the relative colorimetric intent were slightly lower than those for the absolute rendering intent due to the fact that the target L, a, b values had already been adjusted for media whites.

The overall magnitudes of the average color differences from the calculated target CIELAB values (Table 6) were high. Since the results from all the vendors showed similar overall magnitudes of color differences, it was assumed that the calculated values were in error. However, no calculation errors were found, suggesting that the ISO data set for an idealized sRGB display did not provide suitable targets for colorimetric matches or that the output system was not suitably representative of the web offset (SWOP) printing conditions for which the files were designed.

This raised the question of whether the software vendors were in closer agreement with each other than they were with the calculated target values. The calculations from Table 6 were repeated using the average of the four software vendors CIELAB values as the targets. The results from these calculations are shown in Table 7.

	Absolute Colorimetric				Relative Colorimetric			
	Global	Heidelberg	Helios	Kodak	Global	Heidelberg	Helios	Kodak
Overall	**1.58**	**3.64**	**1.70**	**5.88**	**0.77**	**1.86**	**0.75**	**0.83**
Subset	**1.80**	**4.54**	**1.85**	**6.21**	**0.63**	**1.79**	**0.72**	**0.84**
Reds	1.93	3.19	1.96	6.00	0.21	0.38	0.34	0.57
Greens	1.53	4.30	1.72	5.61	0.45	1.41	0.63	0.39
Blues	2.33	6.88	2.33	9.77	1.99	6.42	1.93	2.29
Cyans	2.74	5.10	1.70	6.17	0.31	0.87	0.30	0.80
Magentas	4.46	4.50	2.45	8.38	0.27	0.50	0.38	0.40
Yellows	3.55	5.70	1.57	3.22	0.76	2.50	0.78	0.78
Grays	2.17	2.12	1.23	4.34	0.39	0.41	0.70	0.63

Table 7. Average color differences (ΔE_{2000}) from mean values for colorimetric rendering intents.

The average color differences in Table 7 are lower than those in Table 6. This is not surprising since Table 7 shows differences from mean values as opposed to differences from calculated target values. Several observations were made from the data in Table 7. The overall absolute colorimetric intent data show that Global Graphics and Helios were closer to the mean than were Kodak and Heidelberg. Kodak was further from the mean than Heidelberg, showing particularly high deviations in blues and magentas.

The results for the four software vendors were more uniform for the relative colorimetric intent than for the absolute colorimetric intent. Heidelberg was slightly further from the mean values than the other software vendors overall, with pronounced disagreement on the rendition of blues. The relative colorimetric data shown here for Heidelberg is without black point compensation, but the results with black point compensation applied did not show closer agreement with the mean values.

Analysis of the Absolute and Relative Colorimetric Intents

The results for the perceptual and saturation rendering intents could not be compared with calculated target values because the ICC does not specify gamut mapping targets, but instead leave this to the discretion of the software vendors. Average values were calculated for the four software vendors, and color difference for each color patch and each vendor were computed from the average values. The results are shown in Table 8.

	Perceptual Intent				Saturation Intent			
	Global	Heidelberg	Helios	Kodak	Global	Heidelberg	Helios	Kodak
Overall	**4.88**	**1.39**	**1.51**	**2.48**	**4.81**	**1.38**	**1.57**	**2.37**
Subset	**4.84**	**1.49**	**1.53**	**2.52**	**4.87**	**1.56**	**1.66**	**2.36**
Reds	6.10	1.91	1.99	2.38	6.40	1.72	1.91	2.68
Greens	4.70	1.06	1.00	2.97	4.95	1.31	1.18	2.80
Blues	6.40	1.87	2.14	2.38	6.48	1.82	2.10	2.66
Cyans	4.20	1.50	1.49	2.71	4.42	1.88	1.99	2.21
Magentas	5.91	1.36	1.42	2.99	4.92	1.58	1.52	1.91
Yellows	2.79	1.14	1.00	2.24	3.47	1.17	1.03	2.33
Grays	3.77	1.61	1.69	1.95	3.48	1.45	1.86	1.97

Table 8. Average color differences (ΔE_{2000}) from mean values for perceptual and saturation rendering intents.

Overall, the results from the perceptual and saturation rendering intents were remarkably similar. For both the perceptual and the saturation rendering intents, Heidelberg and Helios were the closest to the average, and the results from Global Graphics were furthest from the average values. The differences were greatest in reds and blues. Since the ICC does not specify a correct gamut mapping strategy for the perceptual and saturation rendering intents, it is not possible to rank the software vendors based on matching target values.

Specific Colors

The purpose of rendering intents is to guide the rules by which colors are mapped from one color space into another, in this case from the sRGB color space into the SWOP color space. To test the effectiveness of the different mapping techniques, the comparative color spaces were examined and colors were selected where substantial gamut mapping would be required. Figure 4 shows a graphic portrayal of the sRGB (wireframe) and the SWOP (solid) color spaces (Neuman).

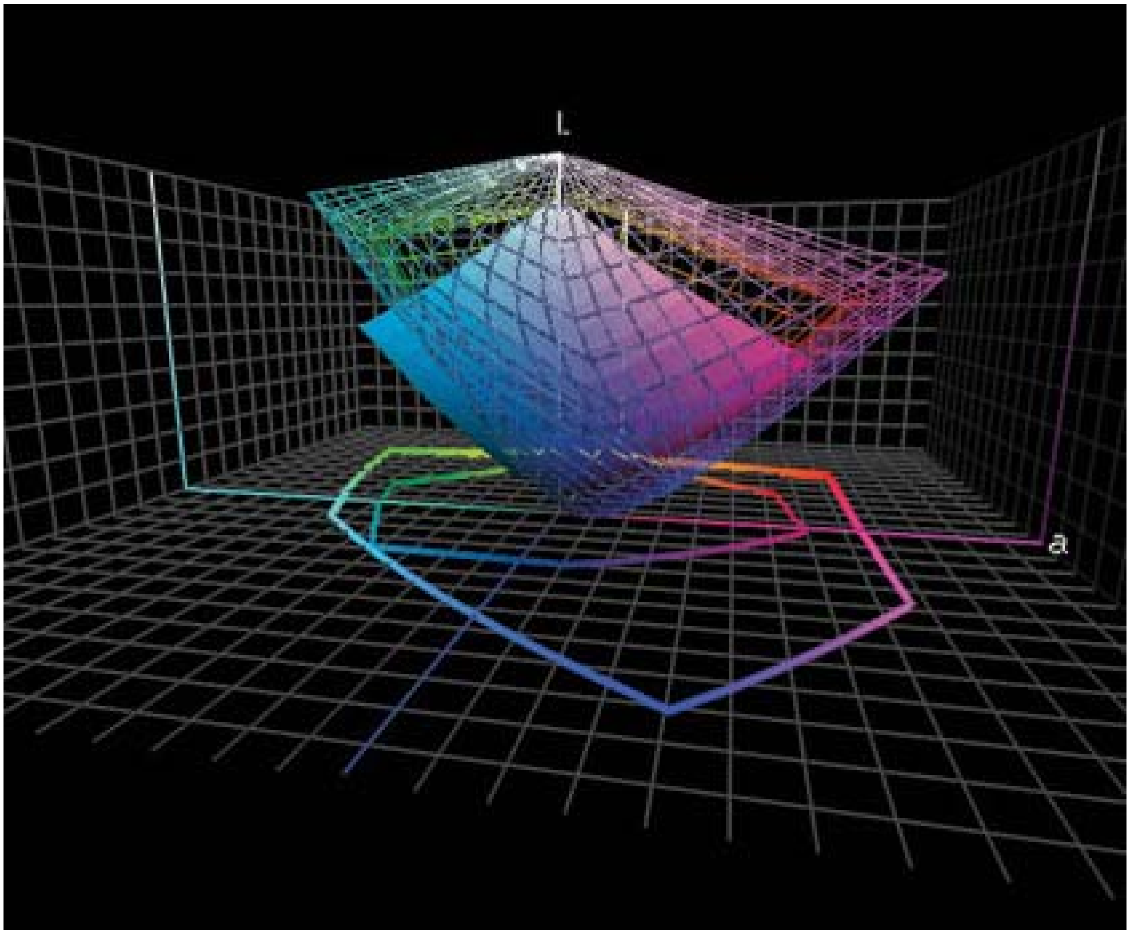
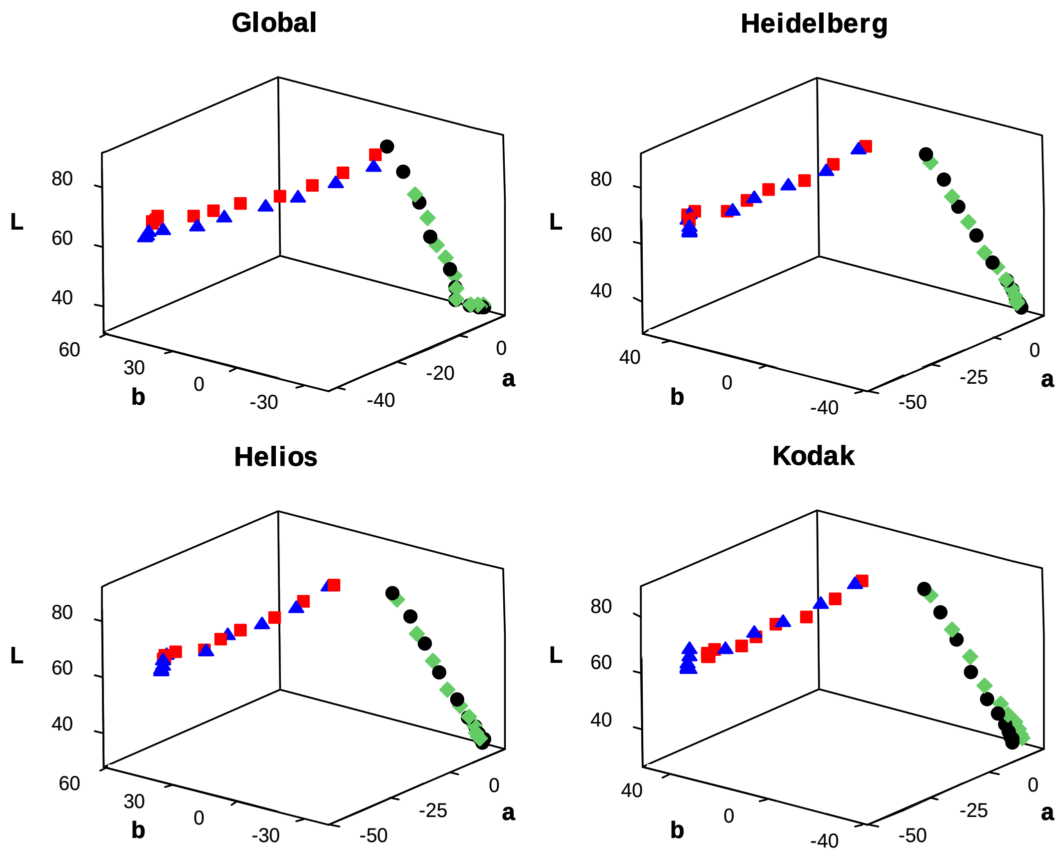


Figure 4. SWOP color space (solid) vs. sRGB color space (wireframe).

The superimposed sRGB and SWOP color spaces in Figure 4 show several areas where considerable gamut compression is needed to render sRGB images in the SWOP color space. The green and blue hues were selected as colors where the effects of gamut mapping should be apparent. The reproductions of the green and blue tone scales (columns T and U on the ISO S6 color field) were analyzed to compare the applications of the perceptual and saturation rendering intents by the software vendors. Three-dimensional plots of the CIELAB coordinates of the green and blue scales are shown in Figure 5 for each of the software vendors.



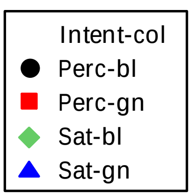


Figure 5. CIELAB plots of the green and blue scales for each software vendor.

Examination of the plots in Figure 5 shows very similar results for Helios and Heidelberg in the application of perceptual and saturation rendering intents. Note that, for these two vendors, the perceptual points are more uniformly spaced than the saturation points in the lighter values, allowing the saturation intent to provide more saturated results for colors throughout the scale. Also, note that Heidelberg and Helios produce highly linear results for each of the colors and rendering intents. Finally, note the concentration of points at the most saturated end of the lines indicating the limits of the SWOP color gamut. The saturation rendering intent results in a greater concentration of points near the gamut limit than does the perceptual rendering intent.

Both the Kodak and the Global results show anomalies that are not present in the Heidelberg and Helios reproductions. The Kodak reproduction of the green scale is similar to the reproductions of Heidelberg and Helios, but the blue scale shows a color shift in the dark tones when the saturation rendering intent is applied. However, since there is no specified method for mapping colors in the saturation rendering technique, Kodak might have determined that a shift in hue for dark blue colors was advantageous when the saturation rendering intent is applied. Global also reproduced the green scale in a manner similar to the other software vendors, although with a slight color shift between the two rendering intents. However, when the saturation rendering intent is applied, the lightest patches of the blue scale are reproduced extremely dark. This is apparent when examining the reproduction and can be seen in Figure 5 as an absence of data points for the saturation intent near the light end of the blue scale line. It seems unlikely that this reproduction outcome was chosen for aesthetic purposes.

Delta E values were calculated for each rendering intent and software vendor between each adjacent step of the green and blue tone scales. For computational simplicity, traditional ΔE values were used for this phase of the analysis rather than ΔE_{2000} values. The data was plotted in two ways: all rendering intents for each vendor, and all vendors for each technique. The full set of graphs is shown in Appendix F.

Some observations from examination of the first eight graphs in Appendix F were that the software vendors showed more consistency between rendering intents with the blue scale than with the green one. Global, for example, had drastically different progressions of color differences between steps on the green scale based on the rendering intent being applied. But for the blue tone scale, the progressions of color differences were more similar for the different rendering intents and more uniform from one to the next. The two graphs for the ΔE changes for Global are shown in Figure 6.

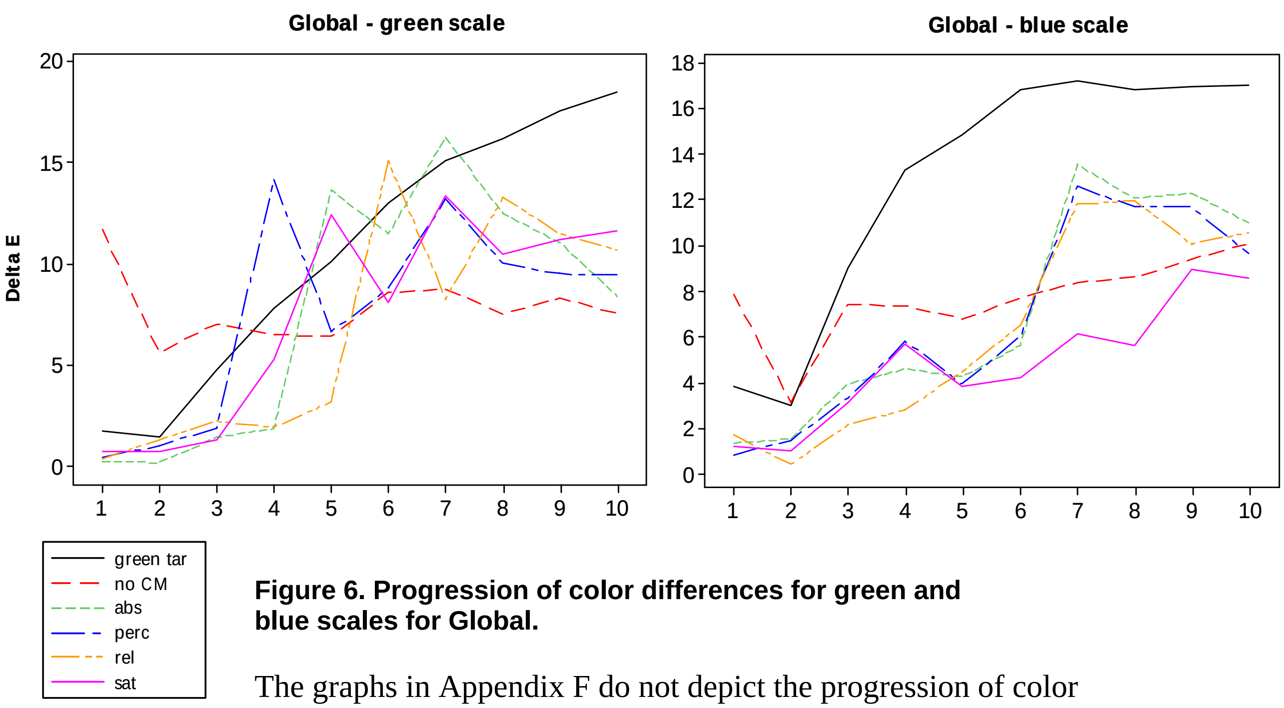


Figure 6. Progression of color differences for green and blue scales for Global.

The graphs in Appendix F do not depict the progression of color differences from the calculated ISO target values because the graphs are depicted at a small size and the extra line confused the information. Figure 6, however, does contain these lines to depict the relationship of color differences from the ISO target. The line depicting the target progression is nearly linear for the green scale and is more curved for the blues. In both cases, the progression of color differences from one patch to the next is fairly smooth, as are the Global renditions for the blue scale, but not for the green. The same relationships are true of the other software vendors to varying degrees. Overall, the Kodak results showed less difference from one rendering intent to another than did the results of the other three vendors. The Heidelberg results showed large color difference jumps between the third and forth patches of the blue color scale for the absolute colorimetric and the relative colorimetric intents (Figure 7), but not for the perceptual or saturation rendering intents.

The second set of eight graphs in Appendix F shows the same data from a different perspective. Each graph shows the results for all of the vendors for a different rendering intent and color scale, thus illuminating cases where a particular vendor is out of synch with the others. Global is divergent from the group in the applications of saturation and perceptual rendering intents, but is at the center of the group with the applications of absolute and relative colorimetric intents. The graphs depicting absolute colorimetric rendering showed the results from Kodak to be out of the mainstream, although they were more smooth and continuous than those from the other vendors.

Figure 7 shows the graphs for the relative colorimetric intent for both green and blue.

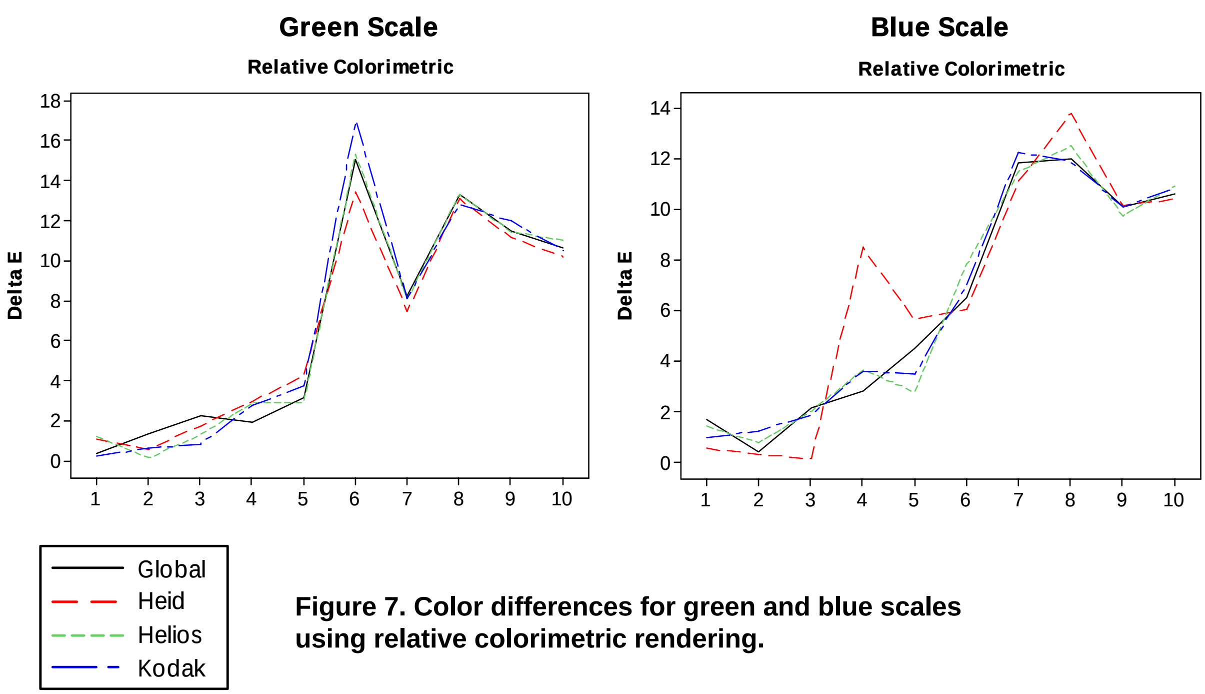


Figure 7. Color differences for green and blue scales using relative colorimetric rendering.

When relative colorimetric rendering was applied, the green scale was reproduced in a very similar manner by all the software vendors. The reproductions of the blue scale also showed a high degree of uniformity; however, Heidelberg was distinctly out of sync with the results from the other vendors.

The uniformity of results between software vendors was greatest for the relative colorimetric intent. The second most uniform results were found with the perceptual rendering technique, which is surprising since specific gamut mapping aims are not given by the ICC for this intent. However, because it is the most commonly used intent, it is a critical focus for all the software vendors.

Outward Gamut Mapping

As can be seen in Figure 4, the sRGB color space subsumes the SWOP color space with the exception of one section, with a lightness near 50, where some blue and cyan values of SWOP are outside of the sRGB space. This is an area where outward gamut mapping should take place, meaning that colors at the boundaries of the sRGB space from the original should be reproduced with greater saturation to utilize the larger capacity of the SWOP space in this area.

The ISO S6 data field was analyzed to identify patches in this region. Four patches were chosen where the calculated L values were between 40 and 60 with a values from -40 to -55, and b values between 15 and 18. The results for each of the experimental treatments were examined for these patches with reference to changes in chroma and lightness. It was hypothesized that chroma in the reproductions would be greater than the calculated sRGB chromas. The changes in chroma and lightness are shown in Appendix G for all the software vendors and rendering techniques. Positive numbers in Appendix G indicate higher values in the reproduction than in the target. The hypothesis was not supported by the data. The chromas in the reproduction were consistently lower for all software vendors and rendering intents. The lightness values were higher in the reproductions whenever color management was used, but lower when no color management was applied.

For the four selected patches, the CIELAB values of the different software vendors were similar in many instances. These data showed an interesting pattern when no color management was applied, as illustrated in Figure 8

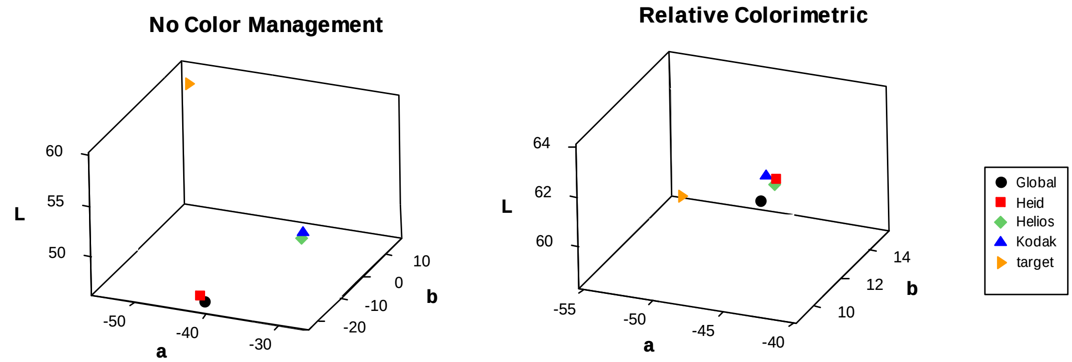


Figure 8 CIELAB values without and with color management from different software vendors for a selected patch.

The 3D graphs in Figure 8 depict the reproductions of a single selected patch without and with the application of color management. The results of the different software vendors are very similar for the relative colorimetric rendering intent, but when no color management was applied the results from Global and Heidelberg were nearly identical as were the results from Helios and Kodak. Yet the two groups were quite dissimilar from each other. These bimodal results might be caused by whether or not a given software vendor honors embedded or default profiles.

Although mapping outside of the sRGB color space could not be demonstrated, there were a total of 298 instances out of 4688 total adjustments of color patches where the chroma values were higher in the reproductions than in the original. These are instances of outward gamut mapping, although in the large majority of the cases, they do not exceed the limits of the sRGB color space. It was assumed that outward gamut mapping would be most common with the saturation rendering intent. Table 9 contains the number of instances of chroma values increased in the reproduction for each rendering intent and software vendor.

	abs	perc	rel	sat
Global	29	23	20	35
Heidelberg	30	8	26	9
Helios	30	8	18	11
Kodak	11	6	21	13

Table 9. Numbers of instances where chroma value was increased in the reproduction.

The most striking finding from Table 9 was that Global was far more likely than the other software vendors to increase the chroma of reproduced colors with the perceptual rendering intent. Also, only Global followed the expected pattern and provided increased chroma values most often with the saturation rendering intent. Heidelberg had the most frequent instances of increased chroma with the relative colorimetric intent, and Kodak had fewer instances of increased chroma with the absolute colorimetric rendering intent.

Conclusion

Color management is a complex and elusive science. It has proved to be hard to measure and compare in an unambiguous way. The ICC, which is the de facto standards body for color management, has not clearly defined the gamut mapping strategies for the perceptual or the saturation rendering intents, making it unfair to suggest that one software company is wrong, while another is right, without first performing extensive and repeated subjective testing which was beyond the scope of this study. Still, some anomalies were found and presented that are clearly neither intentional nor beneficial to good color reproduction.

Overall, it was found that the software vendors were comparable regarding the applications of relative colorimetric and perceptual rendering intents, and less so for the absolute colorimetric and saturation intents. Differences were found between the performances of the different software products based on the colors that were being reproduced. Only the blue and green scales were closely examined in this study, but cursory examination of the other color scales shows similar discrepancies.

The findings of this study should not be interpreted as an indication that color management is flawed and ineffective. The authors believe that color management has become an indispensable component in today’s digital graphics environment. It has improved and continues to improve the consistency and quality of color reproduction in a wide variety of applications. Our hope is that the findings of this study will be a small contribution to the continued improvement and refining of this complex technology.

References

CIE, *Colorimetry, 3rd Edition*, 2004

Berns, Roy S., *Principles of Color Technology*, John Wiley & Sons, Inc., New York, 2000

International Color Consortium, *Specification ICC.1:2004-10 (Profile version 4.2.0.0) Image technology colour management—Architecture, profile format, and data structure*, http://www.color.org, 112pp.

http://www.brucelindbloom.com/

International Color Consortium, *White Paper #9: Common Color Management Workflows & Rendering Intent Usage*, http://www.color.org/whitepapers.html, 8pp.

International Color Consortium, *White Paper #1: Fundamentals of the Version 4 Perceptual Rendering Intent*, http://www.color.org/whitepapers.html, 4pp.

International Color Consortium, *White Paper #2: Perceptual Rendering Intent Use Case Issues*, http://www.color.org/whitepapers.html, 10pp.

Neumann, Eric, "Virtual Proofing For The Real Prepress World," *Newspapers & Technology*, March 2007.

Sharma, G., Wu, W., and Dalal, E.N., "The CIEDE2000 Color-Difference Formula: Implementation Notes, Supplementary Test Data, and Mathematical Observations," *Color Research and Application*, vol. 30. No. 1, February 2005.

Stokes, M., Anderson, M., Chandrasekar, S., and Motta, R., *Standard Default Color Space for the Internet—sRGB*, Version 1.10, http://www.w3.org/Graphics/Color/sRGB, November 5, 1996, 20pp.

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- Lindsay Ferrari, Research Technician, PIA/GATF, who performed all of the colorimetric measurements of the samples used in this study.
- Danny Rich, Ph.D., Sun Chemical, who provided guidance in color calculations.

Appendix A.

Formula for calculating ΔE_{2000} color difference from the CIELAB values of two colors. (Used with permission from the *brucelindbloom.com* web site.)

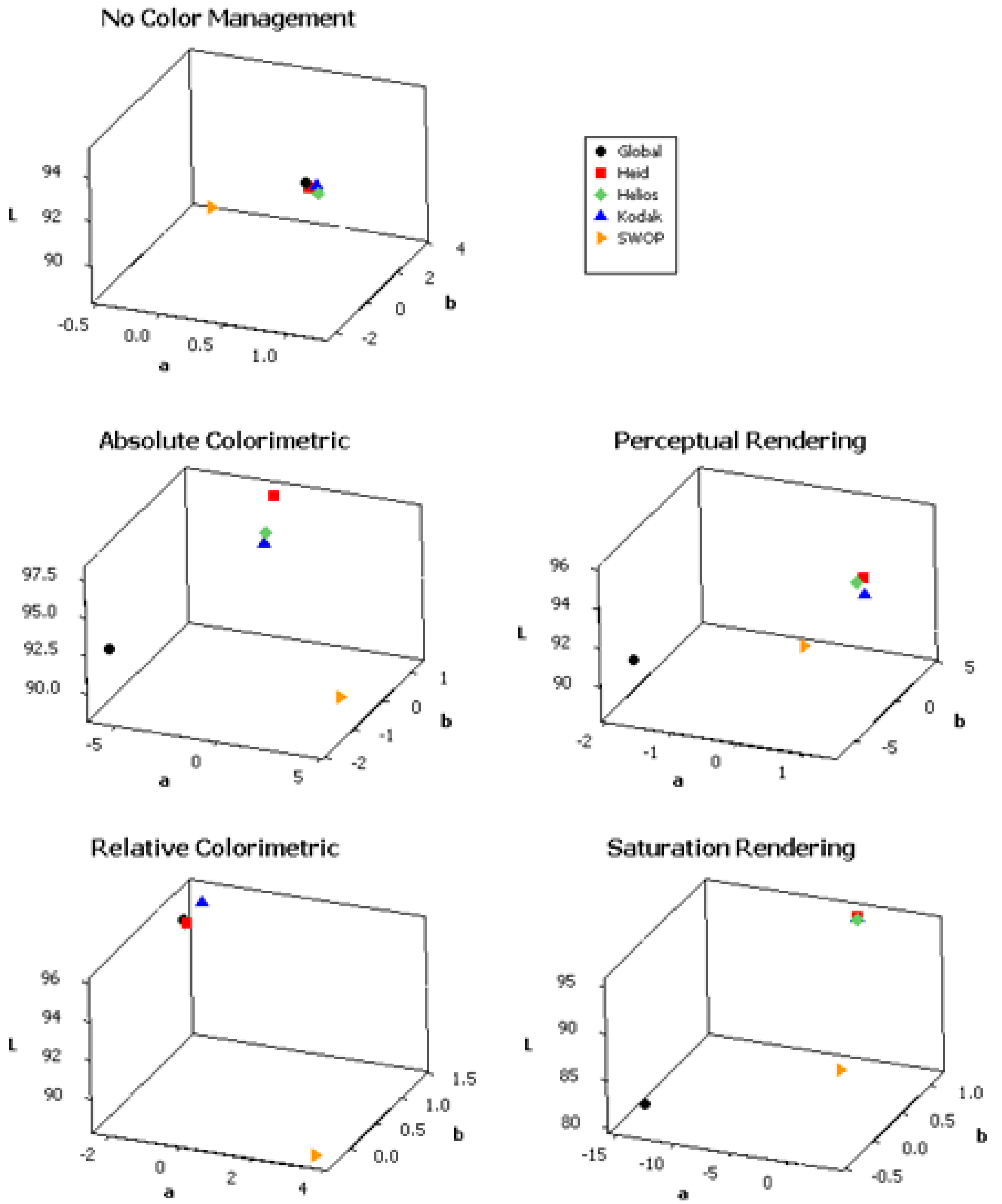
$$\Delta E = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)}$$

where,

$$\overline{L}' = (L_1 + L_2)/2$$
$$C_1 = \sqrt{a_1^2 + b_1^2}$$
$$C_2 = \sqrt{a_2^2 + b_2^2}$$
$$\overline{C} = (C_1 + C_2)/2$$
$$G = \left(1 - \sqrt{\frac{\overline{C}^7}{\overline{C}^7 + 25^7}}\right)\Big/2$$
$$a_1' = a_1(1+G)$$
$$a_2' = a_2(1+G)$$
$$C_1' = \sqrt{a_1'^2 + b_1^2}$$
$$C_2' = \sqrt{a_2'^2 + b_2^2}$$
$$\overline{C}' = (C_1' + C_2')/2$$
$$h_1' = \begin{cases} \tan^{-1}(b_1/a_1') & \tan^{-1}(b_1/a_1') \ge 0 \\ \tan^{-1}(b_1/a_1') + 360° & \tan^{-1}(b_1/a_1') < 0 \end{cases}$$
$$h_2' = \begin{cases} \tan^{-1}(b_2/a_2') & \tan^{-1}(b_2/a_2') \ge 0 \\ \tan^{-1}(b_2/a_2') + 360° & \tan^{-1}(b_2/a_2') < 0 \end{cases}$$
$$\overline{H}' = \begin{cases} (h_1' + h_2' + 360°)/2 & |h_1' - h_2'| > 180° \\ (h_1' + h_2')/2 & |h_1' - h_2'| \le 180° \end{cases}$$
$$T = 1 - 0.17\cos(\overline{H}' - 30°) + 0.24\cos(2\overline{H}') + 0.32\cos(3\overline{H}' + 6°) - 0.20\cos(4\overline{H}' - 63°)$$
$$\Delta h' = \begin{cases} h_2' - h_1' & |h_2' - h_1'| \le 180° \\ h_2' - h_1' + 360° & |h_2' - h_1'| > 180°; h_2' \le h_1' \\ h_2' - h_1' - 360° & |h_2' - h_1'| > 180°; h_2' > h_1' \end{cases}$$
$$\Delta L' = L_2 - L_1$$
$$\Delta C' = C_2' - C_1'$$
$$\Delta H' = 2\sqrt{C_1' C_2'}\sin(\Delta h'/2)$$
$$S_L = 1 + \frac{0.015(\overline{L}' - 50)^2}{\sqrt{20 + (\overline{L}' - 50)^2}}$$
$$S_C = 1 + 0.045\overline{C}'$$
$$S_H = 1 + 0.015\overline{C}'T$$
$$\Delta\theta = 30\exp\left\{-\left(\frac{\overline{H}' - 275°}{25}\right)^2\right\}$$
$$R_C = \sqrt{\frac{\overline{C}'^7}{\overline{C}'^7 + 25^7}}$$
$$R_T = -2R_C \sin(2\Delta\theta)$$
$$K_L = 1 \quad \text{default}$$
$$K_C = 1 \quad \text{default}$$
$$K_H = 1 \quad \text{default}$$

Appendix B.

Graphs of white point CIELAB values for different software vendors and different rendering intents.



Appendix C.

Corrected X, Y, Z target values for D50 illumination for columns 19-25 of the S6 target.

Column	Row	R	G	B	X(65)	Y(65)	Z(65)	X(50)	Y(50)	Z(50)
19	A	255	0	0	41.19	21.19	1.84	41.79	21.19	1.39
19	B	255	17	17	41.54	21.70	2.53	42.14	21.70	1.92
19	C	255	27	27	41.83	22.12	3.10	42.44	22.12	2.35
19	D	255	48	48	42.83	23.59	5.09	43.45	23.59	3.86
19	E	255	71	71	44.63	26.22	8.67	45.28	26.22	6.57
19	F	255	94	94	47.26	30.07	13.90	47.95	30.07	10.53
19	G	255	119	119	51.17	35.79	21.66	51.91	35.79	16.41
19	H	255	145	145	56.48	43.56	32.22	57.30	43.56	24.42
19	I	255	171	171	63.15	53.33	45.49	64.07	53.33	34.47
19	J	255	198	198	71.63	65.73	62.34	72.67	65.73	47.24
19	K	255	226	226	82.16	81.14	83.28	83.35	81.14	63.11
20	A	0	255	0	35.71	71.50	11.84	36.23	71.50	8.97
20	B	17	255	17	36.09	71.68	12.46	36.61	71.68	9.44
20	C	27	255	27	36.41	71.83	12.98	36.94	71.83	9.84
20	D	48	255	48	37.51	72.36	14.79	38.05	72.36	11.21
20	E	71	255	71	39.50	73.32	18.03	40.07	73.32	13.66
20	F	94	255	94	42.40	74.71	22.78	43.02	74.71	17.26
20	G	119	255	119	46.70	76.77	29.81	47.38	76.77	22.59
20	H	145	255	145	52.55	79.58	39.38	53.31	79.58	29.84
20	I	171	255	171	59.90	83.12	51.41	60.77	83.12	38.96
20	J	198	255	198	69.24	87.60	66.69	70.25	87.60	50.54
20	K	226	255	226	80.85	93.18	85.68	82.02	93.18	64.93
21	A	0	0	255	17.99	7.14	95.04	18.25	7.14	72.02
21	B	17	17	255	18.48	7.74	95.13	18.75	7.74	72.09
21	C	27	27	255	18.89	8.24	95.20	19.16	8.24	72.14
21	D	48	48	255	20.33	9.96	95.46	20.63	9.96	72.34
21	E	71	71	255	22.90	13.07	95.92	23.23	13.07	72.69
21	F	94	94	255	26.67	17.60	96.60	27.06	17.60	73.20
21	G	119	119	255	32.25	24.34	97.61	32.72	24.34	73.97
21	H	145	145	255	39.85	33.49	98.97	40.43	33.49	75.00
21	I	171	171	255	49.41	45.00	100.69	50.13	45.00	76.30
21	J	198	198	255	61.53	59.61	102.87	62.42	59.61	77.96
21	K	226	226	255	76.61	77.78	105.58	77.72	77.78	80.01
22	A	0	255	255	53.78	78.72	106.97	54.56	78.72	81.06
22	B	17	255	255	54.04	78.86	106.98	54.82	78.86	81.07
22	C	27	255	255	54.26	78.97	106.99	55.05	78.97	81.08
22	D	48	255	255	55.03	79.37	107.03	55.83	79.37	81.11
22	E	71	255	255	56.41	80.08	107.09	57.23	80.08	81.15
22	F	94	255	255	58.43	81.12	107.19	59.28	81.12	81.23
22	G	119	255	255	61.42	82.66	107.33	62.31	82.66	81.34
22	H	145	255	255	65.49	84.76	107.52	66.44	84.76	81.48
22	I	171	255	255	70.60	87.40	107.76	71.63	87.40	81.66
22	J	198	255	255	77.10	90.75	108.06	78.22	90.75	81.89
22	K	226	255	255	85.17	94.91	108.44	86.41	94.91	82.18

Appendix C (continued).

Corrected X, Y, Z target values for D50 illumination for columns 19-25 of the S6 target.

Column	Row	R	G	B	X(65)	Y(65)	Z(65)	X(50)	Y(50)	Z(50)
23	A	255	0	255	59.26	28.42	96.97	60.12	28.42	73.48
23	B	255	17	255	59.49	28.88	97.05	60.35	28.88	73.55
23	C	255	27	255	59.68	29.26	97.11	60.55	29.26	73.59
23	D	255	48	255	60.35	30.59	97.33	61.23	30.59	73.76
23	E	255	71	255	61.54	32.99	97.73	62.43	32.99	74.06
23	F	255	94	255	63.29	36.49	98.31	64.21	36.49	74.50
23	G	255	119	255	65.89	41.67	99.18	66.85	41.67	75.16
23	H	255	145	255	69.41	48.73	100.36	70.42	48.73	76.05
23	I	255	171	255	73.85	57.61	101.83	74.92	57.61	77.17
23	J	255	198	255	79.48	68.87	103.71	80.63	68.87	78.59
23	K	255	226	255	86.49	82.87	106.05	87.75	82.87	80.37
24	A	255	255	0	76.99	92.77	13.77	78.11	92.77	10.43
24	B	255	255	17	77.10	92.82	14.38	78.22	92.82	10.90
24	C	255	255	27	77.20	92.86	14.89	78.32	92.86	11.28
24	D	255	255	48	77.53	92.99	16.66	78.66	92.99	12.63
24	E	255	255	71	78.14	93.24	19.84	79.27	93.24	15.03
24	F	255	255	94	79.02	93.59	24.49	80.17	93.59	18.56
24	G	255	255	119	80.33	94.11	31.38	81.50	94.11	23.78
24	H	255	255	145	82.11	94.82	40.76	83.30	94.82	30.89
24	I	255	255	171	84.35	95.72	52.56	85.57	95.72	39.83
24	J	255	255	198	87.19	96.86	67.53	88.46	96.86	51.17
24	K	255	255	226	90.73	98.27	86.14	92.05	98.27	65.28
25	A	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
25	B	17	17	17	0.53	0.56	0.61	0.54	0.56	0.46
25	C	27	27	27	1.04	1.10	1.19	1.06	1.10	0.90
25	D	48	48	48	2.81	2.96	3.22	2.85	2.96	2.44
25	E	71	71	71	5.99	6.30	6.86	6.08	6.30	5.20
25	F	94	94	94	10.64	11.19	12.19	10.79	11.19	9.24
25	G	119	119	119	17.53	18.45	20.09	17.78	18.45	15.22
25	H	145	145	145	26.91	28.31	30.83	27.30	28.31	23.36
25	I	171	171	171	38.71	40.72	44.35	39.27	40.72	33.61
25	J	198	198	198	53.68	56.47	61.50	54.46	56.47	46.61
25	K	226	226	226	72.29	76.05	82.82	73.34	76.05	62.76

Appendix D.

Formula for calculating CIELAB coordinates from XYZ tristimulus values. (From Berns, p.69)

$$L^* = 116\left[f\left(\frac{Y}{Y_n}\right) - \frac{16}{116}\right]$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

where $f(Y/Y_n) = (Y/Y_n)^{1/3}$ for Y/Y_n greater than 0.008856 and $f(Y/Y_n) = 7.787(Y/Y_n) + 16/116$ for Y/Y_n less than or equal to 0.008856; $f(X/X_n)$ and $f(Z/Z_n)$ are similarly defined.

and where,

X_n, Y_n, Z_n are the tristimulus values of the reference white point.

Appendix E.

Calculated CIELAB values for columns 19-25 of the S6 target.

Column	Row	R	G	B	L	a	b
19	A	255	0	0	53.71	78.99	63.11
19	B	255	17	17	54.15	77.94	59.88
19	C	255	27	27	55.67	74.40	51.53
19	D	255	48	48	58.25	68.61	41.97
19	E	255	71	71	61.71	61.15	33.29
19	F	255	94	94	66.36	51.76	25.25
19	G	255	119	119	71.93	41.35	18.33
19	H	255	145	145	78.07	30.84	12.67
19	I	255	171	171	84.86	20.29	7.82
19	J	255	198	198	92.19	9.95	3.64
19	K	255	226	226	87.73	-86.30	83.38
20	A	0	255	0	87.81	-85.40	81.89
20	B	17	255	17	87.89	-84.65	80.68
20	C	27	255	27	88.14	-82.12	76.74
20	D	48	255	48	88.60	-77.73	70.52
20	E	71	255	71	89.26	-71.64	62.75
20	F	94	255	94	90.22	-63.27	53.26
20	G	119	255	119	91.50	-52.96	42.84
20	H	145	255	145	93.07	-41.43	32.31
20	I	171	255	171	94.99	-28.51	21.52
20	J	198	255	198	97.30	-14.60	10.70
20	K	226	255	226	32.12	79.66	-108.17
21	A	0	0	255	33.44	76.59	-105.97
21	B	17	17	255	34.48	74.22	-104.22
21	C	27	27	255	37.77	67.26	-98.71
21	D	48	48	255	42.87	57.39	-90.23
21	E	71	71	255	49.01	47.14	-80.10
21	F	94	94	255	56.43	36.56	-67.97
21	G	119	119	255	64.56	27.01	-54.85
21	H	145	145	255	72.89	18.89	-41.59
21	I	171	171	255	81.63	11.74	-27.93
21	J	198	198	255	90.68	5.51	-14.03
21	K	226	226	255	91.11	-48.11	-14.16
22	A	0	255	255	91.17	-47.72	-14.05
22	B	17	255	255	91.22	-47.37	-13.97
22	C	27	255	255	91.40	-46.19	-13.69
22	D	48	255	255	91.72	-44.12	-13.17
22	E	71	255	255	92.19	-41.16	-12.43
22	F	94	255	255	92.87	-36.96	-11.35
22	G	119	255	255	93.78	-31.56	-9.89
22	H	145	255	255	94.91	-25.22	-8.09
22	I	171	255	255	96.31	-17.76	-5.86
22	J	198	255	255	98.00	-9.31	-3.18
22	K	226	255	255	60.27	98.42	-60.93

Appendix E (continued).

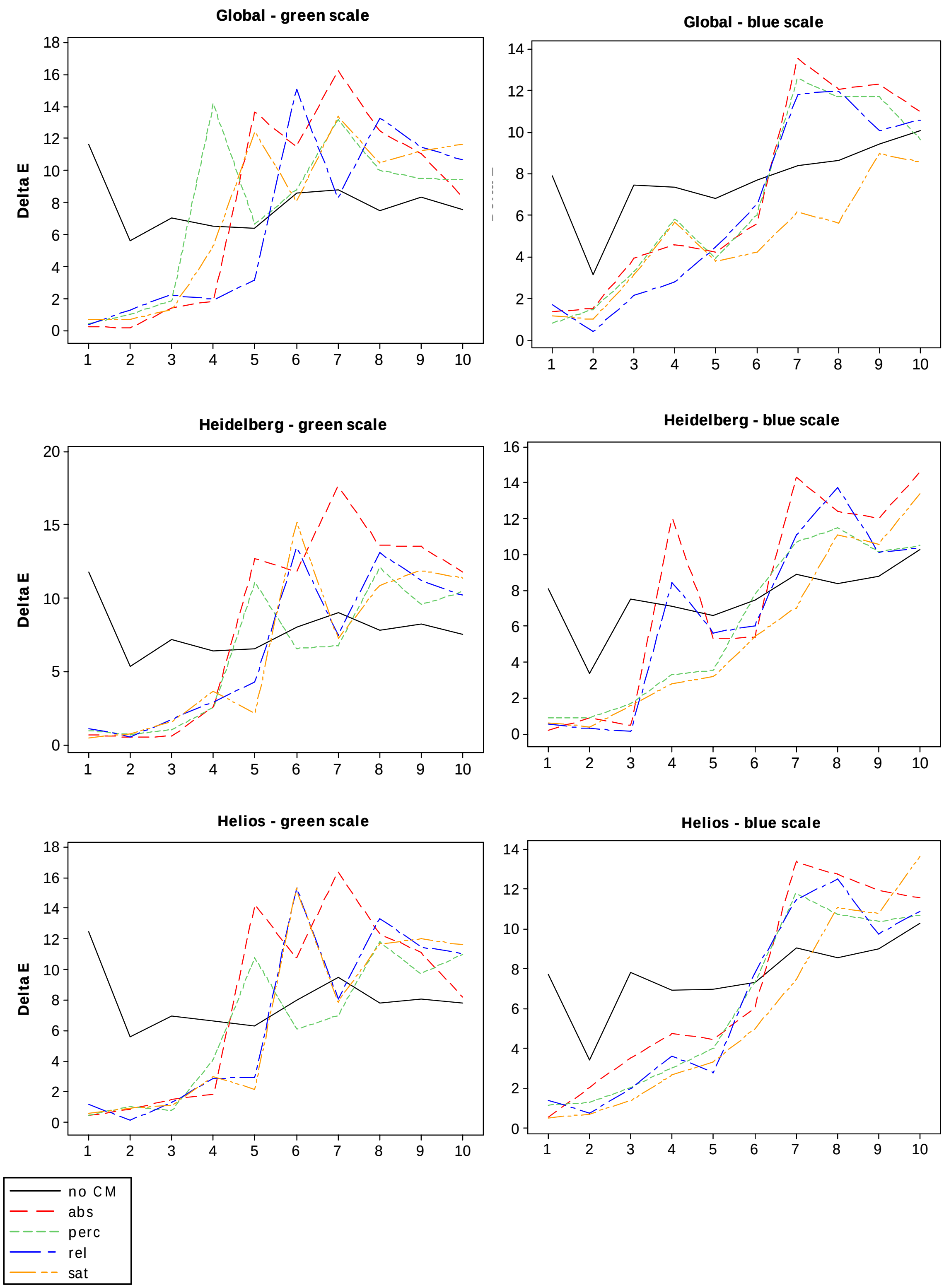
Calculated CIELAB values for columns 19-25 of the S6 target.

Column	Row	R	G	B	L	a	b
23	A	255	0	255	60.68	97.21	-60.28
23	B	255	17	255	61.01	96.22	-59.74
23	C	255	27	255	62.16	92.86	-57.90
23	D	255	48	255	64.15	87.08	-54.73
23	E	255	71	255	66.89	79.33	-50.39
23	F	255	94	255	70.64	69.07	-44.49
23	G	255	119	255	75.28	56.81	-37.26
23	H	255	145	255	80.52	43.63	-29.17
23	I	255	171	255	86.44	29.52	-20.16
23	J	255	198	255	92.96	14.89	-10.39
23	K	255	226	255	97.13	-21.55	94.67
24	A	255	255	0	97.15	-21.41	93.24
24	B	255	255	17	97.17	-21.28	92.08
24	C	255	255	27	97.22	-20.85	88.24
24	D	255	255	48	97.32	-20.06	82.00
24	E	255	255	71	97.47	-18.92	74.00
24	F	255	255	94	97.68	-17.24	63.88
24	G	255	255	119	97.96	-15.00	52.34
24	H	255	255	145	98.32	-12.26	40.21
24	I	255	255	171	98.77	-8.87	27.32
24	J	255	255	198	99.33	-4.78	13.86
24	K	255	255	226	0.00	0.00	0.00
25	A	0	0	0	5.06	-0.09	0.00
25	B	17	17	17	9.80	-0.19	0.10
25	C	27	27	27	19.88	-0.06	0.02
25	D	48	48	48	30.16	0.03	0.00
25	E	71	71	71	39.90	0.04	-0.02
25	F	94	94	94	50.04	-0.03	0.00
25	G	119	119	119	60.17	0.02	-0.01
25	H	145	145	145	69.98	0.03	-0.02
25	I	171	171	171	79.88	0.03	-0.01
25	J	198	198	198	89.88	0.03	-0.01
25	K	226	226	226	72.29	76.05	82.82

Appendix F.

Graphs of progressive changes in delta E for green and blue tone scales.

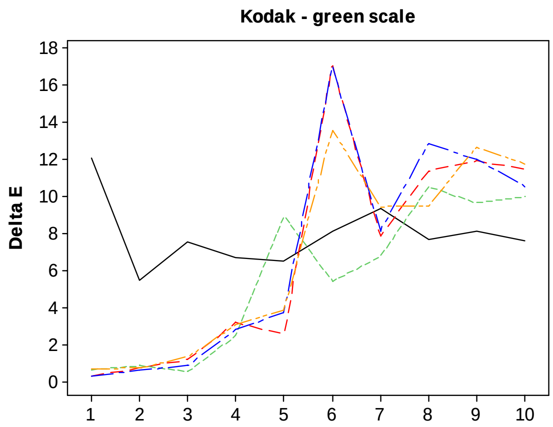
The following graphs show all rendering intents for each vendor:

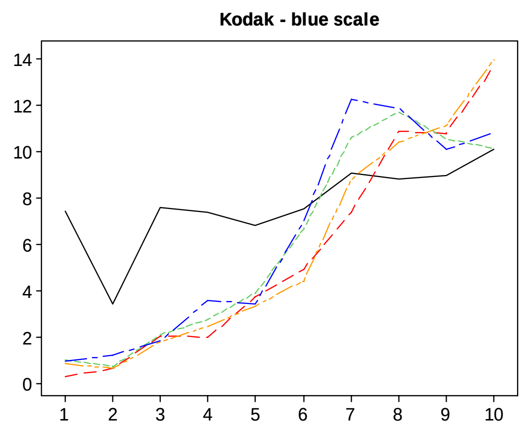


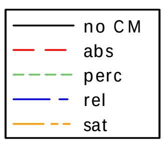
Appendix F (continued).

Graphs of progressive changes in delta E for green and blue tone scales.

The following graphs show all rendering intents for each vendor:

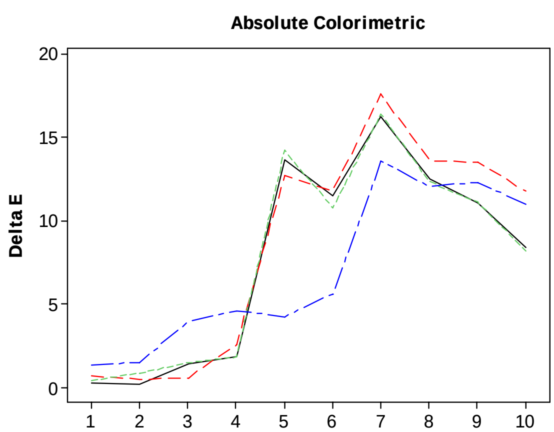


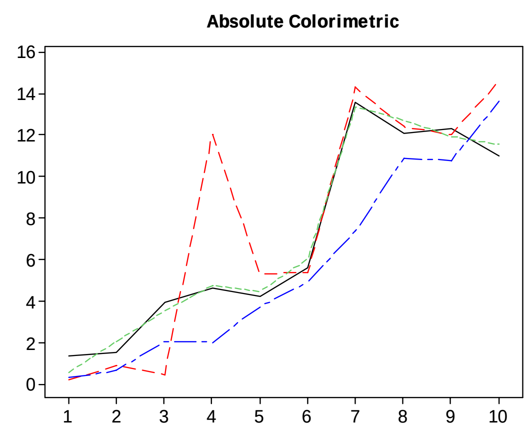


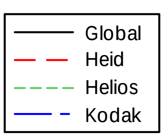


The following graphs show all vendors for each rendering intent:

Greens **Blues**





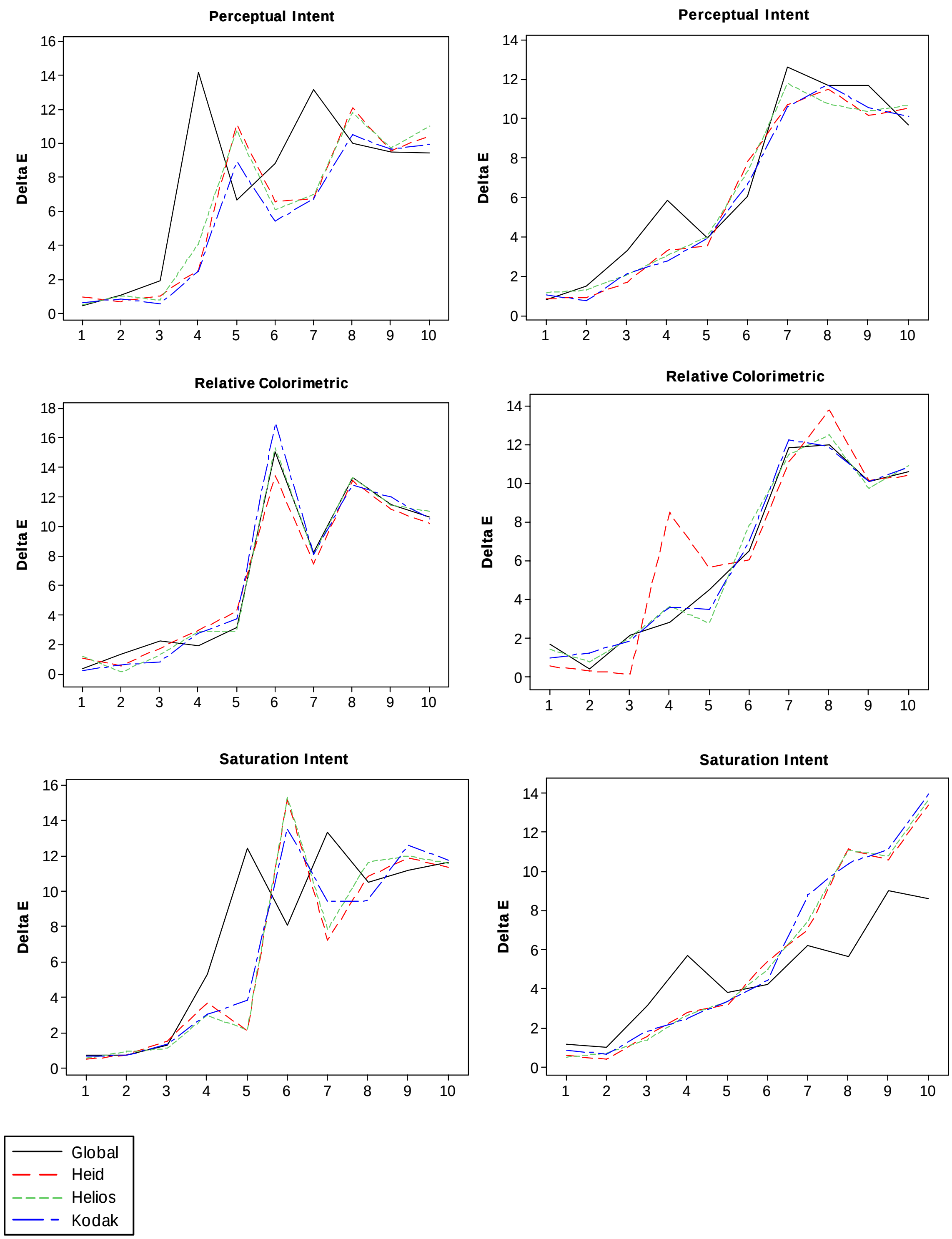


Appendix F (continued).

Graphs of progressive changes in delta E for green and blue tone scales.

The following graphs show all vendors for each rendering intent:

Greens **Blues**



Appendix G.

Changes in chroma and lightness for selected patches from SWOP gamut.

		no CM		Absolute		Perceptual		Relative		Saturation	
	Patch	ΔC	ΔL	ΔC	ΔL	ΔC	ΔL	ΔC	ΔL	ΔC	ΔL
Global	1-I	-13.6	-3.7	-2.7	12.7	-9.8	12.4	-9.4	6.0	-4.4	12.6
	2-I	-26.8	1.2	-3.3	11.9	-9.4	11.1	-9.2	4.9	-4.9	11.5
	7-J	-9.9	-11.7	-18.8	6.7	-19.7	7.3	-12.8	4.2	-16.3	5.5
	8-J	-23.6	-5.9	-18.1	6.8	-18.7	7.3	-11.0	3.8	-15.4	5.4
Heidelberg	1-I	-12.4	-2.9	-2.1	15.0	-15.8	7.3	-11.1	7.5	-12.5	7.3
	2-I	-27.2	2.0	-2.6	14.1	-14.1	6.8	-10.2	6.5	-11.6	6.0
	7-J	-9.3	-11.2	-18.3	9.1	-14.4	5.0	-14.0	5.2	-11.9	3.8
	8-J	-24.0	-5.2	-17.4	9.1	-12.6	4.9	-11.9	4.8	-10.4	3.6
Helios	1-I	-27.8	7.7	-3.1	13.9	-15.2	7.7	-8.5	6.9	-12.5	7.6
	2-I	-31.6	10.4	-3.4	12.8	-13.6	6.8	-8.2	6.0	-11.3	6.4
	7-J	-21.6	-4.3	-19.1	7.4	-13.5	4.9	-12.7	4.3	-11.7	3.8
	8-J	-26.9	-0.8	-17.9	7.4	-11.7	4.7	-11.1	4.1	-9.6	3.4
Kodak	1-I	-27.9	7.8	-12.0	6.8	-17.5	6.8	-8.2	7.2	-11.2	6.3
	2-I	-31.7	10.7	-10.7	5.8	-15.4	5.8	-8.0	6.4	-10.3	5.0
	7-J	-21.9	-3.8	-11.0	3.3	-17.9	2.5	-12.3	4.7	-11.0	1.4
	8-J	-27.0	-0.7	-9.8	3.3	-16.0	1.7	-10.6	4.4	-9.8	1.4