Analysis of Color Rendering in Digital Cameras

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Keywords

Digital Camera, CIE Lab, Colorimetry, ICC profiles, Camera Raw, Rendering

Abstract

Digital photography has now replaced the scanner in most prepress workflows. There remains however considerable confusion regarding the color processing of the images during and after digital capture. Further there is the need to understand the color transformations that are appropriate for images intended for reproduction on press.

Digital camera images consist originally of raw data which must first undergo a mathematical demosaicing and then have a secondary set of color rendering operations applied to them to produce "pleasing" images. When a camera is set to capture jpeg images, the camera internally performs both of these operations; however, if the image is kept in camera raw format, the user is able to manually interpret and adjust image data rather than have the camera make pre-determined generic adjustments and conversions.

The camera raw file format is not standardized, and currently no universal method exists to open and render the raw image data. There are different ways to process a raw image. A raw file may be opened using vendor specific software, such as Canon's File Viewer program, or solutions such as Photoshop's Camera Raw, Apple Aperture or Adobe Lightroom.

In this research we conduct colorimetric analysis of how camera raw files are rendered by various processing software. For this study, a GretagMacbeth Digital ColorChecker SG chart was shot in both raw and JPEG format using a Canon digital SLR camera in a controlled lighting environment. The JPEG file was used to analyze in-camera transformation. The raw file was converted to sRGB using four different software solutions: Adobe Camera Raw, Adobe Lightroom, Bibble Pro, and Canon File Viewer. The results were analyzed by comparing the ΔL, Δa, and Δb of the converted images to the colorimetric readings of the physical target.

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The transformation results were analyzed in terms of different L*a*b* quadrants based on chroma and lightness and then studied to determine if common mapping schemas could be drawn from each program that would illustrate an attempt to distort the colorimetric accuracy of reproduction in an attempt to create an image that is more pleasing to the human eye.

It is very useful to note that a general pattern of darkening existed in almost all the transformations: that is, the L* values of the transformed images were generally lower than the target. This finding contradicted the original hypothesis that the rendering would be brighter (a higher L* value). Neutral colors showed the least amount of deviation from the physical target when rendered.

The project also analyzed the L*a*b* values of the target mapped in 3D Lab space. The 3D analysis revealed an uneven distribution of color patches of the target within the Lab color space, with some quadrants heavily represented, and some with almost no patches at all. Areas with minimal representation on the target provide little training set data and the colorimetric trends are harder to identify.

The findings presented in this paper are relevant to pre-media specialists, color scientists, and photographers as it provides analysis of the differences in the rendering algorithms allowing each type of user to choose an appropriate image processing solution.

Introduction

Recent advancements in digital photography have put extremely high quality digital cameras into the hands of many photography professionals and consumers alike. Where high-end digital imagery was once the realm of expensive digital studios, traditional camera manufacturers such as Nikon and Canon are producing digital SLR (Single Lens Reflex) cameras in excess of 10 mega pixels for well under $2000.00. In many cases, these cameras are capable of capturing resolutions that exceed the capabilities of traditional photographic mediums. With this reality, it is not surprising that digital photography is quickly replacing scanning of traditional continuous tone images as the norm for producing digital images to be used in printing applications.

For anyone that can appreciate the proprietary and secretive nature of traditional photographic emulsion production, it come as no surprise that each camera vendor has a unique and proprietary way of capturing images in digital form. The way that the CCD arrays in the camera capture data, and the way that data is converted into usable RGB pixels varies from manufacturer to manufacturer.

To understand the processing that occurs in a digital camera we need to take a step back and understand how a color image is formed. A digital camera contains a monochrome sensor that is overlaid with red, green and blue filters, commonly called a color mosaic or color filter array [1,2]. Each pixel on the sensor is covered with a red, green, or blue filter. While the premise of the CCD is quite standard, the variability lies with the ability to arrange the color filter array in various configurations. One of the more commonly used filter arrangements is the Bayer pattern, named after the creator and patent holder [3].

Light travels through the filter array, and a signal is formed on the CCD. The signal, immediately after capture, has information about the scene, but is not directly usable. Some of the pixels on the CCD represent red values, some green, and some blue; however, since the CCD itself is monochromatic, the pixels aren't actually RGB. The data from the CCD chip must be further processed into a usable RGB digital image. The generation of full-color (RGB), images from raw sensor data requires mathematical decoding of the raw CCD information. This process is often referred to as color interpolation or color demosaicing [4,5].

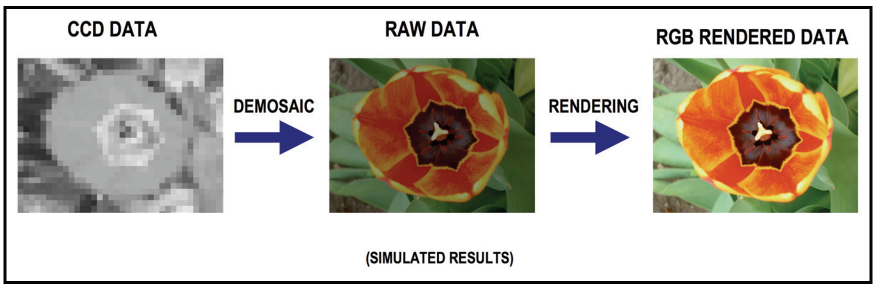

Figure 1: Demosaicing and rendering of camera raw data.

Color demosaicing results in an image that is RGB, dull, dark and "flat" in appearance. For this reason, each camera manufacturer will also "render" the image through color correction and post-processing to make it more pleasing to the eye. Color rendering can incorporate factors such as ISO speed, white balance, contrast, saturation, and sharpness [6]. These manipulations are subjective, and based upon the camera manufacturers' experiential knowledge of what needs to be done to a digital image to make it look pleasing at its final result. Since a vast majority of images can fit into a very small number of standard categories, the results of the rendering can be quite good.

All images captured via a digital camera are subjected to a common internal demosaicing however, there are different methods in which the post-capture rendering can be done. When the digital camera is set to capture images in JPEG (Joint Photographic Experts Group), all the post-processing is done automatically on the camera with no user intervention. This is how point-and-shoot digital cameras handle images.

Digital SLR cameras can capture images in JPEG format, but they also have the ability to shoot images in raw format. Raw images contain all necessary picture information but the data is not processed into usable image data. Rather than relying on the camera to internally render the image, the raw format allows photographers to control post-processing, using software to modify and refine the look of the image to their own specifications. In many ways, the raw format is akin to the traditional darkroom, where photographers could process and develop their own photographs to ensure a personal touch.

There are a number of ways to process a raw file. You can use manufacturer-provided software, such as Canon File Viewer, or third party products such as Adobe Photoshop's Camera Raw plug-in, Apple Aperture or Adobe Lightroom. Each product will allow you to process a raw image and convert it to a jpeg or tiff file. During the processing of a raw file, the user has control over color rendering and look. The user can save the original raw file and work with the processed version, returning to the original again if necessary. The user can even reprocess the raw file many times to achieve different results.

While the idea of camera raw data may sound ideal, problems can arise as a result of the proprietary nature of the raw data encoding , The encoding of Canon raw files is different to the way Nikon raw files are encoded. To date, most vendors have been unwilling to publish their raw data design, and as a result, companies like Apple and Adobe must reverse engineer every raw format in order to read and process them. This can lead to variations on how the file is decoded, which will in turn affect rendering.

This paper arose from an attempt to better understand the subjectivity of color rendering used to convert raw camera data to RGB. The aim of the research was to analyze the color rendering results of different conversion methods to see if predictable patterns could be mapped and consequently predicted.

Research Design and Procedure

Design Overview

The research design for this project involved creating digital images of a measurable target in controlled lighting conditions. These images were then rendering using different methods and software, and the results were compared back to the original target measurements.

Procedure

To control lighting conditions, the experimental procedures for this project were contained within an industry standard viewing booth calibrated to D50 lighting specifications. What follows is a detailed procedural account of the experiment.

1. The target chosen for this study was the GretagMacbeth 140 patch Digital ColorChecker SG chart.
2. The Digital ColorChecker SG chart was measured using a calibrated X-Rite 530 Spectrophotometer. The L*a*b* (D50/2 degree) values for each patch were measured and recorded directly into a spreadsheet using X-Rite's Toolcrib software.

3. The measured L*a*b* values of the chart were compared against suggested L*a*b* values for the target as specified by the manufacturer. The ΔL, Δa, Δb and ΔE values were analyzed to ensure the spectrophotometric measurements of the target were valid and with an acceptable tolerance. A summary of this comparison is presented in Table 2.

Figure 2: GretagMacbeth Digital ColorChecker SG and X-Rite 530 Spectrodensitometer.

4. The Digital ColorChecker SG target was mounted to the back of the viewing booth. A Canon Digital Rebel camera was mounted to a tripod as close as possible to the front of the viewing booth. The camera flash was deactivated and the aperture and shutter speed were adjusted to achieve balanced exposure. The details of the image settings were as follows:

Aperture Value:	5.310704
Exposure Bias Value:	0
Exposure Time:	0.05
FNumber:	6.3
Focal Length:	55
ISO Speed Ratings:	100
Shutter Speed Value:	4.321928

5. Two images were taken with the above settings: The first was captured as a JPEG, the second was captured as raw. To avoid image degradation, the camera's timer function was used so that the camera was not touched at all when the exposure took place.

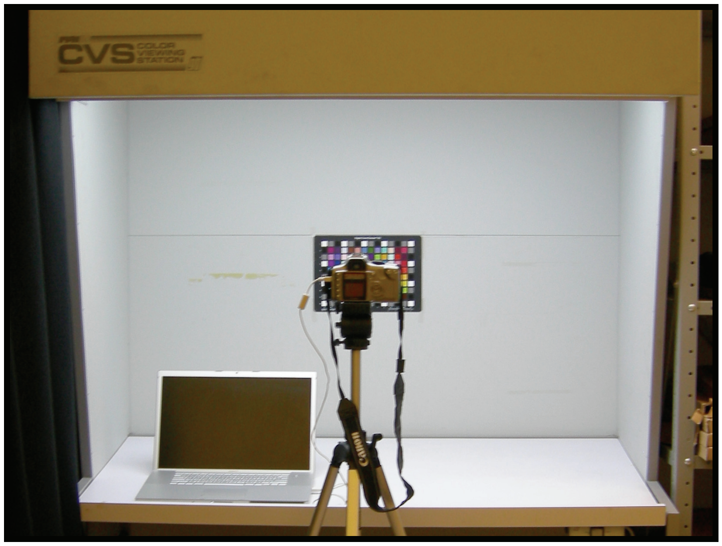

Figure 3: Preparing to shoot the test target.

6. The color settings in Photoshop were adjusted as outlined in Figure 4. This created a standardized color setting that would be used to convert the RGB image data into usable L*a*b* values.

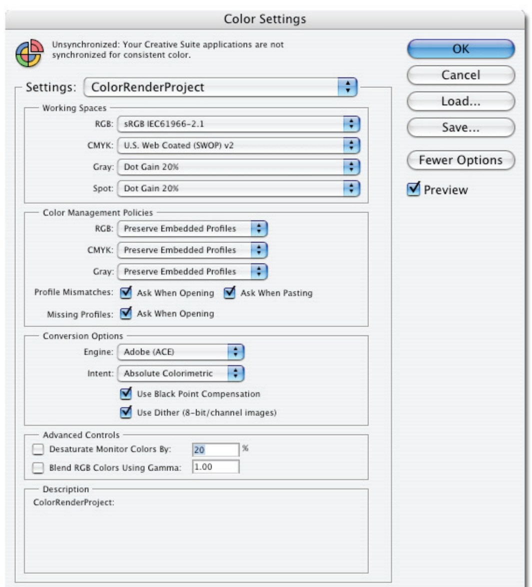

Figure 4: Photoshop CS2 color settings used for rendering

7. The JPEG image was opened in Adobe Photoshop using the color settings mentioned above. To maintain consistency, the JPEG image converted from its embedded camera RGB profile to the working sRGB profile when opened in Photoshop. The image was then converted into L*a*b*, and a rectangular selection was used to record the L*a*b* values of each patch using the histogram tool. This allowed us to average the measurements over 7565 pixels (the number of pixels contained in the selection), as opposed to the limited 5 by 5 average of Photoshop's eyedropper tool.
8. The same procedure was used to record the L*a*b* values for the camera raw image when it was opened using the following software/procedures:
    a. Adobe Camera Raw using the software's default image settings and the sRGB profile.
    b. Adobe Camera Raw using 'linear' image settings, and the sRGB profile.
    c. Adobe Lightroom using default image settings, and the sRGB profile.
    d. Bibble Pro using default image settings, and the sRGB profile.
    e. Canon File Viewer using default image settings, and the sRGB profile.
9. Once the images were opened in Photoshop, the image mode was changed from RGB to L*a*b*. This converted the image from RGB to Lab color using the color settings in Figure 4.
10. For all six rendered images, the L*a*b* values for each patch were recorded using the same selection and histogram methodology used for the JPEG image. The results were recorded and subtracted from the L*a*b* values spectrophotometrically measured on the target to obtain ΔL, Δa and Δb values for each patch. These values were then used to calculate the corresponding ΔE values.
11. The results were broken down and graphed according to the following:
    a. All patches
    b. All color patches
    c. All neutral patches
        i. Neutral patches were determined to be any patch where both the a* and b* values were $\leq \pm 3$
    d. By lab quadrant

12. The results were analyzed for identifiable patterns that could be used to predict the rendering behavior of digital images.

Software Used

Table 1 outlines the software used to complete this project.

Equipment and Materials Used		
Software	**Description**	**Explanation of Use**
Adobe Camera Raw 3.6 (Photoshop Plug-in)	Third Party raw converting software	Used to convert the raw image into 'default' and 'linear' RGB versions of the image
Adobe Lightroom Public Beta 4	Third Party raw converting software	Used to convert the raw image into an RGB image
Adobe Photoshop CS2	Image manipulation Software	Used to manage color conversion, convert images to LAB color, and measure the resulting Lab patch values
Bibble Pro 4.8a	Third Party raw converting software	Used to convert the raw image into an RGB image
Canon File Viewer 1.3.2.9	Camera manufacturer's raw converting software	Used to convert the raw image into an RGB image

Table 1: Equipment and materials used.

Sample Data Gathering

The X-Rite 530 was used to measure the L*a*b* values of all 140 patches of the GretagMacbeth Digital ColorChecker SG target. These measurements were used as the standard from which delta values would be generated. To verify accuracy, the readings were compared to the reference target file for the GretagMacbeth Digital ColorChecker SG that is supplied by GretagMacbeth for use in Profile Maker 5.5. Table 2 summarizes this comparison.

	Comparison of Physical Patch Readings to Reference Patch Values			
AVERAGE	0.53 / -0.70	1.52 / -2.86	0.94 / -0.56	2.58
	ΔL	**Δa**	**Δb**	**ΔE**
MEDIAN	-0.32	0.13	0.64	1.41
STD. DEV.	0.82	3.26	0.96	2.47
MIN	-2.53	-12.48	-1.47	0.13
MAX	3.06	8.85	4.73	13.69

Table 2: Delta values of the Physical Target readings against the target's digital reference file. A table of individual patch values is available upon request.

The next phase of the experiment involved mounting the ColorChecker target to the back of the viewing station. This area was chosen as it would allow an accurate perpendicular mount to the camera lens, and it would be the most shielded from potential contamination from ambient light. The camera was mounted to a tripod near the front of the viewing station, and the camera was set to ideal conditions for the shooting conditions as outlined in the Research and Design section of this paper.

Once the camera was configured, two images were taken of the target: the first image was taken as a JPEG, and the second was taken as a camera raw file. The images were taken one after the other, without any changes to variables. Both images were transferred from the camera onto a Macintosh computer for analysis.

Prior to viewing any images on the computer, the color settings in Photoshop were set and saved. For all images opened and manipulated, the same Photoshop settings along with the sRGB profile were used. Figure 4 shows the Photoshop color settings used for this study.

The JPEG image was opened up directly in Photoshop and assigned the sRGB profile. A selection rectangular was made that held 7565 pixels (approximately 85% of the pixels within one ColorChecker patch). The image was then converted to Lab color mode, and using the selection in conjunction with the histogram tool, average L*a*b* values for each patch were measured and recorded.

The raw file underwent a similar process; however, prior to opening it in Photoshop it had to go through some pre-processing. We chose to pre-process the file using a variety of programs, including Adobe Camera Raw, Adobe Lightroom, Bibble Pro, and Canon File Viewer. In total, we ended up with six rendered images divided into three categories as outlined in Table 3. The

L*a*b* for all the patches on each of the six images were compared against the physical target readings. The resulting ΔL, Δa, Δb, and ΔE measurements were charted and analyzed.

	Rendering Software	Image Format	Profile Assigned
Vendor Solutions (Automatic Color)	Camera (Built-in)	JPEG	sRGB IEC61966-2.1
	Canon File Viewer	Camera Raw	sRGB IEC61966-2.1
Unadjusted Color	Bibble Pro	Camera Raw	sRGB IEC61966-2.1
	Adobe Camera Raw*	Camera Raw	sRGB IEC61966-2.1
Third Party Solutions (Automatic Color)	Adobe Camera Raw**	Camera Raw	sRGB IEC61966-2.1
	Adobe Lightroom	Camera Raw	sRGB IEC61966-2.1

Table 3: Resulting image files after rendering.

To better understand the results, the authors subdivided the data into relevant categories. In addition to looking at the overall trend between the 140 patches, we also separated the patches into neutrals and colors, and by their corresponding L*a*b* quadrants. It was also deemed relevant to compare results by vendor (e.g. Canon JPEG vs. Canon File Viewer), and by color rendering adjustment (e.g. Linear vs. default adjustments). Adobe Camera Raw was used in two modes that are referred to as “linear” and “default”. Linear in this context refers to a special mode that converts camera raw to the specified color space (e.g. sRGB) without any color rendering. Sliders are placed in a special position to achieve this result. The default setting converts camera raw to sRGB using the normal, perceptually pleasing color rendering.

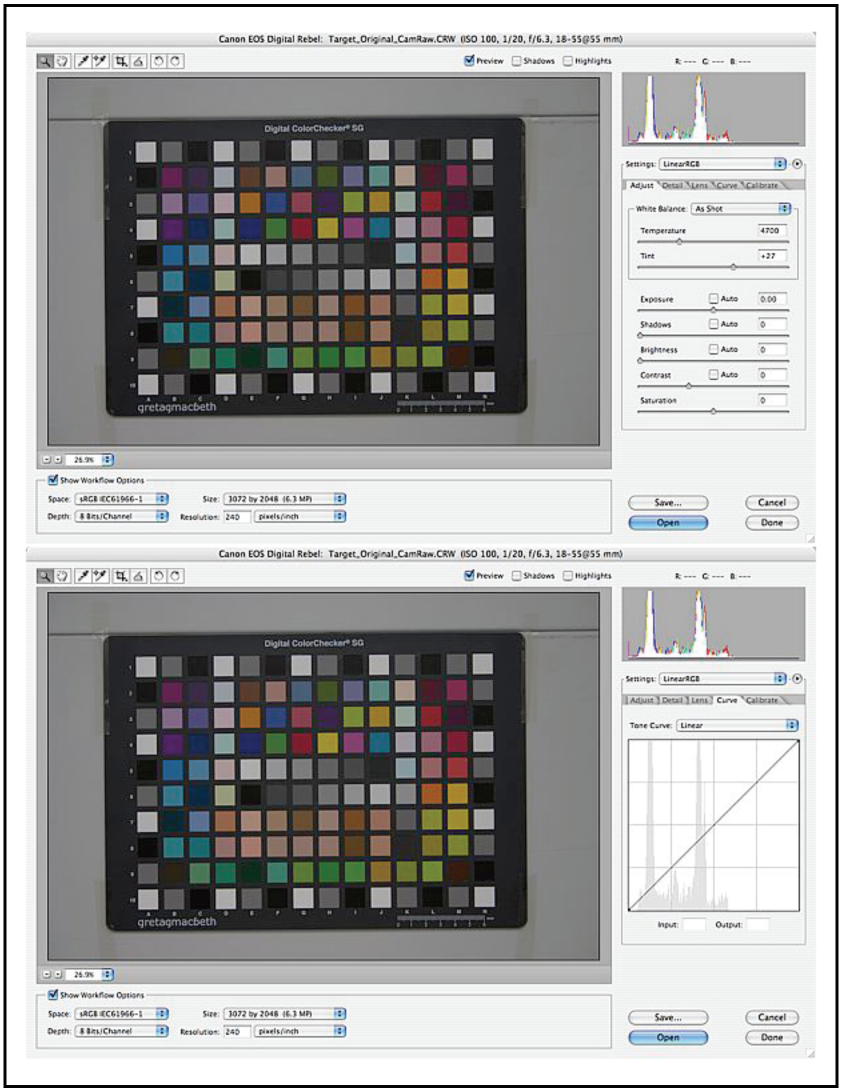

Figure 5: Adobe Camera Raw set to "linear mode" to produced non-rendered RGB data [7].

Results and Discussion

The results showed that colorimetric differences existed between the physically measured L*a*b* values of the target and the corresponding measurements in all six rendered files. The individual results for each patch are too numerous to list in this paper, but a summary of mean delta values is shown in Table 4.

	Average Delta Values for All Rendered Images			
	ΔL_{Pos} / ΔL_{Neg}	Δa_{Pos} / Δa_{Neg}	Δb_{Pos} / Δb_{Neg}	ΔE
Canon JPEG	6.68 / -0.08	3.16 / -5.45	4.19 / -3.10	10.39
Canon File Viewer	7.72 / -0.08	3.27 / -5.69	4.52 / -2.67	11.04
Adobe Camera Raw Linear	21.18 / -2.40	7.83 / -5.64	9.36 / -4.70	25.14
Bibble Pro	16.89 / -2.92	8.10 / -5.21	9.70 / -4.71	20.94
Adobe Camera Raw Default	3.89 / -3.35	6.10 / -3.51	3.45 / -2.83	7.21
Adobe Lightroom	10.94 / 0.00	3.80 / -3.93	3.82 / -1.64	13.13

Table 4: Average Delta Values for all six rendered image files.

When the individual delta values were analyzed, patterns emerged between different rendering methods. These patterns proved to be repeatable, indicating that there is a mappable process for color rendering digital image files.

The data also confirmed the belief that there would be consistencies between the rendering methods offered by the camera manufacturer. The colorimetric values for both the Canon JPEG and the Canon File Viewer are within close proximity to each other. This result is logical, since it can be assumed that the same demosaicing algorithms and color rendering settings would be used in both vendor applications.

Of extreme significance was the relationship between the Adobe Camera Raw Linear image and the Bibble Pro image. In both cases, the software that converted the raw files into RGB was instructed not to render the image. In other words, both Bibble Pro and Adobe Camera raw in a linearized setting are meant to produce an image that is demosaiced but not color enhanced. The results generated from these two programs are the closest possible rendition of a camera raw file that can be generated in RGB. The lack of rendering in both cases produced images that were darker, flatter and duller than any of the other images. This resulted in significantly greater delta variations when compared to rendered versions of the file; however this result was anticipated due to the fact that the image is not rendered for pleasing color.

When the delta charts for the Bibble Pro and Adobe Camera Raw linear files are compared, they are surprisingly similar. This result appears to validate the claim that each program is producing the image in its non-rendered state. So why is this so critical?

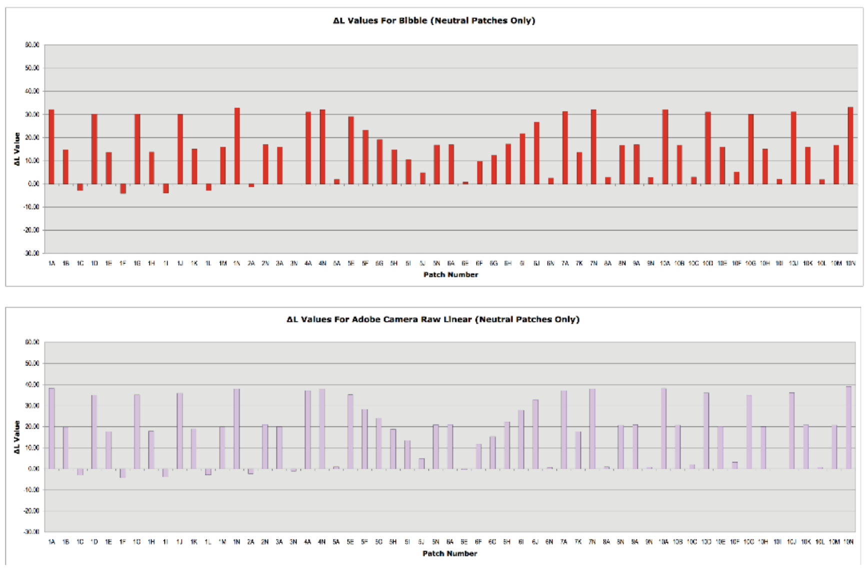

Figure 6: Charts showing the ΔL value for neutral patches in Bibble Pro and Adobe Camera Raw Linear. Patch numbers were used as the x-axis as a constant to compare colorimetric differences.

This method of reading camera raw data may be used as the initial process for creation of an ICC camera profile. There is the general need to characterize digital cameras in order to retrieve colorimetric data from the device. The literature shows examples for food [8], analysis of wounds [9] and mineral analysis [10]. To construct an ICC camera profile it is necessary to have device dependent data (RGB) and device independent data (L*a*b* measurements of the test target) [11]. Bibble Pro or Adobe Camera Raw in the linear configuration both provide a valid starting point for digital camera profiling. It is useful to note that the perceptual intent in an ICC input profile would be used instead of the rendering that has been done by the programs in this study.

If printers are able to produce RGB images that have not had any color rendering applied, it would be possible, at that stage, to apply custom ICC profiles to the image when they are opened in Bibble Pro or Camera Raw, without altering the original raw data. Theoretically, it would be plausible that different ICC profiles could be applied to that same raw file to produced different desired outcomes. The proven predictability of ICC profiling makes this a very attractive alternative to manually adjusting images in an attempt to maximize press conditions. Also, if ICC profiles, along with a calibrated monitor, could be used to accurately display the image on screen, there would be no need to convert the image to CMYK until the very last moment in the workflow. This would be an asset to many printers that have been attempting to managing an RGB workflow for images to increase productivity and flexibility for cross-media publication and re-purposing.

In summary, two significant results were found from the research conducted. First, there is an overall pattern that emerges when the color rendering of raw data is analyzed. Neutrals are the least affected by the rendering, and patterns can be seen in the way color is affected, especially when the results are analyzed by L*a*b* quadrant. In general, rendered images are slightly darker overall when compared to the target. Second, initial testing confirms that software like Bibble Pro and Adobe Camera Raw have the ability to create an RGB representation of raw data without any color rendering, thus making theoretically possible to replace the usual color rendering of the software with rendering done using custom ICC profiles.

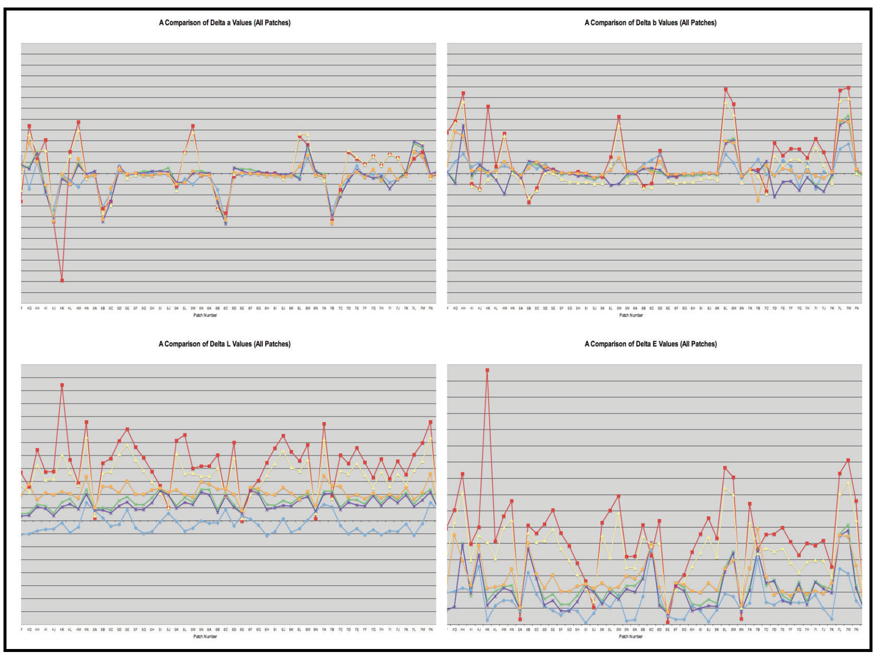

Figure 7: A sampling of trend analysis for Δa, Δb, ΔL, and ΔE.

Unexpected Outcomes

There were a few outcomes that arose from this study that were contradictory to the original hypothesis of the authors. For example, both authors assumed that if color rendering was done in an attempt to make an image more pleasing to the eye, the overall lightness (L*) of the rendered images would be greater than the target. In actuality, the opposite proved to be true. If you refer back to Table 4, you will note that with the exception of Adobe Camera Raw Default, all the rendered images produced a positive ΔL, which means the L* values for the rendered files were lower than the L* values measured on the target.

Another unusual result was found when analyzing the data by vendor. It is a reasonable assumption that two different rendering options made by the same company would yield similar results. This proved true when comparing the in-camera rendering and the File Viewer rendering (Both Canon). When the results produced by the defaults of Adobe Camera Raw were compared to those from Adobe Lightroom, no significant similarity was found. To attempt to explain why this is so would be far beyond the scope of this paper, but it is a valid finding of which the authors have brought to Adobe's attention.

One interesting pattern that emerged was the accuracy of the colorimetric reproduction of the neutral colors within the target. Neutral values in all cases had much lower delta values than the color patches. With commercial printing, neutral values are always the most difficult to achieve and maintain on press, since even the slightest shift in one color will generate a noticeable cast. The fact that the camera reproduced these delicate balances so well was surprising.

When grouping the GretagMacbeth Digital ColorChecker SG patches into their corresponding L*a*b* quadrants, it was discovered that the target was unbalanced; that is, there are some quadrants with significant numbers of patches, and some quadrants with as little as three patches to represent them. This is highly unusual for a test target, which should give even and equal representation to all quadrants of the L*a*b* graph. To illustrate this point, the patches for both the Digital ColorChecker chart and the IT87/2 Print test form were platted in ColorThink Pro. If you refer to Figure 6, you will see that the IT8 target forms a much more uniform scatter outwards from the center axis, with good representation in all quadrants. By contrast, the Digital ColorChecker target is random and sporadic.

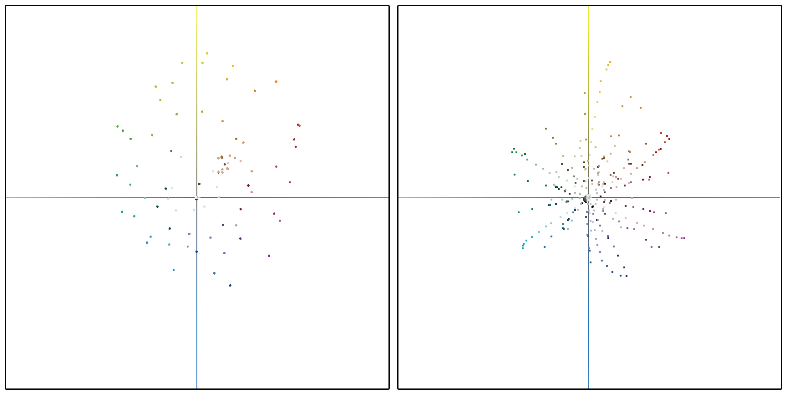

Figure 8: The Target patches for the GretagMacbeth Digital ColorChecker SG Target (Left) are not as uniformly distributed as a standard IT87/2 Print Target.

Conclusion

Summary of Findings

In all six color renderings performed in this experiment, colorimetric differences were evident between the rendered file and the physical target. These differences were the least prominent in the neutral colors. When colorimetric differences were analyzed by L*a*b* quadrant, consistencies emerged that resembled a repeatable pattern. In the authors' opinion, these findings appear to indicate a logical patterning to the rendering of raw camera data, based on algorithms that affect different groupings of colors differently. It may be possible to isolate specific patterns and identify the mathematical formulation behind the patterning, however, more research would be needed before such a step could occur.

Of significant importance to further research initiatives was the success of reproducing very similar non-rendered camera raw files in RGB format using two unrelated products. The implications of this have to do with the potential of replacing the software based, non-standardized rendering with custom ICC profiles that could be used to render images according to specific output targets. Such an achievement would have a significant impact of the graphic communications industry and current image processing workflows.

Currently, many commercial offset printers convert images into CMYK very early on in the workflow. This is done so that the images can be viewed, manipulated, and proofed in ways that will reflect the final output. If our theory of ICC rendering could be applied, this would allow printers to keep the images in an RGB format right until the final output of the job, allowing for much greater flexibility in cross media and repurposing applications.

For Further Study

The authors of this paper would like to further study the implications of using software such as Bibble Pro and Adobe Camera Raw to create linearized camera raw files that can be assigned custom ICC device profiles in an attempt to match printed results on the monitor. In addition, we will explore the feasibility of running non-rendered results through the CIECAM02 color model using Matlab to mathematically predict rendering outcomes.

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