Fidelity of Color Reproduction by Digital Cameras. 2. Adobe Standard and ColorChecker Passport Camera Profiles

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Summary

A raw image of a ColorChecker Classic chart was processed with three camera profiles: an Adobe Standard profile, a profile made with the ColorChecker Passport application, and a "do-it-yourself" profile made by the author. Accuracy of color reproduction was evaluated with the CIEDE2000 color-difference metric. The ColorChecker Passport profile resulted in the least accurate colors, as measured by average CIEDE2000. The author's "do-it-yourself" profile produced the most accurate colors. Passport profile colors are systematically biased in the direction of increased chroma (C^*). The bias is almost certainly intentional, and possible reasons for it are discussed.

Key words: Sony A6500, camera profile, multiple regression, Adobe Standard camera profile, ColorChecker Classic, ColorChecker Passport application, RawDigger, CIEDE2000

1. Introduction

A camera profile is a set of instructions for converting raw *RGB* values to a destination color space. In the case of Adobe Camera Raw and Lightroom, at least, the destination space is CIE XYZ. In principle, however, it could be a linearized version of any standard RGB space (ProPhotoRGB, AdobeRGB, etc.).[1] The basic theory underlying profiling is described in the previous paper in this series.[2] That paper also illustrates the process of deriving a simple profile, using raw data from an image of a reference color chart.

The present paper compares the results of three different profiles when applied to the same raw image of a ColorChecker Classic chart. The three profiles are: (1) the Adobe Standard profile included in Camera Raw; (2) a profile made with the ColorChecker Passport application; and (3) a DIY (do-it-yourself) profile made by me using raw data extracted with RawDigger. Reference color coordinates ($L^*a^*b^*$) for the ColorChecker Classic are published. Thus, a

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[1] By "linearized" I mean not gamma-encoded. CIE XYZ is linear. But the main reason for using it as the destination space for raw conversion is that it encompasses the entire gamut of human color vision. Thus, it includes all visible colors that can be captured by a camera sensor. This has the benefit of separating raw conversion from gamut mapping: the process of assigning colors that are out of gamut in the destination color space to colors that can be displayed in that space.

[2] Service, Phil. 2016. Fidelity of Color Reproduction by Digital Cameras: Theory and Example.

ColorChecker can serve as a reference target for making camera profiles; and those same profiles can be evaluated by comparing the colors in a *processed image* of the ColorChecker with the known reference values.

2. Materials and Methods

A Sony A6500 camera was used to photograph a ColorChecker Classic in direct sunlight at midday.[3] Using Adobe Camera Raw (9.8), a single "well-exposed" image was chosen from a bracketed series. I chose the image in which the Neutral 5 patch of the ColorChecker was closest to its AdobeRGB reference coordinates [120, 120, 120] after white balancing, but without exposure correction. Among other things, this criterion ensured that no patches of the ColorChecker were overexposed. The raw (ARW) image was converted to DNG format and passed to the ColorChecker Passport (1.1.0) application in order to create a profile, hereafter referred to as the CCPassport profile.

The original raw image was re-opened in Camera Raw and processed twice: once using the Adobe Standard profile, and once using the CCPassport profile. In both cases, white balance was set using the Neutral 5 patch, and exposure was adjusted slightly so that the Neutral 5 patch coordinates were as close as practicable to [120, 120, 120]. With one exception to be described below, no other tonal adjustments were made. Both processed images were passed to Photoshop CC (2017). In Photoshop, a 101 x 101 pixel color sample was taken from the center of each color patch. Patch colors of each image were compared to reference values using the ΔE_{00} color-difference metric (also known as CIEDE2000). A ΔE_{00} value of 1.0 corresponds approximately to a just noticeable difference (JND) when two colors are compared side-by-side under favorable conditions.[4]

In addition to processing the raw image with the above two profiles, I used the *same raw image* to make a third profile which I refer to as the DIY (do-it-yourself) profile. The procedure is described in some detail in the previous paper. Briefly, it involves using RawDigger to extract raw *RGB* values from a sample of pixels in the center of each color patch. ColorChecker reference *XYZ* values are then "fit" to the raw data by multiple regression. The result is a set of regression coefficients that can be used to transform the raw *RGB* coordinates into *estimated XYZ* coordinates. In matrix formulation, the transformation that I arrived at is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{est}} = \begin{bmatrix} 4.438339 & 0.654180 & -0.280813 \\ 1.224746 & 2.492683 & -1.204053 \\ -0.023220 & -0.394399 & 3.784297 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{raw}}$$

[3] The ColorChecker chart was the August 2016 Edition. It was purchased from B&H in December 2016. I assume that the colors conform to the reference values applicable to charts manufactured after November 2014. For more information on the importance of date of manufacture see this page at BabelColor.

[4] For more information about ΔE_{00}, and other color-difference metrics, see the previous paper in this series, and references therein.

Estimated *XYZ* coordinates obtained by the above equation represent the "output" of the DIY profile. The differences between output and reference *XYZ* coordinates were summarized by ΔE_{00}, in that same way that differences between the ColorChecker and the images made with the Adobe Standard and CCPassport profiles were summarized. To be clear, however, the original raw file was *not* processed through Camera Raw and Photoshop using the DIY profile. Thus, the DIY RGB-to-XYZ transformation was applied to raw image data that had no white balancing or exposure correction; and the result is a virtual, or synthetic, image — not a conventional image made by post-processing in software.

It is important to realize that the "fit" of reference *XYZ* coordinates to observed raw *RGB* values by linear regression is unlikely to be — in fact, may *never* be — perfect. Thus, when raw *RGB* values are transformed to *XYZ*, the latter are *estimates* of the true *XYZ* coordinates of the object that was photographed. The implication should be clear: *it is unlikely that any camera profile can reproduce all colors with absolute fidelity, even when the "test" of a profile is an image of the object used to make that profile.*

3. **Results**

The results for ΔE_{00} are summarized in Table 1. Visual comparisons of the results of the Adobe Standard, CCPassport, and DIY profiles are shown in Fig. 1, together with a synthetic image of the the ColorChecker that was made using reference color coordinates.[5] The most accurate colors, based on smallest average ΔE_{00}, were obtained with the DIY profile. Surprisingly, the least accurate were obtained with the ColorChecker Passport application. This is particularly noteworthy given that the CCPassport profile was evaluated with the image used to create the profile: in other words it was evaluated in what should be a "best case" scenario. The Adobe Standard profile performed slightly better than the CCPassport profile. It should be noted, however, that the Adobe profile did not have the "benefit" of being created under the lighting conditions and with the image used to test it.[6] Regardless of average performance, ΔE_{00} was greater than the approximate threshold for a just noticeable difference (1.0) for most color patches of all profiles (Table 1). Whether such differences seem subjectively important can be evaluated by looking at Fig. 1.

Summary statistics at the bottom of Table 1 reveal that the CCPassport profile produced colors with increased chroma (positive average ΔC^*). In fact, chroma was increased not just on

[5] Fig. 1 is provided as a separate document, which can be accessed by clicking on this link, or on the links in the text. For compatibility with most viewing environments, Fig. 1 is encoded as an 8-bit sRGB image. However, AdobeRGB was used in the actual processing pipeline. Note that a number of colors produced by the profiles are outside the sRGB gamut, as indicated in Fig. 1.

[6] Presumably Adobe uses procedures roughly similar to those outlined here to make camera profiles, or perhaps in some cases obtains the necessary data from camera manufacturers. The profiles shipped with Camera Raw and Lightroom cannot be made under all conceivable lighting conditions. Instead, inspection of DNG file metadata reveals that Adobe provides two raw RGB-to-XYZ transition matrices (referred to as ForwardMatrix1 and 2): one made under Illuminant A (incandescent) and the other under D65. For an image taken under any other lighting condition, an *ad hoc* forward matrix is estimated by interpolation of the two "canned" matrices; the interpolation being based on white-balance adjustment in ACR, or possibly on a white-balance value in the raw file metadata. Additional information can be found in Ch. 6 of the Adobe Digital Negative Specification.

Table 1. Camera Profile and ΔE_{00} for X-Rite ColorChecker (November 2014)

	Profile†			
	Adobe Standard	CCPassport	CCPassport with -18 Vibrance	DIY
dark skin	3.08	3.13	2.28	4.49
light skin	4.58	4.71	4.90	2.17
blue sky	8.11	5.63	6.70	3.67
foliage	2.90	3.09	1.49	3.45
blue flower	2.31	1.60	2.51	1.94
bluish green	2.85	0.81	2.91	2.53
orange	2.06	4.47	2.22	1.73
purplish blue	5.16	5.88	1.81	3.31
moderate red	7.67	6.91	7.60	4.15
purple	3.57	5.43	4.20	1.29
yellow green	3.67	2.95	1.61	0.48
orange yellow	1.93	3.37	0.26	2.96
blue	6.75	5.94	3.39	3.92
green	5.01	5.72	3.98	3.10
red	2.32	4.97	3.12	1.62
yellow	2.45	2.05	2.19	0.96
magenta	2.16	3.75	1.70	1.91
cyan	4.16	2.49	2.50	2.10
white 9.5 (.05 D)	2.74	2.56	2.89	0.37
neutral 8 (.23 D)	1.92	1.68	1.70	0.90
neutral 6.5 (.44 D)	3.64	3.40	3.47	0.53
neutral 5 (.70 D)	0.22	0.61	0.14	1.82
neutral 3.5 (1.05 D)	4.30	4.48	4.46	1.55
black 2 (1.5 D)	7.13	7.14	7.14	1.72
Avg. ΔE_{00} - Colors	3.93	4.05	3.08	2.54
Avg. ΔE_{00} - Gray Scale	3.33	3.31	3.30	1.15
Avg. ΔE_{00} - All	3.78	3.87	3.13	2.19
Avg. ΔL^* (colors only)	2.60	1.11	1.72	0.27
Avg. ΔC^* (colors only)	-2.31	8.87	-0.62	-0.32
Avg. Δh (abs. value, colors only)	3.12	1.63	1.42	2.06

† The least ΔE for each color patch is indicated by light-blue fill. Positive values of ΔL^* and ΔC^* indicate that the color patch in the image was lighter or more chromatic, respectively, than the reference ColorChecker value.

average, *but for each individual color patch* (data not shown). Table 1 also shows results for an image that was that was processed with the Passport profile (as before), but with Vibrance set to -18 in Camera Raw. As can be seen, average ΔC^* was reduced to less than 1.0 (absolute value), and average ΔE_{00} was consequently also lower.

Chroma is not synonymous with saturation (see Discussion). However, all other things being equal, an increase in chroma means an increase in saturation. The increased saturation that results from the CCPassport profile can readily be seen by comparison to a reference image of the ColorChecker chart (Fig. 1).

4. Discussion

It is clear that quantitative color accuracy was not the intent of the authors of the ColorChecker Passport application. I repeated these "experiments" with a Passport profile made under shady conditions, and with a dual-illuminant profile. The results were the same: chroma is systematically increased. It is not clear why the authors chose that bias. Perhaps they believe that the results are more subjectively appealing to most people. It might also be possible that the results are perceived as more *subjectively accurate.* Actual ColorChecker charts are viewed by reflected light. On the other hand, an *image* of a ColorChecker viewed on a monitor is seen by emissive light. An argument can be made that colors viewed on a monitor are, in fact, less *saturated* than colors with identical chroma seen by reflected light. The reason is that, for many colors, higher absolute chroma can be obtained with emissive light sources.[7] Saturation, more carefully defined, is relative chroma: that is, the chroma (C^*) of a color relative to the maximum possible chroma for that hue (h) and lightness (L^*). Given that maximum possible chroma is generally greater for emissive light sources than for surface colors (those seen by reflected light), it follows that if chroma (C^*) is constant, then saturation will be less for colors seen by emissive light. The bias of ColorChecker Passport profiles toward increased chroma may represent an attempt to compensate for this effect. It is possible that we may be quite sensitive to changes in saturation, as just defined, if experience "tells" us, probably subconsciously, that maximum chroma depends upon type of illumination.

The real value of Passport profiling might be consistency of color across images taken under different conditions. It is quick and easy to make a Passport profile. Take an image that includes a ColorChecker chart; convert the image to DNG format; and drag the DNG onto the Passport application window. After the profile is made, it can be named and will be saved in a location that makes it accessible to Camera Raw. In principle, then, it is not prohibitively difficult or time-consuming to make a profile for every set of images made under the same conditions (a "shoot"). With shoot-specific profiles, it seems reasonable to think that color consistency across shoots will be better than can be obtained by relying on "canned" profiles. However, that assumption remains to be tested.

[7] For example, color spaces used for "wide-gamut" displays, such as AdobeRGB and DCI-P3, can exceed Pointer's gamut for many hues and lightnesses (Service, Phil. 2016. Pointer's Gamut, MacAdam Limits, and Wide-Gamut Displays). (Pointer's gamut is the gamut of real surface colors: that is, actual colors seen by reflected light.)