Fidelity of Color Reproduction by Digital Cameras. 3. Consistency

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Summary

Images of a ColorChecker Classic were taken in direct sunlight and shade. Consistency of color reproduction across lighting conditions was best when using ColorChecker Passport profiles made specifically for each situation. The general-purpose dual-illuminant Adobe Standard profile for the Sony A6500 camera gave less color consistency between sun and shade images. However, the effect of camera profile on consistency, as measured by CIEDE2000, was not large. Average CIEDE2000 between sun and shade images was approximately 2.0 for the Passport profiles; a value that is well above the threshold of just noticeable difference when colors are compared side-by-side. It is likely that no profiling procedure can produce absolute color consistency across different illuminants and shooting situations, given current camera sensor technology.

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

1. Introduction

The previous paper in this series examined the fidelity of color reproduction using three camera profiles: an Adobe Standard profile, a custom profile made with the ColorChecker Passport application, and a custom DIY (do-it-yourself) profile made by me.[1] Overall, the bespoke Passport profile produced the *least* accurate colors. That appeared to be due to an intentional bias toward greater color saturation. I suggested that the main utility of the Passport application might be improved color consistency among images taken under different conditions, especially different illuminants. The ease with which Passport profiles can be made makes it feasible to generate custom profiles for every photographic session (a “shoot”), or even for individual images. It is possible that custom, shoot-specific profiles will produce better color consistency than general purpose profiles such as the Adobe Standard profile — even if the resulting colors are not particularly accurate.

A camera profile is a set of instructions for converting raw *RGB* values to CIE *XYZ* coordinates. In its simplest form, the profile is a 3 x 3 matrix of coefficients that compute *X, Y,*

[1] Service, Phil. 2016. Fidelity of Color Reproduction by Digital Cameras. 2. Adobe Standard and ColorChecker Passport Camera Profiles.

and *Z* from combinations of *R, G* and *B.*[2] Suppose the same object is photographed under two different lighting conditions, say sun and shade. The *RGB* values that correspond to a particular object color will *not* be the same the two raw files.[3] Thus, different matrices are required to convert those different *RGB* values into the same *XYZ* coordinates — assuming that we want the object colors to be the same in both images. In other words, every lighting condition requires its own camera profile. And this does not mean just "big" differences in illumination, such as sun vs. shade vs. incandescent vs. fluorescent, etc. Even the spectrum of direct sunlight varies at different times of the day, at different latitudes, and at different seasons. Obviously, it is not possible for a software developer to include profiles for every likely lighting situation. The general solution is to provide a dual-illuminant profile — that is, a profile that includes conversion matrices for two illuminants of widely varying color temperatures. These two matrices are then used to calculate an ad hoc conversion matrix for each image based on the correlated color temperature of the white balance setting for that image. For example, the Adobe Standard profile for each camera model has camera RGB-to-XYZ matrices for illuminant A (incandescent, 2856º K) and for D65 illuminant (6504º K). The actual conversion matrix used for any raw image is interpolated from these two, possibly modified by other information in the raw file.[4]

An alternative to using a general-purpose dual-illuminant profile is to create a custom profile for each shooting session. That is, to make a profile under the same illumination as a set of images, and then use that bespoke "shoot-specific" profile for raw conversion. The ColorChecker Passport application makes this process quick and easy. All that is necessary is to make an image of a ColorChecker chart, convert the image to DNG format, and then drag the DNG file onto the application window. The custom profile will be saved in a location accessible to Lightroom or Camera Raw. It seems reasonable to think that shoot-specific profiles will result in better color consistency than dual-illuminant profiles across different lighting conditions. This paper reports a limited test of that idea.

2. Materials and Methods

A Sony A6500 camera was used to photograph a ColorChecker Classic in direct sunlight and in shade.[5] Images for analysis were chosen and processed as described in the previous paper.[6] In fact, the "sun" image was the same as used previously. The "sun" and "shade" images

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

[3] The reason is that the camera "sees" the object by reflected light. The *RGB* values in the raw file thus depend on the spectral power distribution of the reflected light. Which, in turns, depends on the spectrum of the illuminant.

[4] See Ch. 6 of the Adobe Digital Negative Specification: Mapping Camera Color Space to CIE XYZ Space. The two camera RGB-to-XYZ matrices are tagged as ForwardMatrix1 and ForwardMatrix2.

[5] The ColorChecker chart was the August 2016 Edition. It was purchased from B&H in December 2016.

[6] Service, Phil. 2016. Fidelity of Color Reproduction by Digital Cameras. 2. Adobe Standard and ColorChecker Passport Camera Profiles. Image processing was the same except that in the present case I used ProPhotoRGB as the working color space.

were each processed through Camera Raw twice: once using the Adobe Standard Profile, and once using an image-specific profile generated by the Passport application.[7] Patch colors were compared between the sun and shade images obtained with each profile. That is, the sun colors obtained with the Adobe Standard profile were compared to the shade colors obtained with that same profile. A similar comparison was made between sun and shade colors obtained with the two custom Passport profiles. Lastly, I made my own DIY (do-it-yourself) RGB-to-XYZ conversion matrices, as described previously, for the sun and shade images. Color consistency obtained with these two DIY profiles was also evaluated.

Sun-vs.-shade color consistency was quantified 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.[8]

3. Results

The results for ΔE_{00} are summarized in Table 1. Overall, consistency was best with the image-specific Passport profiles. Considering just the 18 color patches, three had ΔE_{00} below the likely threshold of just noticeable difference (< 1.0). Another four had ΔE_{00} less than 1.5, and for seven patches, ΔE_{00} was ≥ 2.0. The dual-illuminant Adobe Standard profile performed worst on average, and the two DIY profiles were intermediate in consistency. Considering all 24 patches, the Passport profiles produced the lowest ΔE_{00} for 12. The DIY profiles gave best consistency for 10 patches. The two Passport profiles produced a lower ΔE_{00} than the Adobe Standard profile for 14 of the 18 color patches and all six of the gray-scale patches, although the improvement in consistency might not be apparent in all cases.

There was a noticeable correlation between the ΔE_{00} values produced by the Adobe Standard and Passport profiles. For example, the moderate red patch (ColorChecker second row) had the highest value for both profiles; and the yellow and cyan patches (third row) the lowest values. That suggests an underlying similarity in the way that raw data is used to generate the profiles. On the other hand, the ΔE_{00} values of the DIY profiles were not obviously correlated with other two.

4. Discussion

These results support the idea that image-specific or shoot-specific camera profiles will give better color consistency across different lighting conditions than will general-purpose dual-illuminant profiles. That said, the differences revealed here are not that striking and might not be viewed as important, or worth the trouble of creating additional profiles, in most situations.

It might seem odd that even when custom image-specific profiles are created — as was the case here for the Passport and DIY profiles — color consistency is not perfect. To understand why, it may help to consider the process of making a profile in more detail. Essentially, it involves fitting known CIE *XYZ* coordinates for a set of reference colors (*e.g.,* a

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[7] To be precise, the Passport profiles were made from the *same* images that were used for the analysis.

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

Table 1. Sun vs. Shade ΔE_{00} for X-Rite ColorChecker (November 2014)

	Profile†		
	Adobe Standard	CCPassport	DIY
dark skin	3.27	2.99	1.96
light skin	1.87	1.43	2.65
blue sky	2.26	1.70	0.68
foliage	2.67	2.00	1.46
blue flower	3.52	3.51	4.43
bluish green	3.62	3.01	3.49
orange	1.82	0.78	2.09
purplish blue	1.99	3.60	5.10
moderate red	4.06	4.25	2.37
purple	2.31	1.81	3.06
yellow green	3.61	1.76	1.15
orange yellow	2.33	1.19	2.25
blue	3.33	2.68	2.16
green	2.45	1.09	0.79
red	2.13	1.33	2.89
yellow	0.43	0.58	1.10
magenta	1.62	1.05	3.40
cyan	0.60	0.51	1.91
white 9.5 (.05 D)	2.17	1.79	0.56
neutral 8 (.23 D)	1.92	1.66	0.76
neutral 6.5 (.44 D)	2.19	1.77	1.35
neutral 5 (.70 D)	2.20	1.00	1.59
neutral 3.5 (1.05 D)	1.78	0.78	1.86
black 2 (1.5 D)	1.47	0.81	1.72
Avg. ΔE_{00} - Colors	2.44	1.96	2.39
Avg. ΔE_{00} - Gray Scale	1.96	1.30	1.30
Avg. ΔE_{00} - All	2.32	1.80	2.12
Avg. ΔL^* (colors only)	0.94	0.70	1.87
Avg. ΔC^* (colors only)	3.04	1.67	-1.87
Avg. Δh (abs. value, colors only)	2.23	0.85	1.70

† 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 "shade" image was lighter or more chromatic, respectively, than the color patch in the "sun" image.

ColorChecker) to an observed set of *RGB* coordinates in a raw image of the reference target. For the DIY profiles, the fitting was done by three multiple linear regressions. That is, known *X* coordinates for each of the 24 patches were regressed on raw *R, G,* and *B* coordinates for each patch. Similar multiple regressions were done for the known *Y* and *Z* coordinates, using the same *R, G,* and *B* values.[9] Empirically, the fit of known *XYZ* coordinates to observed *RGB* values seems never to be perfect.[10] That is, not all of the variation in *XYZ* over the 24 patches can be "explained" by the observed variation in raw *RGB* values over those patches. We encountered this "lack of fit" in the previous paper, when considering images taken in sunlight: we saw that no profile produced an image with colors that exactly matched the ColorChecker target. Similarly, we can be quite certain that none of the profiles used for the "shade" images in this paper would produce exact matches to the ColorChecker. So, considering the DIY profiles for example, we have two profiles (sun and shade) each of which separately and imperfectly estimates the true *XYZ* coordinates of the ColorChecker. Given that the two profiles were made by regression using different sets of raw *RGB* values, there is every reason to believe that the profiles themselves will be *different* and, therefore, that the colors of the ColorChecker *images* will also be different. As we saw previously, it is unlikely — perhaps beyond current technology — to create a camera sensor and profile that can simultaneously reproduce a wide range of colors with absolute fidelity. For essentially the same reason, we should not expect to see a wide range of colors reproduced with absolute consistency when objects are photographed under different illuminants. I propose that color *inconsistency* across illuminants is an inescapable "fact of life". It has its roots in the spectral response functions of the camera sensor; in the same way that lack of color fidelity is also due, ultimately, to those same spectral response functions.[11]

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[9] I assume that a fundamentally similar method is used by Adobe and by ColorChecker Passport.

[10] Jiang, J., D. Liu, J. Gu, and S. Süsstrunk. 2013. What is the space of spectral sensitivity functions for digital color cameras? Workshop on Applications of Computer Vision (WACV). For this reason, it is unlikely that the results reported in this paper would be qualitatively different if I had used a different camera model.

[11] Service, Phil. 2016. Fidelity of Color Reproduction by Digital Cameras: Theory and Example.
Jiang, J., D. Liu, J. Gu, and S. Süsstrunk. 2013. What is the space of spectral sensitivity functions for digital color cameras? Workshop on Applications of Computer Vision (WACV).