Fidelity of Color Reproduction by Digital Cameras: Theory and Example

Phil Service
Flagstaff, Arizona, USA
14 November 2016

Summary

Data from the red-, green-, and blue-sensitive receptors of a camera sensor must be converted to a standard color space in order for images to be displayed properly. The CIE 1931 XYZ space, which encompasses the entire gamut of human color vision, serves as an intermediate between camera raw RGB and practical color spaces such as sRGB and AdobeRGB. The process of converting camera raw data to *XYZ* coordinates is explained. Empirically, the conversion seems never to be perfect. Color difference metrics (ΔE) are reviewed, and several color pairs designed to be near the threshold of just noticeable difference are illustrated. Reproduction of a 24-patch Color Checker Classic by a Sony A6300 camera is evaluated. Even with the best transformation investigated, the colors reproduced by the A6300 are generally distinguishable from their Color Checker standards. Camera profiling is the process of finding a set of linear equations that transform camera raw data to *XYZ* coordinates. The data necessary for constructing a profile are extracted from an A6300 raw image, and the transformation equations are estimated by multiple linear regression.

Key words: Sony A6300, Canon 60D, sensor spectral sensitivity, camera calibration, camera profile, multiple regression, Luther condition, CIE 1931 color matching functions, CIE XYZ color model, Color Checker Classic, RawDigger, Delta E, CIEDE2000, CIE94, CIE76, CMC, CMC(l:c), just noticeable difference, JND, BabelColor, Bruce Lindbloom

1. Introduction

Accurate color reproduction is not necessarily an important photographic goal. In fact, color is one of the image qualities that is frequently manipulated for creative effect. Color fidelity is clearly *not* the goal of various in-camera JPEG "styles" or "effects", such as Vivid, Neutral, Standard, Portrait, Landscape, etc. Nevertheless, it may be of at least academic interest to examine how accurately color can be reproduced by digital cameras, when that is a goal. I start by outlining the way in which camera raw RGB color is interpreted in the context of an established system of quantitative color description — the CIE 1931 XYZ color model.[1] Second, I review metrics of color difference, ΔE. Then, in order to gain some insight into what ΔE really means, I show several synthetic examples of color differences that are intended to be near the threshold of perceptibility. Following that, I examine the fidelity of color reproduction by the

[1] CIE stands for Commission Internationale de l'Eclairage: in English, the International Commission on Illumination.

Sony A6300 using a 24-patch Color Checker Classic. In an appendix, I show how the equations for transforming camera raw *RGB* values to CIE *XYZ* coordinates are estimated; using a raw image of a Color Checker Classic and readily available software.

1.1. The Problem — Mapping Camera Raw *RGB* to CIE *XYZ*

A camera encodes colors in a raw file as *R, G,* and *B* values. The task of a raw processor (in or out of camera) is to translate those raw *RGB* values into CIE *XYZ* coordinates. The *XYZ* coordinates are a mathematical description of a color as it appears to a "standard observer". In the abstract, each is computed by summing, over all visible wavelengths, the product of a *color matching function* and the spectral radiance of the light coming from an object. In equation form:

$$X = \mathrm{C}\sum_{\lambda} \bar{x}(\lambda)E(\lambda)$$
$$Y = \mathrm{C}\sum_{\lambda} \bar{y}(\lambda)E(\lambda)$$
$$Z = \mathrm{C}\sum_{\lambda} \bar{z}(\lambda)E(\lambda)$$

where $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the CIE color matching functions, and $E(\lambda)$ is the radiance of the object (usually seen by reflected light) at wavelength λ. The summation is done over all visible wavelengths: often taken to be 380 to 780 nm, although the limits are "fuzzy". C is a scaling constant, that depends on the wavelength interval used for the summation, *e.g.,* 1 nm, 5 nm, etc.; and is generally chosen so that $Y = 1.0$ for "white" light. *XYZ* coordinates are easily transformed into the various standard RGB color spaces — such as sRGB, AdobeRGB, or ProPhotoRGB — that we are familiar with.[2]

In effect, the red, green, and blue photoreceptors of the camera are performing a "calculation" that is analogous to computing *XYZ*. That is, the raw *R* value, say, is the summation (over wavelengths) of the product of the sensitivity of a red receptor to each wavelength times the amount of light at each wavelength. Similar "calculations" are occurring with the green and blue-sensitive photoreceptors. The camera sensor and circuitry can be thought of as calculating the following equations:

$$R = \mathrm{C}\sum_{\lambda} r(\lambda)E(\lambda)$$
$$G = \mathrm{C}\sum_{\lambda} g(\lambda)E(\lambda)$$
$$B = \mathrm{C}\sum_{\lambda} b(\lambda)E(\lambda)$$

[2] The derivation of the CIE color matching functions is described here. A sample calculation of the *XYZ* coordinates for the "foliage" patch of the Color Checker Classic is given in Appendix A.

Where $r(\lambda)$, $g(\lambda)$, and $b(\lambda)$ are the spectral sensitivity functions of the red, green, and blue photoreceptors. In general, the translation of raw *RGB* values to *XYZ* coordinates will not be perfect. An often-stated necessary condition is that the CIE color matching functions must be (exact) linear transformations of the spectral sensitivity functions of the photoreceptors. Or, what is the same thing, that *X, Y,* and Z must be (exact) linear transformations of the raw *R, G* and *B* values. This sometimes referred to as the "Luther condition" (after Robert Luther, 1868 – 1945).[3] One way that the necessary condition could be satisfied is if the spectral sensitivity functions of the sensor were "scale models" of the CIE color matching functions. More generally, *X, Y,* and *Z* are taken to be combinations of all three *RGB,*values, as follows:

$$
\begin{aligned}
X &= c_{11}R + c_{12}G + c_{13}B \\
Y &= c_{21}R + c_{22}G + c_{23}B \\
Z &= c_{31}R + c_{32}G + c_{33}B
\end{aligned}
$$

As a rule, the transformation from camera raw *RGB* to CIE *XYZ* will be done with "error", and the Luther condition is only approximated.[4] Jiang *et al.* (2013) estimated the spectral sensitivity functions of 28 digital cameras.[5] Their Fig. 3 shows that none of the 28 sensors could exactly satisfy the Luther condition. Of those 28, the Canon 60D had one of the smallest errors.[6] The spectral sensitivity functions of the 60D, together with the CIE 1931 color matching functions, are shown in Fig. 1. As a practical matter, it is not necessary to measure the spectral sensitivity of a camera sensor in order to find the best transformation from raw *RGB* to *XYZ*. A procedure for estimating the transformation — that is, a camera profiling procedure — is outlined in Appendix B.

The foregoing explains why white balancing an image by reference to a neutral object is generally only partially successful in correcting color. True, an object that is supposed to be neutral can be made so, and an overall color cast will be removed from the image. However, the underlying problem of translating camera *RGB* to *XYZ* remains.

---

[3] I have not found an explanation for why the transformation needs to be *linear*.

[4] "Error" is used here in the statistical sense of variation in a dependent variable that is not "explained" by an independent variable (or variables). In this case, the dependent variables are the known *XYZ* values of a reference target (*e.g.,* a Color Checker), and the independent variables are the corresponding camera raw *RGB* values.

[5] 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).

[6] A link to the sensitivity function data for all 28 sensors can be found near the bottom of this page.

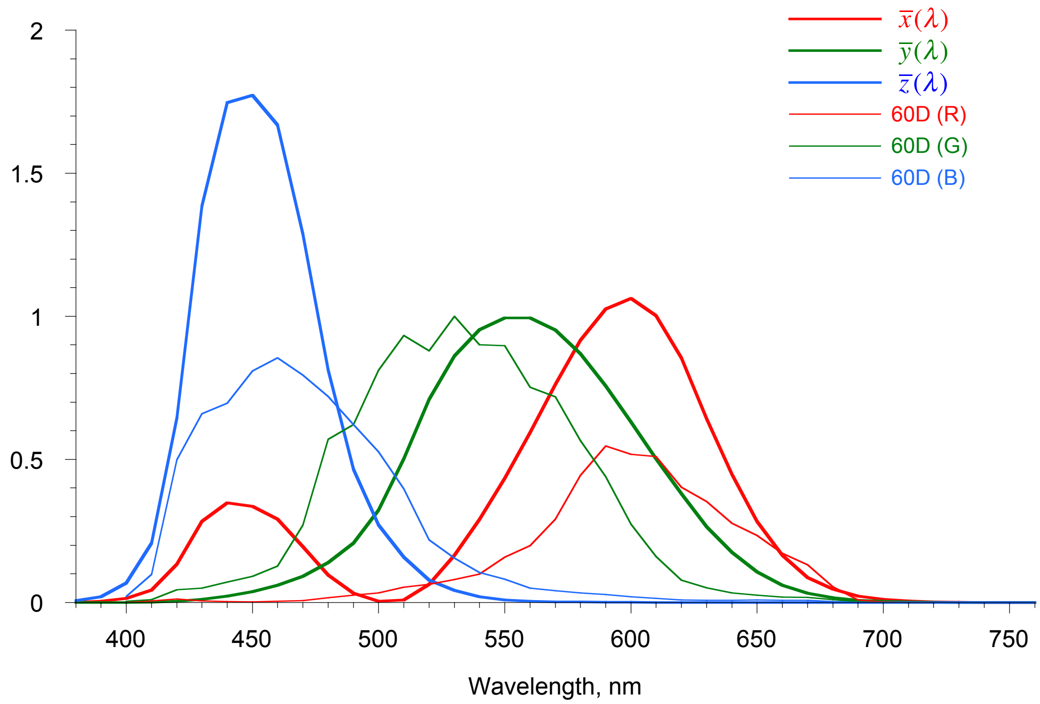

Fig. 1. The CIE 1931 color matching functions (thick lines) and the spectral sensitivity functions of the Canon 60D (thin lines). Data at 10 nm intervals. Differences in heights of the curves (between CIE and Canon) are unimportant artifacts of the different ways in which the curves were "normalized". More important are differences in location and shape of the curves. The Canon 60D data were obtained here.

1.2. Color-Difference Metrics

Quantitative measures of color difference are commonly known as *Delta E* (ΔE).[7] There are at least four different ΔE metrics in use. All are based on the $L^*a^*b^*$ color model (hereafter Lab model), or its transformation to the L^*C^*h model (hereafter LCh_{ab}).[8] The simplest metric is the one established by the CIE in 1976. Strictly speaking, this metric is designated ΔE^*_{ab}. However, it has become common practice to refer to it as CIEDE1976, Delta E (CIE 1976), or simply CIE76. For consistency with subsequent metrics proposed by the CIE, I will use ΔE_{76}. It is just the geometric distance between two colors in three-dimensional Lab space: in other words, the square root of the sum of squared differences in L^*, a^*, and b^*. Although the Lab color model was designed to be perceptually uniform, ΔE_{76} is not. That is, the correspondence between the magnitude of ΔE_{76} and *perceived* color difference is not very strong. Consequently a new metric, ΔE_{94}, designed to have better perceptual consistency was introduced by the CIE in

---

[7] "E" is taken from the German word *Empfindung* which may be translated as "sensation", "feeling", or "perception".

[8] *L** is lightness, which is scaled from 0 (black) to 100 (white). *C** is chroma, with a minimum value of 0 (gray-scale), and a maximum value that depends on lightness and hue. For lack of a better word, chroma is "colorfulness" or intensity of color. Chroma and saturation are *not* synonymous. However, colors that have high chroma are likely also to be considered saturated. *h* is hue, which is expressed as an angle (0 – 360º).

1994. The CIE then made further refinements and ΔE_{94} was superseded in 2000 by ΔE_{00}. Both ΔE_{94} and ΔE_{00} are based on the LCh_{ab} model. The last metric that I will consider was developed in 1984 by the Color Measurement Committee of the Society of Dyers and Colourists (UK). For consistency, I will refer to this metric as ΔE_{CMC}. It is also based on the LCh_{ab} color model. It preceded, and was the model for, development of ΔE_{94}.[9]

Values of ΔE_{94}, ΔE_{00}, and ΔE_{CMC} are generally fairly similar. All three appear to be designed with the intent that a value of about 1.0 corresponds to a just noticeable difference (JND) when two colors are compared side-by-side under favorable viewing conditions. However, none exhibit perfect perceptual uniformity, and it is possible for the JND to be greater or less than 1.0. Formulas for the calculation of all four ΔE metrics can be found at Bruce Lindbloom's web site.[10] Strictly speaking, there are multiple versions of ΔE_{94}, ΔE_{00} and ΔE_{CMC} that depend upon how the lightness, chroma, and hue components of each are weighted. In this paper, ΔE_{94} is calculated in the manner generally recommended for graphic arts. For ΔE_{00} and ΔE_{CMC}, the weighting coefficients are all set to unity, and thus the more complete designations would be $\Delta E_{00}(1{:}1{:}1)$ and $\Delta E_{CMC}(1{:}1)$.

2. Examples of Color Pairs with Approximately Just Noticeable Differences

I chose six colors from the classic 24-patch GretagMacbeth X-Rite Color Checker. The Color Checker has the advantage of being a familiar and frequently-used standard, and the Lab color coordinates are published (as are the coordinates for many RGB spaces).[11] Each of the following figures contains a pair of color squares. Each square is divided into two equal-area halves: either vertically, horizontally, or diagonally. One half of each square is the reference Color Checker color, and the other half is different.[12] For one of the squares in a pair, ΔE_{94}, ΔE_{00}, and ΔE_{CMC} are all < 1.0 (except for one color for which ΔE_{CMC} is just greater than 1.0). For the other square, $1.0 < \Delta E_{94}, \Delta E_{00}, \Delta E_{CMC} < 2.1$. I encourage you to examine the figures without knowing the ΔE associated with each square. The color information and difference metrics are provided in Table 1.

Figures were created in Photoshop CC 2015. They are encoded in 16-bit sRGB color. A stand-alone TIFF of each figure can be downloaded by clicking on the link in the caption. They should be viewed on a properly calibrated display. I encourage you to view the original TIFF figures because colors may be altered slightly when figures are imported into Pages (the application used to create this document), and then converted to PDF format.

---

9 Page 54, CIE Technical Report: Colorimetry. CIE 15:2004. 3rd Edition.

10 http://www.brucelindbloom.com The Lindbloom web site also has a convenient color difference calculator which will compute the four ΔE metrics used in this paper. Other on-line resources for color difference metrics include this Wikipedia page and this page.

11 Reference data for Color Checker Classics (both pre- and post-November 2014) can be found at BabelColor, and at X-Rite.

12 sRGB Color Checker coordinates are those for Color Checkers prior to November 2014. These were obtained from BabelColor, and are referred to there as "Color Checker 2005" data. Anyone wishing to use Color Checkers for estimation of color accuracy would be well-advised to consult the BabelColor Color Checker pages for additional information.

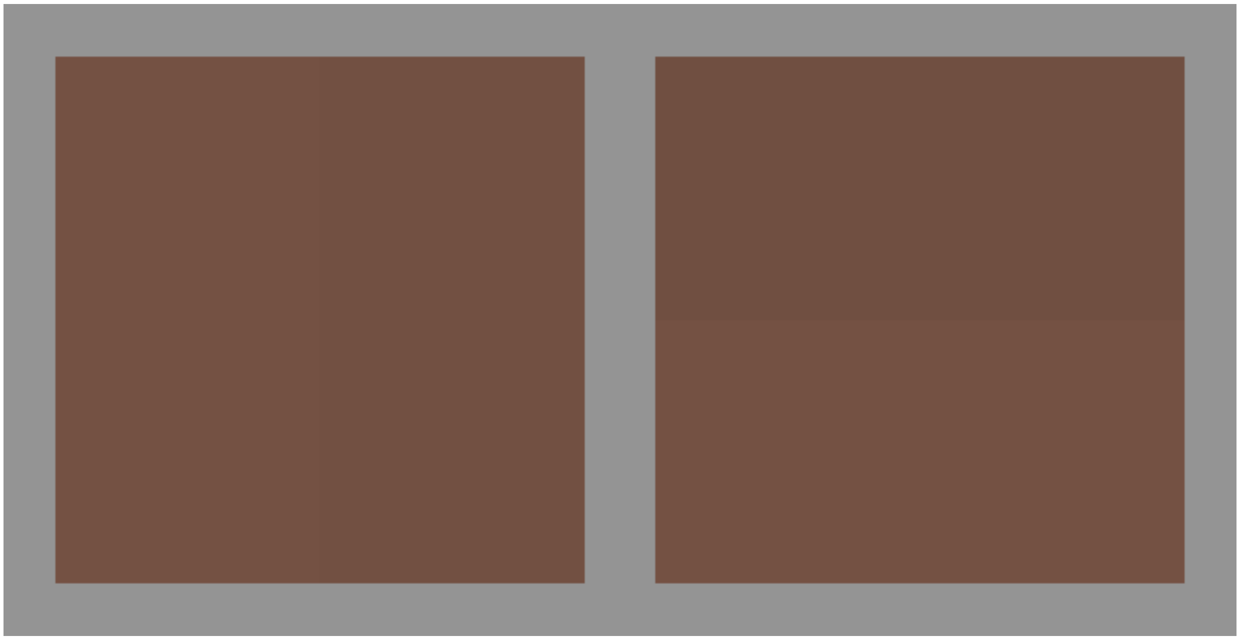

Fig. 2. Dark skin

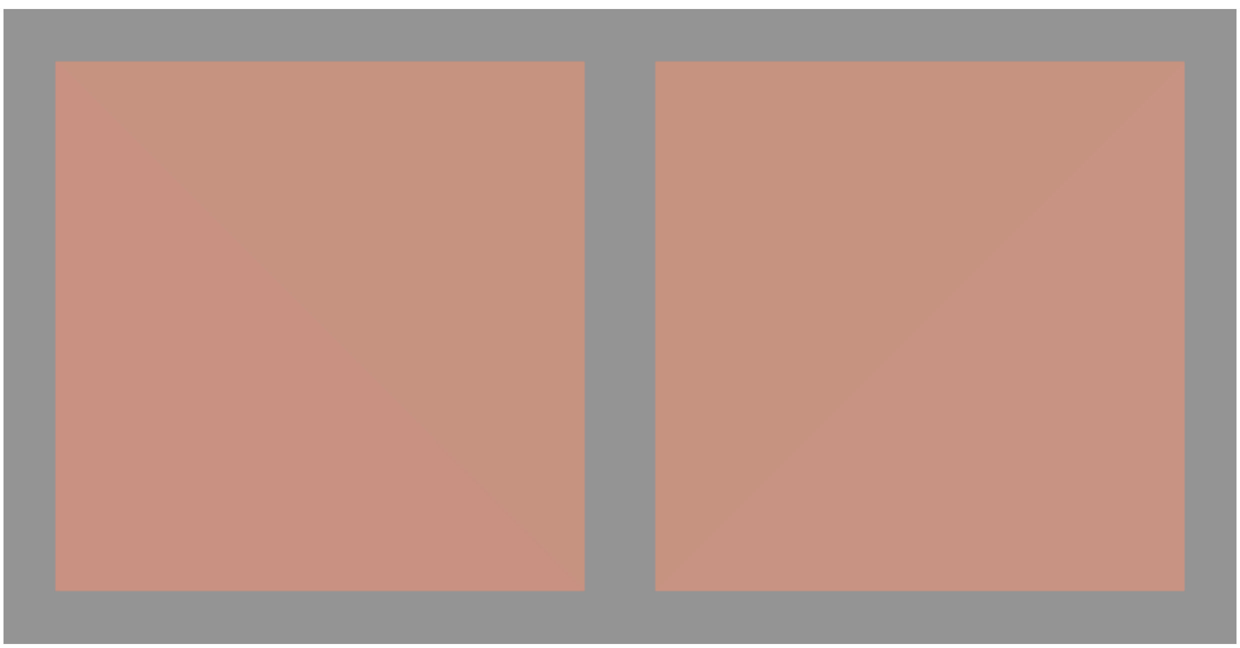

Fig. 3. Light skin

Fig. 4. Foliage

Fig. 5. Blue flower

Fig. 6. Moderate red

Fig. 7. Orange yellow

Table 1. Examples of Color Pairs with Approximately Just Noticeable Differences*

Figure	sRGB			ΔE_{76}	ΔE_{94}	ΔE_{00}	ΔE_{CMC}
	R	*G*	*B*				
Fig. 2. Dark skin - CC	116	81	67				
Left (vertical)	114	80	66	0.6971	0.5970	0.5542	0.6841
Right (horizontal)	112	79	65	1.3960	1.1959	1.1105	1.3721
Fig. 3. Light skin - CC	199	147	129				
Left (diagonal, UL-LR)	201	146	130	1.5015	1.0136	1.1490	1.6680
Right (diagonal LL-UR)	201	148	131	0.7829	0.6620	0.6387	0.8350
Fig. 4. Foliage - CC	90	108	64				
Left (horizontal)	91	106	65	2.0548	1.1380	1.1930	1.2448
Right (vertical)	90	107	65	1.1688	0.6020	0.6069	0.6734
Fig. 5. Blue flower - CC	130	128	176				
Left (diagonal, LL-UR)	130	128	174	1.1104	0.5067	0.5086	0.5850
Right (horizontal)	131	124	175	2.7400	1.8378	1.7791	2.0804
Fig. 6. Moderate red - CC	198	82	97				
Left (horizontal)	200	84	96	1.7008	1.1004	1.1076	1.1712
Right (vertical)	199	83	96	1.1183	0.6811	0.6867	0.7460
Fig. 7. Orange yellow - CC	230	162	39				
Left (diagonal, UL-LR)	230	162	29	2.6697	0.7378	0.8010	1.0339
Right (diagonal, UL-LR)	230	164	31	2.8204	1.0974	1.2490	1.4463

* The first row for each figure gives the Color Checker sRGB coordinates for that color. The second and third rows give the sRGB coordinates of an alternative similar color, and the *ΔE* statistics associated with that color. Notes in parentheses indicate the orientation of the dividing line between the two colors within a square.

Results are summarized in Table 1. I have highlighted those color pairs where I am able to discern a difference reasonably quickly. Color pairs for which ΔE_{94}, ΔE_{00}, and ΔE_{CMC} were all > 1.0 were judged to be different. Differences were also noticeable for two pairs with ΔE_{94}, ΔE_{00}, and ΔE_{CMC} < 1.0 — Fig, 2(left) and Fig. 3(right). Ability to distinguish color differences may depend upon viewing conditions, such as display brightness, ambient light, and nearby colors.

3. Color Accuracy of the Sony A6300

A Color Checker Classic (pre-November 2014) was photographed in full midday sun with a Sony A6300 and Sony/Zeiss Sonnar FE 55mm f/1.8 ZA lens. Raw + JPEG capture was used, with 5-shot exposure bracketing (0.3 EV steps). Exposures were made with in-camera JPEG creative style set to Neutral, Standard, and Portrait. In-camera color space was AdobeRGB. Images for color analysis were selected as follows. I chose the “best-exposed” image from a bracket sequence: “best-exposed” meaning the image in which the AdobeRGB values of the Neutral 5 patch of the Color Checker most closely corresponded to the published standard (120, 120, 121). JPEGs were opened in Camera Raw: exposure was adjusted, if necessary, and white balance was set from the Neutral 5 patch. Thus, both exposure and white balance were “anchored” to the Neutral 5 patch. No other image adjustments were made. Noise reduction and sharpening were disabled. Images were then opened in Photoshop CC 2015.5, and 101 x 101 pixel samples were taken from the center of each color patch. A single raw (ARW) image was chosen and processed in the same way, except that the “Adobe Standard” camera profile was used in Adobe Camera Raw, and the image was evaluated as a 16-bit AdobeRGB file in Photoshop CC 2015.5.[13]

Color difference results using ΔE_{00} are summarized in Table 2. The most accurate color reproduction, based upon smallest average ΔE_{00} was achieved with the Adobe Standard profile applied to a raw image. This is perhaps not surprising because accurate color reproduction is unlikely to be a goal of in-camera JPEG creative styles. It can be seen that Neutral style reduced chroma (C^*), on average: that is, it desaturated colors. On the other hand, Portrait style increased chroma (saturation) by a similar amount. Average lightness (L^*) was close to reference values for all four color modes. However, it should be pointed out that the black patch was consistently rendered too dark, as was the white patch. On average, hue (h) shifts were greatest for Standard style (> 6º).

Of the 96 ΔE_{00} values in Table 2, 82 are greater than 2.0 and almost certainly correspond to noticeable color differences in side-by-side comparison. Of the remaining 14 values, only six are less than 1.0, and four of those are for the Neutral 5 patch that was used to anchor exposure and white balance. It is worth noting that there is a great deal of variation among the color modes in how accurately particular patches are rendered. For example, although the Adobe Standard mode (with raw file) did best overall, it was the worst in rendering the blue patch, and second-to-worst for the green, yellow green, purplish blue, and light skin patches. On the other hand, it was most accurate for the dark skin, foliage, blue flower, bluish green, orange, moderate red, purple, orange yellow, red, yellow, and magenta patches (among the colors; and using this particular difference metric).

A mean ΔE_{00} of about 3.5 (for a raw image using Adobe Standard camera profile) seems to be about average. Jiang *et al.* (2013, their Fig. 3) reported ΔE_{00} results for their 28 cameras. Although they used a set of Munsell color chips, rather than a Color Checker, the reported mean

[13] In fact, the chosen ARW image was the “partner” of the portrait-mode JPEG image.

Table 2. Color Mode and ΔE_{00} for X-Rite Color Checker (2005)

	Color Mode†			
	In-camera JPEG Standard	In-camera JPEG Neutral	In-camera JPEG Portrait	Raw (ARW) Adobe Standard
dark skin	6.78	5.08	5.71	3.43
light skin	3.37	5.29	3.07	3.72
blue sky	3.58	2.16	3.58	2.82
foliage	5.18	3.87	5.38	2.79
blue flower	3.84	2.74	2.58	1.77
bluish green	4.01	5.18	4.28	3.58
orange	6.11	6.04	6.10	2.36
purplish blue	2.11	3.38	5.96	4.37
moderate red	4.03	3.98	4.34	2.79
purple	5.77	4.57	4.76	3.42
yellow green	2.71	5.54	1.38	4.57
orange yellow	6.70	7.45	4.38	2.08
blue	4.85	1.90	4.15	6.06
green	2.68	5.05	1.24	3.71
red	6.58	2.89	7.12	1.93
yellow	8.10	9.45	4.23	2.55
magenta	4.46	4.53	2.78	0.68
cyan	4.58	2.09	4.67	3.36
white 9.5 (.05 D)	3.62	3.65	4.58	3.31
neutral 8 (.23 D)	1.00	0.84	1.00	1.16
neutral 6.5 (.44 D)	3.20	3.48	1.44	3.20
neutral 5 (.70 D)	0.67	0.49	0.34	0.39
neutral 3.5 (1.05 D)	6.47	5.59	4.89	3.92
black 2 (1.5 D)	8.77	7.98	6.37	5.40
Avg. ΔE_{00} - Colors	4.75	4.51	4.21	3.11
Avg. ΔE_{00} - Gray Scale	3.96	3.67	3.11	2.89
Avg. ΔE_{00} - All	4.55	4.30	3.93	3.06
Avg. ΔL^* (colors only)	0.18	0.12	0.26	0.72
Avg. ΔC^* (colors only)	3.30	-6.76	6.33	-1.44
Avg. Δh (abs. val., colors only)	6.28	4.57	4.39	3.54

† ΔE values < 1.0 are highlighted in yellow. Values > 1.0 and < 2.0 are highlighted in green. Positive values of ΔL^* and ΔC^* indicate that the color patch in the image was lighter or more chromatic, respectively, than the reference Color Checker value.

ΔE_{00} varied from perhaps a bit less than two (Canon 300D) to more than seven (Phase One).

4. Discussion

The principal message of this analysis is that it is a non-trivial problem to design a camera sensor that will capture a wide range of colors with absolute fidelity. In fact, I suspect that no cameras can do so.

A shortcoming of the current analysis is the the actual colors of the particular Color Checker that I used are not known. Ideally, I should measure the true spectra of the patches under a controlled illuminant, or I should repeat the test with several different Color Checkers and report an average result. BabelColor has investigated variation among a sample of Color Checker charts. For most patches, the worst example from a sample of 20 charts can be clearly distinguished from the average.[14] Thus, I cannot rule out the possibility that I have a bad copy of the Color Checker, and that the camera more faithfully reproduced the colors than my statistics indicate.

Color difference metrics (ΔE) should not be confused with error in estimating *XYZ* coordinates from raw *RGB* values — the problem discussed in Section 1.1 and Appendix B. There is certainly a correlation, although it is not particularly strong, as can be seen from Fig. 3 of Jiang *et al.* (2013). A principal reason for the weak correlation may be that the CIE 1931 XYZ (or xyY) color space is not perceptually uniform. Thus, relatively large errors in estimating *XYZ* in some regions may lead to much smaller perceived color differences (and *vice versa*).

As a rule, camera sensors are sensitive to the entire range of humanly visible wavelengths (about 380 — 780 nm). As such, they can capture all the colors we can see (Fig. 1). On the other hand, monitors and RGB color spaces currently used for color reproduction fall far short of being able to display all visible colors. Even so-called wide gamut displays which generally attempt to cover the entire AdobeRGB or DCI-P3 spaces cannot reproduce all the colors of Pointer's gamut — the gamut of real surface colors.[15] Only the Rec.2020 RGB space includes all (or very nearly all) of Pointer's gamut. As of this writing, I am not aware of any commercially available Rec.2020 displays.

---

14 http://www.babelcolor.com/colorchecker-2.htm#

15 Service, Phil. 2016. Pointer's Gamut, MacAdam Limits, and Wide-Gamut Displays.

Appendix A

Sample Calculation of a Color Using the CIE 1931 Color Matching Functions and a Measured Reflectance Spectrum

For this example, I will use the Color Checker patch usually described as "foliage". It is the fourth patch from the left on the top row of the familiar 24-patch GretagMacbeth X-Rite Color Checker Classic. The published *XYZ* coordinates (pre-November 2014) are $X = 0.1091$, $Y = 0.1325$, and $Z = 0.0529$, under D50 illuminant. The measured reflectance spectrum of that patch, averaged over 30 charts, can be found in an Excel file linked to the Color Checker pages of the BabelColor web site. The reflectance spectrum and the CIE XYZ color matching functions (D50 adapted) are given in Table 3. The data are given at 10 nm wavelength intervals, which is crude, but sufficient for our purpose: which is to show how the *XYZ* coordinates above are computed from the spectral data and the color matching functions.

Table 3. Computation of CIE *XYZ* Coordinates of the Color Checker Foliage Patch

Wavelength (nm)	CC Foliage Patch Spectral Reflectance	CIE 1931 Color Matching Functions (D50 adapted)			Col.2 × Col.3	Col.2 × Col.4	Col.2 × Col.5
		x-bar(λ)	y-bar(λ)	z-bar(λ)			
380	0.051239	0.001175	-0.000029	0.005274	0.000060	-0.000001	0.000270
390	0.054234	0.003644	-0.000091	0.016395	0.000198	-0.000005	0.000889
400	0.055990	0.012283	-0.000317	0.055481	0.000688	-0.000018	0.003106
410	0.057039	0.037316	-0.000966	0.169593	0.002128	-0.000055	0.009673
420	0.057862	0.115099	-0.002759	0.527923	0.006660	-0.000160	0.030547
430	0.058950	0.242517	-0.002806	1.133113	0.014297	-0.000165	0.066798
440	0.060300	0.296089	0.005084	1.428892	0.017854	0.000307	0.086162
450	0.061314	0.283238	0.020262	1.449704	0.017366	0.001242	0.088887
460	0.062277	0.240871	0.043989	1.366034	0.015001	0.002739	0.085072
470	0.063245	0.156723	0.079730	1.054590	0.009912	0.005043	0.066698
480	0.064783	0.070969	0.133682	0.667116	0.004598	0.008660	0.043218
490	0.067378	0.017409	0.207541	0.383627	0.001173	0.013984	0.025848
500	0.075313	-0.004445	0.326543	0.227124	-0.000335	0.024593	0.017105
510	0.101199	0.002538	0.510770	0.136287	0.000257	0.051689	0.013792
520	0.145361	0.057874	0.721718	0.073176	0.008413	0.104909	0.010637
530	0.178264	0.160301	0.875812	0.044896	0.028576	0.156126	0.008003
540	0.183944	0.285180	0.968464	0.027299	0.052457	0.178143	0.005021
550	0.170111	0.428077	1.008866	0.017327	0.072821	0.171619	0.002947

Table 3. Computation of CIE *XYZ* Coordinates of the Color Checker Foliage Patch							
Wavelength (nm)	**CC Foliage Patch Spectral Reflectance**	**CIE 1931 Color Matching Functions (D50 adapted)**			**Col.2 x Col.3**	**Col.2 x Col.4**	**Col.2 x Col.5**
		x-bar(λ)	**y-bar(λ)**	**z-bar(λ)**			
560	0.149381	0.588908	1.007385	0.012160	0.087972	0.150484	0.001816
570	0.132744	0.756364	0.961976	0.008864	0.100403	0.127697	0.001177
580	0.121861	0.910572	0.876971	0.006250	0.110963	0.106869	0.000762
590	0.115173	1.020812	0.760832	0.003464	0.117570	0.087627	0.000399
600	0.109481	1.057164	0.632176	0.001259	0.115740	0.069211	0.000138
610	0.105359	0.998245	0.502417	-0.000397	0.105174	0.052934	-0.000042
620	0.104342	0.850939	0.379631	-0.001060	0.088789	0.039612	-0.000111
630	0.105989	0.639853	0.263579	-0.001162	0.067817	0.027937	-0.000123
640	0.108906	0.446165	0.173830	-0.000953	0.048590	0.018931	-0.000104
650	0.111894	0.282418	0.106191	-0.000664	0.031601	0.011882	-0.000074
660	0.114062	0.164276	0.060507	-0.000403	0.018738	0.006902	-0.000046
670	0.113953	0.087071	0.031732	-0.000218	0.009922	0.003616	-0.000025
680	0.112398	0.046594	0.016855	-0.000118	0.005237	0.001894	-0.000013
690	0.112153	0.022615	0.008139	-0.000058	0.002536	0.000913	-0.000007
700	0.114819	0.011317	0.004066	-0.000029	0.001299	0.000467	-0.000003
710	0.119765	0.005769	0.002073	-0.000015	0.000691	0.000248	-0.000002
720	0.124595	0.002888	0.001038	-0.000007	0.000360	0.000129	-0.000001
730	0.130305	0.001435	0.000515	-0.000004	0.000187	0.000067	-0.000000
Sum		10.300263	10.685407	8.810757	1.165712	1.426071	0.568416
"Normalized" Sum (= *XYZ*)		0.9640	1.0000	0.8246	0.1091	0.1335	0.0532

The sums of the color matching functions (columns 3 – 5) are normalized so that the sum of $\bar{y}(\lambda)$ is equal to 1.0 (*i.e.,* the sums are divided by 10.685407). The normalized sums at the bottom of columns 3 – 5 are the *XYZ* coordinates of the D50 illuminant white point.[16] The same normalization is performed on the sums of columns 6 – 8. The resulting values are $X_{foliage}$ = 0.1091, $Y_{foliage}$ = 0.1335, and $Z_{foliage}$ = 0.0532. These values are very close to the published coordinates given above. In fact, the ΔE_{00} between the two sets of coordinates is about 0.4, probably well below the threshold of a just noticeable difference.

[16] The published values for D50 illuminant are X_W = 0.9642, Y_W = 1.0000, and Z_W = 0.8252, which are very close to the values in Table 3, even with 10 nm resolution.

Appendix B

Outline of a Procedure for Estimating the Transformation of Camera Raw *RGB* Values to CIE *XYZ* Coordinates: Camera Profiling

[Disclosure: I have no information about the procedures that Adobe, for example, uses to create profiles for Camera Raw. Nor do I have any information about the procedures used by calibrating kits/software, such as ColorChecker Passport. However, the procedure that I outline here is feasible, as I will demonstrate, although it no doubt differs in detail from commercial profiling.]

We start by taking a well-exposed raw image of a color target with known *XYZ* coordinates for each color. Preferably, this is done under controlled conditions with a known illuminant — something like D65.[17] A 24-patch Color Checker Classic will do. The corresponding raw *RGB* values for each color patch are then recovered with software such as RawDigger. The task is to find a set of three equations that translate the camera raw *RGB* values to CIE *XYZ* values. For a given color patch, *i*, we know X_i, Y_i, and Z_i (the reference standard for that color) and we have, from the raw file, R_i, G_i, B_i. The general form of the equation for X_i is:

$$X_i = c_{11}R_i + c_{12}G_i + c_{13}B_i$$

c_{11}, c_{12}, and c_{13} are unknown coefficients that need to be estimated. Similar equations are written for Y_i and Z_i:

$$Y_i = c_{21}R_i + c_{22}G_i + c_{23}B_i$$

$$Z_i = c_{31}R_i + c_{32}G_i + c_{33}B_i$$

These three equations can be represented in matrix form as follows:

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix}$$

In all, there are nine coefficients. The same coefficients are used regardless of the color patch in question. We can use a standard statistical analysis known as multiple regression to estimate the "best" values of the nine coefficients. Three analyses are required, one each for *X*, *Y*, and *Z*. To make things concrete, let's use the raw image that I made with the Sony A6300 and analyzed for

[17] In practice, calibrations are generally done with two different illuminants, say D65 and A, so that colors can be adjusted for any other illuminant by interpolation.

Table 4. Color Checker Raw *RGB* Coordinates From a Test Image, and Reference *XYZ* Coordinates

	Raw (ARW)			Color Checker (Pre-November 2014)*		
	R	***G*****	***B***	***X***	***Y***	***Z***
dark skin	0.018888	0.034112	0.015761	0.115189	0.100802	0.050897
light skin	0.067788	0.124394	0.064493	0.391780	0.349516	0.192284
blue sky	0.024975	0.088775	0.073514	0.168044	0.183576	0.257146
foliage	0.016936	0.050426	0.018633	0.109072	0.132510	0.052930
blue flower	0.034848	0.100500	0.087584	0.241931	0.230385	0.334435
bluish green	0.040637	0.175146	0.104116	0.304231	0.417800	0.346152
orange	0.072227	0.088168	0.020548	0.407181	0.311820	0.049948
purplish blue	0.017129	0.065326	0.078556	0.123261	0.112630	0.298798
moderate red	0.056174	0.058244	0.031808	0.296718	0.193758	0.101560
purple	0.013834	0.028084	0.028718	0.085143	0.063690	0.107728
yellow green	0.055409	0.163868	0.044255	0.353615	0.444556	0.089523
orange yellow	0.075093	0.120054	0.023676	0.487850	0.435713	0.060627
blue	0.009581	0.041675	0.058580	0.068605	0.057520	0.213801
green	0.023265	0.098900	0.035109	0.149844	0.231836	0.079004
red	0.039965	0.032361	0.013318	0.216315	0.125654	0.038476
yellow	0.102941	0.208720	0.045685	0.593415	0.598067	0.071952
magenta	0.052879	0.067322	0.060943	0.310759	0.200866	0.235648
cyan	0.018994	0.102036	0.087317	0.136088	0.193014	0.309427
white 9.5 (.05 D)	0.136452	0.368711	0.222009	0.878151	0.913135	0.739795
neutral 8 (.23 D)	0.087932	0.241467	0.147463	0.565692	0.589371	0.489275
neutral 6.5 (.44 D)	0.055266	0.151433	0.092409	0.348076	0.363230	0.302928
neutral 5 (.70 D)	0.028811	0.078749	0.048116	0.184394	0.191541	0.159175
neutral 3.5 (1.05 D)	0.012857	0.036241	0.022631	0.084664	0.088306	0.075934
black 2 (1.5 D)	0.004794	0.013423	0.008387	0.029897	0.031054	0.026834

* *XYZ* coordinates calculated from *L*a*b** coordinates obtained from X-Rite.
** Average of the two green raw channels.

ΔE using the Adobe Standard profile. The unprocessed raw *RGBG* values were obtained by sampling a large region in the center of each Color Checker patch using RawDigger. The raw values are shown in Table 4 (scaled 0-to-1), together with the reference *XYZ* coordinates for each patch (computed from the published Lab coordinates). These data are the input for the three multiple regression analyses, which were done with Wizard Pro.

The resulting camera RGB-to-XYZ transformation matrix is:

$$\begin{bmatrix} 5.183 & 0.382 & 0.131 \\ 1.676 & 2.368 & -0.851 \\ 0.275 & -0.694 & 4.320 \end{bmatrix}$$

Using these coefficients, the *RGB* values for dark skin (Table 4) are transformed to *XYZ* [0.112994, 0.099020, 0.049608]; which are $L^*a^*b^*$ [37.666, 13.359, 14.180]. After transforming the raw *RGB* coordinates to *XYZ* for the remaining 23 Color Checker patches and converting them to Lab, we can compare the accuracy of our do-it-yourself (DIY) calibration to the Adobe Standard profile for the same image (Table 5). In both cases, the comparison is to the reference Lab coordinates. As can be seen, the average ΔE_{00} values for the DIY profile are considerably

Table 5. ΔE_{00} for X-Rite Color Checker (2005): Adobe Standard vs. DIY Camera Profile†

	Camera Profile	
	Adobe Standard	**DIY**
dark skin	3.43	0.35
light skin	3.72	3.92
blue sky	2.82	0.76
foliage	2.79	0.96
blue flower	1.77	1.13
bluish green	3.58	2.05
orange	2.36	0.41
purplish blue	4.37	1.28
moderate red	2.79	1.72
purple	3.42	0.46
yellow green	4.57	0.50
orange yellow	2.08	2.95
blue	6.06	2.48

Table 5. ΔE_{00} for X-Rite Color Checker (2005): Adobe Standard vs. DIY Camera Profile†

	Camera Profile	
	Adobe Standard	**DIY**
green	3.71	1.49
red	1.93	1.51
yellow	2.55	1.18
magenta	0.68	0.64
cyan	3.36	2.30
white 9.5 (.05 D)	3.31	0.22
neutral 8 (.23 D)	1.16	0.89
neutral 6.5 (.44 D)	3.20	0.68
neutral 5 (.70 D)	0.39	0.71
neutral 3.5 (1.05 D)	3.92	1.28
black 2 (1.5 D)	5.40	1.07
Avg. ΔE_{00} - Colors	3.11	1.45
Avg. ΔE_{00} - Gray Scale	2.89	0.81
Avg. ΔE_{00} - All	3.06	1.29
Avg. ΔL^* (colors only)††	0.72	0.16
Avg. ΔC^* (colors only)††	-1.44	-0.48
Avg. Δh (abs. val., colors only)	3.54	2.08

† In both cases, comparison is to published reference Color Checker coordinates
†† 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.

less than the values for the Adobe Standard profile. This is not particularly surprising: there is obvious circularity in validating a profile with the image used to make it. However, there is value in this exercise. It shows that a very good *linear* transformation from sensor spectral sensitivity functions to CIE color matching functions is possible — at least for the A6300 and the Color Checker Classic when photographed in full sun. In other words, the Luther condition is fairly well approximated. And, if you've understood the presentation up to this point, you now know, in principle, how raw color information captured by a digital camera is converted to a standard format for image editing and display.