Adjusting for the Scene Adopted White

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Abstract

The absence of a white reference in natural scenes greatly complicates the application of color science to the production of photographs. It is necessary to devise a method for determining an adopted white luminance and chromaticity. After determination, methods must be devised for transforming camera data to appropriate scene colorimetry estimates (analysis), and for producing reproduction colorimetry (synthesis). Also, the reproduction colorimetry is typically altered to produce a more pleasing reproduction by one of a variety of methods.

ISO 17321 specifies proposed methods for scene analysis, and for synthesis of reproduction colorimetry in conjunction with the application of a reproduction model. This paper discusses these methods in the context of a pictorial digital image processing pipeline. Adjusting for the adopted white luminance, which is outside the scope of ISO 17321, is also explicitly discussed.

Introduction

In order to produce acceptable pictures, digital cameras must perform two important compensations: adjustment of the raw digital camera data for the scene adopted white, and transformation of the raw data to produce an estimate of the scene colorimetry. These two compensations are linked, and the adopted white adjustment is so important that it has been singled out as the only appearance related consideration included in a new ISO standard under development for the color characterization of digital cameras (ISO 17321).[1] Furthermore, the transformations to scene colorimetry described in this standard preserve white.

Determination of an acceptable adopted white is critically important in digital photography. Many methods have been proposed for such determinations, and some of the most promising are referenced below. However, the purpose of this paper is to describe investigations into the best ways to adjust for the scene adopted white after it has been determined. If adjustment methods are not well understood, the question of whether the most appropriate adopted white for a particular scene has been determined can be confounded with the adjustment. This is why the group developing ISO 17321 chose to standardize adjustment methods, while leaving the processing steps on either side, adopted white determination and rendering, open for competition.[2]

The scene adopted white has two important attributes: chromaticity and luminance. Both of these attributes can be difficult to determine, and can have a profound effect on a digital photograph. Adjustments based on the chromaticity of the adopted white have been investigated for many years, and are referred to in color science as chromatic adaptation transforms. These adjustments are necessary because of a phenomenon called color constancy, which refers to the fact that in most cases (and always with spectrally non-selective objects) the perceived color of an object in a scene does not vary substantially with changes in the scene illumination. Unfortunately, the physiological mechanisms of color constancy are not completely understood. Chromatic adaptation transforms to date have been phenomenologically based. This paper notes an apparent recent convergence in the phenomenological models, and refers to explanations of this convergence based on practical considerations and current physiological understanding.

The other important attribute of the scene adopted white is its luminance. This is the luminance of what would be perceived to be a perfectly reflecting and diffusing surface placed somewhere in the scene. Determination of this luminance is confounded in most real scenes by variations in illumination level across the scene, by the three-dimensional nature of objects in the scene, and by specular reflections and light sources present in the scene. This attribute has been largely neglected, but is of critical importance. The first step in rendering is to place the scene adopted white luminance at the appropriate reproduction luminance. Also, for practical reasons, scene colorimetry estimates are typically relative to some adopted white. Changing the adopted white therefore changes the scene colorimetry estimates significantly. For example, reducing the adopted white luminance increases the chroma estimate for any particular scene color. This paper will also illustrate the effects of choosing different adopted white luminances in colorimetric reproductions of scenes, and briefly discuss the function of rendering with respect to the adopted white luminance.

Methods for Determining an Adopted White

A number of methods have been proposed for determining an adopted white. The two most common are the gray world assumption and max RGB. With the gray world assumption, a mean luminance and chromaticity are determined for the entire scene. The adopted white then has the same chromaticity and a luminance that is some factor higher than the mean. Typical factors range between 4 and 7, depending on the application. The ISO standards for photographic exposure determination specify 5.6 as the ratio of the adopted white luminance to the scene arithmetic mean luminance, and 6.9 as the ratio of the adopted white luminance to the geometric mean luminance.[3,4] While these values are reasonable ensemble averages, they can vary quite dramatically from scene to scene. The results of an analysis of 126 outdoor scenes is presented in Table 1.

Table 1:
Scene Adopted White to Mean Luminance Ratios

Ratio	Ensemble Average	Standard Deviation	Minimum Ratio	Maximum Ratio
White/ AriMean	5.43	3.11	1.89	18.6
White/ GeoMean	8.89	6.31	2.15	27.6

The max RGB method was proposed by Land.[5] A variation is commonly used in the television industry where it is referred to as "white balance." It is arguably more reliable than the gray world assumption, but can still result in the selection of an inappropriate adopted white. In particular, if the synthesis white in typical television systems is set based on the maximum RGB values in a typical scene, the resulting image will be reproduced as unacceptably dark because of the greater than unity system gamma.

Because of the failings of both of these simple methods, most current imaging systems use more complex proprietary methods. For example, the color by correlation method[6-8] shows promise as a means for selecting an appropriate adopted white chromaticity, but does not provide information about the white point luminance. Conversely, a previously described preferred reproduction model[9-11] provides a means for selecting the white point luminance, but not the chromaticity.

Whatever method is used to determine the adopted white, it is important to remember that in digital systems the de-facto adopted white is actually determined by the camera. It is based on the channel integrated responses to the illumination source used, the channel analog and digital gains, and the saturation characteristics of the digital code values produced. This de-facto adopted white need not be tied to any particular luminance or chromaticity in the scene, but it does set the upper limit on the tones that can appear in a reproduction.

Adjusting for the Adopted White Chromaticity

A variety of chromatic adaptation transforms have been proposed in the past, such as CIE XYZ and cone response normalization. Recently, however, a trend has been developing toward the use of relatively sharp RGB response normalization.[7] It is interesting that such an approach mirrors decades of practice in photography and television. It is advantageous that this approach allows for the use of real primaries for both analysis and synthesis. ISO 17321 makes use of real primaries, but the methods for adjusting for the adopted white chromaticity differ between analysis and synthesis. The goal in the analysis stage is to produce white point independent image data based on current understanding of human color perception. The goal in the synthesis stage is to model what happens when real images are produced on media that have different white point chromaticities, and/or are viewable using different illumination sources.

Scene Analysis

The following is a summary of the steps for scene analysis as described in ISO 17321:

1. Select an adopted white spectral power distribution.
2. Linearize the image data output by the digital camera.
3. Measure the spectral sensitivities of the channels of the digital camera.
4. Calculate the actual spectral response functions to the adopted white for each camera channel by multiplying the spectral sensitivities by the adopted white spectral power distribution.
5. Balance the camera channels by multiplying each channel response function by a constant so that each channel produces the same integrated response to the adopted white.
6. Multiply the ISO RGB color matching functions by the adopted white spectral power distribution to produce aim spectral response functions for each channel.
7. Balance the aim spectral response functions as in step 5.
8. Apply the ISO RGB transfer function to both the actual and aim spectral response functions to produce non-linear actual and aim spectral response functions.
9. Determine a white point preserving matrix such that the non-linear actual spectral response functions are mapped to the closest possible least-squares match to the non-linear aim response functions when the *linear* actual spectral response functions are multiplied by the matrix and then the ISO RGB transfer function is applied.

The effect of this procedure is to determine a matrix that is applied to the camera data in linear space to produce the closest non-linear match to the spectral colors. The assumption is that matching the neutral scale exactly, and producing the closest match of spectral colors in the more perceptually even non-linear space, will produce the most visually accurate scene analysis in situations where the spectral correlation statistics of the scene are unknown. Another method for determining transformations is provided in ISO 17321 for situations where the spectral correlation statistics of the scene or original are known.

Reproduction Synthesis

The following is a summary of the steps for reproduction synthesis as described in ISO 17321:

1. Select an adopted white chromaticity and determine normalized CIE XYZ values (Y = 100).
2. Create a diagonal matrix of the XYZ values and pre-multiply the ISO RGB to CIE XYZ conversion matrix

by the diagonal matrix to create a transformation matrix for the selected adopted white chromaticity.

3. Linearize the ISO RGB values, and multiply the linear values by the transformation matrix to transform the image data to CIE XYZ values for the selected adopted white chromaticity.
4. Multiply the CIE XYZ values by a scaling factor to adjust them to the appropriate adopted white luminance.

Note that these steps result in the "floating primaries" shown in figure 1. These primaries approximately reflect what happens when a photographic print or transparency is viewed using illumination sources with different chromaticities. In contrast, CRT displays do not have floating primaries, and adjust the white point by modulating the primary luminance. It is well known that a photographic print or transparency can be viewed using a wider range of white point chromaticities than an image viewed on a CRT display.

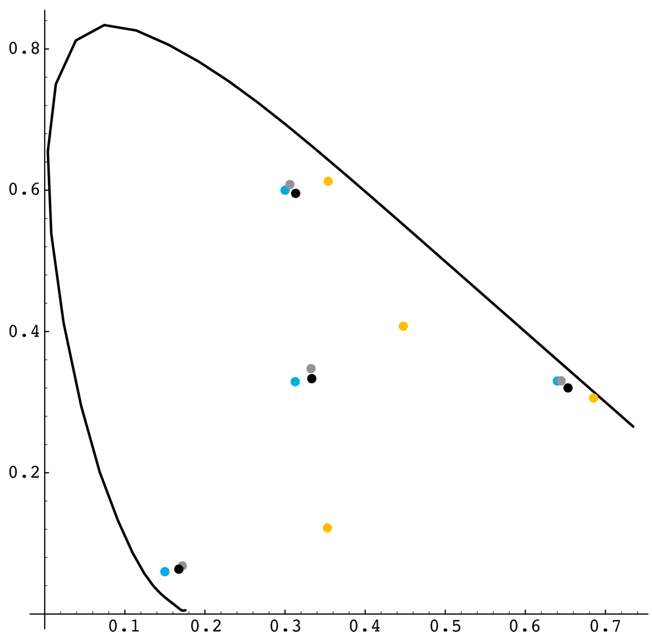

Figure 1. Synthesis primaries and white points based on equi-energy (black dots), and CIE Illuminants D_{65}, D_{55}, and A.

Adjusting for the Adopted White Luminance

The following images (figures 2-7) have been produced using the methods described in ISO 17321, and various reproduction models as noted. In all cases the adopted white spectral power distribution was assumed to be the same as that of CIE Illuminant D_{55}. The image chosen has a statistically average dynamic range and key.

Figure 2. An image where the adopted white luminance is chosen to be 5.6 times the arithmetic mean luminance, and relative colorimetric reproduction is attempted.

Figure 3. The same image as figure 2, except the adopted white luminance is chosen to be 6.9 times the geometric mean luminance.

Figure 4. The same image as figure 2, except that a photographic reproduction model is used instead of attempting relative colorimetric reproduction.

Figure 5. The same image as figure 2, except the adopted white luminance is chosen to be 4 times the arithmetic mean, and a simple video reproduction model (system gamma 1.2) is used.

Figure 6. The same as figure 2, except that the adopted white luminance is chosen to be the estimated maximum luminance of the scene.

Figure 7. The same image as figure 6, except a preferred reproduction model is used to produce the reproduction.

Adopted white luminance selection is also important because of its effect on "gamut" as expressed in many commonly used color spaces. Figure 8 shows the change in sRGB primary and secondary *CIE a*b* coordinates* produced by selecting an adopted white that leaves a half-stop of headroom for specular highlights. The primaries and the spectral radiances and appearance of any image they form remain exactly the same, but leaving this headroom results in a substantial increase in gamut as expressed in the color space. This effect is not due to viewing conditions or other appearance considerations, but is exclusively the result of assigning a lower luminance value as the adopted white. However, selecting an inappropriate value can result in unnatural reproductions.

The ambiguity in color appearance metrics noted above can be taken advantage of in digital photography. With most real scenes, specular highlights, and even diffuse reflections from surfaces oriented to be illuminated more directly by the light source (such as the top of the cotton candy in figures 2-7), frequently exceed the luminance of a perfectly diffusing and reflecting surface oriented toward the camera. Allowing headroom not only prevents clipping in these parts of the image, but also allows for the encoding of a larger apparent gamut into the sRGB gamut. This is generally accomplished using a reproduction model that compresses highlights and colors close to the gamut boundary so that the images produced are not unacceptably dark and desaturated.

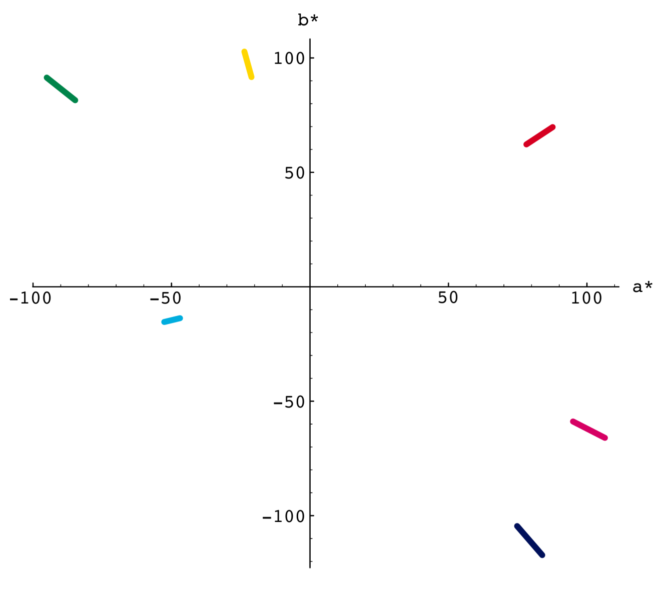

*Figure 8. The change in CIE a*b* values for the sRGB primaries and secondaries caused by changing the image adopted white from {255, 255, 255} to {220, 220, 220}.*

Conclusions

The application of color science to digital photography is profoundly influenced by the absence of clear reference whites in scenes. When color science is used for other applications, such as paint and textile matching, or even graphic arts and softcopy to hardcopy matching, reference whites are available. The lack of any open, unambiguous, and reliable way to specify a reference white for natural scenes causes a fundamental problem which requires reexamination of the approaches used. This reexamination is also dictated by the need to deal with a large variety of scene dynamic ranges using reproduction models.

ISO 17321 begins to address the issue of how to adjust for the adopted white in digital photography, but it is still in the development stage. Even when finished it will not be a complete solution because it does not specify the nature of adopted white determination algorithms and reproduction models. A great deal of research is needed to verify the approaches used in ISO 17321, and to advance the state of the art in digital photography. Such research should also result in significant advances in understanding of the human visual system, since our eyes are almost always viewing natural scenes.

References

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