The Perception of Color at Dawn and Dusk

Paul M. Hubel▲

Hewlett-Packard Laboratories, Hewlett-Packard Company, Palo Alto, California

The illumination of scenes by sunlight at dawn and dusk creates a rich array of colors and long high contrast shadows that make the appearance of the scene more beautiful and allow for better photographic imagery. Photographers often refer to this as when 'the light is right' as opposed to mid-day illumination when the light is 'flat and uninteresting'. When the light of the setting sun illuminates an object or person the surfaces impart a characteristic warm glow - the warm colors of the scene can almost appear self-luminous. This paper addresses this sensation with respect to color constancy, color appearance, chromatic adaptation, and digital photography. Because photographers strive for this kind of illumination it is vital that in the design of a color model for a photographic system that we understand and preserve the photographer's control of this effect.

Journal of Imaging Science and Technology 44: 371–375 (2000)

Introduction

Color constancy and color appearance models consider the color of the illumination in a scene as the primary contributor to chromatic adaptation effects. Under a variety of illuminants, colors are constant: a white surface appears white under both a reddish tungsten light and a bluish daylight illumination. Color constancy theories form an estimation of the illumination color and this estimate can be used to anchor the frame of reference of the perceptual color space.[1] In these methods the illumination estimate is derived for the data present in the photographic image itself. In photographic systems, some kind of prediction and compensation of illumination is necessary to achieve a high level of color image quality. Color appearance models, on the other hand, use a measurement of the scene illumination in an extension of traditional colorimetry to predict perceived color matches under some constrained conditions. Recent research has attempted to extend these models from their color matching origins into the realm of color imaging of complex scenes.[2]

In the recent CIECAM97s color appearance model[3] the concept of *adopted white point* has been introduced to signify the white point which is 'adopted' (i.e. used) in the chromatic adaptation calculation. The introduction of this term stresses the difference between this quantity and the *adapted white point* that is reputed to be the human visual system's internal white point for a given scene. The relationship between the adopted and adapted white point directly effects the color image quality of a scene reproduction. In this study we consider effects of the color of the white points, although we appreciate the importance of white point luminance for image rendering.[4] If the color of the adopted and adapted white points are similar, then the image reproduction will appear like the scene - any deviation of these two white points will cause noticeable and sometimes catastrophic image quality degradation. For a reproduction of a scene to appear natural, these white points must be similar. Although other aspects such as color saturation, brightness, and contrast are often altered for aesthetic intent, the color balance rarely appears attractive if it is not correct (i.e., adopted = adapted).

The case of a scene lit by the sun low in the sky is one of the most interesting cases to consider because of both its esthetic beauty and its ability to break the necessary assumptions of all color appearance models and most color constancy models. These two aspects are clearly related: the exception to the rules are so often the most intriguing and attractive.

The Color of Illumination

The image shown in **Color Plate 16a and 16b (p. 386)** is a scene showing a MacBeth ColorChecker chart illuminated by sunset light (on a clear day in October at about 6:30 pm along the Northern California coast). **Color Plate 16c and 16d (p. 386)**is a scene showing a MacBeth ColorChecker chart lit by studio tungsten light. The color balance in both of these reproductions has been manually adjusted to match the color appearance of the two scenes. If measured with a spectrophotometer, the spectral power distribution of the light emitted by the setting sun in the first scene (outdoor) has a similar distribution and correlated color temperature to that of the incandescent lamp illumination in the second scene (indoor). Figure 1 shows a plot of the spectral power distribution of the sunset light along with the spectrum of the tungsten lamp and the correlated color temperatures are noted. From Fig. 1 it is clear that these two light sources are extremely similar.

There are great differences, however, in the color perception under these two situations. Under sunset illumination the colors of objects impart a warm glow and

Invited paper; Original manuscript received December 24, 1999

Color Plates 16 and 17 are printed in the Color Plate Section of this issue, on page 387.

▲ IS&T Member

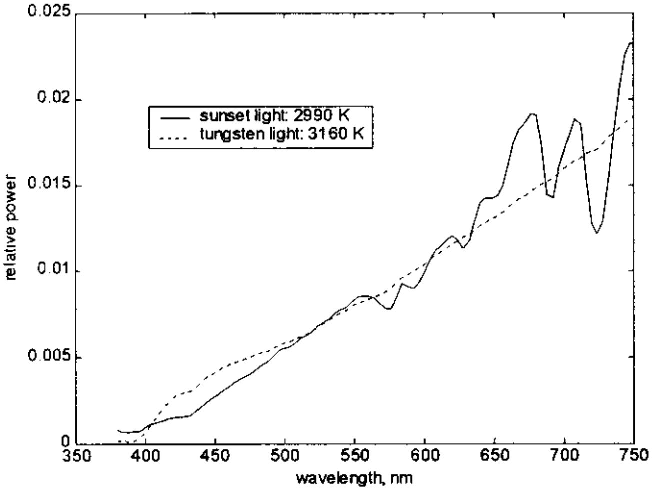


Figure 1. Spectral power distributions of the light from setting sun (solid line) and the light from the tungsten source (dashed line). The spectra and correlated color temperature are both similar, but color perception under these lights is extremely different.

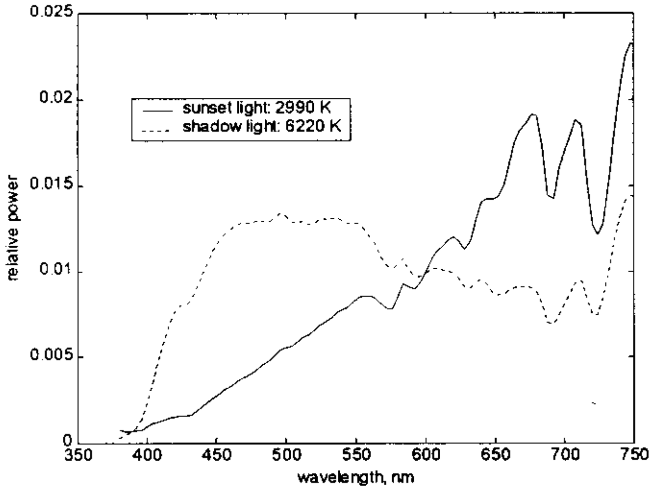


Figure 2. The spectral power distributions of the light from the setting sun (solid line) and the light measured in the shadow region of the image (dashed line).

appear almost self luminous. Although the luminance contrast between the objects lit by the collimated sunlight and the surrounding objects can account for an increase in color saturation, it is not clear how this would cause the warm color hue shifts. In complete contrast to this, an indoor scene illuminated by tungsten light of identical color temperature and spectral distribution (to the sunset light) does not cause any similar perception. In this case, color constancy effects balance the color sensation to the color of the illumination and colors appear much as they would under bluer illumination. Although the overall color sensation under tungsten light has a warmer cast than would be found if the scene were lit by daylight illumination, this effect is slight and the colors do not appear to 'glow' and have the kind of rich warm hues observed under sunset light.

If a reproduction of the scene taken under dawn or dusk illumination *is balanced* using the color of the illumination as the white balance point, then the warm glowing colors observed will not be reproduced and the image will be as cold as if taken at mid-day. This result clearly does not match an observer's sensation, and would be the cause of much frustration for the photographer (especially if the image was taken at dawn!). In the other example, if the reproduction of the image taken under tungsten light *is not balanced* for the illumination, the image appears with a strong orange color cast that again does not match the observer's sensation.

This effect is shown using two renderings of the two images. **Color Plate 16 (p. 386)** shows a matrix of the two different images rendered for two different white points. In the left column the two images are balanced for a white point with CCT = 3000K and on in the right column the images are balanced for a white point where CCT = 5,000K. The manually chosen white points described at the beginning of this section are 5,000K for the sunset scene and 3,000K for the tungsten scene. The image of the sunset is acceptable when balanced for 5,000K but completely unacceptable when balanced at 3,000K. The image taken under tungsten is unacceptable when balanced to 5,000K, and yet is acceptable when balanced at 3,000K. If the scenes are balanced to the color of the illumination then both would be balanced to 3,000K – the tungsten scene would have high image quality and the sunset scene would have poor image quality. This would be the case when the balance point is determined from a colorimetric measurement (such as assumed in a color appearance model) or from the maximum of the image data.

How does the visual system tell that a scene is lit by sunset light and not by tungsten light?

Shadow Light

The image taken under the sunset actually contains more than one illumination source. In fact, all complex scenes contain more than one source (except for two-dimensional color charts such as the ColorChecker or a Mondrian type target). Although the sunlight is the direct illumination of the main objects in the scene, the shadows are illuminated by a second source, the sky, which typically has a correlated color temperature of as much as 10,000 Kelvin. Figure 2 plots the spectral power distributions from the two distinct light sources that illuminate the scene in Color Plate 16b (p. 386). The correlated color temperature of the shadow light measured at the scene is calculated to be 6220 Kelvin. Because at this time of day the shadows are long, they often subtend a larger portion of the visual field and can thus have a dramatic effect on the state of adaptation of the observer. The contrast between the color temperature of the sun and the sky increases as the sun sets[5] (and decreases as the sun rises). When the sun is low in the sky it becomes redder due to atmospheric filtering,[6] and the sky becomes bluer because of Rayleigh scattering.[7] Thus the two illuminant colors become further apart and it is therefore likely that the shadow light has a greater impact on the observer's state of adaptation. This effect also depends on the weather conditions.[8]

In the indoor tungsten image, the shadows are illuminated by ambient light that is typically formed by reflections of the tungsten source off surrounding surfaces. Because indoor ceilings, walls, and objects are generally neutral, the shadow illumination color does not differ greatly from the color of the direct illumination.

Illuminants	CIP Counts	Mask	Raw Prob	Mask	Answer
1 D75	144	1	0.1089	0	0
2 D65	144	1	0.1082	0	0
3 D55	144	1	0.1098	1	1
4 D45	144	1	0.1042	0	0
5 D40	140	0	0.09792	0	0
6 3200	137	0	0.08854	0	0
7 A	124	0	0.07509	0	0
8 2400	106	0	0.05928	0	0
9 dayu	144	1	0.09933	0	0
10 phhcl	135	0	0.08158	0	0
11 156f	113	0	0.06714	0	0

Figure 3. Results of the color by correlation calculation applied to the entire image taken by a digital camera of a scene at dusk.

Analysis

Theories That Break Under These Conditions

This example points out limitations of two important classes of color theories for complex color imaging. In color appearance models, the assumption is made that there is a single illumination source and this can be measured. Clearly this kind of model cannot apply to this kind of scene without extensive additional measurements and assumptions about choosing an adopted white from these measurements. Because this type of imagery is so important for photography, these models are far from the point of useful application to complex color imaging. If the aspects of color appearance models are used alongside an algorithm that determines an estimate of the white point, then these models could have useful application to complex images. Because of this type of effect, color appearance models cannot be reliably used for judging color image quality in digital cameras.[9] The second class of theories that this example disproves are those that obtain the adopted white from either a global or local maximum in the scene (maxRGB, Retinex, respectively). In either global or local maxima, the illumination color of the sunlight will be balanced out of the objects that the sun hits. The warm glow seen by the observer is lost, and the shadows turn blue [as in Color Plate 16a (p. 386)].

Theories That Do Not Break Under These Conditions

Theories that are robust under these conditions compute an estimate of the white point using all of the colors in the scene—both the direct illumination and the shadow areas. These theories include Color by Correlation[10] and Neural Network Color Constancy.[11] In our example image of the ColorChecker lit by sunset light, the adopted white is computed using Color by Correlation to be somewhere between the color of the sunlight and the color of the shadows. The estimated white point is calculated to be D50, which is the same as the balance point manually chosen for the rendering in Color Plate 23b (p. 387). In this kind of image analysis we can tell that there is more than one color of illumination present, and estimate the colors of the individual sources. Given this information we have more control of the adopted white point used in a color correction model and the resulting rendering of the image.

Examples of Image Illumination Predictions

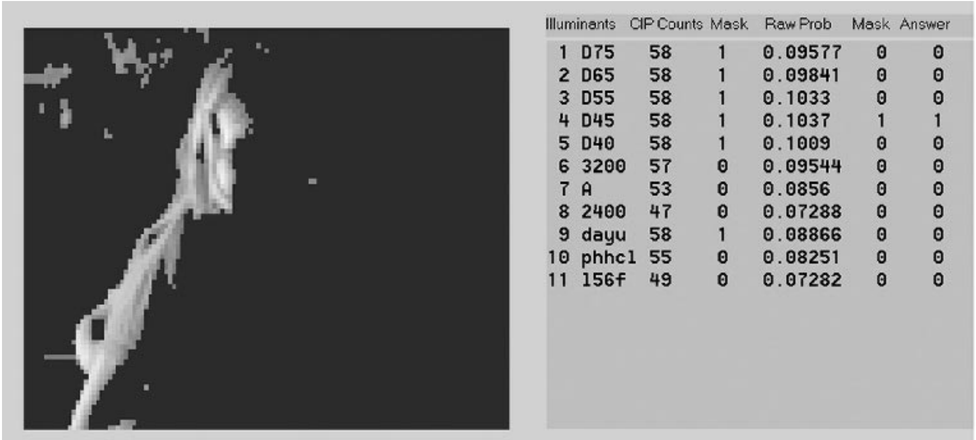
The results of the color by correlation method for an image taken in sunset illumination are shown in Fig. 3. The algorithm estimates D55 as the white point when the entire image is used in the calculation. **Color Plate 17 (p. 387)** shows a rendering of this image balanced for the D55 white point. Figure 3 shows a table of values that are the results of the color by correlation calculation as described in our previous work.[1] The first column lists the light sources considered in the calculation—each row of data contains the possibility and probability estimates for that scene. The second column contains the results of the binary correlation that gives the total number of image chromaticities that are consistent with the given illuminant. The third column applies a threshold value (in this case it was .98) to the data in column 2. The fourth column records the log likelihoods of the given illuminant being the source in the scene. The fifth column applies a threshold value (in this case we used 1.0) to the probability data of column 4. Finally the sixth column is the answer generated from the results of columns 3 and 5. (More detail of this technique is explained in our previous work).

Figures 4 and 5 show the results when only the light or dark areas of the image are analyzed by the color by correlation method. In Fig. 4, when all pixel values below 128 (out of 255) counts are masked out, only the direct illumination is tested. The result here estimates the light to be D45 that is consistent with the color of the light from late afternoon sun. In Fig. 5 the darker shadow areas of the image are estimated to have a white point of D75 (since this was the bluest white-point considered in the calculation, the actual white point of the shadows might have been even bluer than D75).

The example described above shows the importance of considering both the direct illumination and the shadow light when estimating the adopted white point. Not only does the estimation method give a good answer (as determined by the quality of the rendering in Color Plate 17 (p. 387) but can also be used to illustrate how the scene has two distinct light sources of significantly different color.

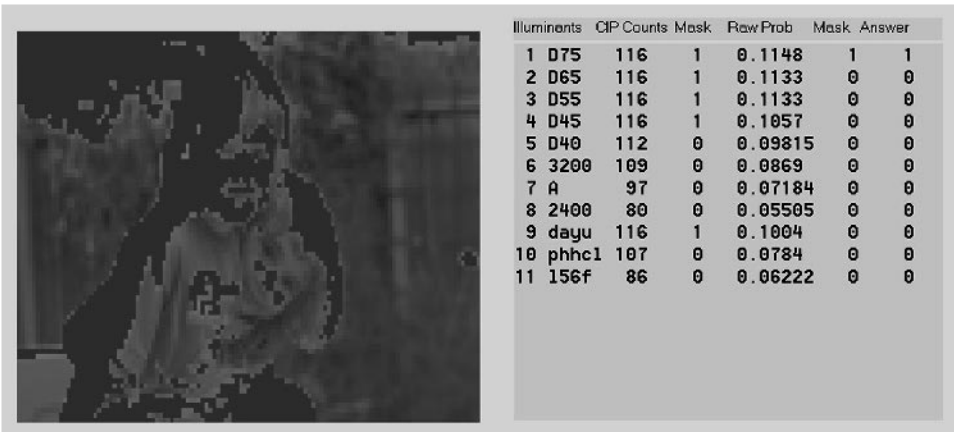
Visual Gamut Size Under Multiple Illuminants

A possible explanation for the beauty and attractive nature of images taken under the sunset/blue shadow conditions is that the color gamut observed in these con-



Illuminants		CIP Counts	Mask	Raw Prob	Mask	Answer
1	D75	58	1	0.09577	0	0
2	D65	58	1	0.09841	0	0
3	D55	58	1	0.1033	0	0
4	D45	58	1	0.1037	1	1
5	D40	58	1	0.1009	0	0
6	3200	57	0	0.09544	0	0
7	A	53	0	0.0856	0	0
8	2400	47	0	0.07288	0	0
9	dayu	58	1	0.08866	0	0
10	phhcl	55	0	0.08251	0	0
11	156f	49	0	0.07282	0	0

Figure 4. Results of the Color by Correlation calculation applied only to the light regions of the dusk scene.



Illuminants		CIP Counts	Mask	Raw Prob	Mask	Answer
1	D75	116	1	0.1148	1	1
2	D65	116	1	0.1133	0	0
3	D55	116	1	0.1133	0	0
4	D45	116	1	0.1057	0	0
5	D40	112	0	0.09815	0	0
6	3200	109	0	0.0869	0	0
7	A	97	0	0.07184	0	0
8	2400	80	0	0.05505	0	0
9	dayu	116	1	0.1004	0	0
10	phhcl	107	0	0.0784	0	0
11	156f	86	0	0.06222	0	0

Figure 5. Results of the Color by Correlation calculation applied only to the light regions of the light scene.

ditions is larger than under a single illumination source. Indoor illumination will give small color contrast between direct illumination and shadows and the color gamut subtended by a set of surfaces is similar to the gamut of a single source. Figure 6 is a plot of 1976 u'v' chromaticitiy coordinates from two ColorCheckers. The solid polygon corresponds to the convex hull of the surfaces lit by direct tungsten illumination and the dashed polygon corresponds to surfaces in the shadow region of the image. There is very little shift of the polygon between direct and shadow illumination.

In the case of sunset illumination, the gamut from the direct illumination and the gamut of the shadow area shift away from each other and the combined total area is larger than would be possible under a single illumination. Figure 7 shows the convex hull polygons of the two ColorCheckers and the large shift due to the different illumination color. Figure 8 shows how the total image gamut of the sunset lit scene is ~75% larger (in this particular chromaticity space) than the gamut area of the surfaces under the just the sun's light (or equivalently the tungsten light).

Although this simple colorimetric analysis has obvious limitations, it does show that the variation of color signals entering the visual system is larger under these multi-illumination conditions.

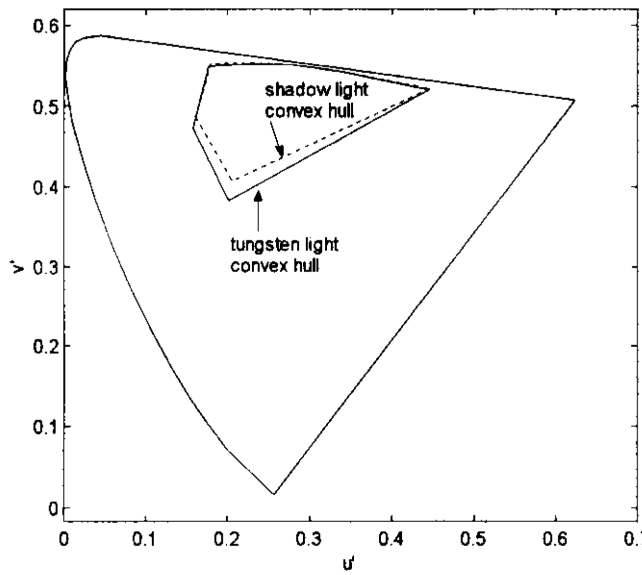


Figure 6. 1976 Chromaticity diagram showing the convex hulls of the MacBeth ColorChecker Chart illuminated by studio tungsten light (solid line) and indoor tungsten shadow light (dashed line).

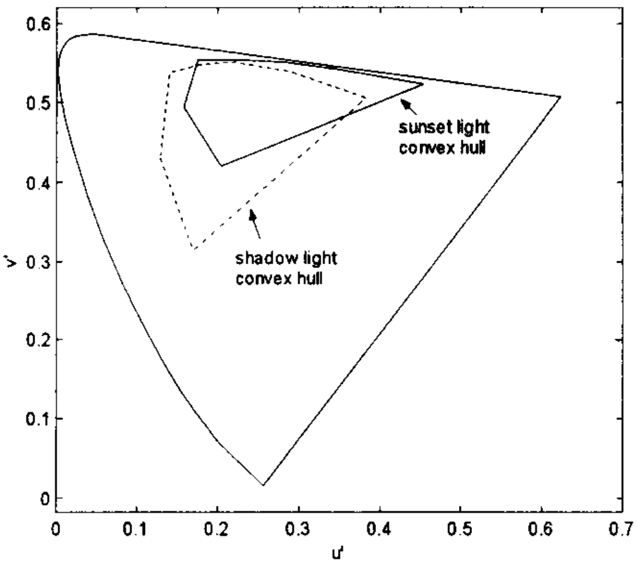


Figure 7. ColorChecker illuminated by sunset light (solid line) and shadow light (dashed line).

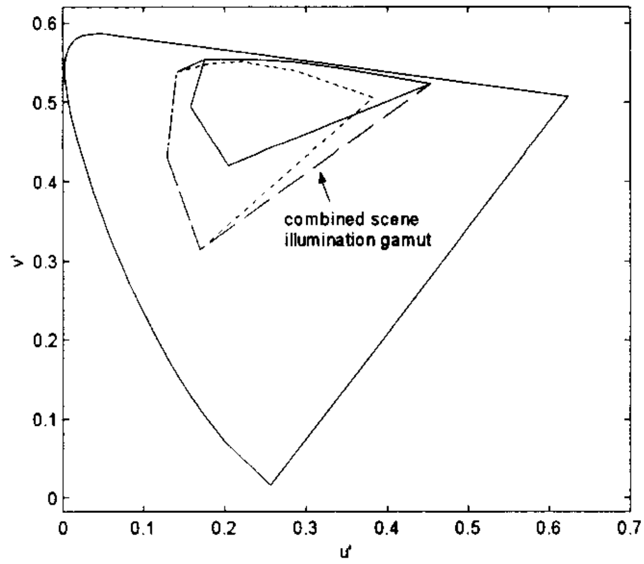


Figure 8. Total gamut of color from sunset light and shadow light (large dashed line).

Discussion: Expected Gamut

An illumination estimation algorithm such as color by correlation takes advantage of the link between colors that the visual system observes and some 'expected' or 'associated' white point. We have proposed that perhaps some associative mechanism operates to balance color signals that have a strong yellow-orange cast to white in order to compensate for tungsten illumination. Perhaps the reverse is also true: given an adapted white point, (the observers internal balance point) the visual system may have some notion of an associated or expected color gamut. As an observer views a scene at dawn or dusk, the observers adapted white point is say, D45, influenced by his total visual field. If the observer then looks up and sees objects lit by a warm sunset source, these color signals would be shifted from their expected position and maybe even out of the observers expected color gamut. The 'warm glow' and 'self luminous' nature of these colors could perhaps be due to the colors being outside the 'expected' gamut—the normal canonical gamut of surface reflectances under a single source.

Conclusion

The color balance of a real photographic image is driven by the complex relationship between the colors of the adopted and adapted white points. In the examples described we have shown that colorimetric measurements and simple white balance techniques are not reliable predictors of the adapted white point. In the case of photographs taken at dawn or dusk, the color of the sky lighting the shadows plays an important roll and must be considered in calculation of the adopted white point.

References

1. P.M. Hubel, J. Holm, and G.D. Finlayson, Illuminant Estimation and Color Correction, in *Colour Imaging in Multimedia*, L. MacDonald, Ed., Wiley, New York, 1999, pp. 73-95.
2. M.D. Fairchild, *Color Appearance Models*, Addison-Wesley, Reading, MA, 1998.
3. R.W.G. Hunt and M.R. Luo, The Structure of the CIE 1997 Colour Appearance Model (CIECAM97), unpublished.
4. J. Holm, Adjusting for the Scene Adopted White, *Proceedings of the 2nd IS&T PICS Conference*, IS&T, Springfield, VA, 1999, p. 158.
5. L.A. Jones and H.R. Condit, *J. Opt. Soc. Am.* **38,** 123 (1948).
6. H.R. Condit and F. Grum *J. Opt. Soc. Am.* **54,** 937 (1964).
7. F.H.G. Pitt and E.W.H Selwyn, *Phot. J.* **78,** 115 (1938).
8. R.W.G. Hunt, *The Reproduction of Color*, Fountain Press, Kingston-upon-Thames, 207, 1995.
9. P.M. Hubel, Color image quality in digital cameras, *Proceedings of the 2nd IS&T PICS*, IS&T, Springfield, VA, 1999, p. 153.
10. G. D. Finlayson, P. M. Hubel, and S. Hordley, Colour by Correlation, *Proceedings of the 5th IS&T/SID Color Imaging Conference*, IS&T, Springfield, VA, 1997, p. 6.
11. B.V. Funt, V. Cardei and K. Barnard, Learning Color Constancy, *Proceedings of the 4th IS&T/SID Color Imaging Conference*, IS&T, Springfield, VA, 1996. p. 58.

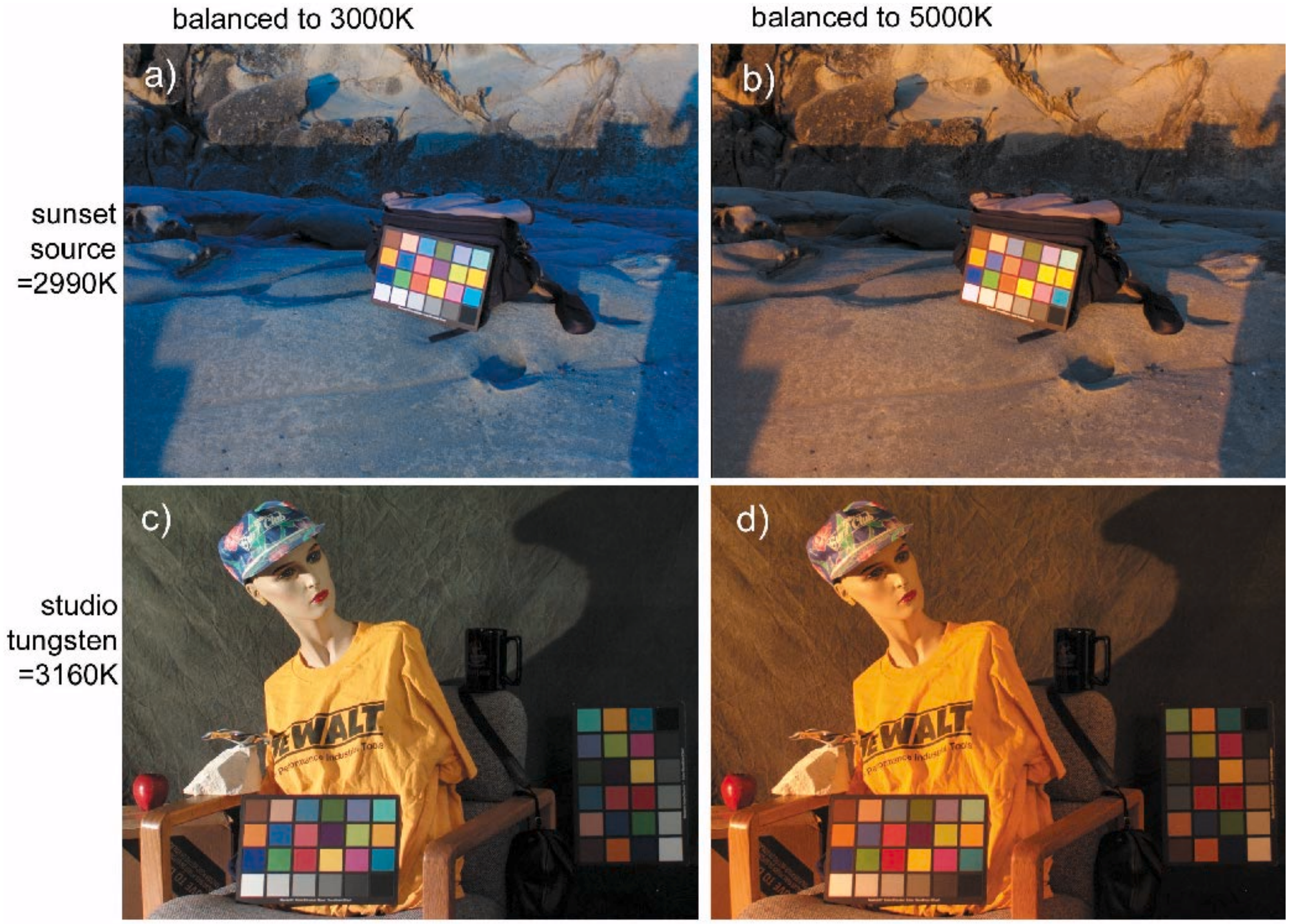


Plate 16. Images a and b are two renditions of a scene showing a MacBeth ColorChecker chart illuminated by sunset light (on a clear day in October at about 6:30 pm aloong the Northern California coast). Image a is balanced for the color of the sunset illumination (~3,000 K) and image b is balanced to the value determined both by manual adjustment and by the Color by Correlation calculation (~5,000 K). Image c and d are two renditions of an indoor scene showing a MacBeth ColorChecker chart illuminated by studio tungsten light. Image 1c is balanced for the color of the source (3,000 K) and image d is balanced for 5,000 K. Both the manual adjustment and the Color by Correlation calculation determined the white balance point to be ~3,000 K. [Hubel, pp.371–375).

Plate 17. The example image described in the text taken at dusk and balanced to a white point of 5500 Kelvin [Hubel, pp.371–375).