Faithful Representation of Colours on a CRT Monitor

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Abstract: A method is described to display faithfully on a CRT monitor the colours of images taken by a calibrated digital camera. A multicoloured "input" image, displayed on a monitor, was photographed with the camera. After correcting the digital image to take into account the gammas of both camera and monitor, the image was redisplayed as an "output" image on the same monitor. An iterative procedure found the linear matrix transformation that minimized the difference between the input and output image RGB values. We compared the efficacy of this method with two conventional methods for displaying photographed images on CRTs: the method of displaying the raw untransformed image, and the method whereby the image is transformed via the CIE common frame of reference. The results of the comparisons suggest that the iterative method produces the most faithful representation of the colours of the original image. © 2007 Wiley Periodicals, Inc. Col Res Appl, 32, 388–393, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20344

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INTRODUCTION

Recent improvements in digital image technology have resulted in an increase in the use of images of natural scenes for visual psychophysics experimentation.[1–4] It is now possible to display large numbers of images of natural scenes to human and animal test subjects in rapid succession on a cathode-ray-tube (CRT) or other display devices. Typically, the scenes will have been photographed by a digital camera. For the most part, images of scenes taken with digital cameras and presented untransformed on a CRT look remarkably realistic. The reason for this is that the camera and CRT are both like the human visual system, that is, are "trichromatic." Just as the visual system represents colours via the relative activations of the long-wavelength-sensitive (L), middle-wavelength-sensitive (M), and short-wavelength-sensitive (S) cones, so too the camera via its red (R), green (G), and blue (B) sensors and the CRT via its R, G, and B phosphors. In other words, the compression of multispectral information by the trichromatic camera and trichromatic monitor mimics the compression of information by our own visual system. Nevertheless, distortions occur. Heavily saturated colours such as monochromatic lights are impossible to reproduce on a CRT, because these colours lie outside the gamut of typical display devices. Furthermore, the limited dynamic range of camera and CRT makes it impossible to reproduce the full range of natural image intensities. Finally, because the spectral characteristics of the camera sensors and monitor phosphors are not matched to those of human cones, the colours or hues of natural scenes will often look slightly different when displayed on a monitor. Although the difficulties with heavily saturated colours and large intensity ranges are unavoidable if one is using a conventional camera and CRT, the distortions of perceived colour can be potentially minimized, and it is with regard to this issue that the present communication is concerned.

Currently the most widely used solution for producing faithful colours on a CRT is to convert the camera to monitor image via a common perceptual frame of reference, typically the CIE XYZ colour space.[5] The CIE XYZ colour space is a three-dimensional space, with luminance defined by the *Y* coordinate. This colour space can be re-expressed in a two-dimensional *x*-*y* coordinate diagram of the gamut of perceptible colours. Because the CIE space is based on human colour

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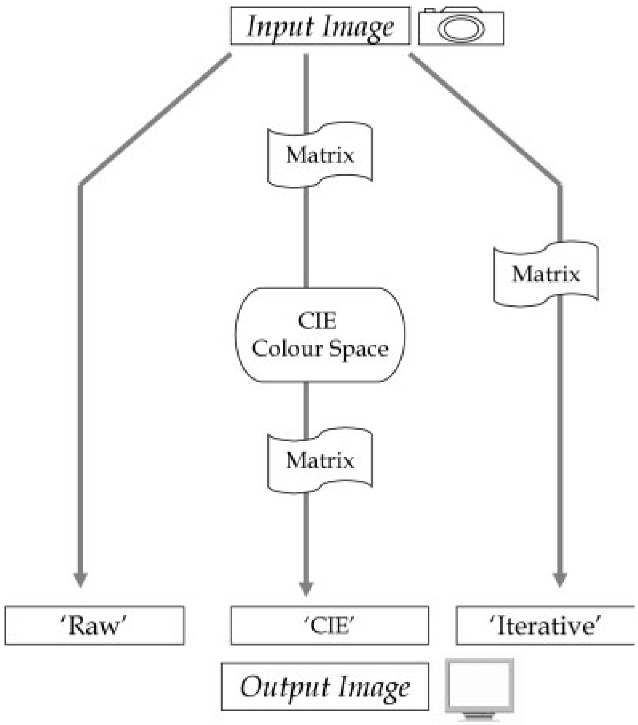

FIG. 1. Three methods for converting a camera to a monitor image.

perception, colours with different spectral functions that nevertheless map onto the same CIE XYZ coordinates will by definition look the same. The CIE-conversion method for producing faithful colours uses the fact that both camera and monitor RGBs can be converted to CIE XYZs via a linear matrix transformation[6] as illustrated in Fig. 1(left). The transformation, however, is not precise, because of the nonlinearities of the camera sensors and the human eye and because of the limits of the mathematical operation.[6,7] The conversion of camera and monitor RGBs to CIE XYZ could be achieved through RGB to XYZ look-up tables, obtained by measuring the CIE XYZs of the phosphors with a spectral radiometer, or via a published standard transformation matrix.[8–12] Because of variations in the illuminant in a scene or between scenes, the correction matrix for converting camera RGB to CIE XYZ is less accurate than a matrix calculated from the full spectral functions of camera and monitor for two reasons. First, because the CIE XYZ values of the colour chart are usually measured under a specific illuminant, and second because the matrix is derived from a much smaller set of measurements. If one measures the spectral characteristics and gamma of the camera sensors and monitor phosphors, the conversion of the RGB values to CIE XYZ can be accomplished by a device-specific transformation matrix that will be more accurate.[8,9] Perceptual frames of reference other than the CIE XYZ can in principle also be used, for example cone excitation space, where each colour is represented by the modeled levels of excitation in the L, M, and S cones.[7]

One of the drawbacks of the CIE method is that because of the many steps involved, the method is vulnerable to an accumulation of measurement error. Here we consider the efficacy of an alternative method for reproducing colours on a CRT that eliminates the need to measure the spectral characteristics of camera and monitor, as well as the need for a perceptual frame of reference. Our "Iterative" method is illustrated in Fig. 1(middle), and uses a single matrix to transform the camera to monitor RGBs. The matrix is arrived at iteratively by minimizing the difference between an "input" and an "output" RGB image that are both displayed on a monitor. The method for deriving the matrix is illustrated in Fig. 2 and is described in detail later.

We carried out three tests to compare the effectiveness of the Iterative method with that of two conventional methods: the "Raw" method of displaying the untransformed camera image, and the CIE method described earlier. The first test involved a comparison of an input and output image, in terms of both RGB and CIE L*a*b*, in which the input image was an image on a monitor and the output image a photograph of the input image redisplayed on the same monitor. The second test compared the colours of two input charts (i.e., not their images) with their reproduced images on the monitor in terms of both CIE XYZ and CIE L*a*b colour spaces. The third test was a psychophysical test in which subjects judged how faithful to the original were monitor images of photographic prints of natural scenes.

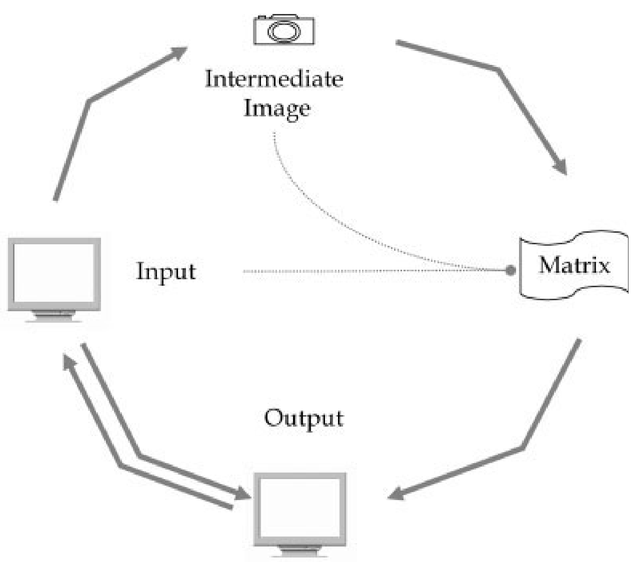

FIG. 2. Method for deriving the conversion matrix for the Iterative method. An image of the Macbeth chart is displayed on the monitor as the Input image. This is then rephotographed—the Intermediate image—then redisplayed on the same monitor as an Output image after conversion via a linear matrix transformation that minimizes the difference between the RGB values of the Input and Output images.

METHODS

Equipment

The photographs were taken with a Nikon CoolPix-7500 digital camera and displayed on a Sony FD Trinitron 17″, GDM F-500 monitor. The digital images were displayed using the VSG graphics board (Cambridge Research Systems) housed in an 1800 MHz PC computer. Pixel resolution was 640 × 480 and monitor refresh rate was 100 MHz. A 24-colour patch Macbeth chart, which includes a range of colours found in natural environments, was used as the test image. In addition, we used another lab-made chart with 13 different but randomly chosen colour patches printed on high-quality photographic paper. For the psychophysics test we used 12 images of natural scenes taken from the McGill Calibrated Colour Image Database[13] and printed onto high quality photographic paper, 12.5 × 9 cm^2, using a Xerox Tektronix Phaser 860 colour laser printer with a resolution of 1200 DPI. We also used two spectroradiometers, Photoscan 645 and 650 from Photo Research, for measuring the spectral properties of the colour patches on both monitor and paper.

Camera Calibration

The procedure for gamma correcting the camera and measuring the spectral sensitivities of its three sensors is detailed elsewhere,[13] and only a brief exposition will be given here. Each of nine grey Munsell papers, illuminated by an incandescent light with a constant-DC power, was photographed and its luminance measured with a Topcon SR-1 spectrophotometer. The resulting plots of luminance versus pixel value were fitted with a gamma function, and this was used to correct the pixel values for gamma-nonlinearity. To measure the camera sensors' spectral sensitivities, a white target was photographed through a series of narrowband optical interference filters from 400 to 700 nm at 10-nm intervals. The resulting spectral sensitivity functions were then gamma-corrected and normalized to produce equal responses to a flat-spectrum light. These functions were used in the CIE method illustrated in Fig. 1(a).

Monitor Calibration

In a dark room, the luminance intensity of each red, green, and blue gun was measured using an OptiCal photometer (Cambridge Research Systems) in the range of 0–255 in 32 steps. The luminance responses were fitted with a gamma function, which was used to equalize the gain of each gun. Hereafter, whenever we refer to RGB values, we mean the gamma-corrected RGB values. To measure the spectral emission functions, the whole screen was filled with maximum intensity red, green, or blue, and the spectra measured using the Optikon SpectroScan® PR 645 spectroradiometer.

Procedures: Three Methods for Reproducing Camera Images on a Monitor

Raw Image Method. In this method, the camera images were gamma-corrected, scaled to fill the range of the monitor, and displayed on the monitor which was itself gamma-corrected.

CIE Method. In order to derive a transformation matrix to convert the camera RGBs to CIE XYZs, the following procedure was performed. A constant light source with a flat broad spectrum was used as the light source. Thirty filters with wavelengths gamma ranging from 400 to 700 nm in 10-nm steps were placed in front of the light source and photographed. The resulting camera RGB values, along with the CIE XYZ values of the lights measured using the spectroradiometer, were recorded. A matrix was calculated to convert the camera RGB values to CIE XYZ and vice versa. The linear conversion matrix was calculated as follows:

$$T = \begin{bmatrix} \Sigma R(\lambda)X(\lambda) & \Sigma R(\lambda)Y(\lambda) & \Sigma R(\lambda)Z(\lambda) \\ \Sigma G(\lambda)X(\lambda) & \Sigma G(\lambda)Y(\lambda) & \Sigma G(\lambda)Z(\lambda) \\ \Sigma B(\lambda)X(\lambda) & \Sigma B(\lambda)Y(\lambda) & \Sigma B(\lambda)Z(\lambda) \end{bmatrix}$$

where $R(\lambda)$, $G(\lambda)$, and $B(\lambda)$ are the camera RGB spectral sensitivities and $X(\lambda)$, $Y(\lambda)$, and $Z(\lambda)$ the corresponding CIE XYZ values.

To derive the transformation matrix to convert the CIE XYZ values to monitor RGBs, we set each phosphor to its highest luminance value and measured its spectral characteristics using the spectroradiometer. A matrix of the same form as the one above was calculated to convert the CIE XYZs to RGBs using the method described by Travis.[9] In summary we derived two matrices, one to convert camera RGBs to CIE XYZs and another to convert CIE XYZs to monitor RGBs.

Iterative Method. The scheme for deriving the conversion matrix is illustrated in Fig. 2. We first photographed the Macbeth Colour Chart and displayed it on the monitor. This image was the input image, and as such it was not necessary for the image to be a faithful reproduction of the original. The input image was then rephotographed by the camera. The new camera image was then γ-corrected for the camera nonlinearity and converted to a γ-corrected output monitor image using a matrix that minimized the difference between the input and output RGBs. The RGB values were taken from a fixed-size area in the center of each square (200 × 200 pixels for the camera, 50 × 50 pixels for the monitor). A matrix of the same form as the one described earlier was calculated to convert the monitor RGBs to camera RGBs. Then, we measured the *chi square distance* ($\chi^2 = \Sigma$[(output–input)^2/input]) between the RGB values of the input and the output images. The output image was the product of the intermediate image and the calculated matrix, as illustrated in Fig. 2. We then used an optimization routine to find the matrix with the smallest chi square distance. For this purpose we used the Solver tool in Microsoft Excel with 100 iterations and a precision of 10^{-7}.

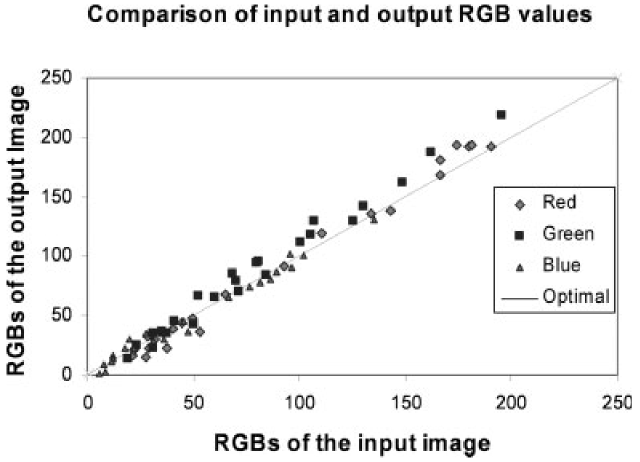

FIG. 3. Relationship between the RGBs of the output (ordinate) and input image of the Macbeth chart (abscissa) obtained using the Iterative method.

RESULTS: THREE TESTS FOR COMPARING THE THREE METHODS

Test 1. Comparison of Input and Output Monitor Images

A Macbeth chart was photographed and displayed on the monitor as the input image. The input monitor image was then photographed and redisplayed according to each of the three methods.

In RGB Colour Space. The RGBs of each patch of the input and output, gamma-corrected monitor images of the Macbeth chart, were correlated using Pearson's r correlation coefficient (24 patches $\times$ 3 RGB $=$ 72 data points). The results were Iterative method, $R = 0.99$; CIE method, $R = 0.98$; Raw method, $R = 0.98$. Figure 3 shows the relationship between the input and output RGBs obtained using the Iterative method. Although correlation is an indication of the consistency in the relationship between two variables, it is not indicative of the magnitude of any difference between the two variables. For this we compared the similarity between input and output RGBs by measuring the Euclidean distance E between them. E was calculated as $E = \sqrt{(R_o - R_i)^2 + (G_o - G_i)^2 + (B_o - B_i)^2}$, where the subscripts i and o refer to the input and output images. The mean Es across all 24 patches were Iterative 13.65; CIE-transformed 42.39; Raw 16.58. A one-way paired t-test was performed to test the hypothesis that the Iterative method produced smaller Es than each of the CIE XYZ and Raw methods, and the result was statistically significant for both Iterative versus Raw ($t(1,23) = -3.267$; $P = <0.005$) and Iterative versus CIE-transformed ($t(1,23) = -9.979$; $P = <0.001$) comparisons.

*In CIE L*a*b* Colour Space*. Neither the RGB colour space nor the CIE-XYZ colour spaces are perceptually uniform, that is equal distances between points are not equal perceptual steps.[8] The CIE L*a*b* colour space is more-or-less perceptually uniform, and therefore, the degree of correlation in this colour space is arguably a better measure of the perceptual covariability between the original and reproduced images. The RGB values were converted to CIE XYZ colour space and from there to CIELAB colour space. The correlations were Iterative method, $R = 0.99$; CIE-conversion method, $R = 0.98$; Raw method, $R = 0.96$. The mean Es across all 24 patches were 8.4, 18.43, and 8.89 for the Iterative, CIE-transformed and Raw methods, respectively. One-way paired t-tests showed a significant difference between the Iterative and CIE-transformed ($t(1,23) = -3.867$; $P < 0.001$), but not between the Iterative and Raw ($t(1,23) = -0.694$; $P = 0.49$) methods.

Test 2. Spectral Comparison of Source Chart and Monitor Image

In this test, we compared the spectral characteristics of the 24 patches of a Macbeth chart (i.e., the original not

TABLE I. Summary of physical test results for the comparison between the input monitor image (top) and input paper (bottom) with the output monitor image.

	RGB			L*a*b*		
	Iterative	CIE	Raw	Iterative	CIE	Raw
Comparison of input monitor image with output monitor image						
R	0.99	0.98	0.98	0.99	0.98	0.96
Mean E	13.652	42.388	16.579	8.399	18.434	8.890
t-Test		Iter. versus CIE, $p = <0.001$*	Iter. versus Raw, $p = 0.003$*		Iter. versus CIE, $p = <0.001$*	Iter. versus Raw $p = 0.494$
	XYZ			L*a*b*		
	Iterative	CIE	Raw	Iterative	CIE	Raw
Comparison of input paper chart with output monitor image						
R	0.981	0.971	0.972	0.957	0.916	0.948
Mean E	0.0442	0.0874	0.0548	16.089	25.736	17.621
t-Test		Iter. versus CIE, $p = <0.001$*	Iter. versus Raw, $p = 0.040$*		Iter. versus CIE, $p = <0.001$*	Iter. versus Raw, $p = 0.208$

*Significant.

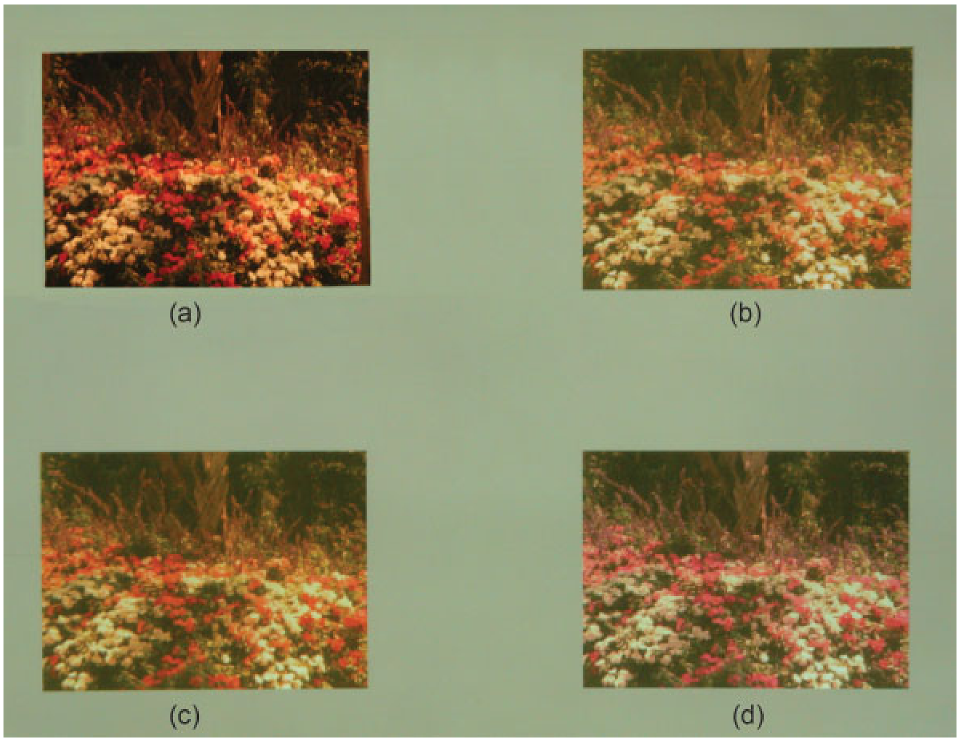

FIG. 4. (a) A print of a natural scene is attached to the upper left quadrant of the monitor. The output images for (b) Raw, (c) Iterative methods, and (d) CIE-conversion.

photographed image) with their monitor reproductions, for each of the three methods. The spectral characteristics of both the original and monitor reproductions were measured in CIE XYZ space and then converted to values in the CIELAB colour space. We performed the same test using a lab-made chart consisting of 13 colours that were perceptibly different from those on the Macbeth chart.

In CIE XYZ Space. The correlations between the input and reproduced images for the Iterative, CIE-transformed, and Raw methods were 0.981, 0.971, and 0.972. The mean Es for the Iterative, CIE-transformed, and Raw methods were 0.044, 0.087, and 0.055. The differences between the Iterative and CIE, and between the Iterative and Raw methods were both significant (Iterative vs. CIE: $t(1, 36) = -6.178$; $P < 0.001$; Iterative vs. Raw: $t(1, 36)$ =-2.133; $P < 0.05$).

In CIELAB Space. The correlations between the input and the output of each method were 0.96, 0.92, and 0.95 for the Iterative, CIE, and Raw methods. The mean Es were 16.089, 25.736, and 17.621 for the Iterative, CIE, and Raw methods. The differences were significant for the Iterative versus CIE comparison (Iterative vs. CIE: $t(1, 36) = -4.920$; $p < 0.001$) but not for the Iterative versus Raw comparison: $t(1, 36) = -1.283$; $p = 0.208$).

The results of all the physical comparison tests are summarized in Table I.

Test 3. Psychophysical Evaluation

Twelve natural scenes were photographed, and a print of each scene was rephotographed in normal room lighting and converted to a monitor image according to each of the three methods under test. On each trial, a print was attached to the upper left quadrant of the monitor screen, and the three test images were randomly displayed in the remaining three quadrants. We used the normal lighting of the room for the experiment, which was different from the light condition of when the scenes were captured. The arrangement is shown in Fig. 4. Subjects were asked to rank the three test images in order of their perceived similarity to the print, by pressing three keys in the order of their ranking. Nine subjects ranked the images. All subjects had normal or corrected-to-normal vision, and their colour vision was tested using the Ishihara plates. For the psychophysical test, out of a total of 108 image presentations (9 subjects $\times$ 12 images), the Iterative method images were chosen as best 58 times (49%), the raw method images 35 times (32%), and the CIE-conversion images 20 times (19%). For statistical analysis, we scored the measurements on the first choice by three, the second choice by two, and the third by one. Then, we ran the Kruskal–Wallis one-way analysis of variance on Ranks, followed by Tukey test for pairwise multiple comparison. The Iterative method was found to rank significantly higher than the CIE ($q = 11.034$, $p < 0.05$, df $= 2$) but not Raw ($q = 2.357$, $p > 0.05$, df $= 2$) method.

DISCUSSION

Of the three methods for reproducing photographed colours on a CRT, the Iterative method overall faired best. Although in the case of the physical correlations the differences between methods were small, the Iterative method consistently produced the highest correlation. The mean Euclidean distance E between the input and output images was invariably smallest for the Iterative method, and except for the Es calculated using the CIELAB space for the Iterative versus Raw comparison, the differences were significant. These findings were true of the tests using colour charts rather than monitor images as the input. Colour charts are the better input, because they are not limited by the gamut of the monitor and because they employ colours that are different from those used to calculate the transformational matrix of the iterative method. In the psychophysical test, subjects ranked the monitor images produced by the Iterative method as most similar to the prints, though the difference in ranking was only significant for the comparison of the Iterative and CIE methods. In summary, it would appear that the Iterative method fares best at reproducing colours either from monitors or from prints.

The first caveat to this conclusion is that because we have not tested the Iterative method using real natural scenes, we cannot rule out the possibility that the other two methods might be superior with real, natural scenes, though we see no reason why they should be and assume that they are not. The second caveat, which we have already mentioned, is that no method involving a conventional camera and CRT is capable of reproducing all the colours found in real scenes.

Notwithstanding these caveats, the Iterative method appears to be an effective method for faithfully reproducing photographed colours on a CRT. Besides reproducing colours more faithfully than other methods, the Iterative method has the added advantage, at least when compared with the CIE-conversion method, of being the easier to implement. With the Iterative method, the spectral characteristics of the camera and monitor do not need to be measured, provided both camera and monitor are gamma-corrected, and a single transformation matrix suffices to convert the camera to the monitor image. Further research is needed to see in what ways the Iterative method can be improved, and how effectively it reproduces the colours of actual natural scenes. In addition, the results of this experiment could be tested with different sets of cameras and monitors.

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1. Bramwell DI, Hurlbert AC. Measurements of colour constancy by using a forced-choice matching technique. Perception 1996;25:229–241.
2. Fine I, Macleod DIA, Boynton GM. Surface segmentation based on the luminance and color statistics of natural scenes. J Opt Soc Am A 2003;20:1283–1291.
3. Parraga CA, Tolhurst DJ. The effect of contrast randomisation on the discrimination of changes in the slopes of the amplitude spectra of natural scenes. Perception 2000;29:1101–1116.
4. Wichmann FA, Sharpe LT, Gegenfurtner KR. The contributions of color to recognition memory for natural scenes. J Exp Psychol Learn Mem Cogn 2002;28:509–520.
5. Sharma G, Trussell H. Digital color imaging. IEEE Trans Image Process 1997;6:901–932.
6. Mark Shaw MF. Evaluating the 1931 CIE color-matching functions. Color Res Appl 2002;27:316–329.
7. Stockman A, Sharpe LT. Human cone spectral sensitivities: A progress report. Vision Res 1998;38:3193–3206.
8. Süsstrunk S, Buckley R, Swen S. Standard RGB Color Spaces. Proc IS&T Color Imaging Conf; 1999;vol. 7:127–134.
9. Travis D. Effective Colour Displays. Academic Press; London, 1991.
10. Kasson JM, Plouffe W. An analysis of selected computer interchange color spaces. ACM Trans Graph 1992;11:373–405.
11. Funt B, Ghaffari R, Bastani B. Optimal Linear RGB-to-XYZ Mapping for Color Display Calibration. Proc IS&T Color Imaging Conf 2004;223–227.
12. Ohno Y, Hardis JE. Four-color matrix method for correction of tristimulus colorimeters. Proc IS&T Fifth Color Imag Conf 1997:301–305.
13. Olmos A, Kingdom FAA. Calibrated Color images database project, http://tabby.vision.mcgill.ca