Camera Sensitivity Evaluation and Primary Optimization Considering Color Constancy

Po-Chieh Hung
Corporate R&D Laboratories, Corporate Technology Center
Konica Corporation
Tokyo, Japan

Abstract

The evaluation of input device spectral sensitivity is often performed in terms of colorimetric quality and potential noise caused by overlaps among spectral sensitivities. Based on the assumption that the white balancing function should aim at color constancy rather than chromatic adaptation, we have proposed a new measure to evaluate camera sensitivities. We measure how accurate camera estimates the colors of typical objects under a standard light source from the ones under different light sources. Firstly, we apply these three evaluation measures, which are colorimetric error, noise amount, and newly proposed color constancy prediction error (CCPE), to eight sets of camera sensitivities. Thus it is found that sensitivity set of a conventional TV camera performs better CCPE than the E-H-P primaries. Secondly, we optimized primary conversion with a linear diagonal matrix transform, a. k. a. von Kries transformation, in order to minimize CCPE. The sensitivity obeying the Luther condition does not necessarily perform the best while the conventional TV camera sensitivity gives the best result. Lastly, we evaluate the optimized results with spectral reflectance database for several light sources including fluorescent lamps. We found that a linear combination of color rendering properties (*Ra*) of light sources and reciprocal color temperature difference from the standard light source well estimates CCPE.

Introduction

In order to quantitize the color reproduction capability of input device, colorimetirc quality evaluation of spectral sensitivity is often used to indicate how close to the Luther condition. Several evaluation methods have been proposed. Neugebauer's CQF (color quality factor) is a classic one.[1] Vora and Trussell have proposed Measure of Goodness in order to unify the independent indexes for each channel into one.[2] The author proposed Camera Rendering Index, which uses eight patches defined in CIE 13.3, and found that the index has a high correlation with spectral reflectance database.[3] These methods quantitize the possibility of potential metamerism problem.

On the other hand, practical cameras need to reproduce colors under different light sources, in addition to a standard light source. For example, Daylight is often regarded as the standard light source in photography. However, objects may be illuminated by an incandescent lamp having a low correlated color temperature, or sky blue having a high correlated color temperature when the objects are in shadow, in practice. Even under these kinds of circumstances, the objects are expected to be reproduced as good colors.

Mostly, the adapted white of scene is adjusted to correspond to the white point of output device. This function in a camera is known as white balance.

Here, a question arises: How to handle chromatic colors? There are two targets: One is to mimic the chromatic adaptation as if camera worked as human visual system, namely chromatic adaptation target, an the other is to reproduce the color as if it were under the reference lighting condition, namely color constancy target.

In this paper, we propose to use the color constancy target for cameras.[4] Firstly we review the proposal. Based on this assumption, color constancy prediction error (CCPE) is evaluated with/without optimization matrix for primary conversion. Secondly, we evaluate this method with artificial light sources and the SOCS database.[5] Lastly we analyze major causes determining CCPE.

Chromatic Adaptation and Color Constancy

The human visual system has the function called chromatic adaptation in order to recognize objects regardless viewing environments such as light sources. On the other hand, in the fields of computer vision and human vision, it is said that the human visual system would have an ability to approximate the colors under a standard light source from colors under different light sources. It is called color constancy.

In order to clarify the relationship between chromatic adaptation and color constancy, we introduce the following hypothesis:

[Hypothesis]

The function of chromatic adaptation has been evolving in order to realize color constancy, but it is not perfect yet.

This hypothesis is convincing us as we consider the variations of viewing environments in our life. For example, animals need to recognize game to survive regardless of lighting condition such as direct sunlight, twilight, and in a shade.

One of circumstantial evidences that our human visual system is not perfect is that, for example, we would feel pale for human faces under blue sky without the direct rays from the sun, and would feel reddish for them under incandescent lamps. Under these conditions, we may often have a sense of incompatibility, and may tend to avoid a critical judgement of human face color.

This hypothesis may give us answers to the following knowledge.

(1) Fundamental primaries optimized in terms of color constancy are introduced into color appearance models because it fits to visual experiments. For instance, the Bradford primaries give a better match with visual experiments. The modified CIECAM97s uses sharpened Bradford primaries in addition to the Estevez-Hunt-Pointer primaries (E-H-P).[6]

Our hypothetical answer is that the visual experiments could not perfectly distinguish chromatic adaptation and color constancy. Therefore the result of the visual experiments may be a compromise between them. The Bradford primaries might be somewhat optimized in the sense of color constancy.

(2) As linear diagonal matrix is optimized in terms of color constancy, the resultant sensitivity derived from color matching functions would be sharper than cone spectral sensitivities.[7]

Our hypothetical answer is that, since human visual sensitivity may not be perfectly optimized for color constancy yet, there may be a different optimum. Some might mix up the spectral sensitivity generated by the diagonal matrix with the real spectral sensitivity.

(3) White balance should be performed at the level of RGB sensors of TV Camera in practice.

Our hypothetical answer is that, if color constancy were the final goal, appropriate spectral sensitivities could be existed. The curve could be coincidentally close to the sensitivities of TV camera.

As discussed above, we come to conclude that our goal for the white balance of camera should be the color constancy target, which may be the goal of chromatic adaptation in our evolution.

Evaluation of Color Constancy Performance

We evaluate two measures, which give how it can predict color constancy with/without optimization using a primary conversion matrix for color constancy. We suppose that gain adjustment with a diagonal matrix transform (DMT) is used for the white balance. This assumption is identical to the paper by Finlayson et al.[7]

We evaluate CCPE using sensitivity curves including the ones used in practice. We use existing color patches for the spectral reflectance of typical object. Illuminant D65 is defined as the standard light source, and black bodies having low and high relative temperatures are used as different light sources.

Evaluation Methods

We evaluate sensitivity from three aspects: colorimetric quality, CCPE (with/without optimization) and noise. The following notations are used to describe the formulae (Each variable is a vector. Transpose signs are neglected):

L: Spectral distribution of light source,
R: Spectral reflectance of patches,
S: Spectral sensitivity,
F: Color matching functions,
A: Primary conversion matrix for color constancy optimization,
B: Estimation matrix from camera output signals to tristimulus values,
M: Diagonal matrix,
T: Tristimulus values,
O: Camera output,
Lab(***T***): Conversion to L^*a^*b,
E*ab(**a**, ***b***): Average of ΔE^*_{ab},

where, subscript i indicates a set of spectral sensitivities, subscript j indicates a type of sample light source, subscript std denotes the standard light source.

Color Reproduction Error (CRE)

Similar to Color Rendering Index,[3] we use a simple equation to quantize the colorimetric reproduction error. When

$$T_{ref} = L_{ref} RF, \quad (1)$$

$$O_{ref\text{-}i} = L_{ref} RS_i,\ O_{j\text{-}i} = L_j RS_i, \quad (2), (3)$$

we define,

$$Ecol = E * ab(\ Lab(T) - Lab(BO)\ ). \quad (4)$$

When $Ecol$ is minimized by Matrix $\boldsymbol{B}$, $Ecol$ is CRE. Figure 1 depicts the schematic diagram of this measure.

Color Constancy Prediction Error (CCPE)

We compare colors under the standard light source and the white balanced colors with DMT from the colors under difference light sources.
When

$$Ecc_i = \sum_{j=1}^{N} w_j E * ab(\ Lab(T_{std}) - Lab(B_i M_{j->std-i} O_{j-i})\ ), \quad (5)$$

Ecc is CCPE, as shown in Figure 2.

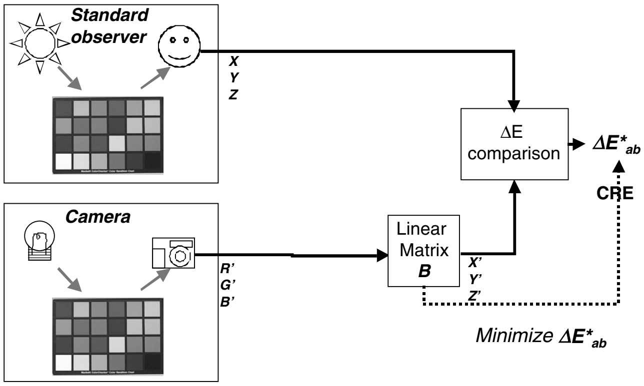

Figure 1. Color Reproduction Error evaluation.

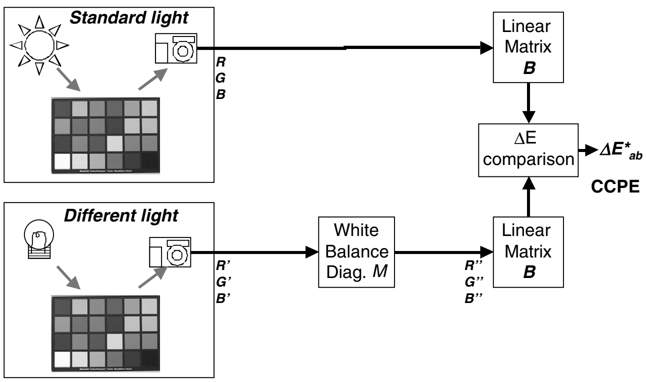

Figure 2. Color Constancy Prediction Error evaluation.

Minimized Color Constancy Prediction Error (MCCPE)

Since the primaries for white balancing can be easily modified by a matrix, we evaluate minimized CCPE with primary conversion matrix A as the following equation. When

$$Emcc_i = \sum_{j=1}^{N} w_j E*ab(\ Lab(T_{std})\ \text{-}\ Lab(B_i A_{j-i}^{-1} M_{j->std-i} A_{j-i} O_{j-i})\ ) \quad (6)$$

is minimized by linear matrix ***A***, *Emcc* is called Minimized CCPE, as shown in Figure 3.

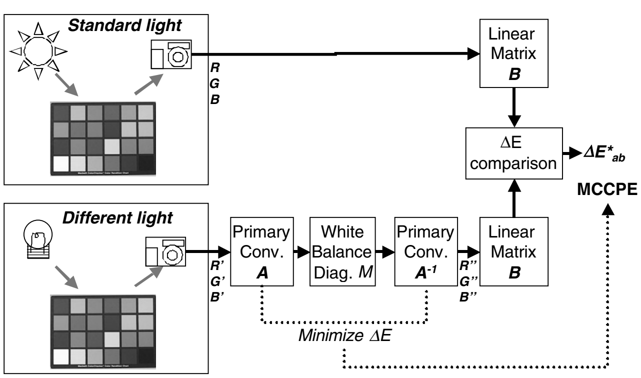

Figure 3. Minimized Color Constancy Prediction Error evaluation.

Noise

Potential noise (mainly chromatic noise) determined by overlaps among spectral sensitivities is evaluated by adding a small fluctuation at a relative luminance of 0.184, which corresponds to L^*=50. When raw sensor values shift plus-or-minus c (constant), we calculate the standard deviations of the fluctuation along the $L^*a^*b^*$ axes. We used c=0.005 for the fluctuation. We define the noise amount by RMS of these standard deviations. The noise amount is indicated by percentage normalized to the case that the E-H-P primaries are used. The reason why we used the E-H-P primaries as reference is that the primaries are thought to be the closest to the real cone sensitivities of the human visual system.

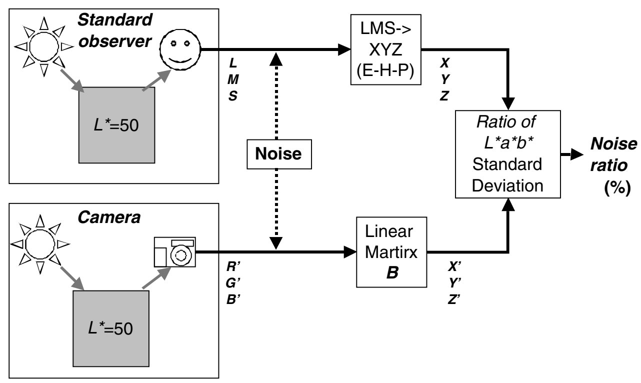

Figure 4. Noise evaluation.

Parameters Used in Simulation

The following parameters are used.

Spectral Sensitivity

Eight sets of camera sensitivities: RGB1, RGB2, CMY1, CMY2 (which are from digital still cameras), TV camera,[8] E-H-P primaries, Bradford primaries, hypothetical sensitivity having three peaks, are used.

Light Sources

Illuminant A, and a black body radiation of 9300K (L93) as different light sources, and Illuminant D65 for the standard light source, are used.

Range and Increment

A wavelength range from 400 nm to 700 nm with an increment of 10 nm is used.

Objects

Twenty-four patches of the Macbeth color checker are used.

Non-Linear Optimization Tool

Non-linear optimization is performed by Solver of Microsoft Excel. We use the following initial values; a linearly optimized matrix for CRE, and a unit matrix for MCCPE.

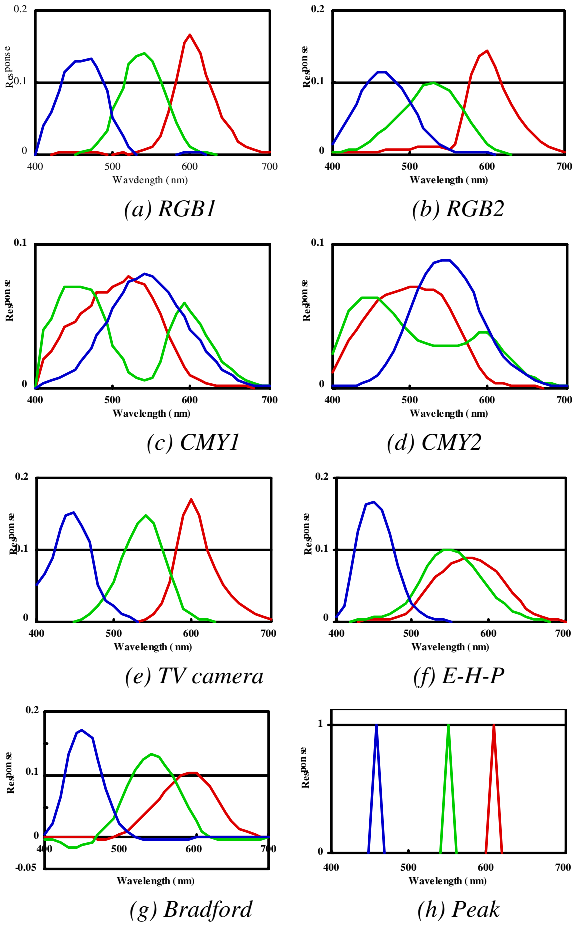

Figure 5. Camera sensitivities used in the simulation.

Result

The result of the combination of the Macbeth patches and D65 as standard light source is shown in Table 1 and Figure 6. While the sensitivity sets obeying the Luther condition give zero in CRE, RGB1, TV camera and Bradford give fairly small values for CCPE. RGB1 and RGB2 give two contrary results: a better CRE for RGB2 while a better CCPE for RGB1.

When the optimized primary conversion is applied to evaluate MCCPE, significant improvements were observed for the CMY sensitivities. They becomes about one-fourth to one-sixth of CCPE. When a set of sensitivities obeying the Luther condition, MCCPEs converge to 1.64. Note that TV camera gives a better score of 1.58. Moreover, TV camera gives a lower noise level than the one of Bradford, by approximately 20 percent.

Optimized sensitivities in terms of MCCPE are shown in Figure 7. It is interesting that all of the curves give a similar shape with peaks at about 450, 550, and 600 nm.

Table 1. CRE, CCPE, MCCPE, and Noise

Sensitivity	CRE	CCPE	MCCPE	Noise
RGB1	1.19	2.30	1.66	37%
RGB2	1.08	4.09	2.10	52%
CMY1	1.52	12.92	2.15	89%
CMY2	2.33	13.78	3.27	99%
TV camera	1.26	2.52	1.58	35%
E-H-P	0.00	4.03	1.65	100%
Bradford	0.00	2.45	1.64	42%
Peak	3.65	3.64	3.64	29%
CMF	0.00	5.43	1.64	64%

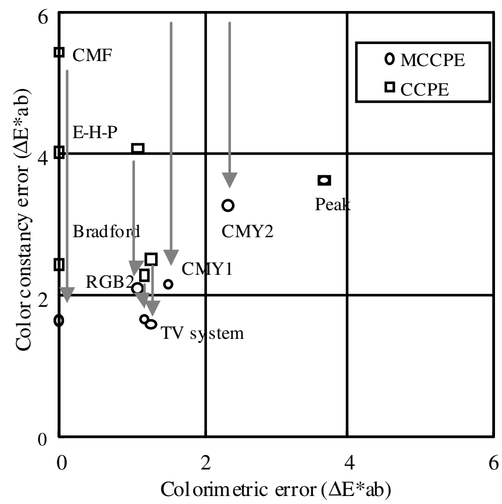

Figure 6. CRE vs. CCPE and MCCPE

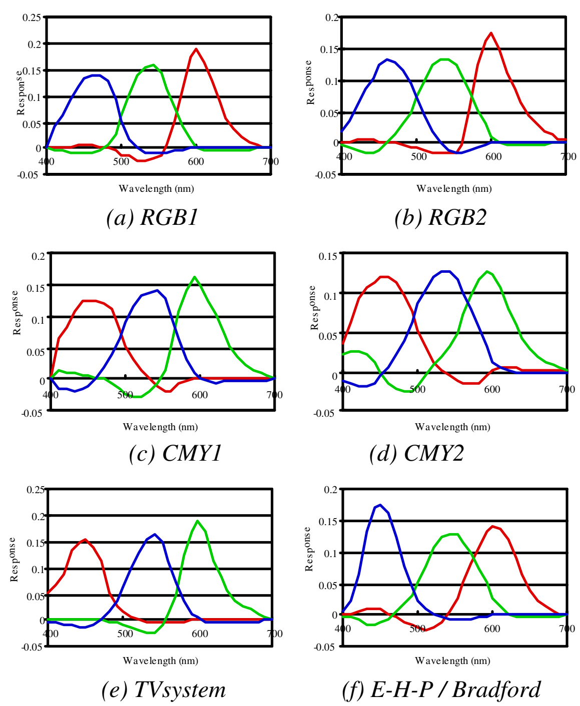

Figure 7. Optimized sensitivities in terms of MCCPE (Peak is omitted because the shape is identical to the Figure 5 (h)).

Evaluation with Several Light Sources and Spectral Reflectance Database

In the above simulation, we used a small number of color patches to derive the CCPE and MCCPE. Here questions arise: Optimized result can be applied to the other spectral reflectance? How about the performance under artificial light sources?

Thus we employ Standard Object Colour Spectra database for colour reproduction evaluation (SOCS)[5] with several light sources including fluorescent lamps.

Error with SOCS

We applied the eight sets of sensitivity with optimized primary conversion matrices calculated in the above against SOCS. In order to avoid the population problem, we use four types of error measures: errors including 95.5% and 99.7% of SOCS data, maximum error and simple average (Notations E95.5, E99.7, E_MAX, and E_MAX are respectively used).

We plot the relation between MCCPE calculated above and SOCS errors. As shown in Figure 8, coefficients of determination (squared correlation coefficient) for these four SOCS errors are 0.94, 0.93, 0.76, and 0.98, respectively. From this result, it is thought that the optimized matrices can be used for real objects.

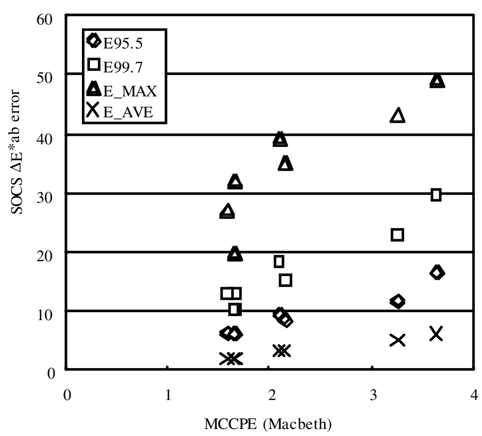

Figure 8. Relation between Macbeth based MCCPE and SOCS errors.

Error with Several Light Sources

We investigate conditions in which other light sources are used as different light sources. Based on the primary conversion matrices optimized for A and L93, the SOCS E99.7 error under Illuminants A, C, D50, D65, L93, F1-12 are evaluated for seven set of camera sensitivities except for Peak. The result is shown in Figure 9. As observed, error levels are depending on types of light sources; while there are small errors for natural and fluorescent light sources having good rendering index such as F7 - F9, there are large errors for the others.

We assume that the error should be determined by color rendering index of light source (Ra) and the difference between standard and different light sources. Figure 10 depicts the relationship between difference of standard (D65 is used) and a different light source in reciprocal color temperature and average E99.7 of the seven sensitivity sets (ΔRCT). As observed, the worse Ra, the worse CCPE.

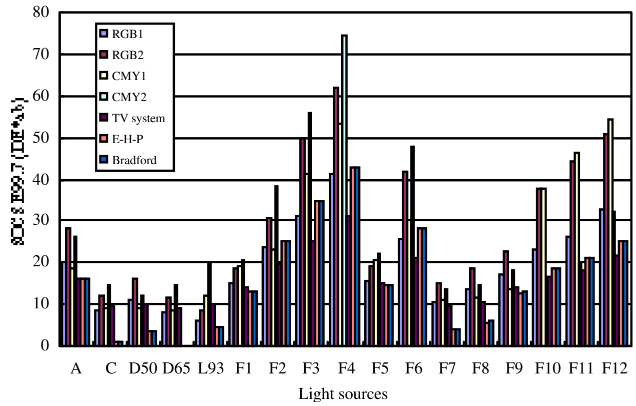

Figure 9. SOCS E97.7 error for various light sources

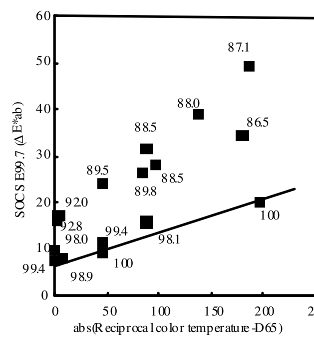

Figure 10. Difference of color temperature and E99.7. Figures in the graph indicate color rendering indexes of light sources. The line is drawn through about Ra=100.

Thus, we derive the following equation to model the relationship.

$$CCPE(E99.7) = -1.543 \cdot Ra + 0.0864 \cdot \Delta RTC + 159.56 \quad (7)$$

The resulted coefficient of determination is 0.93, as shown in Figure 11.

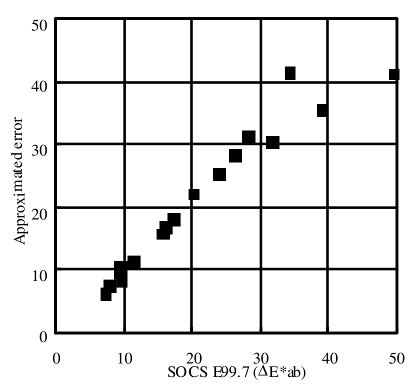

Figure 11. SOCS E99.7 and estimated error.

Discussion

Obviously, the color rendering property of light sources affects to CCPE rather than spectral characteristics of objects. Noguchi proposed to optimize color constancy for several light sources including fluorescent lamps to avoid the unacceptable result in practice.[9] We assume that the reason why his result did not give a significant improvement may be affected by light sources having poor *Ra* indexes. We think that Matrix *A* should be optimized for light sources having good *Ra* indexes; otherwise the resulted optimization would be disturbed by poor light sources.

In practice, the optimization can be easily implemented in camera, because this approach does not require sensitivity measurements but only a capture of small number of color patches is necessary.

Conclusion

Base on the assumption that the realization of color constancy is the goal of camera's white balance, we evaluated color constancy prediction error for eight sets of sensitivities, in addition to color reproduction error and noise. We evaluated errors with SOCS and several light sources including fluorescent lamps.

From our simulation, we conclude that:

1. The sensitivity obeying the Luther condition is not necessarily the best performance in terms of color constancy,
2. There are cases of contrary scores for CRE and CCPE,
3. A sensitivity set of conventional TV camera gives a good compromise in terms of CRE, CCPE and noise.
4. Optimized primary conversion matrix based on a small number of color patches gives a reasonable performance against SOCS.
5. Color constancy prediction error in practical situation is mostly affected by color rendering property of light sources.

References

1. H. E. J. Neugebauer, Quality factor for filters whose spectral transmittances are different from color mixture curves, and its application to color photography, *Journal of Optical Society of America*, **46**, 10, pp.821-824 (1956).
2. P. L. Vora and H. J. Trussell, Measure of goodness of a set of color-scanning filters, *Journal of Optical Society of America*, **10**, 7, pp.1499-1508 (1993).
3. P.-C. Hung, Comparison of Camera Quality Indexes, *The Eighth Color Imaging Conference*, pp.167-171 (2000).
4. P.-C. Hung, A Proposal of Camera Sensitivity Evaluation Considering Color Constancy, *Color Forum Japan 2001* pp. 139-142 (in Japanese) (2001).
5. JIS TR X0012: 1998, Standard object colour spectra database for colour reproduction evaluation.
6. H. Yaguchi、Color Appearance Models (TC8-01)、The 6th JCIE Seminar "Digital Imaging and Technology" (in Japanese), pp.24-30 (2001).
7. G. D. Finlayson, M. S. Drew, and B. V. Funt, Spectral sharpening: sensor transformations for improved color constancy, *Journal of Optical Society of America* (A), 11, 5, pp.1553-1563 (1994).
8. Japan Broadcasting Corporation、NHK Text book of Color Television (part 1), Japan Broadcasting Corporation (in Japanese), p.27 (1980).
9. T. Noguchi, Improving color constancy by optimizing spectral sensitivity functions, *International Congress of Imaging Science 2002*, pp. 328-329 (2002).

Biography

Po-Chieh Hung received his BS and MS degrees in electronic engineering from Waseda University, Tokyo, Japan, and his Ph.D. in imaging science from Chiba University, Chiba, Japan; in 1999, he was appointed Visiting Associate Professor at Chiba University. Dr. Hung is a Chief Research Associate at Konica Corporation's Corporate R&D Laboratories, and is engaged in such digital imaging projects as the development of digital still cameras, scanners, and printers.