Comparison of Camera Quality Indexes

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Abstract

In terms of correlation to the spectral data base SOCS (Standard Object Colour Spectra Database for Colour Reproduction Evaluation), computer simulation was employed to compare five camera quality indexes: CQF (Color Quality Factor) from Neugebauer, Goodness from Vora and Trusell, Squared Difference from ISO 17321 WD1.1, RMS (Root Mean Square) from ISO17321 WD4, and Camera Rendering Indexes (Ra: Average CRI, and R*i*: Special CRI) from Hung. Based on the assumption that SOCS encompasses the spectral reflectance of real objects, SOCS was used to simulate real-world spectra. To avoid the disputed population problem of spectral reflectance in SOCS, we used color differences (ΔE^*_{ab}) containing 95.5%, 99.7%, and 100% (i.e. worst ΔE^*) of the SOCS data, as well as a simple average, as references. Applied to thirteen sets of camera sensitivities, Average CRI gave correlation coefficients of greater than 0.95 against 95.5%, 99.7%, and average ΔE^*, and Special CRI gave the best correlation coefficient with the worst ΔE^* among these quality indexes. Thus, Average CRI appears to be a good index for the evaluation of a camera's colorimetric quality.

Introduction

The emergence of digital still cameras (DSCs) is a salient reminder of the importance of colorimetric quality to input devices. Camera systems using silver halide film present limitations in the selection of sets of sensitivity curves due to the nature of the chemical process. Although it is well known that silver halide systems never obtain a good CQF,[1] they nevertheless deliver satisfactory color reproduction in actual performance. Presumably, this is because CQF is an analytical measure in the spectral domain, and because it ignores the spectral characteristics of real objects. Moreover, a CQF is given for a single sensitivity curve, while cameras should rather be evaluated by a set of sensitivity curves. In response to this problem, Vora and Trusell introduced a measure termed Goodness, in which they combined the CQFs for three or more orthogonalized sensitivity curves.[2] Additionally, ISO 17321 WD1.1 and WD4 presented Squared Difference[3] and RMS,[4] respectively, for the evaluation of sets of sensitivity curves.

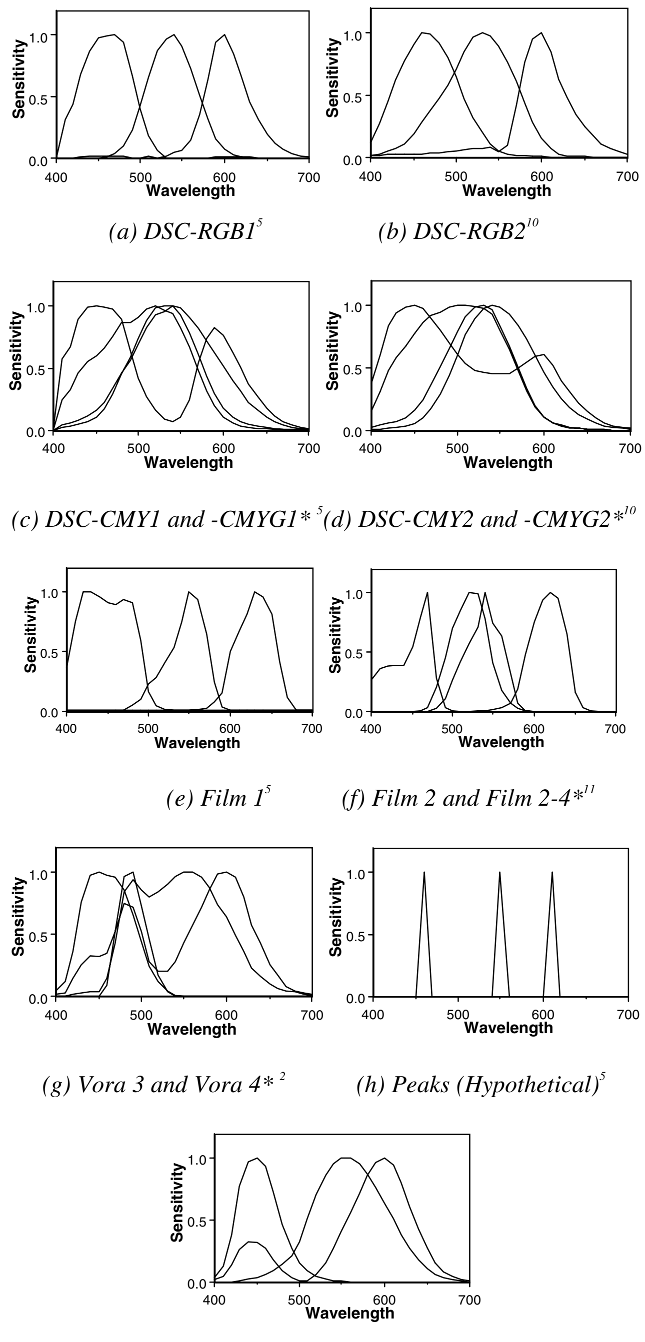
In contrast to these analytical measures in the spectral domain, the author, in 1998, attempted to provide practical and understandable indexes by proposing Camera Rendering Indexes (CRIs), including Average CRI and Special CRI,[5] based on JIS Z8726-1975[6] (the Japanese industrial standard corresponding to CIE 13.1). Average CRI is calculated using eight color patches defined in CIE 13.1, and Special CRI is calculated using the ninth through fifteenth color patches found in JIS Z8726. In this case, the fifteenth color patch is an Asian skin color defined in JIS Z8726 and is added to CIE 13.1's fourteen color patches.[7]

Since a CRI uses a limited number of color patches, the question arises: are CRIs reliable measures? To determine the answer, we used thirteen sets of camera sensitivities and performed computer simulations to evaluate correlation coefficients between the camera quality indexes involved and color differences assessed by SOCS.[8]

Camera Rendering Index

Detailed steps in the CRI procedure of evaluation are presented in the annex. In brief, CRIs are designed to:

(1) Provide an understandable index with a close linear relationship to the color differences of actual objects.
(2) Be based on fifteen color patches, without requiring the measurement of spectral sensitivities.
(3) Use formulae similar to Z8726-1990[9] (the Japanese standard based on CIE 13.3) in order to be consistent with that standard. (In this paper, modified CRIs using CIE13.3 formulae instead of CIE13.1 are used. The differences between original and modified indexes are fractional.)
(4) Use the first eight of fifteen color patches to calculate a linear characterization matrix and to evaluate Average CRI. Average CRI is indexes appropriate for major objects having smooth spectral changes.
(5) Use the seven remaining color patches to evaluate Special CRIs. Special CRIs are indexes appropriate for high-chromatic objects having steep spectral changes.
(6) Have Special CRIs be extendable to objects with unusual spectral characteristics such as self-emitting displays.
(7) Be applicable to camera systems having more than three sensitivities.



(a) DSC-RGB1[5] *(b) DSC-RGB2*[10]

*(c) DSC-CMY1 and -CMYG1**[5] *(d) DSC-CMY2 and -CMYG2**[10]

(e) Film 1[5] *(f) Film 2 and Film 2-4**[11]

*(g) Vora 3 and Vora 4**[2] *(h) Peaks (Hypothetical)*[5]

(i) CIE-CMF

*Figure 1. Spectral sensitivity curves (*Separate evaluations are made of the sets of 3 major curves and the sets of all 4 curves)*

Simulation

Evaluation Procedure

Our evaluation procedure took the following seven steps:

Step 1: Calculation of five camera quality indexes for each set of camera sensitivities.
Step 2: Determination of a linear characterization matrix by linearly optimizing to SOCS.
Step 3: Estimation of tristimulus values using the linear characterization matrix and true tristimulus values for SOCS.
Step 5: Evaluation of color differences.
Step 6: Repetition of Steps 1 through 5 for thirteen sets of camera sensitivity curves.
Step 7: Evaluation of the correlation coefficients of the camera indexes and the color differences.

Parameters Used in the Simulation

(1) Thirteen sets of camera sensitivities

We used thirteen sets of camera sensitivities encompassing digital still cameras, AgX films, and hypothetical sensitivity curves (Figure 1). When a camera had four sensitivities, we evaluated, as sets, both the three major sensitivity curves and the complete set of four sensitivity curves. Note that we presume the fourth sensitivity can be used without any constraints in this simulation.

(2) Quality indexes

We evaluated the camera quality indexes in Table 1.

Table 1. Camera quality indexes evaluated

Camera quality index	Description
Ra	Average CRI (100: perfect match. 50: similar to level of color reproduction under WWF)
Ri, R9-15	Special CRI for i-th color patch and the average from Sets 9 through 15 (same as above)
CQFk, AvgCQF	Neugebauer's CQF[1] for k-th channel, and their average (1: perfect. 0: orthogonal)
Goodness	Vora and Trussel's Goodness[2] (same as above)
SqDif	ISO17321WD1.1 Squared difference[3] (0: perfect)
RMS-WD4	ISO17321WD4 RMS (same as above).

(3) Simulated real-world error

We used color differences (ΔE*ab) based on a linear matrix rendering which was linearly optimized to the tristimulus values of SOCS in order to simulate real-world error. (The total number of spectra was 49,302. SOCS' Krinov data was excluded in light of its problematic reliability.) Since the similarity between the color target population of SOCS and real-world objects has not yet been verified, we used color differences which contain 95.5%, 99.7%, and 100% (worst) of the SOCS target, along with the average color difference.

(4) Light source

We used D65 as both the observing and the capturing light source.

Results

From our results (Table 2), we make two observations. First, although silver halide films win poor scores from such spectral analyses as AvgCQF and Goodness, Ra awards good values (84.7 or better). Second, with AvgCQF, four-color sets obtain worse scores than three-color sets, although cameras having four sensors should perform well.

In order to obtain correlation with simulated real-world error, correlations between camera quality indexes and color differences assessed by SOCS were plotted. Two examples (the best case and the worst case) are shown in Figure 2. Obviously, Ra (Average CRI) has better linearity with color differences with respect to the thirteen camera sensitivity curves. Figure 3 shows the comparison of color indexes and correlation coefficient. It is observed that Ra performs very well in terms of 95.5%, 99.7%, and average. The index R9-15 performs somewhat better than the others for worst ΔE*.

Table 2 Camera quality indexes and simulated real-world error

	DSC-RGB1	DSC-RGB2	DSC-CMY1	DSC-CMYG1	DSC-CMY2	DSC-CMYG2	Film1	Film2	Film2-4	Vora3	Vora4	Peak	CIE-CMF
Ra	94.4	96.3	94.3	95.7	90.8	95.2	84.7	90.7	95.2	98.0	99.8	79.7	100.0
R9	48	49	5	37	5	92	-31	64	58	65	97	70	100
R10	95	95	96	93	94	90	92	97	98	98	100	75	100
R11	95	92	79	78	88	70	31	67	90	95	99	42	100
R12	80	94	84	78	43	23	81	83	92	88	99	52	100
R13	90	95	98	97	84	82	94	90	96	98	100	67	100
R14	90	92	96	93	92	98	95	91	97	96	100	66	100
R15	95	93	74	90	63	87	51	74	92	95	100	50	100
R9-15	84.5	87.2	76.0	80.9	67.1	77.3	58.8	80.7	88.9	90.8	99.2	60.1	100.0
CQF1	0.943	0.929	0.919	0.919	0.915	0.915	0.548	0.775	0.775	0.872	0.872	0.180	1.000
CQF2	0.967	0.953	0.914	0.914	0.914	0.914	0.876	0.908	0.908	0.889	0.889	0.156	1.000
CQF3	0.906	0.867	0.957	0.957	0.974	0.974	0.835	0.778	0.778	0.934	0.934	0.196	1.000
CQF4	-	-	-	0.944	-	0.918	-	-	0.756	-	0.244	-	-
AvgCQF	0.939	0.916	0.930	0.934	0.934	0.930	0.753	0.820	0.804	0.898	0.735	0.177	1.000
Goodness	0.945	0.934	0.944	0.962	0.927	0.948	0.760	0.829	0.856	0.954	0.999	0.179	1.000
SqDif	0.031	0.036	0.031	0.021	0.046	0.036	0.158	0.098	0.077	0.020	0.001	0.445	0.000
RMS-WD4	16.5	16.8	12.2	10.7	18.8	17.3	30.9	26.8	19.1	14.5	3.0	63.2	0.0
95.5%	3.2	3.9	5.0	3.4	5.7	2.7	11.5	7.1	2.5	2.5	0.0	14.4	0.0
99.7%	7.7	10.6	9.3	7.6	13.1	9.7	28.1	17.4	7.4	8.5	0.0	29.3	0.0
Worst	26.0	32.7	32.6	32.5	33.1	26.8	46.5	34.0	24.8	27.6	2.4	49.6	0.0
Average	0.9	0.8	1.5	0.7	1.7	0.8	3.1	1.9	0.6	0.5	0.0	4.2	0.0

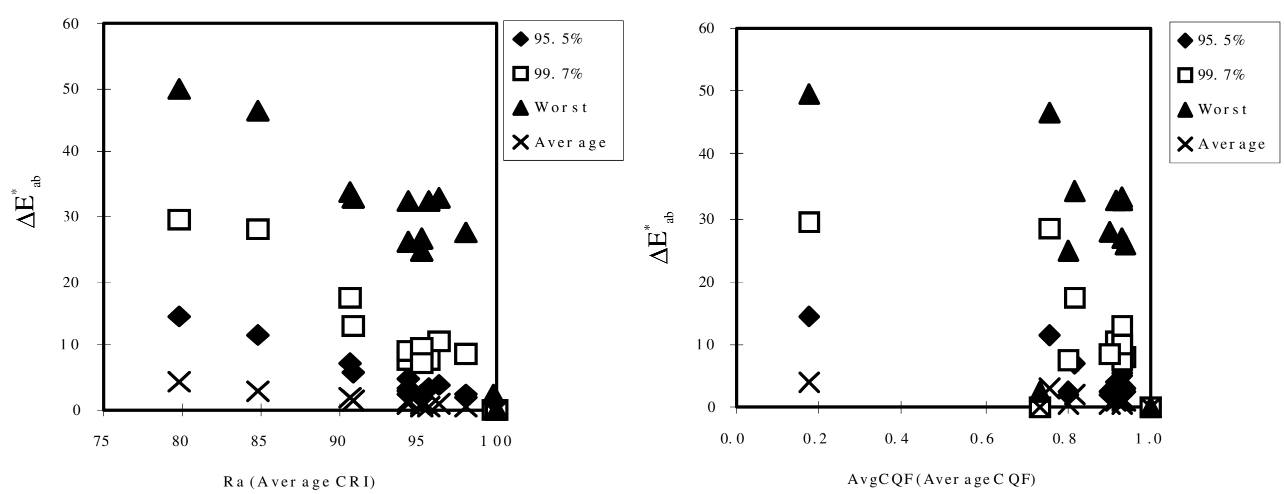


Figure 2. Correlation between quality index and color differences (left: Average CRI, right: Average CQF)

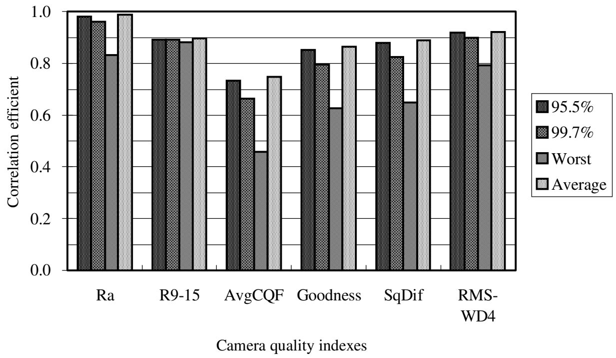


Figure 3. Camera quality indexes vs. correlation coefficients

Discussion

We believe that Ra (Average CRI) gives a better correlation to SOCS than indexes based on spectral analysis because Ra reflects the spectral characteristics of objects. Needless to say, the eight patches employed do not perfectly represent the spectral characteristics of real-world reflective materials, but the correlation of over 0.95 appears trustworthy as a practical evaluation index.

On the other hand, although R9-15 (Average Special CRIs) gives the best correlation with the worst ΔE^*, the obtained correlation efficient of 0.88 is insufficient. The selection of color patches for extended Special CRIs may be necessary. In this simulation, the worst cases were observed in the SOCS categories of "paints" and "sub-dye printers", categories whose spectral characteristics are fairly steep. Considering the fact that no unique selection of color patches is obtained, a framework for determining color patches for evaluation in a specific application must first be determined. Color patch selections for extended Special CRIs are likely targets for future research.

Conclusion

We compared five camera quality indexes using SOCS and thirteen spectral sensitivity sets, and came to two conclusions:

(1) Since Average CRI has good correlation coefficients of more than 0.95 against statistical figures calculated from simulated real-world objects, Average CRI appears to be a useful and reliable color quality index for observer (camera) metamerism.

(2) Special CRI can be used as a rough color quality index to predict the worst case. Better selections of color patches, however, may be necessary in light of users' applications.

References

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Annex: Calculation of Color Rendering Indexes

Step 1: Measurement of camera spectral sensitivities

Measure j channels of spectral sensitivities using IEC 100/PT61966 or an appropriate standard.

Step 2: Selection of light source

Assign an appropriate light source. (Illuminant D65 is used in this paper.)

Step 3: Calculation of sensor outputs and tri-stimulus values

Calculate tristimulus values X_i, Y_i, Z_i, and sensor outputs $Ch1_i$, $Ch2_i$,..., Chj_i using the following equations. Here, $R_i(\lambda)$ is one of the spectral reflectances of color patches used in JIS Z8726-1990 (CIE 13.3), and $chj(\lambda)$ is the sensitivity of the j-th channel (j<9).

Thus, tristimulus values are calculated by the following equations:

$$X_i = \int L(\lambda) R_i(\lambda) \bar{x}(\lambda) d\lambda \quad (1)$$

$$Y_i = \int L(\lambda) R_i(\lambda) \bar{y}(\lambda) d\lambda \quad (2)$$

$$Z_i = \int L(\lambda) R_i(\lambda) \bar{z}(\lambda) d\lambda \, . \quad (3)$$

Sensor outputs are calculated by the following equation:

$$Chj_i = \int L(\lambda) R_i(\lambda) chj(\lambda) d\lambda \,. \quad (4)$$

Note that Steps 1 through 3 can be substituted for by the direct measurement of appropriate color patches, if necessary.

Step 4: Color rendering matrix

Calculate the optimized linear matrix using the following formulae:

$$A = TS^T \left(SS^T\right)^{-1} \quad (5)$$

where,

$$T = \begin{bmatrix} X_1 & \cdots & X_i & \cdots & X_8 \\ Y_1 & \cdots & Y_i & \cdots & Y_8 \\ Z_1 & \cdots & Z_i & \cdots & Z_8 \end{bmatrix}, \quad (6)$$

$$S = \begin{bmatrix} Ch1_1 & \cdots & Ch1_i & \cdots & Ch1_8 \\ \vdots & & \vdots & & \vdots \\ Chj_1 & \cdots & Chj_i & \cdots & Chj_8 \end{bmatrix}. \quad (7)$$

A new set of estimated tristimulus values is calculated using:

$$T_k = AS_k \quad (8)$$

where,

$$S_k = \begin{bmatrix} Ch1_k \\ \vdots \\ Chj_k \end{bmatrix}, \; T_k = \begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix}. \quad (9), (10)$$

Note that a measure for a system having more than three channels may not be realized due to practical processing limitations.

Step 5: Calculations of Average CRI and Special CRI

Calculate Average CRI and Special CRIs using the equation identical to JIS Z8726-1990 (CIE 13.3):

$$u'_k = u_r \,, \; v'_k = v_r \quad (11), (12)$$

$$u'_{k,i} = \frac{10.872 + 0.404 \frac{c_r}{c_k} c_{k,i} - 4 \frac{d_r}{d_k} d_{k,i}}{16.518 + 1.481 \frac{c_r}{c_k} c_{k,i} - \frac{d_r}{d_k} d_{k,i}}, \quad (13)$$

$$v'_{k,i} = \frac{5.520}{16.518 + 1.481 \frac{c_r}{c_k} c_{k,i} - \frac{d_r}{d_k} d_{k,i}} \quad (14)$$

$$c = \frac{1}{v}\left(4.0 - u - 10.0v\right), \quad (15)$$

$$d = \frac{1}{v}\left(1.708v + 0.404 - 1.481u\right). \quad (16)$$

$$W^*_{r,i} = 25(Y_{r,i})^{\frac{1}{3}} - 17 \,, \quad (17)$$

$$U^*_{r,i} = 13W^*_{r,i}(u_{r,i} - u_r) \,, \quad (18)$$

$$V^*_{r,i} = 13W^*_{r,i}(v_{r,i} - v_r) \,. \quad (19)$$

$$W^*_{k,i} = 25(Y_{k,i})^{\frac{1}{3}} - 17 \,, \quad (20)$$

$$U^*_{k,i} = 13W^*_{k,i}(u_{k,i} - u_k) \,, \quad (21)$$

$$V^*_{k,i} = 13W^*_{k,i}(v_{k,i} - v_k) \,. \quad (22)$$

$$\Delta E_i = \left\{ \begin{aligned} &\left(U^*_{r,i} - U^*_{k,i}\right)^2 + \left(V^*_{r,i} - V^*_{k,i}\right)^2 \\ &+ \left(W^*_{r,i} - W^*_{k,i}\right)^2 \end{aligned} \right\}^{\frac{1}{2}} \quad (23)$$

$$R_i = 100 - 4.6\Delta E_i \,, \; R_a = \frac{1}{8}\sum_{i=1}^{8} R_i \quad (24), (25)$$

u_k , v_k : Estimated UCS chromaticities of white (light source)

u_r , v_r : Real UCS chromaticities of white (light source)

$W^*_{k,i}, U^*_{k,i}, V^*_{k,i}, u_{k,i}, v_{k,i}$: Estimated lightness and chromaticities of test target *i*

$W^*_{r,i}, U^*_{r,i}, V^*_{r,i}, u_{r,i}, v_{r,i}$: Real lightness and chromaticities of test target *i*

R_i, R_a : Special CRI and Average CRI

where,

$$u = \frac{4X}{X + 15Y + 3Z}, \quad (26)$$

$$v = \frac{6X}{X + 15Y + 3Z}. \quad (27)$$

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 Central Research Laboratory, and is engaged in such digital imaging projects as the development of digital still cameras, scanners, and printers.