Multi-spectral Image Acquisition and Spectral Reconstruction using a Trichromatic Digital Camera System associated with absorption filters PART III Samples and Spaces

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Abstract

This part reports the experimental procedure characterizing the samples and comparing spaces applied to predict the spectral reflectance from the eigenvectors.

I) **Measurement of samples**

Three targets were used in this experimental part. The Macbeth ColorChecker and two different sets of painted patches, respectively 147 and 105 painted patches, were used in the experiment. The 147 and 105 painted patches were created using different inks. The Macbeth ColorChecker and a subset of the 147 and 105 painted patches are shown respectively in Figures 1a, 1b and 1c.

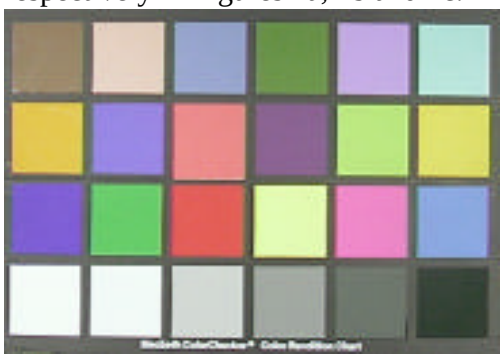


Figure 1a. Macbeth ColorChecker.

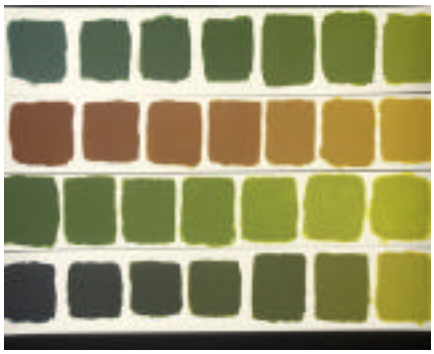


Figure 1b. Subset of the 147 painted patches.

Figure 1c. Subset of the105 painted patches

The spectral reflectances of the Macbeth ColorChecker were measured in wavelength intervals of 10 nm from 400nm to 700nm using the Macbeth ColorEye 7000 spectrophotometer with integration sphere (specular included, UV excluded); the paint patches were measured using GRETAG SPM60 45/0 spectrophotometer.

The distribution in a* x b* space of Macbeth ColorChecker for D50 illuminant and 2° observer is shown in Figure 2.

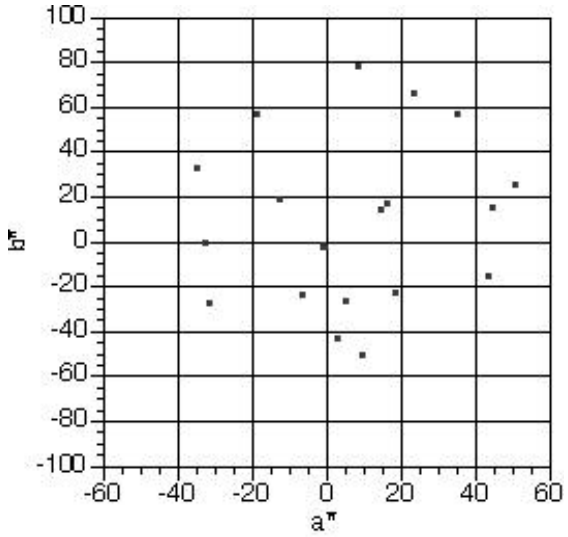


Figure 2. a*b* plot for Macbeth ColorChecker (D50 illuminant, 2° observer).

The a* x b* distribution for D50 illuminant and 2° observer of the 147 painted patches is shown in Figures 3.

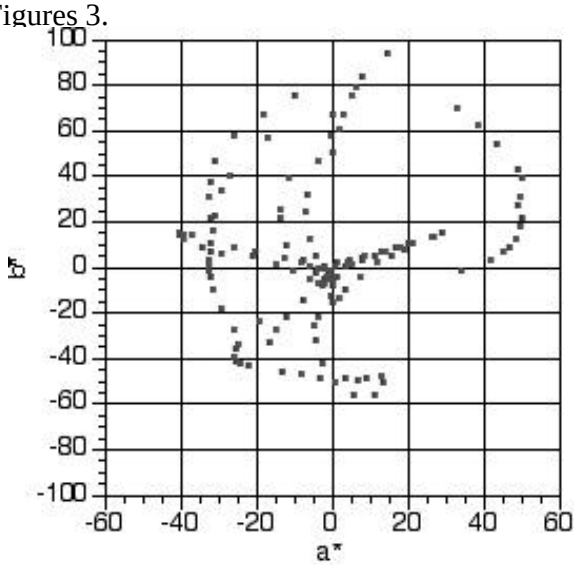


Figure 3. a*b* plot for 147 painted patches (D50 illuminant, 2° observer)

The spectral reflectance curves of the 105 paint patches as well and its a* x b* distribution for D50 illuminant and 2° observer is shown in Figures 4.

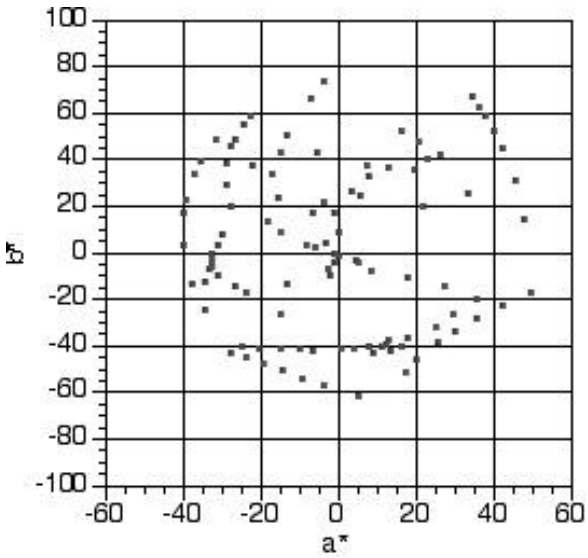


Figure 4. Spectral reflectances of 105 painted patches (D50 illuminant, 2° observer)

II) **Spectral Analysis**

Principal component analyses was performed for the Macbeth ColorChecker and for both 147 and 105 painted patches in reflectance, K/S and new empirical space proposed by Tzeng and Berns.

A) **Reflectance space**

Principal component analyses was performed in reflectance space and figures 5a, 5b, and 5c show the plot of the 1st to 6th eigenvectors of Macbeth ColorChecker, 147 painted patches and 105 painted patches, respectively.

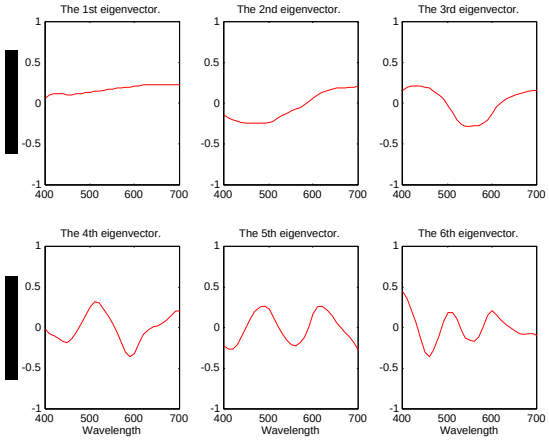


Figure 5a. Plot of the first to sixth eigenvectors of Macbeth ColorChecker reflectances.

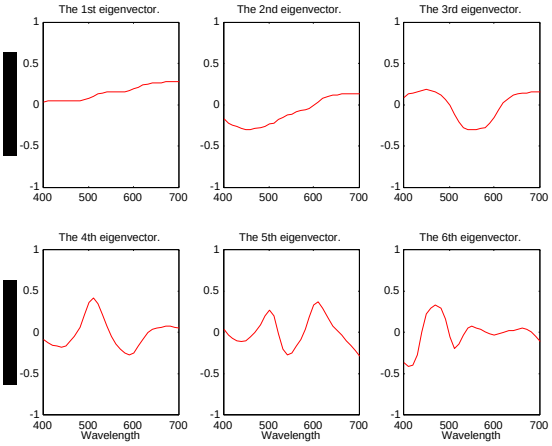


Figure 5b. Plot of the first to sixth eigenvectors of 147 painted patches reflectances.

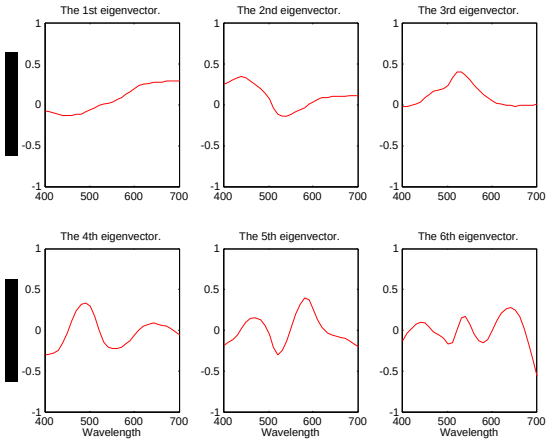


Figure 5c. Plot of the first to sixth eigenvectors of 105 painted patches reflectances.

Comparing Figure 5b and 5c it is possible to observe that the eigenvectors of 147 and 105 painted patches reflectances differ from each other. Therefore, the painted patches sets are statistically different.

Table I summarizes the cumulative contribution of the eigenvectors for Macbeth ColorChecker and the sets of painted patches.

Table I. Cumulative contribution of the eigenvectors in reflectance space.

Number of eigenvectors	Cumulative Contribution (%) for Macbeth Color Checker	Cumulative Contribution (%) for 147 painted patches	Cumulative Contribution (%) for 105 painted patches
1	65.99	65.81	65.18
2	90.14	86.91	88.05
3	98.34	98.50	96.69
4	99.20	99.47	98.60
5	99.66	99.73	99.23
6	99.80	99.83	99.60
7	99.87	99.92	99.86
8	99.94	99.95	99.95
9	99.97	99.98	99.97
10	99.98	99.99	99.98
11	99.99	100.00	99.99
12	100.00	100.00	100.00

Table II shows the influence of the number of eigenvectors on the colorimetric and spectral accuracy of the spectral reconstruction of each patch. The colorimetric accuracy is calculated using CIE94 under D50 and 2° observer. Figures 6a, 6b, and 6c show the histogram of ΔE^*_{94} between the measured spectral reflectance and the spectral reflectance predicted using 6 eigenvectors for Macbeth ColorChecker, 147 painted patches and 105 painted patches, respectively.

Table II. Influence of the number of eigenvectors in reflectance space used in the spectral reconstruction on the colorimetric and spectral error.

Number of eigenvectors	Macbeth ColorChecker		147 painted patches		105 painted patches	
	Mean ΔE^*_{94}	rms reflectance factor	Mean ΔE^*_{94}	rms reflectance factor	Mean ΔE^*_{94}	rms reflectance factor
1	24.6	0.140	26.58	0.140	45.4	0.181
2	16.8	0.076	15.64	0.068	49.2	0.127
3	3.07	0.032	4.10	0.027	3.08	0.036
4	1.23	0.022	1.28	0.016	1.79	0.019
5	0.67	0.015	0.66	0.012	1.19	0.015
6	0.26	0.013	0.37	0.009	1.03	0.012
7	0.24	0.011	0.32	0.007	0.32	0.006
8	0.13	0.010	0.19	0.005	0.18	0.004
9	0.16	0.007	0.10	0.004	0.08	0.003
10	0.05	0.003	0.05	0.002	0.08	0.003
11	0.02	0.002	0.02	0.001	0.07	0.002
12	0.002	0.002	0.01	0.001	0.06	0.002

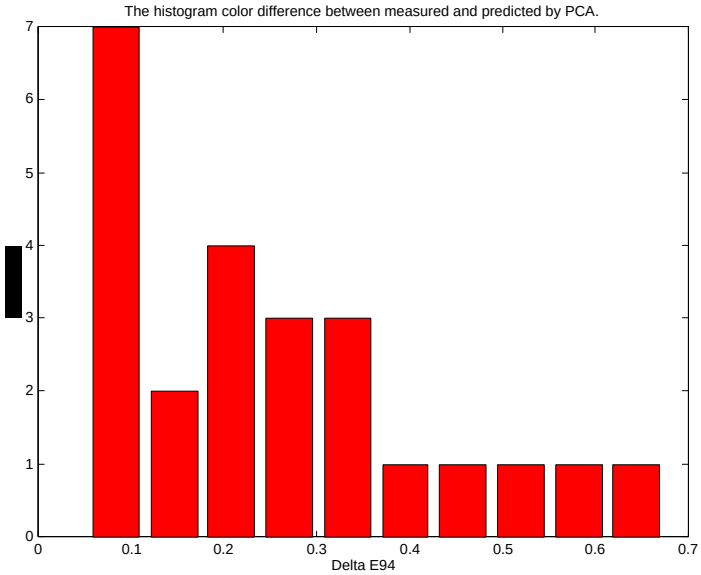


Figure 6a. ΔE^*_{94} histogram for Macbeth ColorChecker reconstructed using 6 eigenvectors in reflectance space.

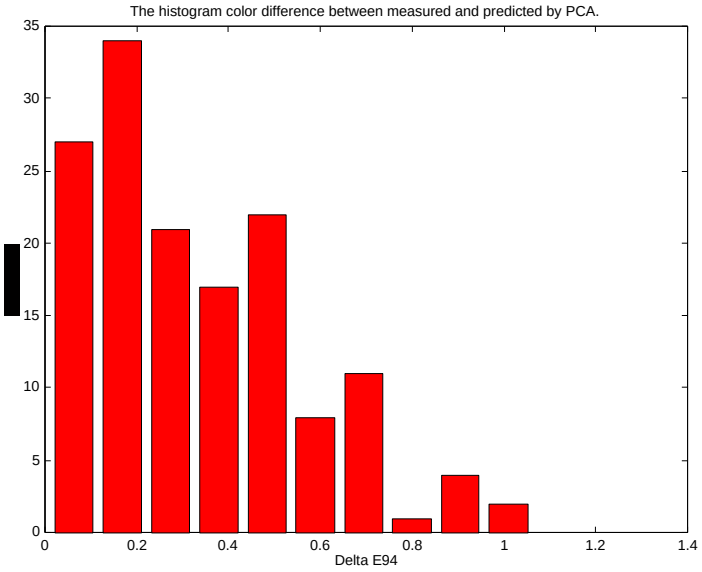


Figure 6b. ΔE^*_{94} histogram for 147 painted patches reconstructed using 6 eigenvectors in reflectance space.

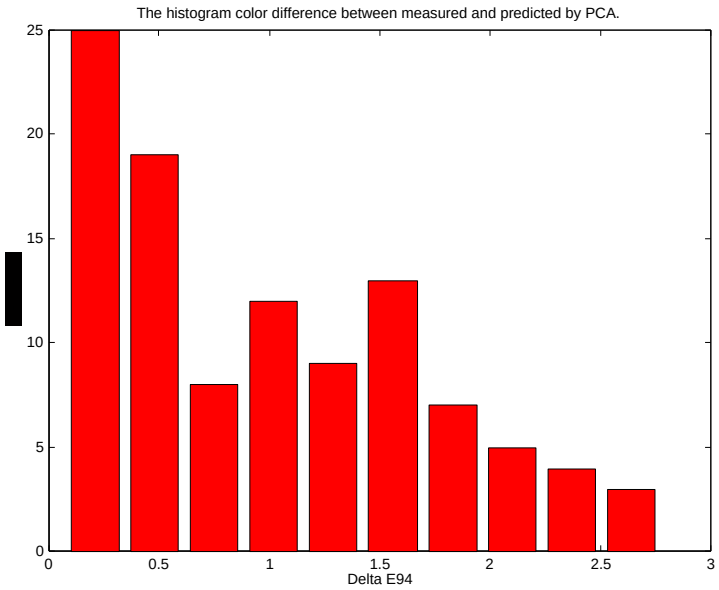


Figure 6c. ΔE^*_{94} histogram for 105 painted patches reconstructed using 6 eigenvectors in reflectance space.

From the results above, the use of 6 eigenvectors is not sufficient in reflectance space if the goal is the reconstruction of the spectral reflectances with reflectance factor rms error less than 1% and ΔE^*_{94} less than a unity, because the poor performance for the set of 105 painted patches. The reflectance of 105 painted patches were reconstructed using 9 eigenvectors instead of 6 and the colorimetric and spectral performance is summarized in Table III and the ΔE^*_{94} histogram is shown in figure 7. The metameric index was calculated using Fairman metameric black method, between standard illuminant D50 and reference illuminant A using ΔE^*_{94} in the calculations.

Table III. Colorimetric and spectral performance of the reconstruction of spectral reflectance of 105 painted patches using 9 eigenvectors.

Parameter	**ΔE^*_{94}**	**Spectral reflectance factor rms error**	**Index of metamerism**
Mean	**0.084**	**0.003**	**0.037**
Standard deviation	**0.057**		**0.028**
Maximum	**0.247**		**0.124**
Minimum	**0.006**		**0.004**

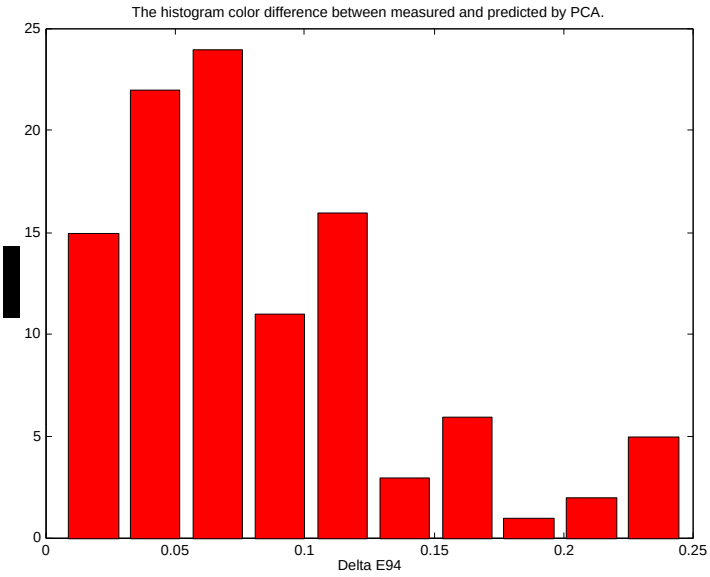


Figure 7. ΔE^*_{94} histogram for 105 painted patches reconstructed using 9 eigenvectors in reflectance space.

Although the use of 9 eigenvectors produced very good results, the increase of 3 channels also implies increase in the cost (memory and processing time) and these factors should be considering when deciding what is the reasonable number of eigenvectors used in the spectral reconstruction.

B) **Kubelka-Munk K/S space**

Principal component analyses was performed in Kubelka-Munk K/S space and figures 8a, 8b, and 8c show the plot of the 1st to 6th eigenvectors of Macbeth ColorChecker, 147 painted patches and 105 painted patches, respectively.

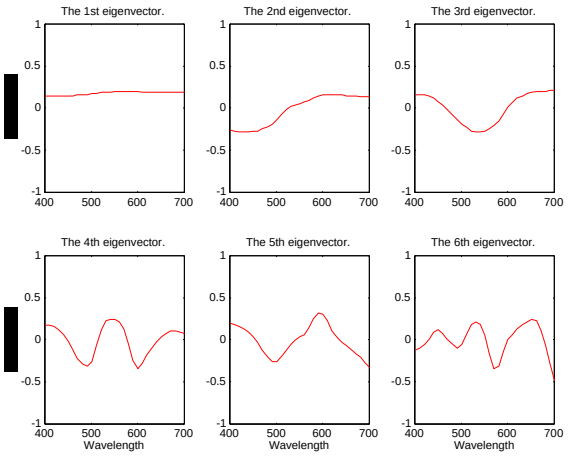


Figure 8a. Plot of the first to sixth eigenvectors of Macbeth ColorChecker K/S values.

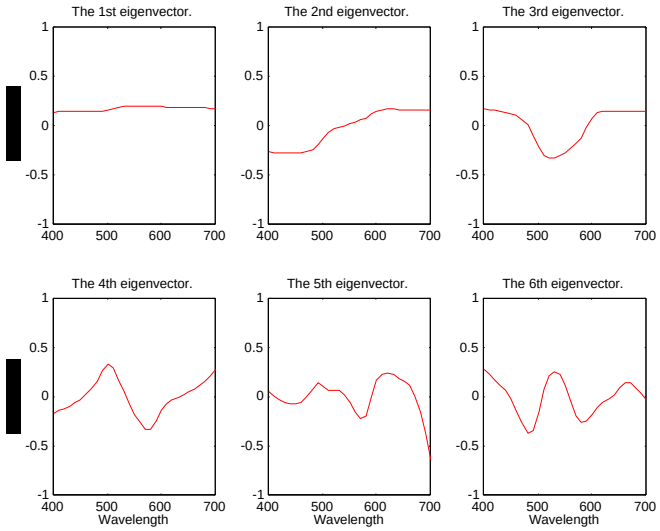


Figure 8b. Plot of the first to sixth eigenvectors of 147 painted patches K/S values.

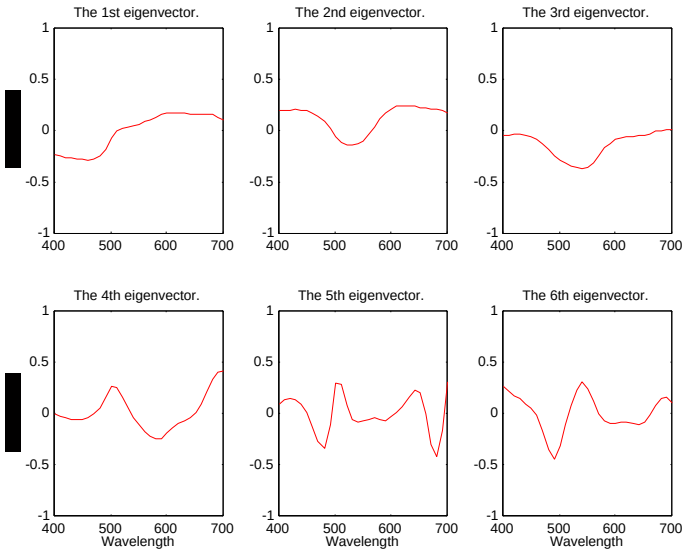


Figure 8c Plot of the first to sixth eigenvectors of 105 painted patches K/S values.

Table IV summarizes the cumulative contribution of the eigenvectors in K/S space for Macbeth ColorChecker and the sets of painted patches.

Table IV. Cumulative contribution of the eigenvectors in K/S space.

Number of eigenvectors	Cumulative Contribution (%) for Macbeth Color Checker	Cumulative Contribution (%) for 147 painted patches	Cumulative Contribution (%) for 105 painted patches
1	69.27	60.20	64.81
2	90.20	90.35	86.40
3	98.86	99.18	98.42
4	99.45	99.65	99.81
5	99.86	99.84	99.93
6	99.92	99.92	99.98
7	99.96	99.96	99.99
8	99.98	99.98	100.00
9	99.99	99.99	100.00
10	100.00	100.00	100.00
11	100.00	100.00	100.00
12	100.00	100.00	100.00

Table V shows the influence of the number of eigenvectors on the colorimetric and spectral accuracy of the spectral reconstruction of each patch. The colorimetric accuracy is calculated using CIE94 under D50 for the 1931 observer. Figures 9a, 9b, and 9c show the histogram of ΔE^*_{94} between the measured spectral reflectance and the spectral reflectance predicted using 6 eigenvectors for Macbeth ColorChecker, 147 painted patches and 105 painted patches, respectively.

Table V. Influence of the number of eigenvectors in K/S space used in the spectral reconstruction on the colorimetric and spectral error.

Number of eigenvectors	Macbeth ColorChecker		147 painted patches		105 painted patches	
	Mean ΔE^*_{94}	rms reflectance factor	Mean ΔE^*_{94}	rms reflectance factor	Mean ΔE^*_{94}	rms reflectance factor
1	24.3	0.182	23.3	0.171	46.9	1.974
2	13.4	0.018	15.5	0.078	61.9	0.986
3	4.09	0.010	1.94	0.050	2.77	0.011
4	3.00	0.038	1.62	0.030	1.13	0.019
5	1.33	0.025	1.21	0.033	0.76	0.022
6	1.35	0.039	0.88	0.022	0.48	0.012
7	1.15	0.029	0.39	0.019	0.20	0.012
8	0.40	0.027	0.33	0.022	0.16	0.009
9	0.26	0.027	0.18	0.016	0.13	0.008
10	0.15	0.019	0.16	0.017	0.06	0.005
11	0.12	0.018	0.18	0.017	0.03	0.003
12	0.15	0.017	0.16	0.014	0.02	0.001

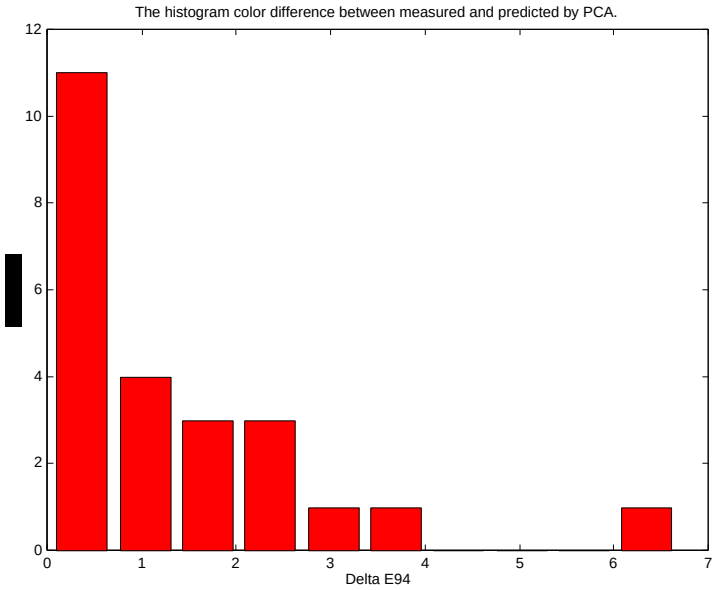


Figure 9a. ΔE^*_{94} histogram for Macbeth ColorChecker reconstructed using 6 eigenvectors in K/S space.

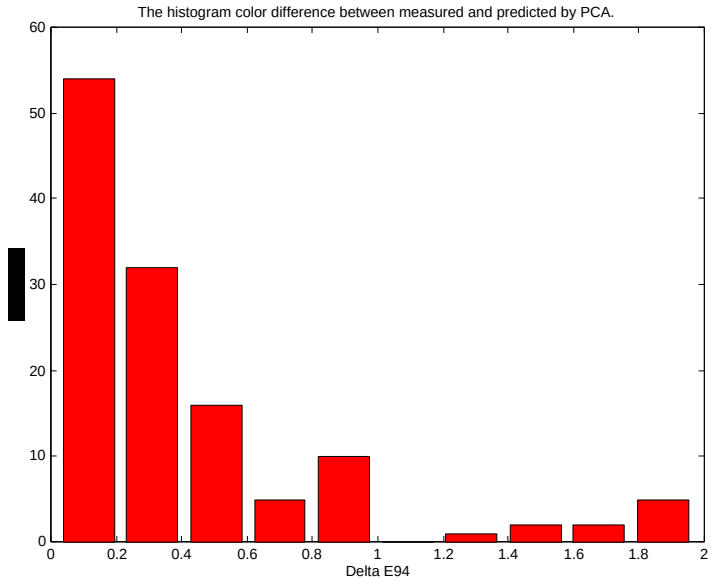


Figure 9b. ΔE^*_{94} histogram for 147 painted patches reconstructed using 6 eigenvectors in K/S space.

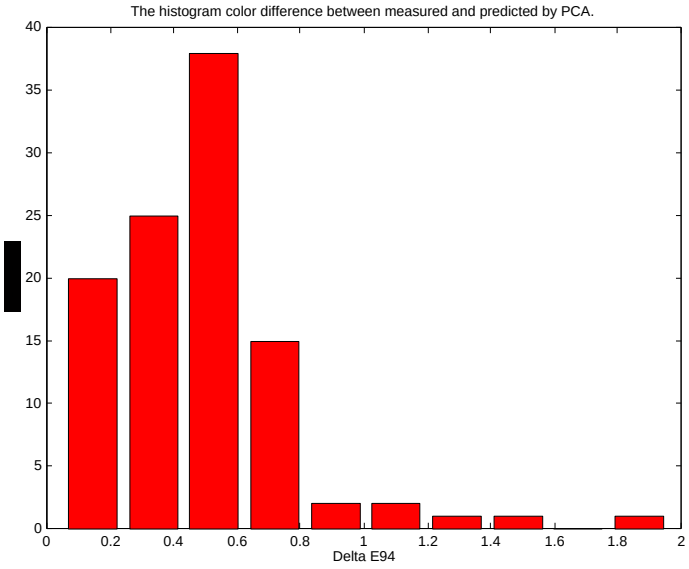
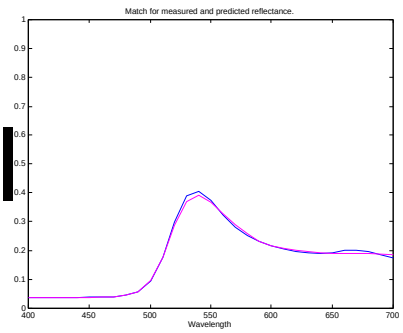


Figure 9c. ΔE^*_{94} histogram for 105 painted patches reconstructed using 6 eigenvectors in K/S space.

Except for the spectral reconstruction of 105 painted patches, the spectral reconstruction in K/S space presented worse results than the spectral reconstruction in reflectance space. Analyzing the spectra matching it was possible to observe that the spectra reflectance reconstruction worked well in K/S spaces for low reflectances but there were mismatches in spectral curves with high reflectance factor values. It happened because high reflectance factor values leads to very small absorption values that can produce negative values in a square root in Kubelka-Munk equations. For example, in the reconstruction of 147 painted patches, the figure 10a shows a good match between measured and predicted reflectances, but figure 10b shows a mismatch between measured and predicted spectral reflectances due to the influence of high spectral reflectance by Kubell



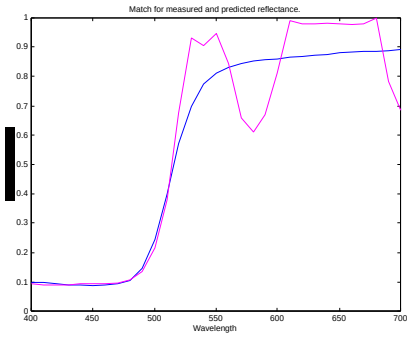


Figure 10a. Match between measured and predicted spectral reflectances using

Figure 10b. Mismatch between measured and predicted spectral reflectances using

eigenvectors in K/S space. eigenvectors in K/S space.

C) **New empirical space**

Principal component analyses was performed in the new empirical space and figures 11a, 11b, and 11c show the plot of the 1st to 6th eigenvectors of Macbeth ColorChecker, 147 painted patches and 105 painted patches, respectively.

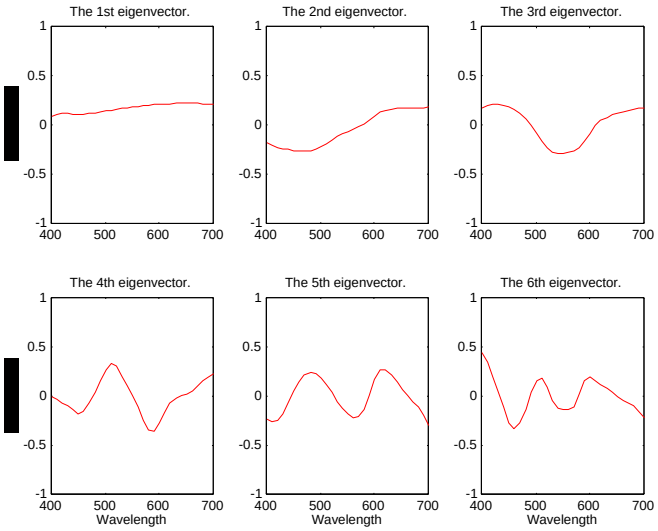


Figure 11a. Plot of the first to sixth eigenvectors of Macbeth ColorChecker reflectances in the new empirical space

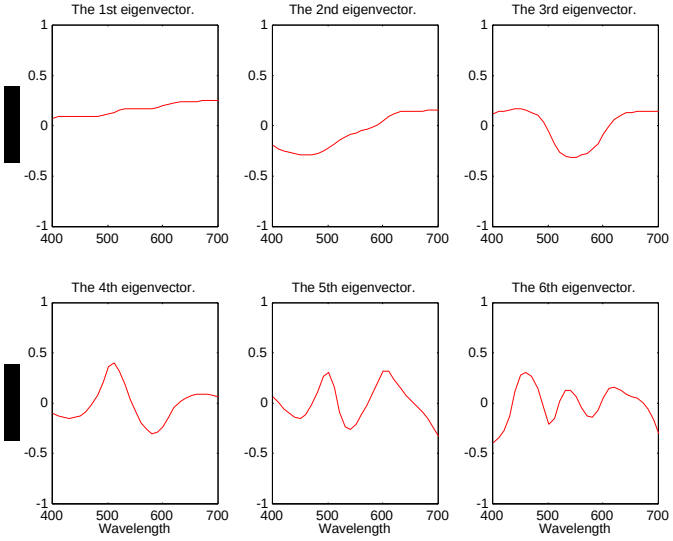


Figure 11b. Plot of the first to sixth eigenvectors of 147 painted patches reflectances in the new empirical space.

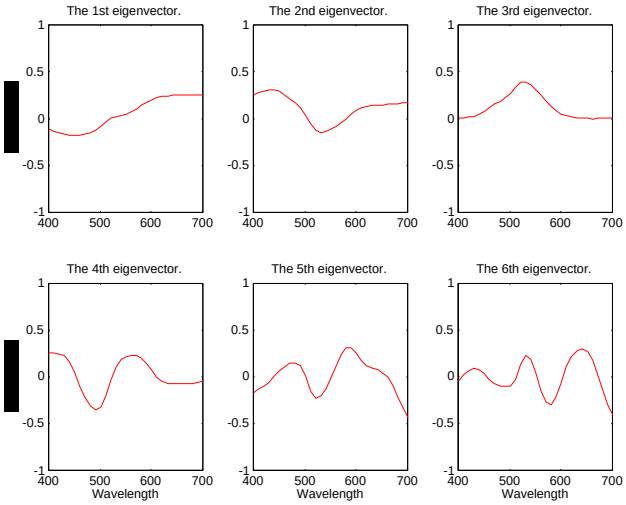


Figure 11c. Plot of the first to sixth eigenvectors of 105 painted patches reflectances in the new empirical space.

Table VI summarizes the cumulative contribution of the eigenvectors in the new empirical space for Macbeth ColorChecker and the sets of painted patches.

Table VI. Cumulative contribution of the eigenvectors in the new empirical space.

Number of eigenvectors	Cumulative Contribution (%) for Macbeth Color Checker	Cumulative Contribution (%) for 147 painted patches	Cumulative Contribution (%) for 105 painted patches
1	61.81	63.70	62.98
2	88.13	89.95	87.40
3	98.49	98.57	97.48
4	99.19	99.53	98.88
5	99.69	99.75	99.40
6	99.84	99.85	99.70
7	99.90	99.93	99.87
8	99.94	99.97	99.96
9	99.97	99.98	99.98
10	99.99	99.99	99.99
11	99.99	100.00	100.00
12	100.00	100.00	100.00

Table VII shows the influence of the number of eigenvectors on the colorimetric and spectral accuracy of the spectral reconstruction of each patch. The colorimetric accuracy is calculated using CIE94 under D50 and 2° observer. Figures 12a, 12b, and 12c show the histogram of ΔE^*_{94} between the measured spectral reflectance and the spectral reflectance predicted using 6 eigenvectors for Macbeth ColorChecker, 147 painted patches and 105 painted patches, respectively.

Table VII. Influence of the number of eigenvectors in the new empirical space used in the spectral reconstruction on the colorimetric and spectral error.

Number of eigenvectors	Macbeth ColorChecker		147 painted patches		105 painted patches	
	Mean ΔE^*_{94}	rms reflectance factor	Mean ΔE^*_{94}	rms reflectance factor	Mean ΔE^*_{94}	rms reflectance factor
1	29.1	0.187	32.7	0.192	36.9	0.386
2	14.4	0.074	13.6	0.068	44.0	0.279
3	2.52	0.025	3.31	0.025	1.79	0.022
4	1.18	0.018	1.02	0.013	1.39	0.015
5	0.67	0.012	0.50	0.009	0.54	0.011
6	0.21	0.009	0.30	0.007	0.49	0.007
7	0.15	0.007	0.20	0.006	0.21	0.005
8	0.10	0.005	0.09	0.004	0.06	0.002
9	0.09	0.004	0.03	0.003	0.05	0.002
10	0.03	0.003	0.02	0.002	0.03	0.001
11	0.02	0.002	0.01	0.001	0.02	0.001
12	0.01	0.001	0.00	0.001	0.01	0.000

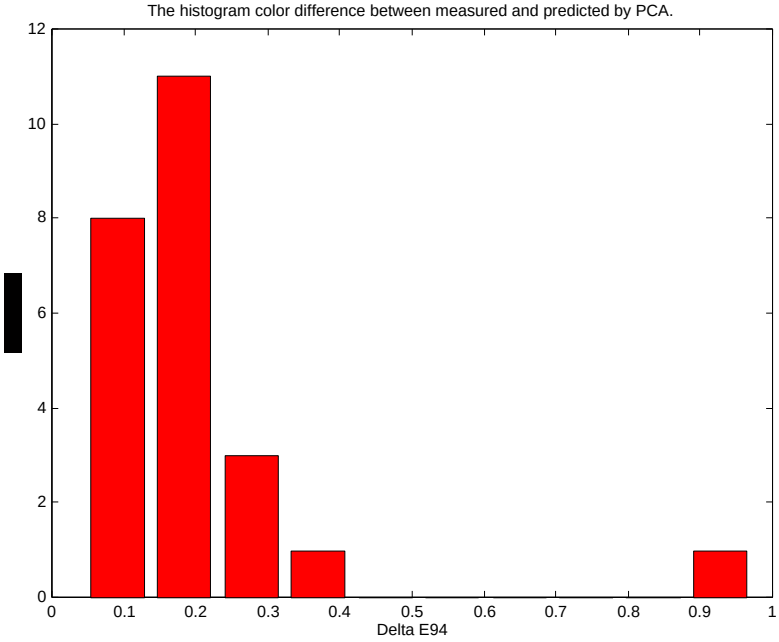


Figure 12a. ΔE^*_{94} histogram for Macbeth ColorChecker reconstructed using 6 eigenvectors in the new empirical space.

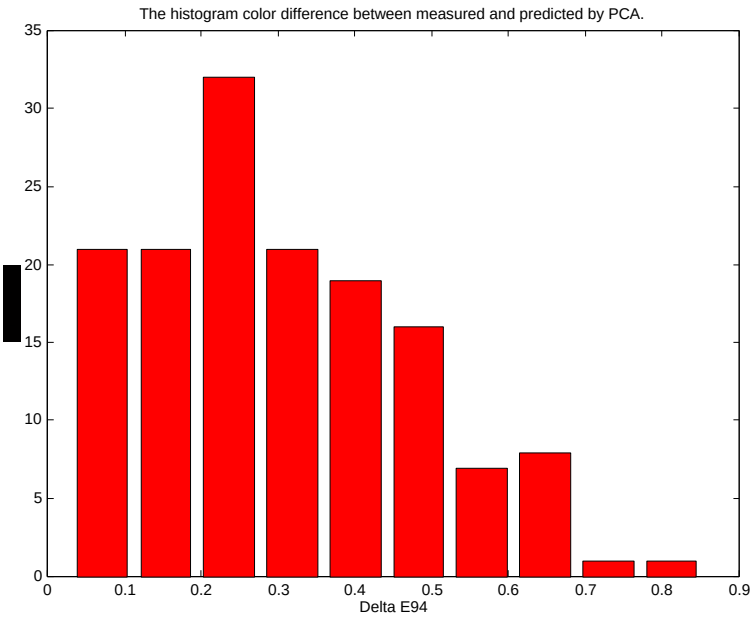


Figure 12b. ΔE^*_{94} histogram for 147 painted patches reconstructed using 6 eigenvectors in the new empirical space.

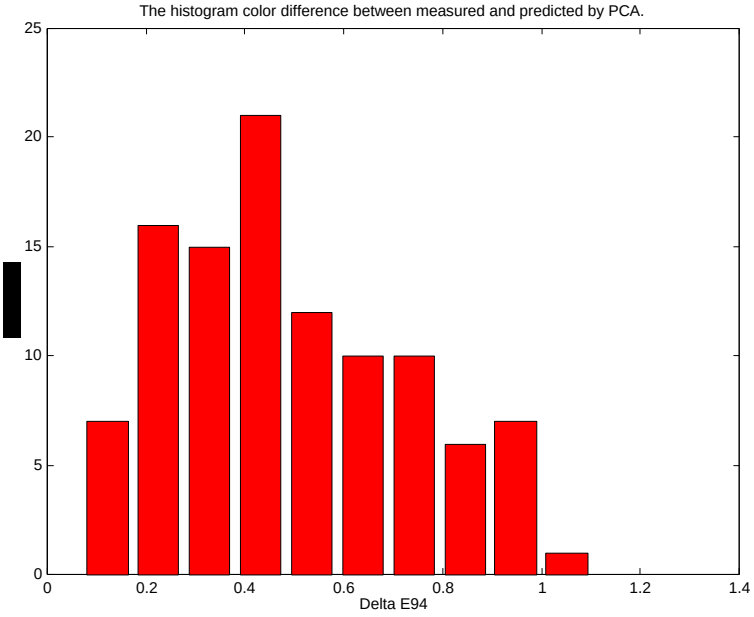


Figure 12c. ΔE^*_{94} histogram for 105 painted patches reconstructed using 6 eigenvectors in the new empirical space.

It is possible to see from the results above that the spectral reconstruction in the new empirical space presented better spectral and colorimetric accuracy than the reconstruction in reflectance and Kubelka-Munk spaces. Ideally, in order to achieve a spectral reconstruction that gives ΔE^*_{94} less than 1.0 and spectral reflectance rms error less than 1%, at least, 9, 12 and 6 eigenvectors should be used, respectively, in reflectance, Kubelka-Munk and new empirical spaces.