Pigment Identification of Artist Materials Via Multi-Spectral Imaging

Roy S. Berns and Francisco H. Imai
Munsell Color Science Laboratory, Rochester Institute of Technology
Rochester, New York, USA

Abstract

Visible reflectance spectrophotometry is a valuable tool in art conservation. In particular, the spectral data can be used to evaluate potential pigment combinations for inpainting to insure metamerism is minimized. Minimizing metamerism can be a critical criterion because of the wide range of museum lighting and difficulties in image archiving caused by the mismatch between many imaging systems' and the human visual system's spectral sensitivities. Recently, a new method for pigment selection for inpainting was developed that is successful in minimizing metamerism. Normally, small-aperture spectrophotometers are used. An experiment was performed to test whether this technique could be used with direct-digital capture of artwork. If successful, it could be possible to develop spatial maps of paintings, providing tremendous insight to a given artist, and aid in pigment identification and selection. Multi-filter RGB images were used to estimate spectral reflectance factor. The accuracy of the spectral estimation depended on the spectral properties of the system calibration target. The new method of pigment selection was able to correctly identify pigments from the estimated spectra. The reported results focus on blue pigments, often a cause of significant metamerism when poorly matched.

Introduction

Many paintings require visual compensation for losses in their paint film and for many conservators, the goal is to treat these losses such that they are indistinguishable from the surrounding undamaged surface when viewed under typical museum conditions. In order to achieve this level of reintegration, the inpainted area should have nearly identical optical properties, specifically, close matches in spectral (color and transparency) and geometric (gloss, texture, and impasto) properties. The conservator controls these properties through the choice of fill material, pigments, binder, varnish, and application technique. Occasionally, there are limited options in selecting the binder and method of application, particularly if the painting is not varnished or the paint film is sensitive to solvents, although there can be a variety of pigments capable of matching a specific color. The choice of pigments has a dramatic effect on whether the treated area is indistinguishable in color. An indiscriminate selection can result in severe metamerism.

Recently, a new technique has been developed for pigment selection for inpainting using a small-aperture, portable spectrophotometer.[1] The technique is a simplification of instrumental-based color matching, practiced routinely in the paint, plastics, and textiles industries, among others and employs a spectral-matching algorithm.[2] The simplification involves the use of single-constant Kubelka-Munk theory and limiting the wavelength range such that differences in the absorption properties of white pigments (e.g., titanium, zinc, lead) do not influence the spectral-matching outcome. The technique has been used successfully at the National Gallery of Art, Washington in selecting pigment mixtures for difficult inpainting where any color (and spatial) mismatch is readily visible because the paint losses are large and correspond to very uniform regions of color. Examples include Dionysius by Barnett Newman and Siout, Egypt by Sanford Robinson Gifford. (Images available at nga.gov.) Minimizing metamerism was a critical restoration requirement. During development, an analysis was performed to identify sets of unknown pigment mixtures from a database of five green, two yellow, and three blue pigments, many with quite similar spectral characteristics. Six two-chromatic pigment mixtures were prepared by dispersing dry pigments in polyvinyl acetate. The model fits are shown in Figure 1. The spectral properties were well estimated. The specific pigments were correctly identified in all cases.

The authors have been active in developing methods of estimating spectral reflectance from direct digital capture of two-dimensional works of art.[3-5] These estimated spectra can be used in similar fashion to direct spectral reflectance measurements.

As a long-term goal, we envision a multi-modal imaging system that can capture ultraviolet fluorescence, visible spectral reflectance, infrared reflectance in specific spectral bands, surface topography, and goniophotometric properties. Such a system would enable the complete optical characterization of cultural heritage and provide a powerful tool for conservation. As an analytical tool, the visible spectral data could be used as an aid in pigment selection for inpainting and pigment identification. It would be very intriguing to have the capabilities to develop spatial maps of each pigment used in a given painting. Research has been performed in Italian[6-9] and British[10] museums, unfortunately, with limited success, primarily a result of performing analyses on spectral reflectance data rather than absorption and scattering data. Because of the effectiveness of the Berns, et al. method,[1] we were interested in evaluating this technique as a component of an image-analysis system capable of pigment identification and spatial mapping.

Experimental

An IBM Pro/3000 near-colorimetric trichromatic scanning digital camera was used as the image-input device.[11] RGB images were captured both excluding and including a Wratten 38 light-blue filter, positioned in front of the camera lens. These multi-filter images of an appropriate calibration target with known spectral-reflectance spectra were post-processed resulting in a transformation from multi-filter images of any arbitrary object to estimated spectral images.[12] The technique involves using principal component analysis to determine six basis functions capable of accurate spectral estimation. Samples forming the calibration target are defined by these basis functions and corresponding scalars. Linear or nonlinear transformations are derived to relate the pair of RGB signal values to the scalars. Developing a "universal" calibration target is a current research project. For this experiment, the GretagMacbeth ColorChecker Color Rendition Chart was used. This target is often used as a calibration target for artwork imaging, for example reference 13.

A target of 68 artist oil paints was created. (Typical materials are described at www.gamblincolors.com.) Each paint was mixed with titanium white in order to maximize the spectral "fingerprint" of a given pigment with the goal of matching the lightness of a light gray sample with L* equal to 70 as noted by Johnston.[14] Their log(K/S) spectra are plotted in Figure 2. Log(K/S) is used to minimize the effects of unmatched pigment strength and concentration.

The paint target was imaged using the multi-filter technique. Raw 12-bit photometrically-linear data were spatially averaged for each painted patch and converted to spectral reflectance factor between 400 and 700 nm.

The paint target was also used to produce the spectral database for pigment identification. Each sample was measured with a GretagMacbeth SpectroEye bidirectional reflectance spectrophotometer. The spectral data were converted to Kubelka-Munk absorption and scattering ratios while taking suitable account of the absorption properties of titanium white via scaling and subtraction in K/S space.

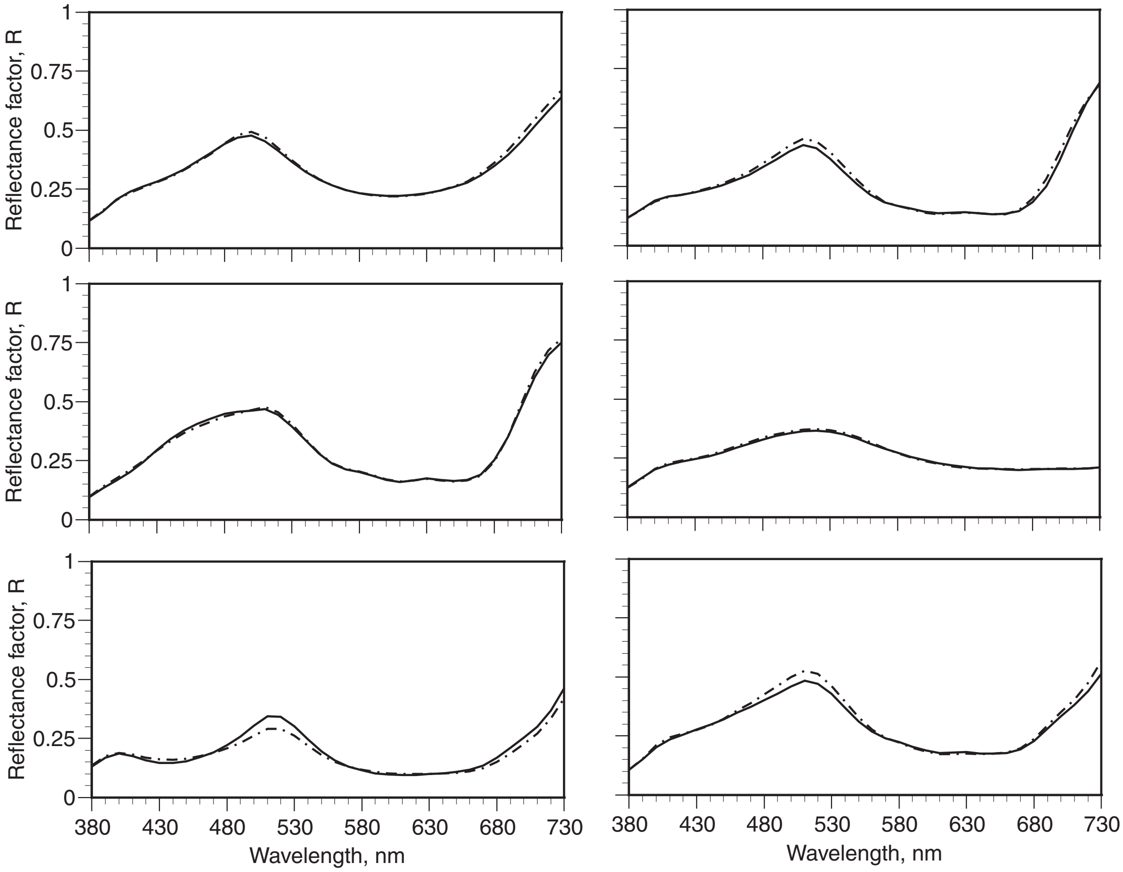

Figure 1. Measured (solid lines) and estimated (dot-dashed lines) spectra of six unknown two-chromatic pigment mixtures using the Berns, et al. method[1]

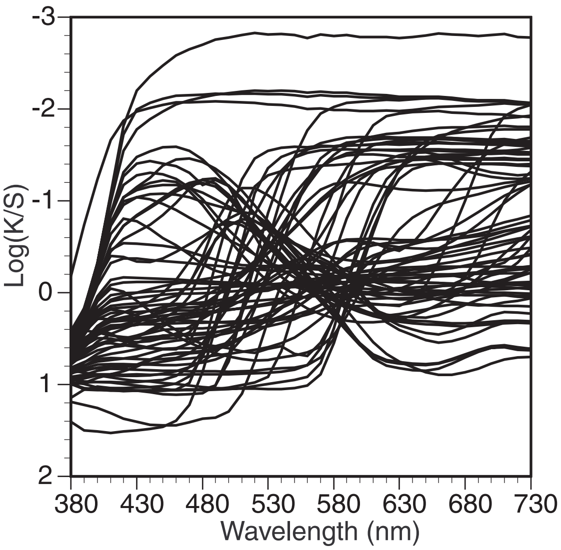

Figure 2. Log(K/S) spectra of the the 68 pigment artist-oil test target.

Results and Discussion

The quality of the spectral estimation for the artist-oil target was quantified by RMS spectral error, CIE94 color differences for D65 and the 1931 standard observer, and an index of metamerism[15] for illuminant A and the 1931 standard observer under the assumption of a colorimetric match for D65, summarized in Table I. Because the spectral estimation optimization was based on an RMS error criterion, the colorimetric significance should be evaluated by the index of metamerism. This performance was quite reasonable for this technique. If the goal was colorimetric rather than spectral estimation, it should be possible to achieve this level of accuracy.

The correct identification of blue pigments is very critical for inpainting in order to minimize metamerism.[16] The measured and estimated spectra for cobalt, ultramarine, manganese, and prussian blue pigments are plotted in Figure 3. The fits are fairly typical of spectral-estimation techniques: the estimates tend to have greater spectral selectivity. The overall shapes were reasonably predicted.

Table I. Performance metrics for spectral estimation accuracy of the artist-oil target.

Statistics	Spectral RMS Error	Color Difference (ΔE^*_{94})	Index of Metamerism (ΔE^*_{94})
Average	0.034	2.0	0.4
Standard Deviation	0.018	0.9	0.3
Maximum	0.106	4.5	1.4
Minimum	0.008	0.3	0.0

The pigment identification technique was evaluated for these four pigments using the estimated spectra as input to the identification system. A spectral-matching algorithm was used with the match criterion one of minimizing spectral reflectance error between 420 and 700 nm. The underlying color-mixing model was the single-constant form of Kubelka-Munk turbid-media theory. Of the 68 pigments forming the spectral database, the specific blue pigments included cobalt, ultramarine, manganese, prussian, phthalocyanine, cerulean, and indanthrone. Their spectra, converted to log(K/S) and normalized at 460nm are plotted in Figure 4. Some of the spectra are quite close in shape. If the pigment identification technique using digital imaging was accurate, this indicates its effectiveness for spatial-pigment mapping. The cobalt and ultramarine blue spectra were correctly identified. Manganese blue was incorrectly identified as phthalocyanine blue. This was due to the secondary peak at 650 nm in the estimated spectrum. The prussian blue sample was incorrectly identified as manganese blue.

The spectral estimation had insufficient accuracy for accurate pigment identification. The problem lies with the ColorChecker; its spectral properties have insufficient variability as a universal target. The spectral estimation was repeated, except that spectral information from the entire painted target was used in place of the ColorChecker. The estimated spectra are also plotted in Figure 2. In all cases the spectral fits were improved. The pigment identification was repeated. Only the prussian blue sample was incorrectly identified, again as manganese blue. Given the known similarity in spectral properties between prussian and manganese blues,[16] also evident in Figure 4, these results were very encouraging.

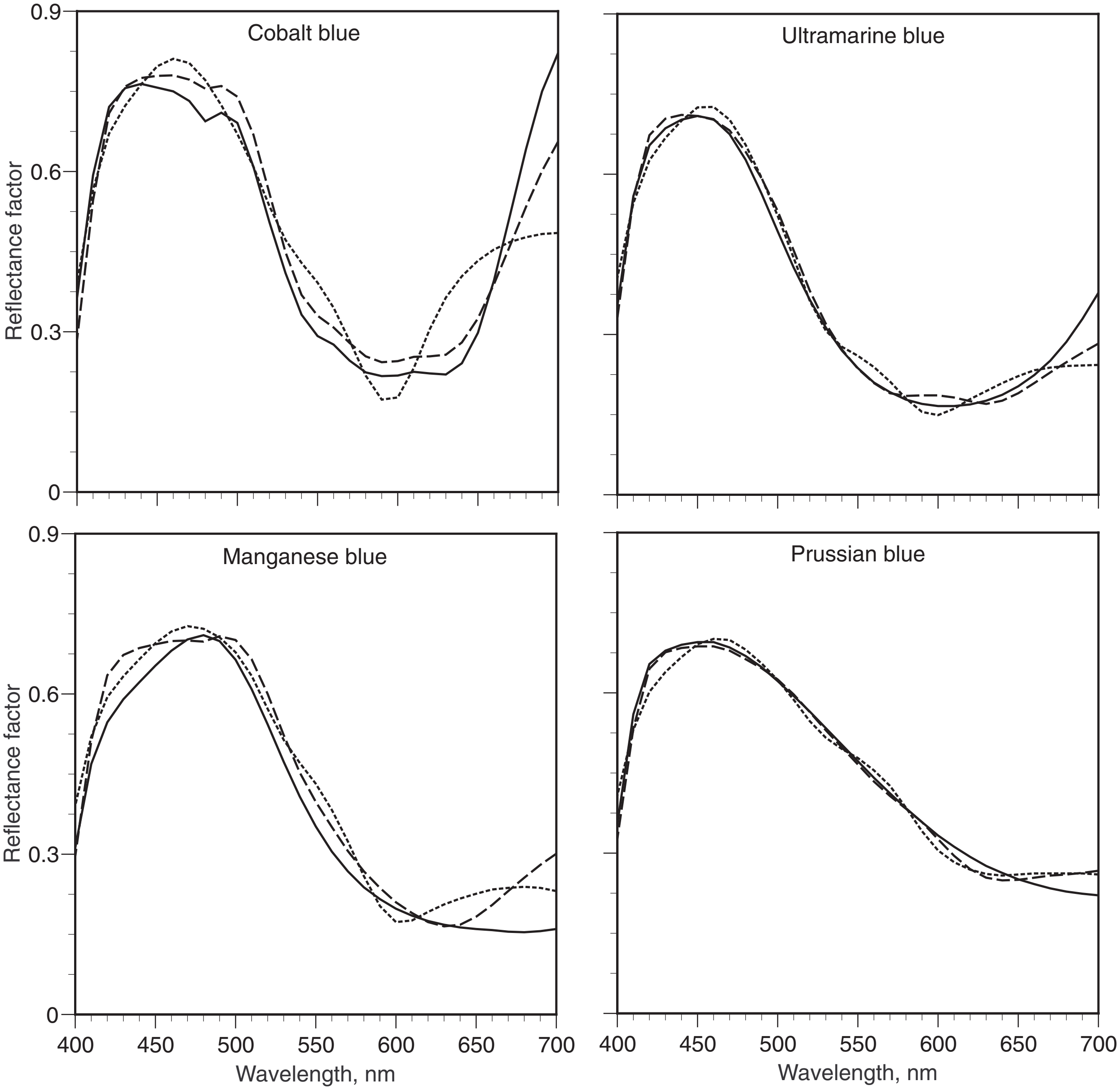

Figure 3. Spectral estimation of four samples from the artist oil-paint target: measured (solid line), estimated from spectral data of ColorChecker (dotted line), estimated from spectral data of the entire target (dashed line).

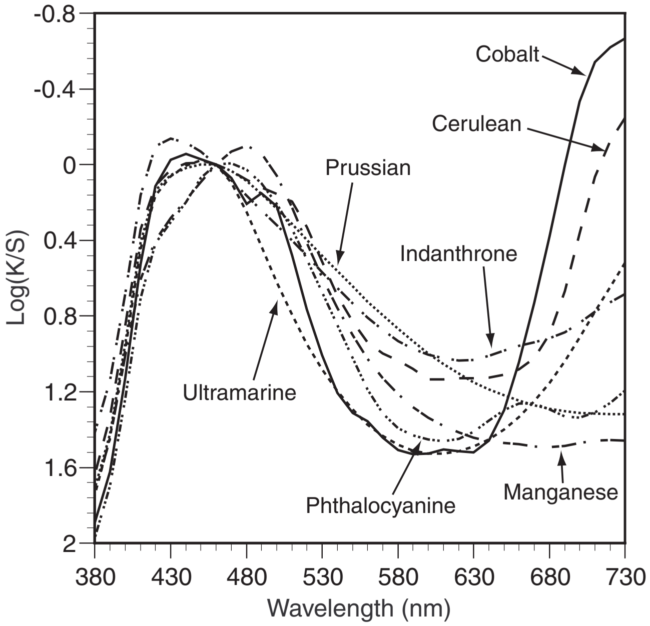

Figure 4. Log(K/S) spectra of the blue pigments contained in the 68 pigment artist-oil test target.

Conclusion

The key criterion for this technique to be effective is spectral-estimation accuracy. Typically, estimation techniques relying of principal-component analysis result in spectra with excessive modulation. This will compromise the effectiveness of the spectral matching. We have begun to evaluate other techniques of spectral estimation such as Wiener estimation.[17] The choice of calibration target also affects estimation accuracy. It is critical that the calibration target spans both the spectral and colorimetric descriptions of object colors. In addition to gamut considerations, the distribution of the colors is particularly important. Oversampling a particular spectral shape (and color) has a dramatic effect on the most-statistically-significant eigenvectors. Thus far, a target has yet to be developed which meets all of these requirements. If estimation techniques prove ineffective, visible spectrum imaging using liquid-crystal tunable filters, interference filters, or techniques common to remote sensing[18] will be required.

References

1. Berns R. S., Krueger, J., and Swicklik, M., ‘Multiple pigment selection for inpainting using visible reflectance spectrophotometry,’ *Studies in Conservation*, in press (2001).
2. Berns, R. S., *Billmeyer and Saltzman’s Principles of Color Technology*, 3rd ed, John Wiley & Sons, New York pp. 181 - 182 (2000).
3. Imai, F. H. and Berns, R. S., ‘High-resolution multi-spectral image archives: A hybrid approach,’ *Proc. of The Sixth Color Imaging Conference: Color Science, Systems, and Applications*, IS&T, Springfield, Virginia, 224-227 (1998).
4. Imai, F. H, Rosen, M. R., and Berns, R. S., ‘Multi-spectral imaging of van Gogh’s self-portrait at the National Gallery of Art, Washington, D.C.,’ *Proc. of IS&T’s PICS Conference*, IS&T, Springfield, Virginia, 185-189 (2001).
5. Imai, F. H. and Berns, R. S., ‘Spectral estimation of artist oil paints using multi-filter trichromatic imaging,’ *Proc. of AIC Colour 01*, in press, (2001).
6. Bacci, M. Baronti, S., Casini, A., Lotti, F., Picollo, M. and Casazza, O., ‘Non-destructive spectroscopic investigations on paintings using optical fibers,’ *Proc. Materials Res. Soc. Symp*. 267 265-283 (1992).
7. Bacci, M., Picollo. M., Radicati, B., and Belluci, R., ‘Spectroscopic imaging and non-destructive reflectance investigations using fibre optics,’ *4th Inter. Conf. Non-Destructive Testing Works of Art* 162-174 (1994).
8. Baronti, S., Casini, A., Lotti, F., and Porcinai, S., ‘A multispectral imaging system for mapping of pigments in works of art by the use of principal-component analysis,’ *Appl. Optics* **37** 1299-1309 (1998).
9. Casini, A., Lotti, F., Picollo, M., Stefani, L., and Buzzegoli, E., ‘Image spectroscopy mapping technique for non-invasive analysis of paintings,’ *Studies in Conservation* **44** 39-48 (1999).
10. Thoma, J., Cupitt, J., and Saunders, D., ‘An investigation of the potential use of visible-region multispectral imaging for pigment identification in paintings,’ *Proc. Colour Image Science 2000*, Colour and Imaging Institute, University of Derby 95-106 (2000).
11. Giordano, F. P., Braudaway, G. W., Christensen, J., Lee, J., and Mintzer, F. ‘Evolution of a high-quality digital imaging system’ *Proc. SPIE* **3650** 110-118 (1999).
12. Berns, R. S. and Imai, F. H., ‘Spectral estimation using trichromatic digital cameras,’ *Proc. Intl. Sym. Multispectral Imaging and Color Reproduction for Digital Archives*, Chiba University, Soc. Multispectral Imaging Japan 42-49 (1999).
13. Saunders, D., Cupitt, J., ‘Image processing at the National Gallery: The VASARI project,’ *National Gallery Tech. Bull.* **14** 72-86 (1993).
14. Johnston, R. M. and Feller, R. L., ‘The use of differential spectral curve analysis in the study of museum objects,’ *Dyestuffs* **44**(9) 1-10 (1963).
15. Fairman, H. R., ‘Metameric correction using parameric decomposition,’ *Color Res. Appl*. **12** 261-265 (1987).
16. Staniforth, S., ‘Retouching and colour matching: the restorer and metamerism,’ *Studies in Conservation* **30** 101-111 (1985).
17. Tsumura, N., Sato, H., Hasegawa, T., Haneishi, H., and Miyake, Y., ‘Limitation of color samples for spectral estimation from sensor responses in fine art painting,’ *Optical Review* **6** 57-61 (1999).
18. Colwell, R.N., Ed. *Manual of Remote Sensing* Vol 1, 2nd ed, American Society of Photogrammetry, Falls Church, Va (1983).

Biography

Roy S. Berns is the Richard S. Hunter Professor in Color Science, Appearance, and Technology at the Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology. He directs a research group active in spectral color reproduction with an emphasis on cultural heritage. He is active in the CIE; on the editorial board of *Color, Research, and Application*; and the author of the third edition of *Billmeyer and Saltzman's Principles of Color Technology*. He is a member of IS&T and received their 1998 Journal Award.

Francisco H. Imai received his Ph.D. in imaging science from Chiba University, Japan in 1997. Since 1997 he has worked at the Munsell Color Science Laboratory, where currently he is a senior color scientist. His research has been focused on multi-spectral color reproduction and spectral reconstruction. He was named as the recipient of the 1998 Itek Award for the best student paper in 1997 by IS&T. He is a member of IS&T and ISCC.