The use of multi-channel visible spectrum imaging for pigment identification

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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. This is a critical criterion because of the wide range of museum lighting and observers, including imaging devices. Recently, a new method of pigment selection for inpainting was developed that successfully minimizes 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. Multi-filter colour 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 in many cases. The reported results focus on blue pigments, often a cause of significant metamerism when poorly matched.

Keywords

pigment identification, digital imaging, multi-spectral imaging, multi-channel visible spectrum imaging, metamerism

Introduction

Many paintings require visual compensation for losses in their paint film, and for many conservators the goal is to treat these losses so 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, there should be close matches in spectral (colour 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 when 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 colour. The choice of pigments has a dramatic effect on whether the treated area is indistinguishable in colour. An indiscriminate selection can result in severe metamerism.

Recently, a new technique has been developed for pigment selection for inpainting. A small-aperture, portable spectrophotometer is used to measure the spectral reflectance properties of similarly pigmented adjacent areas. Using a predetermined database of pigments, also evaluated spectrally, a set of pigments are selected that when combined result in a close spectral match with minimal metamerism (Berns et al. 2002). The technique is a simplification of instrumental-based colour matching (Berns 2000), practised routinely in the paint, plastics and textiles industries, among others. The specific mathematics is often referred to as a 'spectral-matching algorithm'. The simplification involves using single-constant Kubelka-Munk theory and limiting the wavelength range such that differences in the absorption properties of white pigments (e.g. titanium, zinc or lead white) do not influence the spectral-matching outcome. Kubelka-Munk theory is a turbid-media theory that considers light travelling in only two opposite directions. A colorant is characterized by its absorption and scattering properties as a function of wavelength.

The pigment-selection technique has been used successfully at the National Gallery of Art in Washington D.C., which selects pigment mixtures for difficult inpainting where any colour (and spatial) mismatch is readily visible. The Gallery does so because the paint losses are large and correspond to uniform regions of colour. Examples include *Dionysius* by Barnett Newman (1949, gift of Annalee Newman, in honour of the 50th anniversary of the National Gallery of Art) and *Siout, Egypt* by Sanford Robinson Gifford (1874, New Century Fund, gift of Joan and David Maxwell, National Gallery of Art). Minimizing metamerism was a critical restoration requirement.

During development of the pigment-selection technique, a pilot experiment was performed. Green paint-outs were prepared containing two coloured pigments and titanium white dispersed in polyvinyl acetate. The coloured pigments were selected from a database of five green, two yellow and three blue pigments, many with quite similar spectral characteristics, particularly in the long-wavelength region of the visible spectrum. The paint-outs were measured spectrally and

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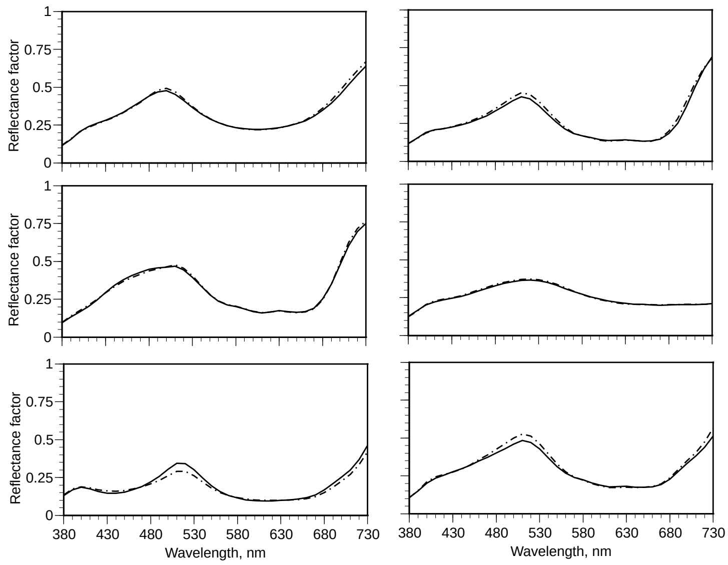

Figure 1. Measured (solid lines) and estimated (dot-dashed lines) spectra of six unknown two-chromatic pigment mixtures using the Berns method (Berns et al. 2002)

evaluated to determine their composition. In all cases, the specific pigments were correctly identified. The technique can also predict the spectral properties of the identified mixture, shown in Figure 1. These reflectance spectra were reasonably well estimated, particularly in general shape. The fits are not perfect because of the simplifications described above.

The authors have been active in developing methods of estimating spectral reflectance from direct digital capture of two-dimensional works of art (Imai and Berns 1998, 1999, 2001, Imai et al. 2000a, 2000b, 2001). 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 (Bacci et al. 1992, 1996, Baronti et al. 1998, Casini et al. 1999) and British (Thoma et al. 2000) museums. Unfortunately, this research has had limited success, primarily because the researchers analysed spectral reflectance data rather than absorption and scattering data. Because of the effectiveness of the Berns method (Berns et al. 2002), 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 scanning digital camera (Giordano et al. 1999) was used as the image-input device. The camera employs a monochrome scanning linear array and a filter wheel with custom-designed red, green and blue filters that improved colour accuracy over most commercial digital scanbacks. Raw, 12-bit-per-channel colour-image datafiles were used. The Imai and Berns spectral-estimation method requires that colour images be captured using either two different light sources or a single light source with and without a colour filter. For this experiment, a Wratten 38 light-blue filter was positioned in front of the camera lens for the second colour image. A calibration target of a grid of colours is measured using a reflectance spectrophotometer and imaged with and without the light-blue filter. A mathematical transformation is derived that converts the digital image data to spectral reflectance factor data on a pixel basis (Imai and Berns 1999). The

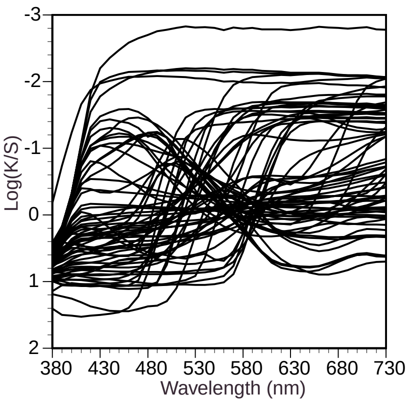

Figure 2. Log(K/S) spectra of the 68-pigment paint target

transformation 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. (These basis functions can be thought of as statistical colorants and their scalars thought of as colorant amounts.) Linear or nonlinear transformations are derived to relate the digital code values from the pair of images to the scalars (see Berns, in press). For this experiment, the GretagMacbeth ColorChecker Color Rendition Chart was used as the calibration target. This target is often used for artwork imaging (see for example Saunders and Cupitt 1993). Following system calibration, spectral reflectance as a function of spatial position can be estimated for any imaged object.

A test target of 68 modern artist oil paints was created. Rather than use the oil paint directly from the tube, each paint was mixed with titanium white so that the paint mixture's lightness matched visually a light grey (about Munsell Value 7 or CIE $L^* \approx 70$). This was done to maximize the spectral 'fingerprint' of a given pigment (Johnston and Feller 1963). Their log(K/S) spectra are plotted in Figure 2. Rather than plot reflectance, the logarithm of the Kubelka-Munk absorption and scattering ratio is plotted. This minimizes the effects of unmatched pigment strength and concentration on the curve shape. The paint target was imaged and the average digital code values of each target patch was transformed to an average spectral reflectance factor.

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 reflectance data were converted to K/S. One of the target patches was the titanium white used to lighten each paint. Its K/S values were subtracted from the K/S values of each mixture in order to remove the absorption properties of titanium white, especially at short visible wavelengths.

Results and discussion

Prior to imaging the paint target, the colorimetric performance of the ColorChecker was evaluated as a systems check. The measured and estimated reflectance spectra for each colour patch were used to calculate CIELAB coordinates and colour differences for CIE illuminant D65 (natural daylight) and the CIE 1931 standard observer. The ColorChecker was estimated to an average accuracy of $0.3\Delta E^*_{94}$ ($1.6\Delta E^*_{ab}$), typical for multi-channel estimation methods such as VASARI (Saunders and Cupitt 1993) and much better than commercial scanbacks, digital cameras or digitized film systems, even following colour management (Berns 2001).

The quality of the spectral estimation for the paint target was quantified using three metrics. The first was the root-mean-square (RMS) spectral error between each target sample's measured and estimated reflectance spectrum. The second metric was CIE94 colour difference, calculated for illuminant D65 and the 1931 standard observer. The third metric was an index of metamerism for CIE illuminant A (incandescent). The metameric index utilized a parameric correction (Fairman 1987, Berns 2000) that corrected the estimated spectrum resulting in a perfect colorimetric match for D65. A CIE94 colour difference for illuminant A defining the index of metamerism provides a spectral-matching metric in colorimetric units. The results are given in Table 1. 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.

Table 1. Performance metrics for spectral estimation accuracy of the paint target

Statistics	Spectral Reflectance RMS Error	Colour Difference Illuminant D65 (ΔE^*_{94})	Index of Metamerism Illuminant A (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

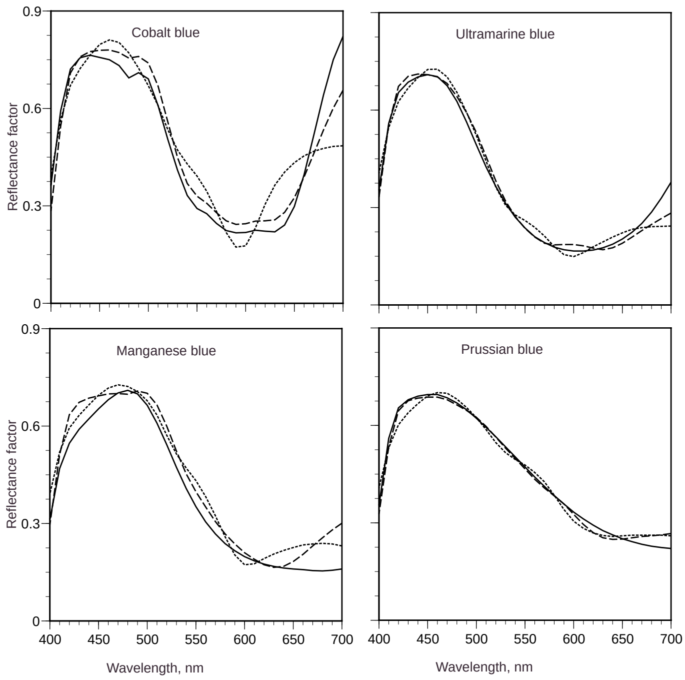

Figure 3. Spectral estimation of four samples from the paint target: measured (solid line), estimated from spectral data of ColorChecker (dotted line), estimated from spectral data of the entire target (dashed line)

The correct identification of blue pigments is very critical for inpainting in order to minimize metamerism (Staniforth 1985). 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 of the spectral curves were reasonably predicted.

The pigment identification technique was evaluated for these four pigments using the estimated spectra as input to the identification system. Of the 68 pigments forming the spectral database, the specific blue pigments were cobalt, ultramarine, manganese, Prussian, phthalocyanine and cerulean blue, and indanthrone. Their spectra, converted to log(K/S) and normalized at 460 nm 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. The spectral estimation was repeated, except that the system calibration was performed using the paint target in place of the ColorChecker. The estimated spectra are also plotted in Figure 3. 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 blue (Staniforth 1985), also evident in Figure 4, these results were very encouraging.

Conclusion

The key criterion for this technique to be effective is spectral-estimation accuracy. Typically, estimation techniques relying on principal-component analysis result in spectra with excessive modulation. This will compromise the effectiveness of the pigment identification. We have begun to evaluate other techniques of spectral

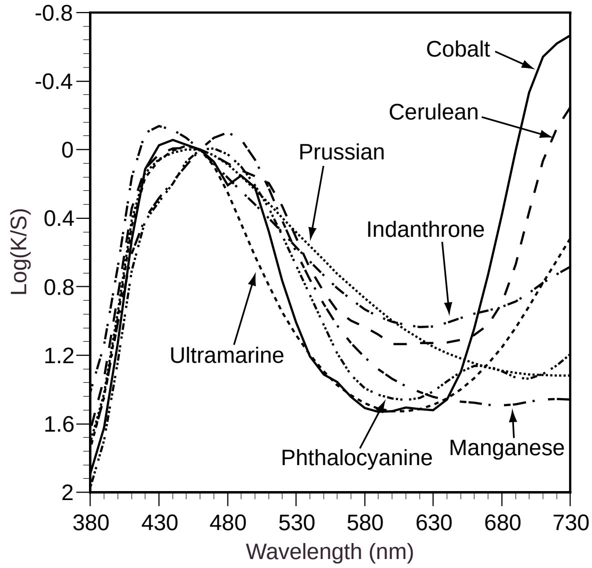

Figure 4. Log(K/S) spectra of the blue pigments contained in the paint target: each curve was translated to coincide at 460 nm

estimation such as Wiener estimation (Tsumura et al. 1999). 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 colours. In addition to a gamut of considerations, the distribution of the colours is particularly important. Oversampling a particular spectral shape (and colour) has a dramatic effect on the most statistically significant eigenvectors. Thus far, a target has yet to be developed that meets all of these requirements. This is a current topic of research. If estimation techniques prove ineffective, narrow-band, visible spectrum imaging using liquid-crystal tunable filters or interference filters (Berns, in press) or techniques common to remote sensing (Colwell 1983) will be required.

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