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Front cover: Giampietrino, *Salome*; detail of Plate 1, page 4.

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Long-term Colour Change Measurement: Some Results after Twenty Years

DAVID SAUNDERS, HELENE CHAHINE AND JOHN CUPITT

Some twenty years ago, after a period of research and development,[1] the Scientific Department at the National Gallery began to make accurate colour measurements on a number of paintings in the Collection, with a view to detecting and measuring any subsequent changes.[2] Ten years later, an analysis of the results obtained using the Wright-Wassall reflectance spectrophotometer detected changes at the surface of the painting due to the slight yellowing or matting of the varnish layer, but found no indication of colour changes in the pigments resulting from long-term display in the galleries.[3]

Unfortunately, it became clear some years ago that certain components in the spectrophotometer, particularly the fibre-optic link from the monochromator to the measuring head, were gradually deteriorating, causing considerable differences in the colour measurements. Although these parts could be replaced, the reproducibility of colour measurement could not be ensured. When it was clear that the colour measurements being made were no longer comparable to those recorded some years earlier, the long-term monitoring of paintings using the spectrophotometer ceased.

By this time, the programme of direct colour measurement from paintings by means of electronic imaging, first developed in the early 1980s,[4] had reached a stage where digital images of paintings that afforded accurate colorimetric information were being made. In the long term, direct comparison of images made at, for example, five-yearly intervals will be used to assess and quantify changes in appearance. Although the electronic imaging system has been used to measure colour in paintings before, during and after conservation treatment,[5] no painting has yet been remeasured after a period of 'normal' display in the Gallery.

While waiting for sufficient time to elapse to make meaningful comparisons between colorimetric images of paintings, we were anxious to make use of the measurements made in the 1970s and 1980s using the Wright-Wassall spectrophotometer. This is particularly important as the few studies of colour changes in works of art under display conditions either covered relatively short periods[6] or are still in their early stages.[7] Accordingly, we have set out to compare colour measurements made with the spectrophotometer with those being made with the electronic imaging system, and in so doing, to assess the degree of colour change that has occurred over a period of up to twenty years.

Comparing the colour data from the two techniques

The colour data from the Wright-Wassall spectrophotometer are expressed in the form of CIE L^*, a^* and b^* values for a number of areas on the surface of each painting studied.[8] The instrument measured spectral reflectance from a roughly circular area of diameter *c.* 4mm. As previously described,[9] the colour data are accompanied by a photographic record of the position of each measurement. This record was intended to allow the spectrophotometer to be repositioned precisely during subsequent remeasurement. These photographs, a series of black and white 35mm negatives, have allowed us to locate accurately the area of each original reflectance measurement so that the corresponding data can be extracted from the high-resolution colour image of the painting. The procedure for comparison is described below and illustrated in Plate 1, using as an example one area from *The Adoration of the Kings* by the Master of Liesborn (NG 258), illustrated in

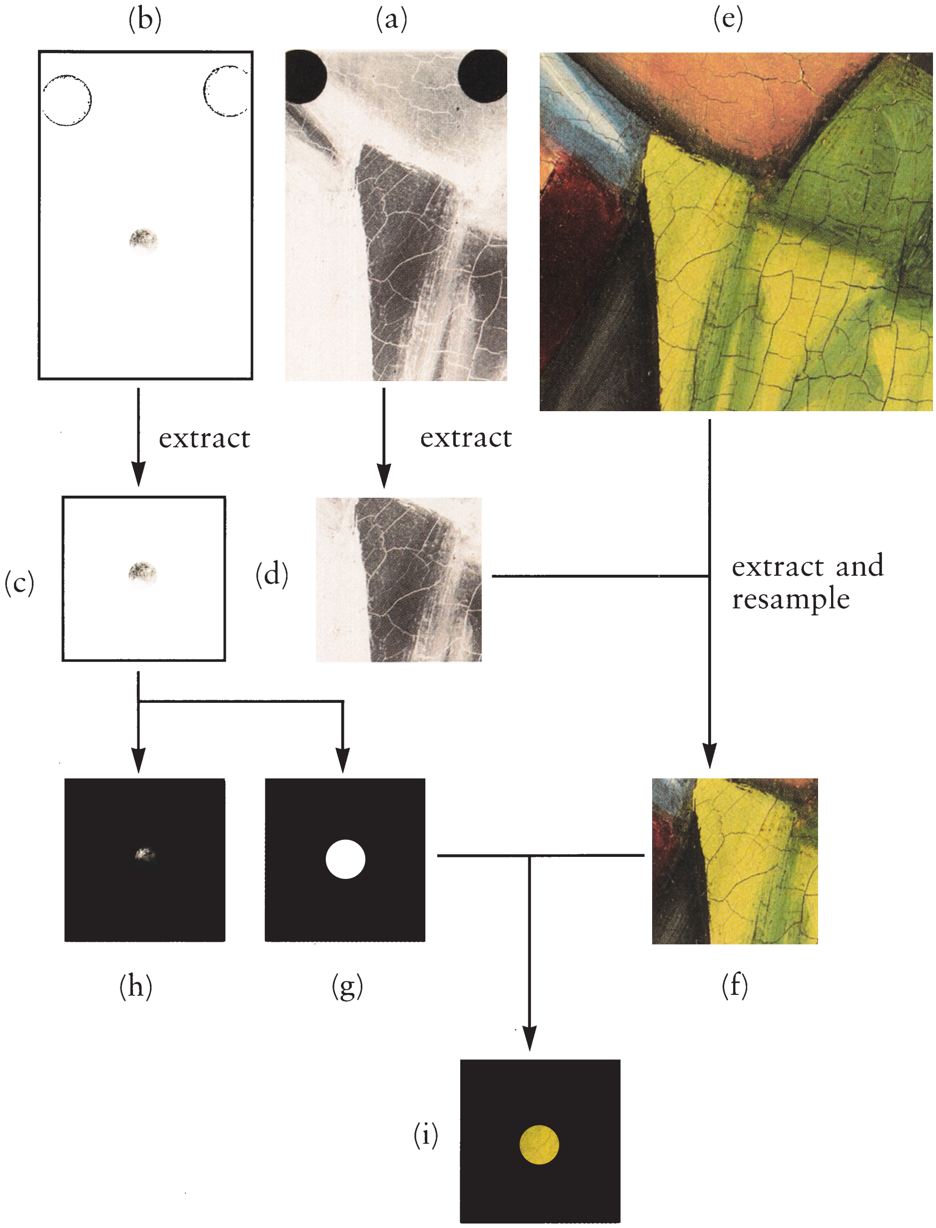

Plate 1 Schematic representation of the procedure for determining CIE data from the colorimetric image:

(a) digitised image of the 35mm negative made during the spectrophotometric measurement of the green area of *The Adoration of the Kings* (NG 258) marked as point 2 in Plate 2
(b) digitised image of the 35mm negative showing the 'spot' covered by the spectrophotometer during colour measurement of *The Adoration of the Kings*
(c) region extracted from image b
(d) corresponding region extracted from image a
(e) sub-image extracted from the region of the high-resolution digitised image of *The Adoration of the Kings* centred on point 2 in Plate 2
(f) region of image e after extraction and resampling so as to coincide exactly with image d
(g) circular mask created with the same centre and diameter as the spot in image c; white represents a numerical value of one, and black a value of zero
(h) mask created by scaling the lightness values of the spot in image d to fall within the range zero to one; white and black again represent one and zero respectively, while intermediate values appear as shades of grey
(i) image created by combining the circular mask represented by image g with the resampled colour image, image f

Plate 2. The sample area chosen is on the sleeve of the green robe of the right-hand figure, marked on Plate 2 as point 2.

Analysing the photographic record

The first step in the comparison process is to digitise the 35mm negatives that record the measurement sites for the spectrophotometer using a commercial slide- or desktop-scanner. Plate 1a shows the digitised image of the negative made during the spectrophotometric measurement of point 2. The optics of the spectrophotometer were designed so that, theoretically, the 4mm diameter measurement area 'spot' would be at the centre of the negative. It is clear, however, that slight variations in position exist. To determine the exact position of the spot, we were fortunate to have additional 35mm negatives, made at the time of each measurement, that show the position and shape of the spot. These were also digitised, Plate 1b, and used to identify the exact area on which the original measurement was made. A square region is extracted from the image of the spot. This image is chosen so that its centre corresponds to the centre of the spot, Plate 1c. From the image of the measurement area (Plate 1a) an identical region is extracted, Plate 1d.

Analysing the colorimetric image

The colour images that provide information on the current colour of the painting are acquired using the VASARI image processing system described in an earlier paper.[10] Recent improvements in the equipment and calibration procedures have increased the colour accuracy of the images used in this study.[11] First, an area on the colour image roughly corresponding to that covered by the 35mm negative is extracted from the image of the whole painting, Plate 1e. By selecting 'tie points' that appear on both this image and on the region extracted from the monochrome image (Plate 1d), the former is resampled to coincide exactly with the latter.[12] The resampled colour image is shown in Plate 1f.

The next step is to extract from the resampled colour image that region which corresponds to the area of the spot measured by the spectrophotometer. Two methods of extraction were investigated. In the first, a circular 'mask' is created, which has the same centre and diameter as the spot illustrated in Plate 1c. All the pixels within the circle have a value of one, while all those in the surrounding region are set at zero. This first mask is represented in Plate 1g (zero is represented as black and one as white). In the second method, the value of each pixel within the circular mask was determined by scaling the image of the spot to fit in the range zero to one. Plate 1h illustrates the second mask, which represents more accurately the distribution of the incident illumination during the original spectrophotometric measurement.

By combining the chosen mask with the extracted, resampled, colorimetric image and then averaging the CIE L^*, a^* and b^* values within that region, it is possible to calculate the current CIE L^*, a^* and b^* coordinates for the area studied previously with the spectrophotometer;[13] the result of combining the circular mask (Plate 1g) with the resampled colour image (Plate 1f) is shown in Plate 1i. Finally, the colour difference between the two measurements (spectrophotometer and imaging system) is calculated and expressed in the CIE units of colour difference, ΔE.[14]

A series of tests was conducted to assess the effect on the average colorimetric data of using the two types of mask described above to extract the information from the resampled colorimetric image. It was found that using a mask that simulated the exact shape of the spot measured by the spectrophotometer, shown in Plate 1h, produced results that were virtually indistinguishable from those produced using a mask in which the spot was simulated by a perfect circle, shown in Plate 1g.[15] Since the latter is more easily generated, we used a simple circular mask in all subsequent studies.

Results and discussion

During 1994 and 1995 a number of the paintings that had been measured with the spectrophotometer have been imaged colorimetrically with the VASARI system and the current colour compared with the Scientific Department's record of colour measurements in the 1970s and 1980s using the procedure outlined above.

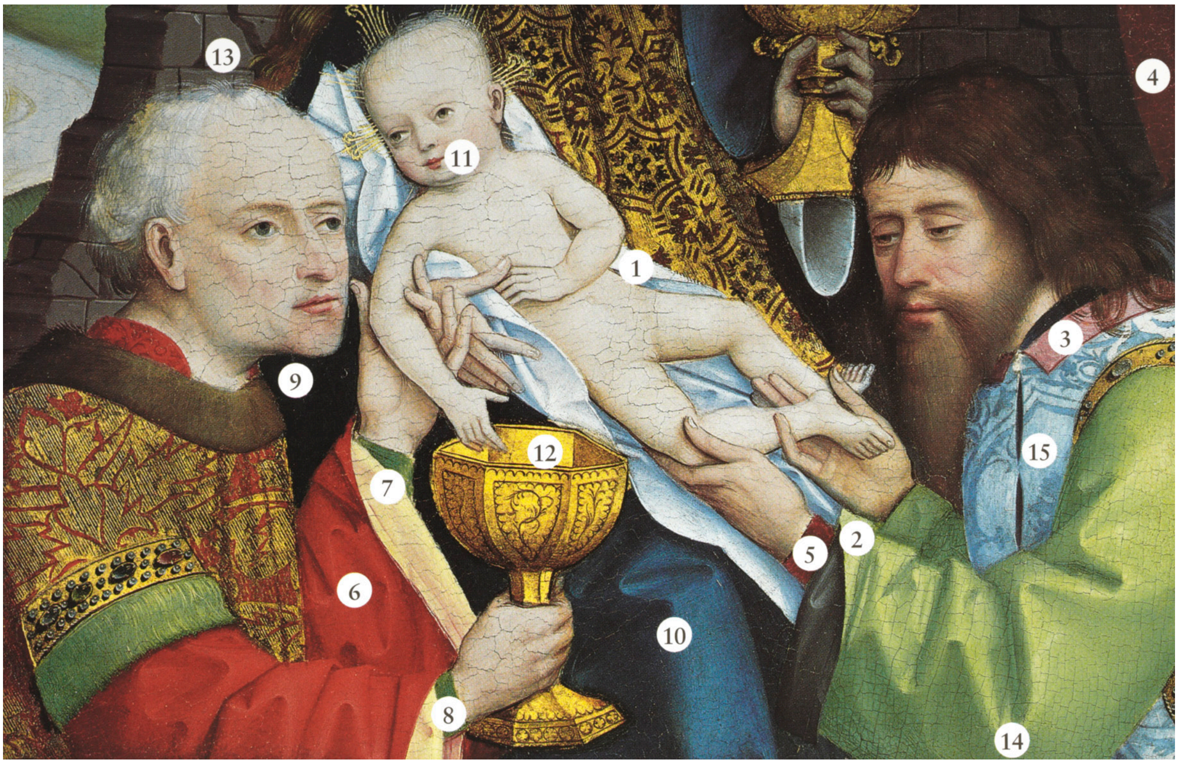

Plate 2 The Master of Liesborn, *The Adoration of the Kings* (NG 258). The areas on which colour measurements were made are indicated; the numbering corresponds to entries in Table 1.

Table 1 Colour and colour change data for the Master of Liesborn, *The Adoration of the Kings*

Point number and colour description	CIE Colour coordinates (1994)			Colour change from 1984 to 1994			
	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE
1. White	69.59	1.00	6.92	0.56	0.90	0.03	1.06
2. Pale green	58.38	–10.05	23.58	1.25	1.37	–1.19	2.20
3. Pink	45.60	20.91	5.60	1.13	–0.41	1.12	1.64
4. Crimson	7.78	34.59	8.42	–10.09	10.83	–1.44	14.87
5. Crimson	10.31	22.97	10.66	–6.98	5.82	2.89	9.53
6. Red	33.50	36.95	38.51	–1.24	4.70	9.72	10.87
7. Yellow	63.21	1.17	23.62	–0.53	–1.68	–3.09	3.56
8. Green	35.00	–16.73	21.60	–1.49	–0.94	2.91	3.40
9. Dark blue	6.63	–7.31	0.80	–7.85	–3.85	2.63	9.13
10. Blue	30.22	–9.36	–13.47	–1.14	–0.57	–0.43	1.35
11. Flesh	52.61	9.00	11.41	–0.17	1.21	0.23	1.25
12. Gold	61.49	7.06	43.45	–0.60	1.72	1.16	2.16
13. Red	34.06	7.02	6.75	–0.84	0.17	0.93	1.27
14. Green	41.14	–18.06	18.67	–3.00	–0.90	–1.38	3.42
15. Pale blue	55.91	–3.87	–3.40	–0.19	–0.33	–0.01	0.38

Colour difference data for the three paintings in which significant colour changes were detected are given in Tables 1 to 3. As the electronic imaging system has an accuracy of approximately 1.5–2.0ΔE units,[16] we have assumed, in the discussion below, that colour changes of less than 4.0ΔE units (twice the maximum error) are not significant, although we believe that some changes below this threshold are not attributable to experimental error. The majority of the areas studied showed colour differences of less than 4.0ΔE units, and often less than 2.0ΔE units, indicating no measurable colour change. For each painting for which data are tabulated there were, however, significant changes in one or more of the areas investigated, which we have attempted to describe and explain in the sections that follow.

The Master of Liesborn: *The Adoration of the Kings*

This painting is illustrated in Plate 2, which shows the areas at which colour measurements were made; the colour and colour change data are presented in Table 1. Only four of the fifteen areas studied show significant colour differences. Of these four, three (two areas of crimson and one of dark blue) have very low lightness, with an L* of *c.*10 or less. Several possible sources of error were investigated to determine whether this was purely coincidental. Colour change in only the dark areas suggested that perhaps the less rigid geometry of illumination used in the imaging system might cause some specular reflection to enter the camera. In the spectrophotometer, the angle of illumination is exactly 45° to the surface of the painting, while the lighting system in the imaging system is only approximately at this angle. The changes observed are not, however, consistent with such an effect. If specular reflection were present, an increase in lightness and a decrease in saturation (colourfulness) would be expected. It is clear that in this painting the colour change is characterised by decreased lightness and increased saturation. We believe that the reason for the colour differences for the very dark areas in this painting is light scatter within the camera optics. The calibration procedure for colorimetric imaging optimises the system for imaging a calibration target comprising the 24 patches of the Macbeth ColorChecker Chart, which have an average L* of 47.59. If there are particularly dark regions, as in this painting, there will be less scatter and the colours will appear darker and more saturated. At present we are attempting to model better the scattering effect so that we can compensate for this problem, which can afflict all imaging systems, electronic or conventional.

The fourth area, the red sleeve of the figure to the left (point 6), is much lighter and thus unlikely to be affected by the light scatter problem. This is borne out by the observation that the colour difference is largely due to changes in a* and b*. The main colour change in this area is an increase in b*, or an increased yellowness. No such change in b* is exhibited by any of the other areas of measurement suggesting that this is a localised yellowing and not an overall yellowing of the varnish. Why only this robe, which seems to be painted using vermilion with a red lake glaze in the shadows[17], should have yellowed is not clear.

The remaining eleven areas investigated show small colour differences, indicating that there are no other colour changes occurring in the painting. The absence of colour change in the pink collar of the king at the right is particularly interesting, as it seems likely that the same lake pigment that occurs in the two deep crimson areas (points 4 and 5) has also been used here, mixed with white.[18] Although the results for the two darker areas are inconclusive, due to the problems with colour measurement in the darker areas described above, it seems reasonable to conclude that these will not have not changed either, since it is known that mixtures with white are more prone to colour change than the pure lake.[19]

Corot: *The Roman Campagna, with the Claudian Aqueduct*

This painting is illustrated in Plate 3, which shows the areas at which colour measurements were made; the colour and colour change data are presented in Table 2. Some colour change was observed in the two green areas monitored and a smaller change in the dark purple area on the horizon, Plate 3. The two green areas show sizeable changes in b*, but in one case an increase and in the other a decrease. The two

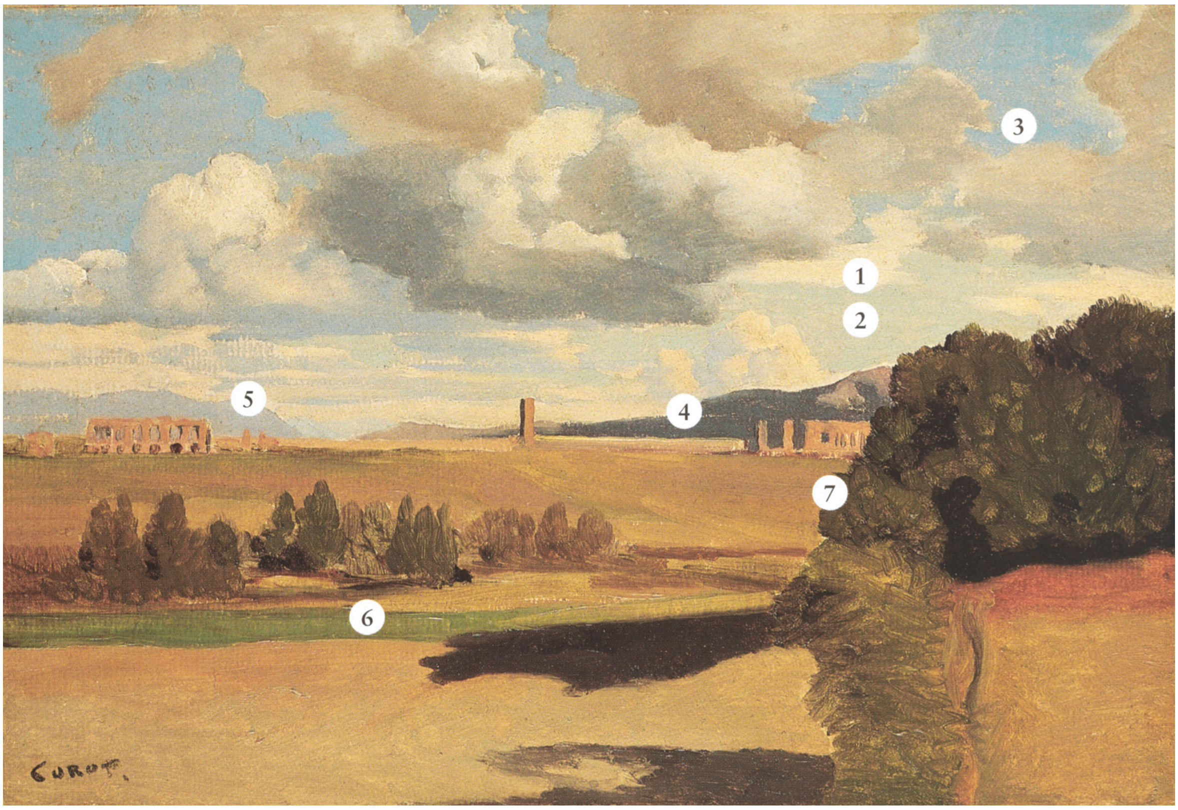

Plate 3 Jean-Baptiste-Camille Corot, *The Roman Campagna, with the Claudian Aqueduct* (NG 3285). The areas on which colour measurements were made are indicated; the numbering corresponds to entries in Table 2.

Table 2 Colour and colour change data for Corot, *The Roman Campagna, with the Claudian Aqueduct*

Point number and colour description	CIE Colour coordinates (1995)			Colour change from 1982 to 1995			
	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE
1. White	70.69	3.01	20.77	2.78	0.33	0.52	2.85
2. Turquoise	60.71	–4.05	11.87	1.09	0.58	0.03	1.23
3. Blue sky	51.13	–4.06	–4.89	1.09	1.54	–0.46	1.94
4. Dark purple	29.94	2.64	–5.47	–4.05	2.39	–1.00	4.81
5. Light purple	54.84	2.13	1.30	–0.57	1.64	0.84	1.87
6. Green	45.57	–3.56	14.45	2.17	0.00	–8.02	8.31
7. Green	28.12	–0.19	31.66	–5.82	0.23	11.34	12.75

areas are quite different and illustrate two of the problems which can arise when determining the exact position of the mask on the colour image.

First, some regions on each painting contain few distinctive features by which to make the image comparison between the extracts from the high-resolution image and the monochrome image of the 35mm negative. In such cases, including the uniform streak of green paint on which point 6 lies, it is difficult to determine the exact position of the spot. Fortunately, as these areas tend to be homogeneous, the need to locate the mask with high accuracy is less, and we have found that displacement of the spot by around 20% of its diameter produces little change in the average L*, a* and b* values.[20]

The second area (point 7), in a bush to the right of the painting is, like many areas studied, very inhomogeneous in colour. We therefore investigated the effect of displacing the mask from its calculated position by up to 20% of its diameter. None of the colour measurements for this painting, including those for point 7, showed any significant colour change when the spot was moved away from its calculated position.[21] Where small colour changes have been observed on shifting the mask, L^* was most affected with only small changes to a^* and b^*; that is, the lightness changed but the hue remained invariant.

Because of its small size we were able to examine the surface of the painting under the optical microscope at high magnification.[22] The purple paint comprises vermilion and cobalt blue, with some carbon black in the darker areas. It is conceivable that the colour change in this region has occurred because the vermilion component has darkened, but in view of the increase in redness (increase in a^*), this seems unlikely. We were concerned that this change might be due to another potential source of error in the calibration procedure. The figure quoted earlier for colour accuracy, 1.5 to 2.0ΔE units, is an average for the 24 patches in the Macbeth chart used in the calibration procedure. We were also concerned that although the average might be as low as 1.5ΔE units, the greatest colour difference for one individual patch might be considerably higher, implying that the colour accuracy of the image was poor for certain colours. We have therefore compared the colour difference data for each area that we believe has changed with the colour difference data for the Macbeth patch closest in colour to the area under investigation. In this painting the highest colour error for any of the individual patches was 2.6ΔE units, and the error for the purple Macbeth patch (closest in colour to the area under study) was only 0.9ΔE units.

Examination under the microscope revealed that the green paint comprises a stable inorganic green with varying amounts of a yellow earth pigment and carbon black. The mixture also contains some large translucent dull-yellow particles that may be a yellow lake pigment or another organic yellow. If such a lake pigment faded in the mixture, an increase in lightness and a decrease in yellowness might be expected, exactly as observed for the pale green streak at point 6.

Uccello: *Saint George and the Dragon*

This painting is illustrated in Plate 4, which also shows the areas at which colour measurements were made; the colour and colour change data are presented in Table 3. *Saint George and the Dragon* was one of the first paintings to be recorded by the colour measurement programme in 1974. Much interest centred on the area of grass at the lower edge that had been protected from light in the past by a frame rebate. As the painting has subsequently been framed in such a way as to expose this area to light, it is of concern to discover whether the then relatively unchanged area of 'copper resinate' at point 1 has now changed. The data in Table 3 indicate that this is one of the few areas of this painting where any significant change has occurred: there has been a slight decrease in lightness and a more marked increase in yellowness. Because this area of the painting depicts blades of grass, it is particularly inhomogeneous in colour. The position of the mask is, therefore, very important if a meaningful comparison is to be made. Displacing the mask, as described previously, results in little change in the value of Δb^*, but has rather more effect on the value of ΔL^* which can be as much as -2.98. The changes of colour observed are consistent with a shift from green towards brown in this region, but it remains for the future to see if this trend will continue.

Conclusions

In spite of the considerable differences between the two techniques for colour measurement, it has been possible to make meaningful comparisons between the colour data recorded up to twenty years ago using the spectrophotometer, and those being made today with the electronic imaging system. This is particularly important since there would be no way to replace the early data.

Several sources for potential error in the comparison process have been investigated and all except the problem associated with the measurement of very dark colours have been overcome satisfactorily. An improved calibration procedure, which compensates for light scatter when measuring dark colours, is being explored. As it is usually the lighter colours that

Plate 4 Paolo Uccello, *Saint George and the Dragon* (NG 6294). The areas on which colour measurements were made are indicated; the numbering corresponds to entries in Table 3.

Table 3 Colour and colour change data for Uccello, *Saint George and the Dragon*

Point number and colour description	CIE Colour coordinates (1995)			Colour change from 1974 to 1995			
	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE
1. Green	24.27	–3.76	18.06	–0.70	1.02	8.34	8.43
2. Brown	14.94	0.24	7.49	–3.65	0.10	2.51	4.43
3. Blue †	26.78	–8.49	–3.78	3.98	–2.40	–2.77	5.41
4. Pale blue †	43.10	–6.94	1.37	3.15	–1.22	1.13	3.56
5. Blue †	23.90	–9.62	1.13	0.21	–1.53	–0.25	1.56
6. Dark pink †	26.67	17.36	5.61	3.17	1.41	–1.28	3.70
7. Pale pink †	46.10	9.14	7.48	4.15	1.45	1.00	4.51
8. Red †	30.97	5.70	6.81	2.50	1.00	–0.89	2.83
9. Red †	32.06	25.51	23.58	0.87	3.29	4.36	5.53
10. White †	45.35	0.89	10.74	3.43	0.58	1.25	3.70
11. Green †	20.62	–4.27	17.71	–1.80	6.09	5.03	8.10
12. Beige †	38.75	5.91	5.30	3.30	2.81	0.13	4.34

† Area first measured in 1980. Colour change is for the period 1980 to 1995.

are most prone to colour change,[23] the lack of data for the dark regions of some paintings is not too serious.

In the majority of the paintings studied, no significant colour changes have been detected. In a few cases, some of the areas examined have shown differences in colour that might be explained by the presence of pigments known to be susceptible to colour change over time. In a final, very small group, are changes that cannot easily be attributed to known pigment alteration processes but which do not seem to be purely the result of experimental error.

A particular difficulty in trying to make comparisons with the data from the spectrophotometer is that each colour measurement corresponds to a single point. It is not possible to assess whether a change noted in one 4mm diameter region within a larger area of a single colour is a 'rogue' result, or reflects a change throughout the area painted with that pigment. When, in the future, colorimetric images of the painting are compared, this problem should be minimised as the area of paint will be covered by many thousands, or tens of thousands, of pixels, each of which will provide colour information.

The present study has provided information to bridge the old and new regimes for long-term colour measurement. The images we are recording now will provide our successors with a colour record with which to make comparisons in twenty years time, and meanwhile maintain continuity with the original spectrophotometric measurements made twenty years ago.

Acknowledgements

We are grateful to Ashok Roy, Marika Spring, Jo Kirby and Rachel Billinge for their observations on, and identification of the pigments in, Corot's *The Roman Campagna, with the Claudian Aqueduct* and *The Adoration of the Kings* by the Master of Liesborn. We would also like to thank Kirk Martinez of Birkbeck College, University of London, for his expertise, and assistance in digitising the 35mm negatives. The imaging systems and software described in this paper were developed in the European Community-funded ESPRIT projects VASARI (No. 2649) and MARC (No. 6937). Hélène Chahine, from the Ecole Nationale Supérieure Physique de Strasbourg, was a researcher in the Scientific Department during 1994–5.

Notes and references

1. M.P. Wassall and W.D. Wright, 'A special-purpose spectrophotometer', *Colour 73,* London 1973, pp. 469–71; G. Thomson, 'Current Researches on Colour Change in Paintings at the National Gallery, London', *Preprints of the International Council of Museums Committee for Conservation,* 4th triennial meeting, Venice 1975, 75/19/1.
2. The long-term monitoring of paintings using the Wright-Wassall spectrophotometer was first reported in L. Bullock, 'Reflectance Spectrophotometry for Measurement of Colour Change', *National Gallery Technical Bulletin,* 2 , 1978, pp. 49–55.
3. D. Saunders, 'The Measurement of Colour Change in Paintings', *European Spectroscopy News*, 67, 1986, pp. 10–18.
4. The stages of development of the programme of long-term monitoring of paintings by image processing are described in G. Thomson and S. Staniforth, 'Identification and Measurement of Change in Appearance by Image Processing', in *Science and Technology in the Service of Conservation*, eds. N.S. Brommelle and G. Thomson, London 1982, pp. 159–61; D. Saunders, 'Colour Change Measurement by Digital Image Processing', *National Gallery Technical Bulletin*, 12, 1988, pp. 66–77, and D. Saunders and J. Cupitt, 'Image processing at the National Gallery: The VASARI project', *National Gallery Technical Bulletin,* 14 , 1993, pp. 72–85.
5. H. Chahine, J. Cupitt, D. Saunders and K. Martinez, 'Investigation and modelling of colour change in paintings during conservation treatment', in *Imaging the Past*, British Museum, Occasional Paper 114, eds. T Higgins, P.L. Main and J.L. Lang, London 1996.
6. A study of the changes in colour shown by a number of textiles during three months on display in a temporary exhibition is described in B.L. Ford, 'Monitoring Colour Change in Textiles on Display', *Studies in Conservation*, 37, 1992, pp. 1–11.
7. The Getty Conservation Institute have measured the colour of a number of areas at the surface of the wall paintings in the tomb of Nefertari before and after restoration. It is proposed that the same areas be monitored periodically in the future, see M. Schilling, 'The Color Measurement Program in the Tomb of Nefertari' in *Art and Eternity: The Nefertari Wall Paintings Conservation Project 1986–1992*, eds. M.A. Corzo and M. Afshar, Los Angeles 1993, pp. 83–93; and M.R. Schilling, 'Color Measurement

of the Wall Paintings in the Tomb of Nefertari', *Preprints of the International Council of Museums Committee for Conservation,* 10th triennial meeting, Washington DC 1993, pp. 42–9.
8. The CIE colour coordinates L*, a* and b* correspond to three attributes of a colour. L* represents the lightness of a colour on a scale from 0 (black) to 100 for a pure white. The a* coordinate represents a red-green scale. A positive value for a* indicates redness, while a negative value symbolises greenness. In the same way, b* is a yellow-blue scale with positive values of b* signifying yellowness. See Commission Internationale de l'Eclairage, 'Recommendations on uniform color spaces, color difference equations, psychometric color terms', Supplement No.2 to *CIE Publication No. 15 (E–2.3.1), 1971/(TC–1.3)* (1978).
9. See notes 2 and 3.
10. See D. Saunders and J. Cupitt, 'Image processing at the National Gallery: The VASARI project', cited in note 4.
11. Since the electronic imaging system was first described in D. Saunders and J. Cupitt, 'Image processing at the National Gallery: The VASARI project', cited in note 4, a 12-bit camera has been installed which has improved the signal to noise ratio in the images. This, combined with a more efficient method for determining the white and black points for the image, has resulted in much greater colour accuracy in the final images. The average colour accuracy, calculated from the colour differences between measured and actual colours for the 24 colours in the Macbeth ColorChecker Chart, is now in the region of 1.5 – 2.0ΔE units.
12. The resampling is achieved by selecting matching points on the monochrome and colour images using a process analogous to that described in D. Saunders and J. Cupitt, 'Elucidating Reflectograms by superimposing Infra-red and Colour Images', *National Gallery Technical Bulletin,* 16, 1995, pp. 61–5. Although the correlation between the two images is often poor, making the selection of tie-points difficult, the accuracy required in this step is not great, since average colour values are to be calculated after resampling.
13. The circular mask generally contains around 1500 pixels. The L*, a* and b* values of the corresponding pixels in the resampled colour image are summed and divided by the number of pixels in the mask to give average L*, a* and b* values. When using a mask that simulates the shape and lightness of the spot, the L*, a* and b* values in the colour image are weighted using the corresponding pixel in the mask. The weighting is taken into account when calculating the average colour coordinates.
14. Values of colour difference, ΔE, were calculated using the method described in British Standard 6923:1988, *British Standard method for calculation of small colour differences*, British Standards Institution, Milton Keynes 1988.
15. For example in *The Adoration of the Kings* by the Master of Liesborn the CIE data determined for point 1 on Plate 2 using a circular mask were: L* = 69.68, a* = 0.39, b* = 6.50. The corresponding data for the mask which reflects the shape of the spot were: L* = 70.10, a* = 0.44, b* = 6.92. The equivalent data for point 2, the point used as an example in Plate 1, were, circular mask: L* = 58.69, a* = –9.90, b* = 23.46, spot mask: L* = 58.03, a* = –10.07, b* = 23.34.
16. See note 11.
17. Examination of the robe to the left of *The Adoration of the Kings* by the Master of Liesborn under magnification suggested that the main pigment was vermilion. No sample was taken to confirm this identification. In the shadows a red lake glaze has been used, but measurement point 6 does not lie in an area to which such a glaze has been applied.
18. High-performance liquid chromatography was used to examine red lake samples from a number of the fragments from the dismembered altarpiece from the Benedictine Abbey at Liesborn (NG 256–261). Where dyestuff identification was possible, madder lake was found. See the article 'The Identification of Red Lake Pigment Dyestuffs and a Discussion of their Use' in this *Bulletin.*
19. D. Saunders and J. Kirby, 'Light-induced Colour Changes in Red and Yellow Lake Pigments', *National Gallery Technical Bulletin,* 15, 1994, pp. 79–97.
20. For the relatively homogeneous green area at point 6 on *The Roman Campagna, with the Claudian Aqueduct* by Corot the measured differences were: ΔL* = 2.17, Δa* = 0.00, Δb* = –8.02. Shifting the circular mask by up to 20% of its diameter gave minimum values of: ΔL* = 2.17, Δa* = –0.59, Δb* = –8.00.
21. For the inhomogeneous green bush at point 7 on *The Roman Campagna, with the Claudian Aqueduct* by Corot the measured differences were: ΔL* = –5.82, Δa* = 0.23, Δb* = 11.34. Shifting the circular mask by up to 20% of its diameter gave minimum values of: ΔL* = –3.57, Δa* = 0.06, Δb* = 11.34.
22. Examination of cross sections under the microscope by Ashok Roy confirmed the pigment identifications made when examining the painting under high magnification.
23. See note 19.