IIC

TRADITION AND INNOVATION
ADVANCES IN CONSERVATION

Contributions to the Melbourne Congress
10-14 October 2000

RECENT APPLICATIONS OF DIGITAL IMAGING IN PAINTING CONSERVATION: TRANSPORTATION, COLOUR CHANGE AND INFRARED REFLECTOGRAPHIC STUDIES

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ABSTRACT

In recent years digital imaging has proved to be a useful tool for documenting and examining paintings. These techniques can yield permanent records that are potentially more accurate than photographic images. The key applications in which digital imaging is superior to other techniques are those where short- or long-term changes are measured. The paper describes the imaging systems developed in a ten-year collaboration between the National Gallery, London and the Doerner-Institut, Munich and the geometric transformation algorithms which have allowed accurate comparisons of 'before' and 'after' images to be made. Recent results obtained from a long-term study of colour changes caused by display in the museum and short-term changes caused by transportation to loan exhibitions are presented. Improvements made to the procedure for acquiring, processing and presenting infrared reflectogram mosaics are also detailed. Finally, other conservation-related and archival uses for the colour-accurate, high-resolution digital images are discussed.

INTRODUCTION

In the four decades since the IIC Rome Conference the increased use of computers and their greater sophistication has opened new possibilities for the application of digital imaging in conservation. To date, there have been examples of successful applications of imaging techniques in documentation and examination of works of art. However, many of those applications lack convincing advances over existing, traditional methods. For example, there are instances of image-processing algorithms being used to enhance visibility in very poor quality X-radiograph images when a new exposure could have been made, expending less time and resources. During our research and subsequent work we have noticed that not only does digital imaging allow permanent records of a work of art to be made that are potentially more accurate than photographs but that, even more importantly, these can act as a 'baseline' against which to compare images of the same object made at a later date. This comparison has proved to be the key application for digital imaging, which cannot easily be accomplished by the human eye or other conventional methods. To realize this potential the National Gallery, London and the Doerner-Institut, Munich have collaborated for more than a decade in the development of high-resolution digital imaging systems and their application to painting conservation issues [1], particularly long-term changes caused by display and short-term changes caused by transportation to loan exhibitions or conservation treatment.

Before such studies were possible, a method of obtaining accurate, reproducible images of paintings was needed. Until recently, no commercially-available camera was capable of producing images of sufficient quality to allow such comparisons between different 'states' of a painting to be made; one example is the condition of an object before and after transportation. It became clear that the first stage of the project would be the design and building of an imaging system.

DEVELOPMENT OF IMAGING SYSTEMS IN LONDON AND MUNICH

Two imaging systems have been developed as a result of our collaboration, each named after the European Community supported project out of which they arose. Here we provide brief descriptions, as more details have appeared in previous publications.

VASARI

The VASARI (Visual Arts: System for Archiving and Retrieval of Images) imaging systems were constructed in London and Munich between 1989 and 1992 to allow images of paintings to be made with a resolution of up to 20 pixels per millimetre on the painting surface [2]. In essence, the systems in each city are the same, but they differ in appearance as some of the bulkier components were purchased locally; the Munich scanner is built from modular components used in industrial robotic applications, which allow the system to be configured rapidly for different applications [3]. In both systems, paintings are placed on a rigid easel and images are made by moving a camera across a plane parallel to the painting surface using the accurate mechanical positioning (robotic) system. Depending on the application, the camera can be either a monochrome digital camera or an infrared Vidicon system. To obtain sufficient resolution, images are made of a small portion of the painting; these sub-images are calibrated, corrected and assembled into an image of the whole painting [3, 4], rather like the tiling on a bathroom wall.

In the London system, colour information is obtained by making a series of images of each sub-area while illuminating the surface with light transmitted by one of a series of broad-band interference filters; typically seven bands, from 400 (violet) to 700nm (red) are used. Calibration targets allow accurate colour measurements to be derived from the seven-band data. The colour information is stored as standard CIE L* a* b* colour co-ordinates [5], although the seven-band data are also archived. Colour accuracy is determined by comparing the colour data obtained from measuring a set of 24 colour standards with their absolute colour data, measured spectrophotometrically. Initially, the average error in the colour measurements over these 24 samples was around 2.3 ΔE^*_{ab} units (roughly one ΔE^*_{ab} unit corresponds to a just-visible difference), but refinements in the calibration process over 10 years have reduced this to 1.1 ΔE^*_{ab} unit. The main drawbacks of the VASARI systems are that they are more or less immovable once installed and can only measure smaller paintings (up to 1350 × 960mm), although the system in Munich has been used to image larger paintings, such as the two panels of Dürer's *Vier Apostel* (Bayerische Staatsgemäldesammlungen, Munich Nos. 545 and 540) each measuring about 212 × 76cm, by twice changing the position of the painting on the easel. The final infrared image of each painting comprised around 600 single frames [6, 7].

MARC

The MARC (Methodology for Art Reproduction in Colour) camera effectively combines the VASARI scanner and its camera into a single compact unit. It was developed during the eponymous project from 1993 to 1996, is portable and, with appropriate optics, can image paintings of any size [8]. In the MARC camera, a colour image is made in a single long exposure, during which the charge-coupled device (CCD) sensor is translated in two dimensions across the focal plane. The photosensitive sites on the CCD are masked with red, green or blue filters, allowing colour information to be derived from the raw camera data. A colour target and a calibration process similar to that used in the VASARI system allow accurate colour data to be obtained. Initially, the colour error of the MARC camera was of the order

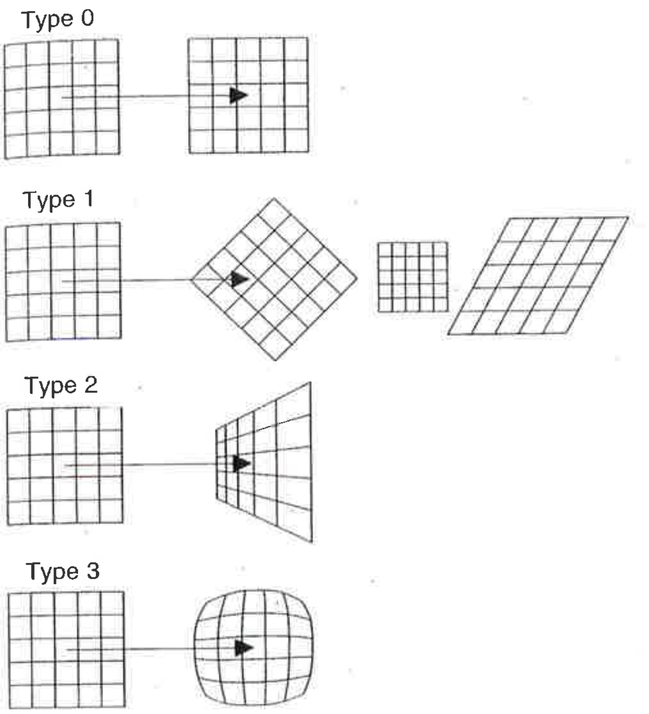

Fig. 1 Types of geometric distortion. Type 0 – translate, $x' = x + c_1$. Type 1 – rotate, scale, skew, $x' = x + c_1 + c_2x + c_3y$. Type 2 – perspective, $x' = x + c_1 + c_2x + c_3y + c_4xy$. Type 3 – barrel, pincushion, $x' = x + c_1 + c_2x + c_3y + c_4xy + c_5xx + c_6yy$.

of 3 ΔE^*_{ab} units, but this has recently been reduced to *c.* 2 ΔE^*_{ab} units, principally by the introduction of new HMI (halide metal inert gas) light sources for imaging.

IMAGE CORRECTION AND COMPARISON

Equipped with imaging systems that can provide high-resolution images with accurate colour, it has been possible to examine short- and long-term changes in paintings associated with periods on display, transportation to exhibitions and conservation treatment. An essential part of such comparisons is a method of bringing the 'before' and 'after' images into exact superposition; memory alone, or comparison of 'before' and 'after' photographs, are not adequate for such a task.

There are two principal causes of geometric differences between 'before' and 'after' images. First, changes in the imaging equipment and the imaging set-up, which cause differences in scale, rotation and perspective created by slight differences in angle between the painting surface and camera focal axis during discrete imaging sessions. The second cause of geometric differences is change in the object, for example warping caused by variation in relative humidity. We have described previously a simple method by which images may be brought into superposition using translation and scaling alone [9]. In the studies reported here we have used a more sophisticated second-order 'rubber sheeting' technique to transform one image to ensure correlation with a second.

Figure 1 shows a classification of types of geometric distortion: types 0, 1 and 2 are typically caused by acquisition errors, while type 3 or higher changes are usually associated with a change in the object. Higher order corrections have not been used, as we must compromise between the need to correct for differences in image acquisition parameters, and the possibility of removing relevant alterations in the geometry of the object.

Once a type of geometric change has been chosen which will bring two images into alignment, the problem is to determine parameters for the model. For a type 2 transformation, for example, eight constants must be calculated, c1 to c4 for both *x* and *y* directions (Fig. 1). Values must be selected that minimize average differences between the two images over the whole of their surfaces, which can be a very time-consuming problem, typically requiring the selection of many tie-points. Fortunately, if the images being compared are sufficiently similar, it is possible to use entirely automatic procedures to derive the parameters to a high degree of accuracy [10]. This automatic procedure has made it possible for us to compare very large images taken many years apart.

The procedure has some limitations. The transformation cannot be applied to pairs of images that have very different content, for example an image of a painting and its X-radiograph, and, as mentioned above, may compensate for certain changes, such as deformation of a stretcher during transportation, that are not due simply to differences in the image acquisition geometry.

Table 1 Paintings for which colour change analysis has recently been conducted.

Painting[(a)]	*First imaged*
Workshop of Campin, *The Virgin and Child in an Interior*, NG No. 6514	May 1993
Master of Liesborn, *The Adoration of the Kings*, NG No. 258	March 1994
Van der Weyden, *The Magdalen Reading*, NG No. 654	February 1995

(a) NG No. is the National Gallery, London, acquisition number.

CONSERVATION APPLICATIONS

Colour difference

The digital imaging techniques developed in the VASARI project are designed to allow the detection of differences in colour between two images, so that any long-term colour changes can be detected in paintings imaged at different times. The project is the successor to previous spectrophotometric [11] and image-processing methods of detecting colour changes [12, 13]. In an interim study, colour information from the VASARI scanner was compared with that from spectrophotometric measurements made in the 1980s; no changes were detected in the colour of the paintings examined [14]. Now that some years have passed since the first VASARI colour images were made [15], meaningful comparisons between images can be made.

The type 2 transformation has been used to bring images made in 1999 into superposition with those made earlier in the decade (Table 1). Once the images coincide, the colour difference (ΔE^*_{ab}) between individual pixels can be determined using a simple colour difference equation (a process described in more detail elsewhere [4]):

$$\Delta E^*_{ab} = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{0.5}$$

where ΔL^*, Δa^* and Δb^* are the differences in the values of L^*, a^* and b^* stored for the 'before' (*c.* 1994) and 'after' (1999) images. The ΔE^*_{ab} values can be presented as a scaled monochrome image, in which white areas represent the largest changes in colour and black areas indicate that no change has occurred.

One example has been chosen to illustrate our findings. The image in Figure 2a is such a monochrome representation, showing colour differences between the images of *The Virgin and Child in an Interior* by the workshop of Campin, made in 1993 and 1999; for reference, the image made in 1999 is shown in Figure 2b. The average colour change across the whole image has not been calculated, as there are some differences between the images, explained below, that would render this figure meaningless. Instead, the average colour difference has been examined in small, representative regions to establish whether any changes have occurred to particular pigments or pigment mixtures. This analysis indicates that there are no significant changes in colour that can be attributed to colour alterations in the painting. In particular the cushion to the right of the painting, which contains

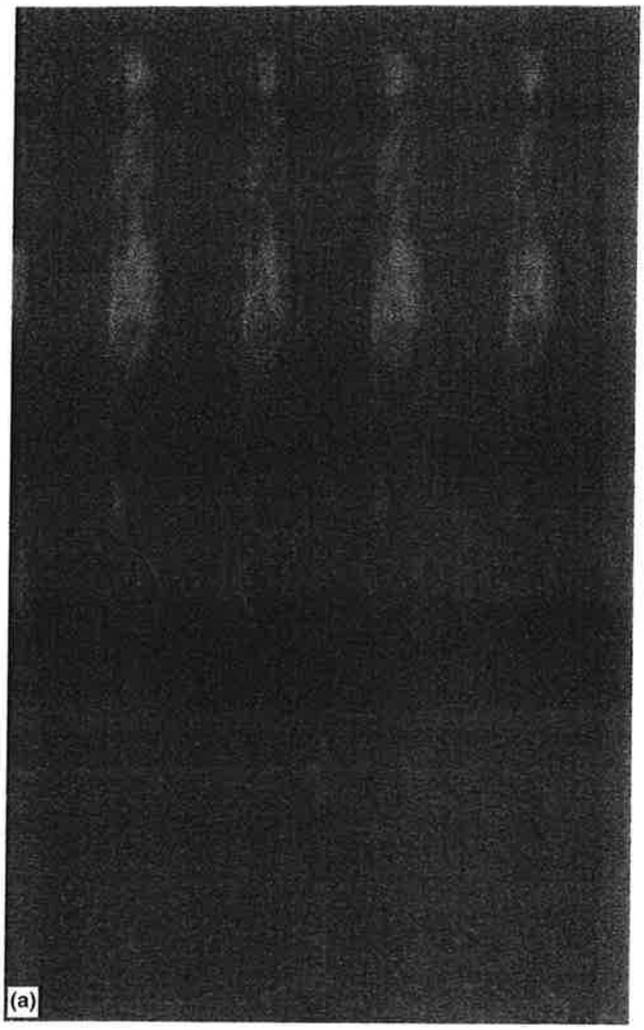

Fig. 2 (a) Colour difference image for *The Virgin and Child in an Interior* from the Campin workshop. (b) Black-and-white rendering of the colour image of the painting made in 1999. Both are low resolution versions of the original images.

a red lake pigment, shows no fading. This is reflected in the overall darkness of the difference image.

There are, however, some light areas in the difference image. Five common sources for these features have been identified:

1. The accuracy of the type 2 transform has limits, so that some small differences due to image misalignment are observed; these features generally occur along high contrast edges, so their source is usually obvious.
2. At the left and right edges of the painting are regions of greater difference. This painting has an integral frame and shadows from the light sources are inevitable. Slight differences in lighting in 1993 and 1999 are responsible for these 'shadows'.
3. Slight differences in the lighting angle can create specular reflections in one of the images. These appear as very light areas in the difference image, for example at the edge of the fabric hanging above, and to the right of, the Virgin's head.
4. Small dust particles or fibres attach themselves to the painting or are lost during time, which show up as changes in the difference image.
5. Optical flare has already been identified as a major factor when comparing images made with a digital camera [14]. Although not apparent in the difference image for *The Virgin and Child in an Interior*, problems with flare were noticed when making the image comparison for *The Adoration of the Kings* by the Master of Liesborn.

The results presented here confirm that flare, shadow and gloss must be considered carefully during image acquisition. Since the interim study that highlighted the problems of flare, measures have been taken to eliminate this effect, using an extra calibration step. The images made in 1993–95, used for comparison here, were made before this additional calibration was available, rendering direct comparison of the dark areas of some of the paintings more difficult. In the future, comparisons between flare-free images should make colour difference assessments more straightforward. Although no significant colour changes have been detected in the paintings examined to date, a programme of continuing measurement is in place.

Transportation damage

Another core objective in building the VASARI scanners was to allow images to be made before and after paintings were transported to exhibitions. A general description of the methodology used in these studies has been given elsewhere [3]. These first applications showed that the technique had great potential for detecting alterations in the condition of paintings under study. Works of art by Kirchner, Sisley, Memling, Marc, Degas and Nolde have already been monitored [16–18]. Here we report further case studies, some advances in the techniques employed, and an interim appraisal of our approach.

Compared to the studies published so far, the main technical

Table 2 Paintings for which transportation damage analysis has recently been conducted.

Painting[a]	Dust particles	Displacement parallel to surface		Displacement perpendicular to surface	Artefacts[b]
		At canvas edge	Not at edge		
Cézanne, *Selbstbildnis*, canvas, BSTG No. 8648	20	6			1
Cézanne, *Stilleben mit Kommode*, canvas, BSTG No. 8647	99	11	1	1	2
Cross, *Küstenlandschaft*, canvas, BSTG No. 8657	5	14	1	1	8
Daumier, *Don Quixote*, canvas, BSTG No. 8698	53	18			4
Gauguin, *Bretonische Bäuerinnen*, canvas, BSTG No. 8701	9	8	8		16
Guillaumin, *Gebirgige Landschaft*, canvas, BSTG No. 8700	2	20			

(a) BSTG No. is the Bayerische Staatsgemäldesammlungen, Munich, inventory number.
(b) Includes changes due to altered gloss, shadow and other technical reasons.

improvements arise from the use of the rubber-sheeting algorithm to compare images made before and after transportation, as well as the use of the high-resolution MARC camera to make images of some of the paintings examined. The methods for acquisition and computer-aided comparison, given previously [3], have been made faster, and the technical difficulties experienced during data capture and image processing have been overcome.

The logistics of a comprehensive monitoring programme dictate that not all of the paintings owned by the Bayerische Staatsgemäldesammlungen, Munich on loan each year (around 400) can be assessed. New case studies are reported in Table 2. The changes noted can be divided into several categories, ranging in severity from loss or gain of dust particles on the painting surface (as found in the colour change study) to displacement of paint particles. Most of the displacements occur at or near the edge of the painting; canvas fibre deformations also occur near the edge of the painting.

As in our colour change study, alterations in shadow and gloss create artefacts that produce differences that are clearly not attributable to physical changes. A more severe problem is that experience suggests that three-dimensional changes, such as blisters and loosening of tiny particles, are hardly detectable. In addition, the application of the rubber-sheeting algorithm improves image registration, but makes it extremely difficult to detect any deformation of the stretcher, and hence of the canvas, that might be caused by transportation or by climate changes. The detection of dust on the surface, here and in the colour change study, is, however, indicative of the overall sensitivity of the methods applied. As pointed out in the introduction, the main advantage of the procedure lies in the computer-aided comparison of two images; the digital techniques are clearly superior to a simple comparison by eye. Physical changes are mainly located at the edges, which confirms our expectations. In Gauguin's *Bretonische Bäuerinnen*, the extremely brittle layers may have contributed to the high proportion of changes in the central part of the painting, underlining the risks associated with transportation.

Improved infrared images

Since the early 1960s, infrared reflectography has proved itself an invaluable tool in non-destructive investigation of paintings. Major technical improvements to the method were made only in the late 1980s. Some groups focused on replacement of the Vidicon (lead sulphide) detector by solid state infrared-sensitive arrays [19, 20], while we have concentrated on improving the image quality of the commonly-used Hamamatsu infrared Vidicon system by digital image processing. From the outset, it was clear that the VASARI system could play an important part in these technical developments. In Munich, each component of the infrared reflectography set-up was analysed individually [21], leading to the first fully automatic acquisition of a reflectogram mosaic image of a painting by Johann Georg von Dillis. In London, new software was developed to improve the reflectogram mosaic assembly procedure [22]. Following earlier non-destructive spectroscopic differentiation of drawing inks [23–25], a system for multichannel imaging spectroscopy, based on the VASARI scanner, was developed [26–28].

Most effort was, however, devoted to improving the quality of digital infrared reflectograms. In Munich, the signal-to-noise ratio of the Vidicon camera has been improved by cooling the sensor with Peltier elements and by averaging each frame 32 times over a period of around 35 seconds; the resulting signal contains 7.5 bits of information and is digitized to 8 bits. Further corrections compensate for 'ghost image' effects of the Vidicon tube, dark current leakage, and inhomogeneity in the lights, optics and sensor, including gamma differences across the sensor surface. Some of these innovations have also been implemented in London.

Geometric distortions, mainly from the sensor itself, but also from the optics and focal plane misalignment, are corrected using the second-order (type 3) transformation described above. In this case, the 'before' and 'after' images are a synthetic image of a regular grid and the image of an identical grid made with the Vidicon camera under exactly the same conditions that will be used to acquire the infrared reflectograms. The parameters generated by this transformation are applied during the acquisition to correct individual frames. Finally, the lightness of each single frame is adjusted by an iterative process, which minimizes the difference between all the sub-images before the final mosaic assembly is made.

The image acquisition, correction and assembly are fully automated. In addition to storing the infrared data archivally on CD-ROM and DAT (digital audio tape), black-and-white photographic negatives are made from the digital information. Negatives and life-size prints have been made of the infrared reflectograms of some paintings to assist in art-historical study, technical examination and conservation treatment. For books and catalogues, infrared reflectograms can be reproduced either from the photographic negatives or directly from the digital data (Fig. 3). Recent examples include monographs on Lucas Cranach the Elder [29, 30] and Albrecht Dürer [6], and a catalogue of fifteenth-century Netherlandish paintings [31].

Conservation documentation

As a side-effect of long-term colour measurement and condition assessment before and after transportation, paintings are being

Fig. 3 Digital infrared reflectogram of *Die Heilige Familie mit Johannes dem Täufer, Elisabeth und zwei Engeln* by Andrea del Sarto (poplar, 137 × 104cm, Bayerische Staatsgemäldesammlungen, Munich Inv. No. 501). The image consists of 575 sub-images; for further details of the experimental conditions see [21].

Fig. 4 (a) A region of the image of *The Virgin and Child* by Jan Gossaert before cleaning. (b) Same region after cleaning, re-sampled to coincide with area (a). (c) Colour difference image created from comparison of images (a) and (b).

imaged colorimetrically at a resolution of around 15 pixels per millimetre. These digital VASARI or MARC images can replace conventional photographs and may be exploited for other purposes. From a preventive conservation point of view this is an important spin-off, as their permanence reduces the number of occasions on which paintings, particularly those that are in greatest demand, need to be taken off display for photography and exposed to the risk associated with unframing and transportation within the museum.

High-resolution images are also being made of paintings at each stage of a conservation treatment. These not only provide an irreplaceable and immutable record of the state of a painting before cleaning, but also allow comparisons to be made between colour before and after cleaning [32]. Figures 4a and 4b show corresponding details from the high-resolution images of *The Virgin and Child* by Jan Gossaert (National Gallery, London, No. 1888) acquired before and after the recent cleaning that revealed this painting to be the work of Gossaert, rather than a seventeenth-century copy as had been thought previously [33]. The image of the painting before cleaning provides evidence of the disfiguring craquelure that led to the misinterpretation of its age; this is particularly obvious in the flesh-coloured passages. The image in Figure 4b has been re-sampled using the rubber-sheeting technique so that it coincides exactly with that in Figure 4a. These two images can therefore be used to produce a colour difference image, using the same technique as applied to images when assessing long-term colour change. Figure 4c illustrates this colour difference image. The dark areas indicate that little or no colour change has occurred, while the white areas indicate changes in colour during cleaning. Changes due to the removal of the old varnish and craquelure can be seen. Particularly striking are the white areas on the Virgin's shoulder, where part of her garment was previously obscured, and in Christ's outstretched hand, whose gesture had been altered in an earlier restoration.

CONCLUSIONS

The VASARI and MARC projects have led to the production of permanent, accurate, high-resolution digital images suitable for a number of conservation-related and archival programmes [34–36]. The quality of these images, combined with type 2 transformation algorithms, has allowed the condition of paintings to be compared before and after conservation treatment, transportation on loan and long-term display, as well as improving the quality of infrared reflectogram mosaic images. By virtue of their high resolution and excellent colour quality, MARC images have also been used in publishing catalogues and prints; the first of these was a catalogue of Flemish Baroque painting [37]. Technical details of the methods used for colorimetric printing of digital images have also been published [38–40]. More recently, we have used calibrated, large-format printers to produce colour-accurate life-size prints of paintings to act as reference images during conservation treatment, a programme that will be described in more detail in due course.

ACKNOWLEDGEMENTS

The VASARI and MARC projects were partly funded by the European Commission (ESPRIT Nos. 2649 and 6937). Work in Munich on imaging spectroscopy and infrared reflectography has been funded by the Bundesministerium für Forschung und Technologie (03-BU9MUE). Studies of colour change in London have been supported by an external grant from Hewlett Packard Laboratories. We acknowledge the support of our many colleagues in the VASARI and MARC projects, many of whom appear in the reference list.

REFERENCES

1 Burmester, A., 'Zehn Jahre digitale Bildverarbeitung in der musealen Anwendung', *Proceedings of the Electronic Imaging and the Visual Arts EVA*, Berlin (1998) VI; *Jahresbericht der Bayerischen Staatsgemäldesammlungen*, Munich (1998) 25–33.

2 Burmester, A., Cupitt, J., Derrien, H., Dessipris, N., Hamber, A., Martinez, K., Müller, M., and Saunders, D., 'The examination of paintings by digital image analysis' in *3rd International Conference on Non-Destructive Testing, Microanalytical Methods and Environmental Evaluation for Study and Conservation of Works of Art*, Viterbo (1992) 201–214.

3 Burmester, A., and Müller, M., 'The registration of transportation damages using digital image processing', *Zeitschrift für Kunsttechnologie und Konservierung* 6 (1992) 335–345.

4 Saunders, D., and Cupitt, J., 'Image processing at the National Gallery: the VASARI project', *National Gallery Technical Bulletin* 14 (1993) 72–85.

5 'Recommendations on uniform colour spaces, colour difference equations, psychometric colour terms', Supplement No. 2 to *CIE Publication No. 15 (E-2.3.1), 1971/(TC-1.3)*, Commission Internationale de l'Eclairage (1978).

6 Goldberg, G., Heimberg, B., and Schawe, M., editors, *Albrecht Dürer — Die Gemälde der Alten Pinakothek*, Munich (1998).

7 Burmester, A., 'Dürer durchleuchtet' in *Albrecht Dürer — Die Gemälde der Alten Pinakothek*, ed. G. Goldberg, B. Heimberg and M. Schawe, Munich (1998) 120–125.

8 Cupitt, J., Martinez, K., and Saunders, D., 'A methodology for art reproduction in colour: the MARC project', *Computers and the History of Art* 6 (1996) 1–20.

9 Saunders, D., and Cupitt, J., 'Elucidating reflectograms by superimposing infra-red and colour images', *National Gallery Technical Bulletin* 16 (1995) 61–65.

10 Lenz, R., *Ein Verfahren zur Schätzung der Parameter geometrischer Bildtransformationen*, Nachrichtentechnische Berichte Bd. 15, Technical University, Munich (1985).

11 Bullock, L., 'Reflectance spectrophotometry for measurement of colour change', *National Gallery Technical Bulletin* 2 (1978) 49–55.

12 Thomson, G., and Staniforth, S., 'Identification and measurement of change in appearance by image processing' in *Science and Technology in the Service of Conservation*, IIC, London (1982) 159–161.

13 Saunders, D., 'Colour change measurement by digital image processing', *National Gallery Technical Bulletin* 12 (1988) 66–77.

14 Saunders, D., Chahine, H., and Cupitt, J., 'Long-term colour change measurement: some results after twenty years', *National Gallery Technical Bulletin* 17 (1996) 81–90.

15 Martinez, K., Cupitt, J., and Saunders, D., 'High resolution colorimetric imaging of paintings', *Proceedings of the Society of Photo-Optical Instrumentation Engineers* 1901 (1993) 25–36.

16 Burmester, A., Müller, M., and Schwemer, F., 'Locating transportation damages by digital imaging: two case studies' in *ICOM Committee for Conservation 10th Triennial Meeting*, Washington DC (1993) 401–405.

17 Müller M., and Burmester, A., 'Registration of transportation damages using a high resolution CCD camera', *Proceedings of the International Society for Optical Engineering* 1987 (1993) 111–117.

18 Burmester, A., and Wei, W., 'All good paintings crack: non-destructive analysis of transport damage of paintings using digital image processing' in *Proceedings of the 4th International Congress on Non-Destructive Testing of Works of Art*, Berlin (1994) 114–126.

19 Walmsley, E., Fletcher, C., and Delaney, J., 'Evaluation of system performance of near infrared imaging devices', *Studies in Conservation* 37 (1992) 120–131.

20 Bertani, D., Cetica, M., Poggi, P., Puccioni, G., Buzzegoli, E., Kunzelman, D., and Cecchi, S., 'A scanning device for infrared reflectography', *Studies in Conservation* 35 (1990) 113–116.

21 Burmester, A., and Bayerer, F., 'Towards improved infrared-reflectograms', *Studies in Conservation* 38 (1993) 145–154.

22 Billinge, R., Cupitt, J., Dessipris, N., and Saunders, D., 'A note on an improved procedure for the rapid assembly of infrared reflectogram mosaics', *Studies in Conservation* 38 (1993) 92–98.

23 Burmester, A., and Renger, K., 'Neue Ansätze zur Erforschung von Handzeichnungen: Untersuchung der "Münchner Rembrandt-Fälschungen" im Nahen Infrarot', *Maltechnik/Restauro* 92(3) (1986) 9–34.

24 Renger, K., and Burmester, A., 'The Munich Rembrandt forgeries reconsidered: a new technical approach to the investigation of drawings', *Masterdrawings* 23/24(4) (1985/86) 526–537.

25 Burmester, A., 'The study of drawings in the near infrared' in *Analysis and Examination of an Art Object by Imaging Technique*, 12th International Symposium on the Conservation and Restoration of Cultural Property, Tokyo National Research Institute of Cultural Properties (1988) 64–88.

26 Bayerer, F., 'Die Untersuchung von Kunstobjekten mit Hilfe der bildgebenden Spektroskopie: Theoretischer Hintergrund, experimenteller Aufbau, multivariate statistische Bewertung und Anwendung', dissertation, Technical University, Munich (1996).

27 Burmester, A., and Bayerer, F., 'Remote imaging spectroscopy of drawings' in *Proceedings of the 4th International Congress on Non-Destructive Testing of Works of Art*, Tokyo National Research Institute of Cultural Properties (1994) 183–192.

28 Bayerer, F., and Burmester A., 'Nondestructive imaging spectroscopy of drawings and paintings' in *Spectrometric Examination in Conservation*, 18th International Symposium on the Conservation and Restoration of Cultural Property, Tokyo National Research Institute of Cultural Properties (1996) 76–86.

29 Schawe, M., 'Das Tafelgemälde "Kreuzigung Christi" Lucas Cranachs des Älteren von 1503' in *Unsichtbare Meisterzeichnungen auf dem Malgrund, Cranach und seine Zeitgenossen*, ed. I. Sandner (1998) 160–166.

30 Burmester, A., 'Das Tafelgemälde "Kreuzigung Christi" Lucas Cranachs des Älteren von 1503: Zur Aufnahmetechnik der digitalen Infrarotreflektographie' in *Unsichtbare Meisterzeichnungen auf dem Malgrund, Cranach und seine Zeitgenossen*, ed. I. Sandner (1998) 167–168.

31 Campbell, L., *The Fifteenth Century Netherlandish Schools*, National Gallery Publications, London (1998).

32 Chahine, H., Cupitt, J., Saunders, D., and Martinez, K., 'Investigation and modelling of colour change in paintings during conservation treatment' in *Imaging the Past*, British Museum Occasional Paper No. 114, London (1996) 23–34.

33 Campbell, L., and Dunkerton, J., 'A famous Gossaert rediscovered', *Burlington Magazine* CXXXVIII (1996) 164–173.

34 Saunders, D., 'High-quality imaging at the National Gallery: origins, implementation and applications', *Computers and the Humanities* 31 (1998) 153–167.

35 Martinez, K., Cupitt, J., Saunders, D., Abbood, A., and Chahine, H., 'Applications of high quality digital images of art', *Computers and the History of Art* 7(2) (1997) 87–96.

36 Murray, A., and Saunders, D., 'Imaging the effects of relative humidity on canvas paintings', *Canadian Association for Conservation of Cultural Property Conference* (1997).

37 Burmester, A., Raffelt, L., Renger, K., Robinson, G., and Wagini, S., *Flämische Barockmalerei — Meisterwerke der Alten Pinakothek München/Flemish Baroque Painting — Masterpieces of the Alte Pinakothek München*, Munich (1996).

38 Burmester, A., Raffelt, L., Robinson, G., and Wagini, S., 'The MARC project: from analogue to digital reproduction' in *Flämische Barockmalerei — Meisterwerke der Alten Pinakothek München/Flemish Baroque Painting — Masterpieces of the Alte Pinakothek München*, Munich (1996) 11–26.

39 Burmester A., and Raffelt, L., 'Acquiring and printing high resolution colorimetric digital images of Flemish masterworks: presentation of the MARC-book' in *Proceedings of the Electronic Imaging and the Visual Arts EVA*, London (1996) 9-1–9-10.

40 Burmester, A., 'Der Barock ist auch nur eine Benutzeroberfläche — In elektronischer Treue fest zum Original: Ein neues digitales Verfahren zur farbigen Reproduktion von Gemälden', *Frankfurter Allgemeine Zeitung* 5.9.1996.

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