In situ colour measurement on works of fine art using a non-destructive methodology

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Colours in paintings are one of the means by which artists express their feelings. The determination and the interpretation of these colours are very important for art historians because they lead us to a deeper understanding of the artist's cultural background. Even if the pictorial colours are subjectively selected by the artist, they can be objectively determined through physics by a total of interrelated factors which are calculated by the help of appropriate mathematical methods. In the present research study a non-destructive methodology for *in situ* colour measurement on fine art paintings is suggested using a 3CCD colour detector. From the results obtained, it is suggested that the approach employed is sufficiently accurate for it to be applied in the investigation of works of fine art.

INTRODUCTION

Pictorial colours in paintings are one of the means by which artists express their feelings. The determination and the interpretation of these colours are very important for art historians because they lead us to a deeper understanding of the artist's cultural background. Even if the pictorial colours are subjectively selected by the artist, they can be objectively determined through physics by a total of interrelated factors which are calculated by the help of appropriate mathematical methods.

Nowadays the most accurate colour measurement is provided by the use of classical reflectance spectrophotometers. In the case of colours in paintings classical reflectance spectrophotometers cannot be used because the measurement is destructive. Researchers working in the physicochemical analysis of art works propose different solutions to this problem, for example, the use of non-destructive devices, like the portable reflectance spectrophotometer and, more recently, colorimetry devices equipped with fibre optics.

Portable reflectance spectrophotometers are already used in colour measurement on wall paintings with interesting results [1]. Unfortunately, in the case of works of fine art, and especially in paintings of small and medium dimensions, the measurement aperture of reflectance spectrophotometers has proved to be too large even if it is no bigger than 3 mm.

Experiments realised with the above mentioned colorimetry devices have demonstrated that fibre optic reflectance spectroscopy is a powerful method to collect colour information from paintings [2]. However, this method is laborious when trying to determine the palette an artist used in one of his paintings since it requires an enormous number of measurements. Furthermore, when a problem of colour ageing must be investigated, it is very difficult with this system to take measurements exactly at the same site where the first measurements were completed.

In the present study a non-destructive methodology for *in situ* colour measurement on works of fine art is suggested using a 3CCD colour detector. With this methodology colour measurements can be easily realised on every pixel of the digitised image of the painting. The image can be recorded in order to be compared with future images to assess possible colour changes in more specific studies.

The accuracy of this methodology in colour measurement on uniformly painted patches has already been tested in our previous research with satisfactory results [3]. Colour measurement on uniformly coloured surfaces is easier because there is no influence of the colour of a pixel on the digitised image by the neighbouring coloured environment, as happens in the case of a digitised painting. The aim of this work is to demonstrate that accuracy at a satisfactory level can be achieved with the use of our developed methodology even in *in situ* measurements on paintings. For this reason an experimental painting that had been painted using a well known procedure was considered. The physicochemical characteristics of the pigments used were also well known to the authors. The painting was specially created for the present study in order to estimate the accuracy of the experimental findings.

Firstly a colorimetric calibration of the digitised system used was developed with the help of a chart including twenty manufactured coloured patches distributed in different areas of the visible spectrum and with a surface texture similar to the one created by the artist. In other words the transformation matrix of the R, G and B values measured by the detector was calculated by regression analysis on the colour patches, taking into consideration the tristimulus values X_{sp}, Y_{sp} and Z_{sp} measured by spectrophotometry on the same colour patches on the basis of the CIE 1931 XYZ colorimetric system. In this way the tristimulus values X_{cam}, Y_{cam} and Z_{cam} were obtained.

Next, the tristimulus values X_{cam}, Y_{cam} and Z_{cam} were calculated for twelve colour areas on an experimental painting, of an established depiction procedure, using the transformation matrix achieved. The values obtained were transformed into the L^*_{cam}, a^*_{cam} and b^*_{cam} values in the CIELAB system and compared with the relative values provided by a portable reflectance spectrophotometer on the same colour areas. Finally the colour difference, ΔE^*_{CMC}, in the CMC uniform colour space between the L^*_{sp}, a^*_{sp} and b^*_{sp} values provided by spectrophotometry and the ones obtained using the 3CCD detector, was calculated in order to evaluate the colour accuracy of the proposed methodology. The CMC system was adopted because it gives greater correspondence between the measured colour differences and the colour discriminating ability of the human eye.

EXPERIMENTAL

In order to perform the proposed methodology the following equipment was used:

- A Minolta CM-2002 portable reflectance spectrophotometer including, a xenon lamp, a UV radiation cutting filter and an integrating sphere which allows measurement of the diffused reflection from the whole surface samples, with simultaneous filtration of the specular reflected radiation being cut. Its measurement aperture presents a diameter of 3 mm.
- A Sony DXC-3000P 3CCD detector equipped with a Tamron TV Zoom 18–108 mm, 1:2.5 lens and an Oriel 57401 IR radiation cutting filter placed in front of the detector lens in order to limit its spectral response, to the visual region of the spectrum only. The detector is much less sensitive to the shorter wavelengths (blue area) than it is to the medium (green area) and longer wavelengths (red area). However, the exact spectral sensitivity of this detector is not made available by Sony because it is an outdated model.
- A light source consisting of four incandescent tungsten filament Osram Nitraphot, 150 W, 220–230 V, 3200 K lamps. The angle between the normal to the coloured surface and the axis of the incident beam of the light source is 45°.
- A Compaq Deskpro 386/20 MHz electronic computer including a Matrox MVP-AT digitising card.
- A Nec Multisync visualisation monitor. All measurement processes were accomplished with the Samba-IPS software.
- A colour chart comprising twenty manufactured patches (4×4 cm^2). The pigments used on their painted surfaces are listed in Table 1.
- A painting; a recent copy of a byzantine icon of the 14th century, depicting the Deposition from the Cross supplied by the Holy Convent of the Annunciation of the Mother of God at Ormylia Halkidiki. The experimental set up for colour measurement using the Sony DXC-3000P 3CCD detector is represented in Figure 1.

Table 1 Pigments used in the present study

Pigment no	Identity
1	Titanium white
2	Cadmium red and cadmium yellow
3	Cobalt green
4	Cobalt blue
5	Cadmium yellow
6	Cadmium red
7	Cadmium red and lead white
8	Cobalt blue and lead white
9	Cobalt green and cadmium yellow
10	Cobalt blue and cadmium yellow
11	Malachite
12	Cobalt blue and cobalt green
13	Cobalt blue and cadmium red
14	Cadmium orange
15	Lapis lazuli
16	Vermilion
17	Madder lake pale
18	Mars orange
19	Ochre light yellow
20	Ochre yellow

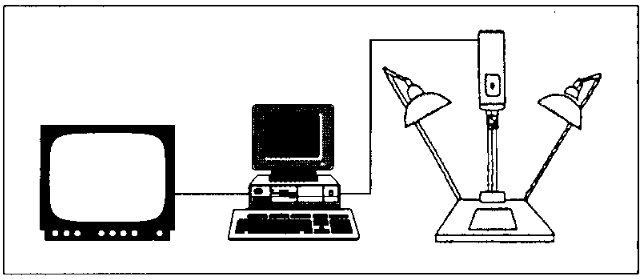


Figure 1 Experimental set up for colour measurement using the Sony DXC-3000P 3CCD detector

COLOUR MEASUREMENT BY REFLECTANCE SPECTROPHOTOMETER

A portable reflectance spectrophotometer was used for the colour measurements. Before each series of measurements it was calibrated with a white ceramic tile. This material has high spectral reflectance values in the visible spectral range and it is suitable as a working standard [4].

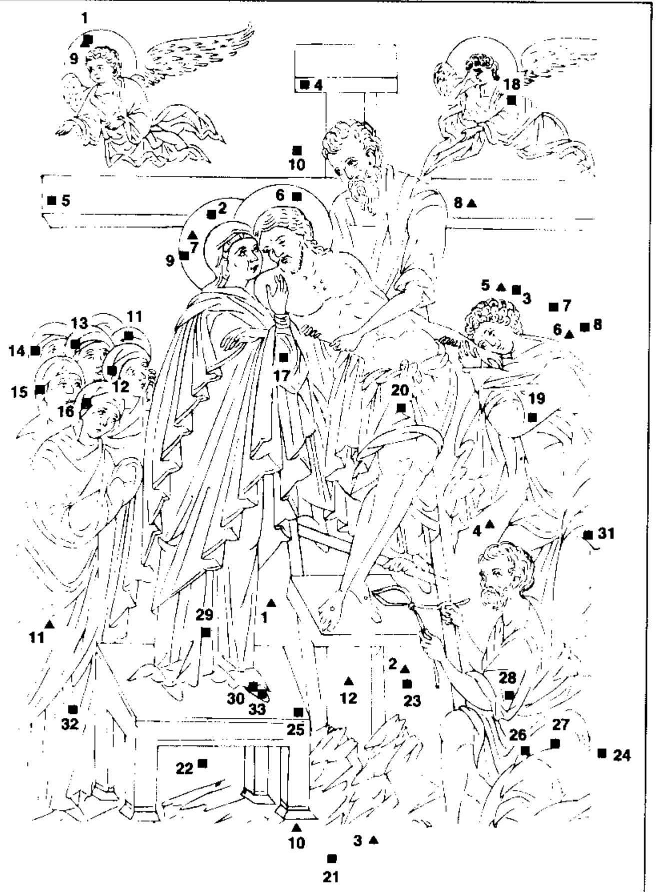
The spectral reflectance factor was measured by spectrophotometry in the range 400–700 nm for every one of the twenty patches on the colour chart as well as for every one of the twelve coloured areas on the surface of the experimental painting (Figure 2). These areas were selected taking into account two parameters:

(a) They are uniformly painted for a diameter of 3 mm at least, the diameter of the measurement aperture of the reflectance spectrophotometer used
(b) They are distributed in different areas of the visible spectrum with different rates of saturation in order to estimate the accuracy of the proposed methodology for a large range of colours; the wavelength pitch is set to 10 nm according to the instrument specifications.

The tristimulus values X_{sp}, Y_{sp} and Z_{sp} of these areas were calculated afterwards, on the basis of the CIE 1931 *XYZ* standard colorimetric system for standard illuminant A, selected because it is a very convenient representation of the tungsten lamps which were used during the digitised procedure. The colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ as well as the relative spectral radiant power distribution of the standard illuminant A are given in the literature [4].

The incremental 10 nm interval between measurements was considered satisfactory, the peaks obtained for the pigments used being broad, thus excluding substantial loss of information. Earlier results had indicated that tristimulus values X_{sp}, Y_{sp} and Z_{sp} calculated from spectrophotometric measurements of the reflectance factor at 1 or 10 nm intervals in the range 400–700 nm did not lead to significantly different tristimulus values X_{cam}, Y_{cam} and Z_{cam}.

Table 2 shows the tristimulus values X_{sp}, Y_{sp} and Z_{sp} calculated using the portable reflectance spectrophotometer as well as L^*_{sp}, a^*_{sp} and b^*_{sp} values for every one of the twenty patches of the colour chart, and of the twelve selected colour areas on the painting surface. The values a^*_{sp} and b^*_{sp} are presented in Figures 3 and 4.



▲ The twelve selected colour areas on which measurements were made by spectrophotometry and by the 3CCD detector
■ The selected colour areas on which measurements were made by the 3CCD detector

Figure 2 Selected colour areas on the experimental painting

COLOUR MEASUREMENT BY 3CCD DETECTOR

Before each series of measurements the zero signal and the dynamics of the detector must be adjusted. The Samba-IPS software allows, for given exposure conditions, automatic adjustments in two steps. The appropriate 'offset' numerical parameter of the digitising card was chosen in complete darkness (closed shutter) in order to achieve a weak zero signal. Next, the suitable 'gain' numerical parameter of the same digitising card for a lens aperture value was found by the acquisition of white patch 1 of the colour chart in order to avoid the effects of white saturation and colour imbalance.

The Sony DXC-3000P 3CCD detector gives a non linear response. Its γ correction factor for every channel was determined using a Kodak chart including 20 grey level patches of known absorbances. Every one of these levels was digitised using the 3CCD detector. Eqns 1–3 were used:

$$\text{Red channel} \quad \log R_f = \frac{1}{\gamma R_f d_f} + a_R \qquad (1)$$

$$\text{Green channel} \quad \log G_f = \frac{1}{\gamma G_f d_f} + a_G \qquad (2)$$

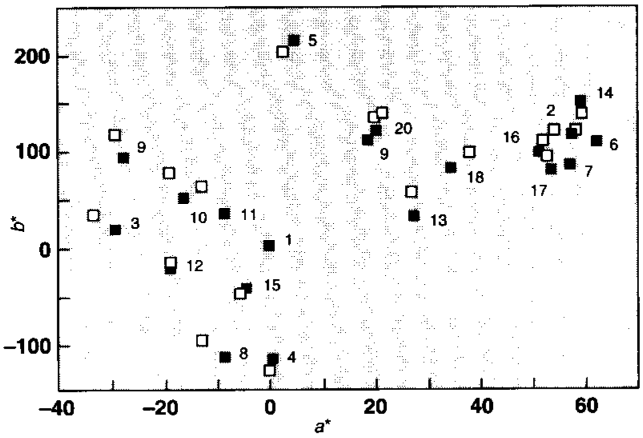
$$\text{Blue channel} \quad \log B_f = \frac{1}{\gamma B_f d_f} + a_B \qquad (3)$$

where d_f is the absorbance of each level f, R_f, G_f and B_f are the mean vlaues of a predetermined area on each level, γ_R, γ_G and γ_B are correction factors for each channel, and a_R, a_G and a_B are constants. The values of γ_R, γ_G and γ_B were calculated by a least-squares method and found to be:
Red channel γ_R = 1.5110
Red channel γ_G = 1.4188
Red channel γ_B = 1.5605

Our synthesised colour chart was then digitised under the same experimental conditions. The *R*, *G* and *B* values, which were the mean values measured by the detector on a predetermined area on each one of the twenty patches of the colour chart, were transformed to X_{cam}, Y_{cam} and Z_{cam} tristimulus values (Table 3), after photometry and gamma corrections [9–11]. A first-order regression model was used (Eqn 4) [12,13]:

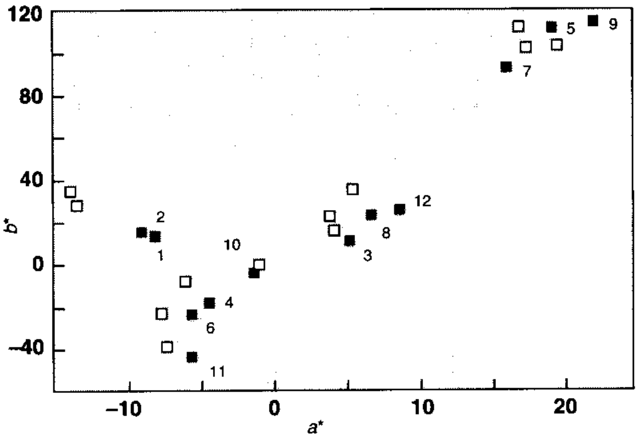
Table 2 Tristimulus values X_{sp}, Y_{sp}, Z_{sp} and L^*_{sp}, a^*_{sp}, b^*_{sp} calculated after spectrophotometric measurements performed using the Minolta CM-2002 portable spectrophotometer, on 20 patches of the colour chart and on twelve selected areas of the experimental painting

Patch/ area	X_{sp}	Y_{sp}	Z_{sp}	L^*_{sp}	a^*_{sp}	b^*_{sp}
1	98.4496	89.2639	29.6544	100	0	0
2	41.8894	23.0426	1.9121	57.8601	57.7058	117.8642
3	9.275	12.0696	3.2579	43.5384	−29.1194	17.1599
4	5.6679	5.0962	7.0535	28.6664	0.5383	−117.267
5	84.5486	74.3977	3.9519	93.1656	4.7217	215.1484
6	36.2577	18.5159	1.5564	52.6669	62.4197	108.7746
7	43.3631	24.1142	3.1864	58.9877	57.2046	85.5169
8	20.7604	20.4779	17.6451	55.0114	−8.4759	−114.463
9	22.3325	26.2438	3.2753	61.1332	−27.5331	92.5743
10	16.2546	17.4682	3.2601	51.3465	−15.9879	50.762
11	12.806	12.8062	2.7955	44.7257	−8.4092	34.1901
12	6.5154	7.7137	3.4222	35.2846	−18.8087	−22.3764
13	12.2967	7.8566	1.6374	35.5993	27.5246	32.0146
14	49.9594	27.9637	1.6285	62.7827	59.2339	149.5299
15	6.3699	6.1848	3.73	31.6439	−4.6332	−45.1585
16	33.9958	19.1429	1.9126	53.4334	51.5025	98.7663
17	28.0752	14.9054	1.7567	47.8774	53.7753	80.4212
18	22.3764	14.1834	1.6007	46.8289	34.3231	81.8512
19	30.5381	23.3339	2.1642	58.17	18.7657	110.7498
20	35.3636	26.8898	2.4151	61.761	20.2506	118.4469
1	13.9099	13.8297	3.9784	46.3022	−8.1247	12.5815
2	14.2729	14.2897	4.0661	46.9855	−8.8238	13.6594
3	7.0505	5.9079	1.6695	30.9221	5.387	10.6178
4	7.5326	7.5226	3.0876	34.2416	−4.2929	−18.6645
5	43.2359	33.5597	3.7019	67.7218	19.1854	110.9801
6	7.1485	7.0072	3.2103	33.6685	−5.4934	−24.2106
7	32.8126	25.8094	3.2193	60.7053	16.0405	92.1048
8	8.5296	7.037	1.6745	33.7388	6.8544	22.5677
9	40.9512	30.9438	3.1537	65.4874	22.0006	114.3486
10	67.9727	62.1204	21.2025	86.7963	−1.1676	−4.0104
11	10.209	9.9149	5.4391	39.7608	−5.4427	−43.7374
12	8.8617	7.1305	1.6435	33.9581	8.7439	24.7042



■ a^*_{sp}, b^*_{sp} values of the twenty patches of the colour chart calculated using the portable reflectance spectrophotometer
□ a^*_{cam} and b^*_{cam} values of the twenty patches of the colour chart provided by the Sony DXC-3000P 3CCD detector

Figure 3 a^*b^* diagram (CIELAB 1976 system)



■ a^*_{sp} and b^*_{sp} values of the twelve colour areas on the experimental painting calculated using the portable reflectance spectrophotometer
□ a^*_{cam} and b^*_{cam} values of the same colour areas provided by the Sony DXC-3000P 3CCD detector

Figure 4 a^*b^* diagram (CIELAB 1976 system)

Table 3 Colour measurements by the Sony 3CCD DXC-3000P detector on 20 patches of the colour chart and on twelve colour areas of the experimental painting

Patch/ area	R	G	B	X_{cam}	Y_{cam}	Z_{cam}	L^*_{cam}	a^*_{cam}	b^*_{cam}
1	232.9497	237.0981	233.7655	93.33	83.64	27.9225	100	0	0
2	165.2219	46.1464	31.2693	42.2671	24.0849	2.1015	60.6011	53.7927	119.0737
3	39.7479	79.631	56.9093	9.9527	13.2607	3.0235	46.783	−33.51	32.2993
4	29.2392	34.6278	100.5153	5.2	4.6592	7.0997	28.302	0.01242	−125.804
5	222.8009	204.3845	57.6859	81.6822	71.9385	4.5294	94.3165	2.7666	202.8144
6	151.8009	29.0297	21.8226	36.314	19.3441	1.494	55.2037	58.1109	118.5034
7	168.0656	50.3443	47.3349	43.7222	25.2344	3.1608	61.8008	52.9779	93.4772
8	84.6893	112.5989	180.8267	24.5902	24.7393	17.9431	61.2887	−12.5997	−98.3296
9	88.7402	132.9851	54.6249	26.2467	30.3715	3.1304	66.7577	−29.1316	115.6211
10	77.7323	101.9646	56.4824	20.1775	21.8002	3.1938	58.098	−19.2978	76.6781
11	60.5665	72.0451	43.7411	13.3008	13.7702	2.1458	45.577	−12.8694	61.4624
12	34.5933	53.8709	61.5918	6.9822	8.1063	3.3729	37.2837	−18.9892	−17.4936
13	70.2362	28.8434	25.4477	12.2124	7.8267	1.0909	36.6638	26.8424	57.3392
14	183.4832	44.8312	25.1228	48.9758	27.1436	1.9366	63.7154	59.6945	138.1704
15	35.2353	39.9713	65.4857	6.1285	5.9472	3.6994	32.0571	−5.4232	−47.7529
16	146.3121	37.9233	28.6382	35.0062	19.6575	1.7931	55.5862	52.0267	108.3354
17	132.5555	30.4768	26.9297	29.9351	16.4353	1.5902	51.4392	51.5739	98.3169
18	110.501	39.6811	25.2659	23.6472	14.4585	1.3428	48.6191	37.8593	96.7048
19	134.3289	84.0905	30.3853	34.6697	25.8683	1.8084	62.4469	21.2955	137.3396
20	138.5555	89.454	35.1902	36.5928	27.6291	2.1236	64.1879	20.3178	133.7968

Table 3 *Contd.*

Patch/ area	R	G	B	X_{cam}	Y_{cam}	Z_{cam}	L^*_{cam}	a^*_{cam}	b^*_{cam}
1	61.3222	73.3616	60.9355	14.4827	15.026	3.6947	49.4642	−13.4415	27.34056
2	60.2327	73.3038	57.2273	13.9121	14.5267	3.3194	48.7205	−13.8573	33.1171
3	40.8849	31.6974	33.0559	6.5227	5.4992	1.4367	30.8187	4.1499	15.8359
4	40.3333	42.7564	50.2413	7.4508	7.2448	2.7055	35.3249	−5.935	−8.4223
5	150.2517	105.7231	56.9279	43.8501	34.389	3.9344	70.2567	16.9082	111.6139
6	39.0524	44.1007	58.2558	7.2231	7.1784	3.2575	35.1676	−7.4729	−23.7626
7	132.7166	89.8424	50.4601	35.5819	27.5169	3.2114	64.0792	17.3849	102.0139
8	47.9481	38.0875	37.4678	8.3887	7.1227	1.7467	35.035	3.9939	21.4948
9	146.9147	98.2039	57.2426	41.0943	31.4625	3.8175	67.7371	19.4494	103.3559
10	201.0696	200.7636	201.2484	75.9977	68.4896	23.1037	92.5246	−0.8721	−1.6244
11	51.2079	57.4674	80.2935	11.0266	10.7632	5.5263	42.5644	−7.088	−38.9496
12	47.3581	35.3258	30.2972	8.0524	6.6935	1.3135	33.9886	5.4703	34.9745

$$\begin{bmatrix} X_{sp} \\ Y_{sp} \\ Z_{sp} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{4}$$

The transformation matrix was calculated taking into consideration the tristimulus values X_{sp}, Y_{sp} and Z_{sp} of the twenty colour patches calculated using spectrophotometric measurements and the R, G and B corrected values of the same patches. The best values of the matrix elements using a least squares method were found to be:

$$\begin{bmatrix} 0.2625 & 0.0925 & 0.0110 \\ 0.1251 & 0.2049 & -0.002 \\ 0.0063 & 0.0004 & 0.1028 \end{bmatrix}$$

Table 3 also shows the L^*_{cam}, a^*_{cam} and b^*_{cam} values for every one of the twenty patches of the colour chart, while the values a^*_{cam} and b^*_{cam} are presented in Figure 3.

The mean value of the CMC colour difference, ΔE^*_{CMC}, for every one of the twelve colour areas was calculated and found to be 3.07.

Moreover, in order to demonstrate that the achieved accuracy of the proposed methodology in colour measurement is sufficient for assistance in conservation research and for computer-aided study of art works, several colour areas on the experimental painting were selected. The L^*_{cam}, a^*_{cam} and b^*_{cam} values of these areas were calculated through the R, G and B values measured by the detector (Table 4).

Table 4 Colour measurements by the Sony 3CCD DXC-3000P on the selected colour areas of the experimental painting

Area	L^*_{cam}	a^*_{cam}	b^*_{cam}
1	67.9523	18.8387	106.064
2	65.5410	16.5947	104.5057
3	70.4564	17.5398	112.4945
4	48.8863	10.0114	59.6839
5	49.8154	11.1529	60.3963
6	66.2877	15.9911	106.9874
7	35.8096	−7.2249	−9.5474
8	36.8443	−8.8385	−15.9571
9	84.6951	−0.2851	9.4361
10	85.5317	−2.4237	−6.4625
11	60.5319	19.1248	95.6922
12	45.9462	−12.6152	15.2247
13	40.3853	−6.0839	−51.1156
14	43.615	30.40633	60.3319
15	59.3323	20.2872	29.9963
16	43.6223	−5.7416	−29.4247
17	48.9624	−6.4812	−34.4102
18	58.1725	24.1421	29.3745
19	57.2562	−4.7883	55.2007
20	77.6481	12.7093	34.0294
21	33.1553	4.8845	32.7394
22	51.2722	−11.8747	40.7907
23	50.1884	−12.4295	43.508
24	52.1245	−13.1456	39.4467
25	76.0007	10.4649	79.6392
26	93.1253	−0.853	−3.8222
27	73.6979	−2.5167	−15.2901
28	77.532	12.3783	96.7243
29	42.7843	−8.5137	−33.046
30	48.8675	42.5508	92.6069
31	71.3432	−11.1669	22.7338
32	67.3997	17.2117	62.5819
33	57.3907	47.4476	120.2866

DISCUSSION

It has been already found that the tristimulus values X_{cam}, Y_{cam} and Z_{cam} or L^*_{cam}, a^*_{cam} and b^*_{cam} values which were calculated through the R, G and B values measured by the detector on the twelve selected areas of the painting surface, did not exactly coincide with those derived from spectrophotometric measurements performed using the portable reflectance spectrophotometer.

The reasons for the resulting differences are various and have been already reported in detail [3], and can be summarised as follows:

- When a detector is used, it is not possible to suppress the spectral reflectance, which occurs inside the integrating sphere of the spectrophotometer

- The spectral radiant distribution of the tungsten filament light source can only be considered to constitute approximately the spectral radiant power distribution of the standard illuminant A
- Errors arise from constructional and functional defects of the detector and from the electronic noise of the system used
- There are errors due to the digitising procedure
- Non-uniform illumination of the surface sample gives rise to errors
- There are errors induced because of the different kind of standards used for white calibration of the portable spectrophotometer and during colour measurement with the 3CCD detector.

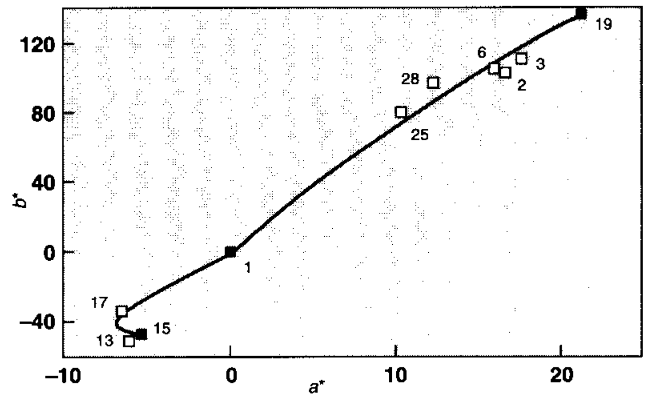
In addition, the colour measurement spot areas of the detector and those of the portable Minolta reflectance spectrophotometer were not exactly the same (the reflectance spectrophotometer measurement spot area having much less restricted dimensions than those of the detector) and this unavoidably led to different colour co-ordinates calculated for the same colour. This was due to the inhomogeneity of the colours of the painting.

Also the colour co-ordinates provided by the detector were influenced by the neighbouring colour environment. This was especially the case when the width of the measured area was small, colour measurements by spectrophotometry being performed in contact with the painted surface.

The mean value of the CMC colour difference on the colour areas of the painting has been compared with the average colour accuracy ($\Delta E^*_{CMC} = 2.3$) achieved by the VASARI project with colour measurements on the patches of a Macbeth Colorchecker chart [14] (Appendix 1). The authors estimate that the attained accuracy of their proposed methodology is sufficient for colour measurements on paintings, considering the variation in coloration and the irregularities of the coloured areas of the experimental painting. On the contrary the Macbeth patches are uniformly coloured without prominent irregularities on their surface. Further it is pointed out that the proposed digitised system used in this study is much cheaper than the one used for the VASARI project.

A significant number of colour measurements was realised on the surface of the experimental painting. The measurement locations were selected in order to represent the various colours used on the painting. Figure 5 represents the chromaticities of colour areas 2, 3, 6, 13, 17, 25 and 28 on the surface of the experimental painting as well as the chromaticities of areas 1 (pure titanium white), 15 (pure lapis lazuli) and 19 (pure yellow light ochre) patches of the colour chart on the CIELAB 1976 a^*b^* chromaticity diagram derived after colour measurements performed using the Sony DXC-3000P 3CCD detector.

It is obvious from this diagram that the chromaticities of colour areas 2, 3, 6, 25 and 28 belong to the same geodesic line with the patches 1 and 19, as they are painted by a mixture of yellow ochre with different concentrations of titanium white. Besides the chromaticities of blue colour areas 13 and 17 belong to the same geodesic line with the chromaticities of patches 1 and 15 of the colour chart. Here the colour areas were painted by a mixture of lapis lazuli and titanium white in different concentrations.



■ a^*_{cam} and b^*_{cam} values provided by the Sony DXC-3000P 3CCD detector on the patches No. 1, 15 and 19 of the colour chart
□ a^*_{cam} and b^*_{cam} values provided by the Sony DXC-3000P 3CCD detector on the colour areas No. 2, 3, 6, 13, 17, 25 and 28 of the experimental painting

Figure 5 a^*b^* diagram (CIELAB 1976 system)

CONCLUSIONS

The results of the present research demonstrate that the proposed non-destructive method lends itself as a sufficiently accurate method to be used in the investigation of paintings through measurement of the used colours. The coloured areas of the experimental painting which present a difference in white concentration were specially selected, as the depiction procedure of the paintings was well known to the authors, in order to demonstrate that small colour differences can be easily detected by the proposed methodology.

It is of note that other kinds of colour differences may also be detected, for example, due to yellowing varnish or by changes in hue of certain pigments with age.

For all these reasons the authors suggest that the proposed methodology constitutes a powerful, sufficiently accurate, reproducible and non-destructive tool for colour investigation of paintings, which has the further advantage of been of lower cost than other systems.

* * *

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REFERENCES

1. M R Schilling, ICOM Committee for Conservation, Vol. 1, (1993).
2. M Bacci *et al.*, Proc. Mat. Res. Soc. Symp., Vol. 267 (1990).
3. M Vallari, Y Chryssoulakis and J M Chassery, *Mes. Sci. Technol.*, 5 (1994) 1078.
4. G Wyszecki and W S Stiles, *Color science: concepts and methods, quantitative data and formulae*, (New York: John Wiley, 1982).
5. J F Blinn, *IEEE Comp. Graphics Appl.*, (July 1989) 100.
6. Sony Camera Glossary.
7. C L Novak, S A Shafer and R G Willson, SPIE Perceiving, Measuring and Using Color, Vol. 1250 (1990), 54.
8. K A Parulski, B L Benamati, L J D'Luna and P R Shelley, *SPIE Camera and input scanner systems*, Vol. 1448 (1991) 45.
9. J McClellan, *SPIE Optics, illumination and images sensing for machine vision 4*, Vol. 1194 (1989) 62.
10. G Healey and R Kondepudy, *SPIE Optics, illumination and images sensing for machine vision 6*, Vol. 1614 (1991) 121.
11. A M Mumzhiu and C D Bunting, *SPIE Color hard copy and graphic arts*, Vol. 1670 (1992) 371.
12. H Brettel, *SPIE Image processing 2*, Vol. 1027 (1988) 107.
13. G W Meyer, *SPIE Perceiving, measuring and using color*, Vol. 1250 (1990) 54.
14. K Martinez, J Cupitt and D Saunders, *SPIE*, Vol. 1901 (1993) 25.

APPENDIX 1

VASARI (Visual Arts System for Archiving and Retrieval of Images) project is realised inside the VASARI Consortium which is carried out as part of the ESPRIT II project. Other institutions involved in this project were:

– Birkbeck College, University of London, UK
– The Doerner Institut, Munich, Germany
– Brameur Ltd, UK
– ENST, Telecom Paris, France
– Thomson-CSF, Rennes, France
– TUV-Bayern, Munich, Germany.

The VASARI project aimed to build a high-resolution colorimetric image capture system equipped with a high-resolution camera in order to record images for conservation research in works of fine art and publishing.