Spectral imaging of Leonardo Da Vinci's Mona Lisa: A true color smile without the influence of aged varnish

P.Cotte, D.Dupraz
Corresponding author: P.Cotte (cotte.pascal@free.fr)

Abstract

Two photos of the famous Mona Lisa were taken in October 2004 to contribute towards improving the technical and scientific data of the masterpiece before moving it in April 2005. The capabilities of the multispectral system developed by the LUMIERE TECHNOLOGY Company within the scope of the European CRISATEL project have made it possible to achieve optimal spatial resolution on the masterpiece, the highest level of sharpness ever achieved in the field of infrared reflectography, and a level of accuracy regarding color information which cannot be achieved with traditional technologies. Based on this new data, we suggest in this publication that the influence of aged varnish be removed, the significant discoloration of which alters the readability of the masterpiece.

1. Introduction

High-resolution spectral imaging allows us to obtain new data in order to study fine art paintings. The main tools available include global spectrophotometry in the visible and near infrared as well as magnifying of the details of the painting. A portable nondestructive system makes it possible to produce high-fidelity color images and to consider virtual restoration. This technique has been used to improve knowledge of the world's most famous painting – the *Mona Lisa*. After a presentation of the masterpiece, equipment and relevant calibration of the latter, the first part of this article describes the digitization of the painting. The second part describes the target dedicated to modeling the optical properties of the varnish and its selective absorption. We shall apply these changes to the *Mona Lisa*'s spectral data and, based on indicators, we shall assess the chromatic changes of our suggestions for remodeling.

2. The painting

The *Mona Lisa* – which is exhibited at the Louvre in Paris, INV 779 – was painted between 1503 and 1506 by Leonardo Da Vinci. This masterpiece has always been linked with the Louvre and more generally speaking with art. The perfect pictorial technique is one of the numerous elements that contribute towards the myth and gives the masterpiece remarkable realism (rendering of the flesh). This oil painting is set on a thin poplar 77 cm × 53 cm wood panel support and now relocated – in April 2005 to the "Salle des États" – the largest room in the museum with its new protective enclosure and lighting. Extensive scientific and technical research was carried out prior to moving the masterpiece in order to check its state of conservation. Within the scope of this study and in addition to the usual experiments carried out by the French Museum Research and Restoration Center (C2RMF), the Louvre called in several external teams of scientific experts. Pascal Cotte and his team brought along their know-how in the field of high-definition multispectral digitizing of fine art paintings and took photos of this famous masterpiece with their equipment during the night of 19^{th} October 2004.

3. Experimentation

In addition to all the necessary precautions required when handling precious, fragile masterpieces, extremely minute and confidential experiments were carried out on this unique masterpiece. The equipment was set up in the photographic studio several days beforehand in order to design the stand dedicated to holding the painting and to carry out a series of preliminary tests. Meanwhile, François Perego developed a varnish target, the manufacturing details of which discussed further below.

3.1 Equipment and calibration

The high-resolution spectral imaging system (see Figure 1) is based on a CCD sensor array of 12,000 pixels and achieves an optimal definition of 360 Mega-pixels for each channel. This 13-channel acquisition system uses interference filters in a half-cylinder and covers the visible spectral range with a 40-nm bandwidth and three additional IR filters with a 100-nm bandwidth. A high-resolution scanning system equipped with a dedicated synchronized lighting system was developed and patented by LUMIERE TECHNOLOGY.

Figure 1: Installation of the spectral imaging system. © Pascal COTTE 2004

This lighting system is composed of two elliptical projectors with eight HQI metal discharge lamps and projects a combined narrow light beam synchronized with the CCD sensor displacement. The device and protocol used to takes photos of this painting were described recently in a previous publication[1]. Three different targets are selected to evaluate system performances: the GretagMacbeth color checker DC target, the CRISATEL project's acrylic and oil Pébéo charts. The variety and homogeneity of pigments differ from one chart to another. The test charts were completed by Spectralon reflectance standards featuring the following characteristics: 99, 50, 28 and 12% reflectance and 99% Teflon white. In addition to its portable nature, this new masterpiece analysis technique must protect the material's integrity. All the parameters linked with their potential deterioration have been studied. The light beam enables a 50 mm wide beam of maximum lighting, then rapidly decreases to a value lower than 800 lux outside the focused beam. The unit of the total exposure dose received by a document is in millions of lux per hour (Mlxh) and the unofficial standard sets the total exposure of a document to

0.36 Mlxh/year – enabling calculation of total exposure dose received by the masterpiece during the digitization. Based on the digitization parameters (pixel resolution and integration time for each channel), the total exposure dose obtained for shot No. 1 is 0.020 Mlxh and that obtained for shot No. 2 is 0.018 Mlxh. In comparison, when in its former protective enclosure, the *Mona Lisa* was exposed to a level of illumination of 180 lux lighting during 9 hours a day, i.e. a total of 0.00162 Mlxh. A photo of this masterpiece is therefore equivalent to ten days' exposure in the museum. We shall comment on this result in the applications section further below. The lighting projectors incorporate a preventive conservation device with heat filters at the front and a UV stabilizer directly integrated into the lamp bulbs. The microclimate of the room had been monitored in order to study the evolution of temperature and hygrometry.

TED (Mlxh)	RH (%)	Temperature (°C)	UV (µW/lumen)
0.038	50	20.3	13.4

Table 1: Parameters linked with preventive conservation.

An ultraviolet radiation measurement was carried out using a radiometer. All the parameters linked with the conservation of the masterpiece are contained in one single painting (see Table 1) and the values testify to compliance with museum standards. Once the camera parameters are set – diaphragm, exposure time and gain, the calibration phase may start in order to achieve the same level of response for each digitization session. Before placing the painting on the easel, two extra digitization series are required, recording of a white reference with a specific spectral nature and that of the camera response in the dark. The post-processing sequence starts by removing dark noise from the raw image, compensating inter-pixel differences and adjusting the lack of homogeneity of the lighting and the lens in order to obtain a calibrated image. Image resizing is required in order to obtain an adaptive method taking into account inconstant distortions in the images – homothetic transformations, rotations and translations. The solution derives from 3D morphing techniques (i.e. homography). This method utilizes points of reference and resolution targets that are present in the various layers. The results achieved using this technique are excellent and the registration problems become invisible on the final images.

3.2 Acquisition and image processing

After the essential calibration and setting phases, the system is ready to digitize works of art. On 19th October, we had the honor of meeting Mona Lisa and taking photos of her authentic smile. The shots were taken in two phases: global frames of the entire masterpiece followed by macro frames of the face (see Figure 2). The second series was not originally planned but was nevertheless carried out given the participant's enthusiasm when viewing the appearance of the first images on the screen. A first series of 18 shots (13 at f/8 and 5 at f/11) was conducted by the photographer Pascal Cotte and represents new documentary reference data on the masterpiece. The entire digitization session lasted 91 minutes. The second series required a modification of the system to accommodate extremely short remaining times available. The camera was moved closer until it stood 60 cm away from the masterpiece to capture the details of the face. A series of four shots was taken with the filters centered on 560, 800, 900 nm and a last one without filters. Each photo was taken with two spaced out focusing processes given that the depth of field was reduced and finding sharpness was tricky. The entire digitization session for this second image lasted 34 minutes and enabled a remarkable rendering of the details. The performances achieved during this photographing session are unique (see Table 2).

	Global:	Macro:
Resolution (dpi):	372	1523
Resolution (pixels per mm^2):	216	3627
Pixel size of image (µm):	68	16.7
Definition (Mpixels):	137	240
Scan area w x h (mm):	779 x 818.67	333 x 200

Table 2: System performance.

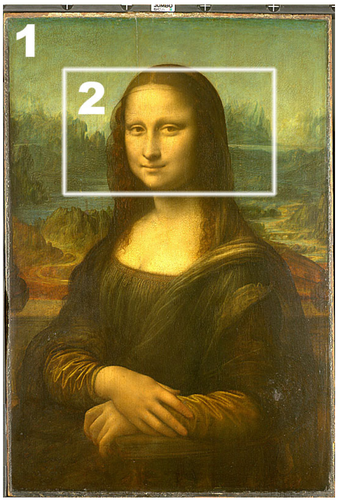

Figure 2: Mona Lisa global frame (1) and macro frame (2). © Pascal COTTE 2004

From these 13 filters, the camera reflects 13 digital values for each pixel. A reflectance curve of the sampling interval is defined using a minimum of 41 values in the 380-780 nm interval. An estimated reflectance curve from the camera is defined using 61 values in the 400-1000 nm interval. Several methods may be used to create these intermediate points: direct or indirect reconstruction and interpolation reconstruction. Direct reconstruction is based on a thorough knowledge of the acquisition system, the implementation of which is tricky due to the determination of the noise. Indirect reconstruction or acquisition reconstruction requires the presence on the images of a standard color test chart. A transfer function between the spectra measured on the test chart and the camera response is generated by extrapolation. Interpolation reconstruction solely focuses on the camera response and does not require any color test chart in the image, only a white reference. After standardization with this white reference standard, the camera is considered as a spectrum sampler that records a specific point of the curve once every 40 nm in the visible range. We must then interpolate to find the missing points. Once the images have been processed, the results are like rediscovering the masterpiece. Saving the images requires a 24 GB storage capacity. Through a 40 nm bandwidth followed by a 100 nm bandwidth in the near infrared, the portrait reveals new details (see color Figure 10). Spectral reconstruction produces a high-fidelity digital color original, the results of which are really excellent (see Table 3) given the complexity of the test target used as representative of the 19th and 20th centuries. The interpolation method offers performance stability as described in a previous publication[5]. The estimated spectral curves are very close to those measured and enable pigment identification. By comparison, for information purposes the performance values regarding indirect reconstruction of the aforementioned test targets are: Colorchecker DC ΔE_{00} = 1.22 (0.12 – 8.1) and Pébéo ΔE_{00} = 1.24 (0.23 – 10.9) using D65 and a 2° observer.

Table 3: Spectral and color fidelity based on the interpolation method.

Targets:	ΔE_{00}	RMS (%)	GFC	Metameric Index (ΔE_{00})
Pébéo	2.13	4.8	0.996	0.39
Colorchecker DC	1.86	6.2	0.997	0.41

The nature of the data makes it possible to simulate the lighting of the masterpiece under various illuminants and to suggest virtual restorations. Lastly, the reading of spectral samples allows us to visualize and compare the reflectance curves with typical signatures of a spectral and pigment library. The high definition image enables examination of each segment of the painting as a new independent entity and makes it possible to retrace the pictorial technique and study the patchwork of cracks.

3.3 Method

We obtained a high-fidelity color digital original. We visually observed the action of the coat of aged varnish applied as a protective layer within the scope of a restoration process at the beginning of the 17th century – probably in order to offset dampness problems. It acts as a filter and contains colored loads, the effect of which is characterized by significant yellowing of the masterpiece. We asked François Perego – restorer and expert in painting and graphic arts material – to develop a specific target (see Figure 3). Previous publications dealt with the influence of neutral varnish[2] on paintings, but we needed a new tool in order to characterize the discoloration of the oxidized varnish. The chosen resins are typical of that used in the days of Leonardo Da Vinci. The target comprises 9 pigments and two types of varnish (see table 4).

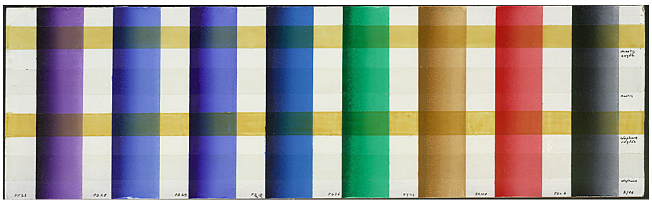

Figure 3: Specific targets for studying the varnish. © F. PEREGO, P. COTTE 2006

Materials:	Color Index:
Dioxazine purple	PV23
Cobalt blue	PB28
Ultramarine blue	PB29
Phthalo blue	PB15
Phthalo green	PG36
Yellow ocher	PY43
Cadmium red	PR108
Lamp black	PBk6
Titanium white 1	PW6
Rosin	-
Mastic	-

Table 4: Materials used in the specific target dedicated to the varnish.

There is no link between the type of pigments and the period of the painter, but we have favored selective reflectance curves in a given shade to optimally assess distortions. The yellowing effect more significantly alters complementary colors; we therefore suggest that blue-colored pigments be increased. The substrate is a compact-particle medium on which two layers of titanium white-based preparation (PW6) have been placed and sanded. This substrate will be used as a white optical background for all measurements. Each application is divided into 15 variations, a first series being equivalent to three mixtures with various proportions of titanium white. Each mixture is then covered with both types of neutral varnish and artificially aged. The varnish is oxidized using a heating magnetic stirring bar at a temperature of 150°. The resin is thus melted and exposed to UV lighting set to 365 nm during 48 hours (see Figure 4). The results were compared with that of naturally-aged resins from the Perego collection.

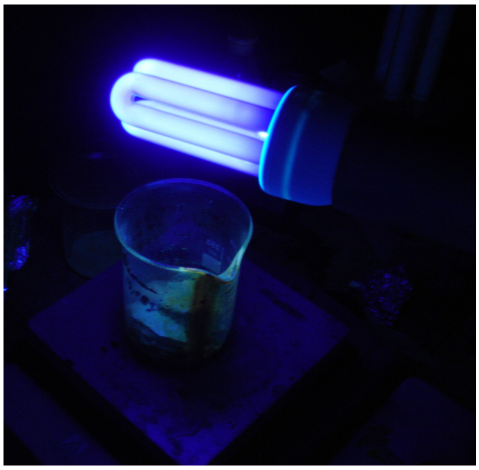

Figure 4: Artificial aging of varnish. © Pascal COTTE 2005

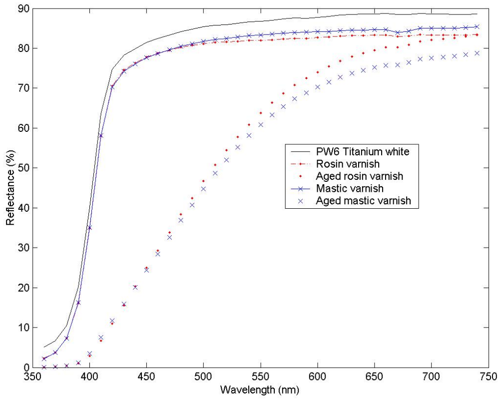

Figure 5: Reflectance of neutral and aged varnish.

We consider varnish applications as filters and will confirm this hypothesis experimentally based on the SCE measurement of our specific target. We use color difference equations CIE ΔE_{00} to assess performance by using illuminant D65 and observer 2°. The density calculation for each varnish (see Table 5) leads to similar results for the neutral or aged version of both rosin and mastic. The mastic-based oxidized varnish is slightly more opaque, but the absorption bands and colorimetric coordinates observed show a similar type of yellowing on the b* axis. As an example, we state the color difference ΔE_{00} between neutral and oxidized varnish against a white background. The influence of aged varnish is therefore extremely important as regards perception of the masterpiece.

	Rosin	Aged rosin	Mastic	Aged mastic
Density	0.03	0.17	0.02	0.19
Reflectance	0.94	0.68	0.95	0.65
L*	92.57	83.65	93.1	82.06
a*	-1.18	-0.86	-1.35	-0.97
b*	3.77	42.12	4.71	40.49
ΔE_{00}		19.85		19.24

Table 5: Aged and neutral varnish.

Based on these first results, we shall use aged rosin as the typical and likely alteration on the masterpiece. The varnish – which is liquid upon application – hardens once it has dried in order to protect the paint layer. This transparent and neutral application also has optical properties and adds depth to colors by increasing contrast and darkening the entire painting. We can observe a marked reduction of the reflectance factor linked with the change of interface between the air and the painting. The specular reflections become more important due to the decreasing differences between the dispersion indexes ($n_{air} - n_{pigment} > n_{air} - n_{rosin}$). The result is a fall in the intensity of incident light, which decreases at the surface of the pigments, and improved transmission in the pigment layer (multiple reflections), which saturate the colors.

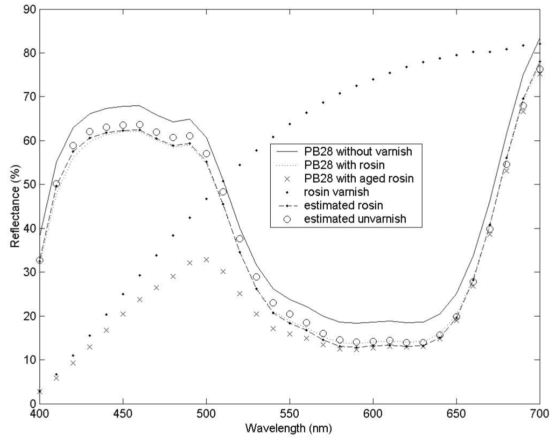

Figure 6: Cobalt blue pigment with the influence of varnish.

The glazing technique implemented by Leonardo Da Vinci to achieve the *Mona Lisa* is based on the same principles and, due to the numerous thin transparent layers, it enables efficient transmission of the incident light following the subtractive synthesis process. Existing publications dealing with the effect of neutral varnish define its action through two possible types of linear transformation: translation and spectral homothetic transformation. The former is more specifically dedicated to the surface finish of the paint layer (smooth or rough). On a sample of cobalt blue (see Figure 6), we can observe the action of the varnish, the behavior of which may be simulated through a 5.46 value translation. The varnish solely reduces the microroughness of the surface. In altered varnish version, the dividing of its reflectance measured by that of the oxidized varnish brings back the curves to the original reflectance of the pigment with unaltered varnish. We have tested two methods to determine this filter. The first method is based on the measurement of the oxidized varnish against a titanium white background; the influence of this background is removed through a measurement without varnish. The second method is based on the average quotient between the applications with oxidized varnish and that with neutral varnish. The results are summarized in Table 6 below. Method 1 leads to slightly better results.

	ΔE_{00}	GFC
Method 1	3.55 (1.71-6.84)	0.9961 (0.9894-0.9996)
Method 2	4.03 (2.29-5.66)	0.9927 (0.9757-0.9992)
Aged / Neutral	14.38 (1.94-31.3)	0.9326 (0.8152-0.9990)

Table 6: Performance of two different methods to determine the varnish filter.

This thus confirms the action of the oxidized varnish as a filter for all the pigments of the target (see Figure 7). The gain is significant compared with the chromatic distortion of the oxidized varnish, the average color difference of which is equivalent to 14.38 ΔE_{00}. The errors in the suggested correction are mainly located on the luminance axis and may be linked with the use of a gradation to white which does not enable sufficient accuracy between measures with and without varnish.

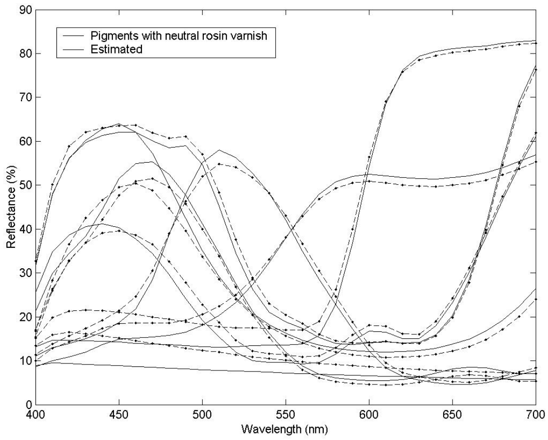

Figure 7: Pigment assessment without the influence of aged rosin.

4. Results

The materials of this famous masterpiece have been modified over time due to prevailing conservation conditions. The wooden support has shrunk and influenced type of cracks. The features of the binder, pigments and varnish have changed due to their own aging process or due to the interaction with other materials. The loss of opacity of the lead white is an example of pigment modification. The binder also has tended to turn yellow. Based on the above measurements of the period varnish target and a series of spectra reconstructed based on images of the Mona Lisa, suggestions for removing the varnish have been implemented.

4.1 Method 1& 2: Varnish filter with specific target

Within the scope of the reconstruction process, we apply under a specific illuminant the filter described above using the varnish target. In the absence of accurate knowledge regarding the materials which make up the paint layer, we have searched for an area which can be assimilated with a type of white. It is extremely rare not to be able to find hints of pure white in a painting – e.g. a collar on clothing –, but no obvious hint of white has been visually observed on the Mona Lisa. This could be due to the loss of lead white opacity over time. The research criteria have turned to colorimetric coordinates with a high level of brightness. Eliminating specular reflection has enabled us to reveal three groups with this specific feature over the entire image (see Figure 8). We have selected the one with the largest surface. This type of data retrieval may be carried out solely due to the high definition technology used, given that the size of the target area is equivalent to 0.07 mm^2 (4×4 pixels) on the painting. First, we shall use this data to observe the action of the suggestions for removing the varnish, then we shall consider a new correction method aiming at giving this area the reflectance of a potential pure white pigment – lead white (PW1).

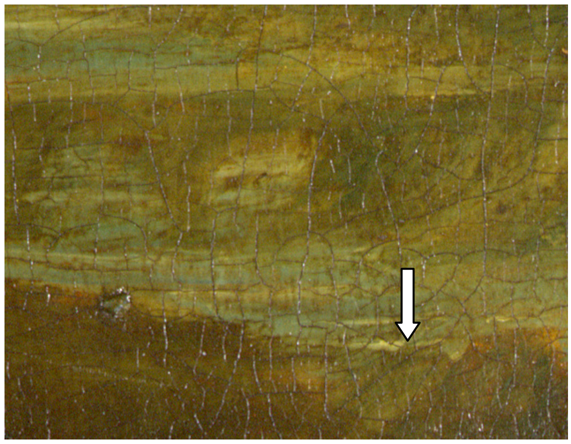

Figure 8: Location of a white area under the bridge. © Pascal COTTE 2004

The reconstructed reflectance curves are similar to that of an achromatic pigment (see Figure 9). The discoloration decreases, but the thickness of the varnish placed on the specific target is not identical to that found on the painting. The potential thickness of the filter is modified in order to refine the correction. The CIELAB colorimetric coordinates of the original area are compared with the new assessments without oxidized varnish (see Table 7). In both cases, the yellow factor strongly decreases, and taking the thickness into account, optimizes spectral matching with an optimal compromise obtained with a coefficient of 1.3.

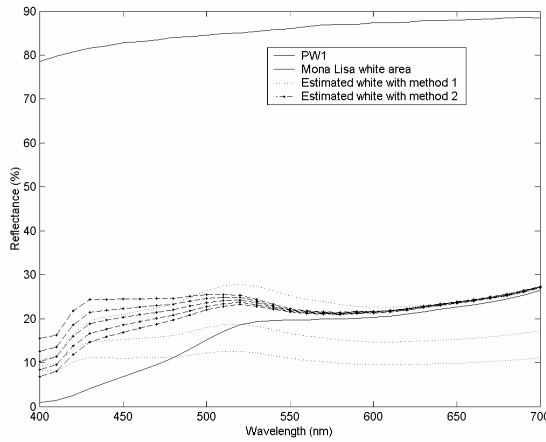

Figure 9: Pigment estimation without the influence of aged rosin.

	L*	a*	b*
Original	50.75	-6.03	29.98
Estimated M1	56.9	-7.88	6.28
Estimated M2	53.71	-4.67	9
Estimated M1'	49.38	-5.06	2.47
Estimated M2'	54.37	-3.51	3.77
Fresh PW1	94.37	-0.03	2.6

Table 7: Comparison of original white and estimated M1: Method 1, M2: Method 2 M': optimized thickness.

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Figure 10: Reconstruction of Mona Lisa under illuminant D65.
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Figure 12: Method 2' correction.
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Figure 11: Method 1' correction.
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Figure 13: Method 3' correction.
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As regards brightness, we can notice that the assessed spectra are below the value of fresh lead white; we shall take this into account later. Application to the image enables a new vision of the masterpiece (see color Figures 11 & 12). The shades of blue reappear, the lake and river come back to where they belong and the light shades become natural again. The composition and interpretation change completely. Comparing the original with the corrections makes it possible to confirm the existence of a global influence, given that they apply to almost the entire image without discontinuity. On the other hand, the sky does not recover its expected hue – yellow areas remain visible. The various interactions between the binder and the white-based mixture required to achieve the sky and different varnish thicknesses are possible hypotheses which may explain these local differences. The existing achromatic specular reflection on the edges of the image is enhanced through switching towards the blue shade. We are currently working on selective reconstruction solutions which would make it possible to manage specular reflection areas differently. The two correction methods suggested (method 1 and 2) make it possible to eliminate the yellowing of the varnish and the binder, but the global brightness of the painting nevertheless remains low.

4.2 Method 3: Varnish filter with white area of the Mona Lisa

Starting with the potential white area, we shall complete the alteration correction by taking into account the loss of opacity of the white area or its relevant darkening. We therefore resort to a third method, which consists in taking fresh lead white as a reference and applying the correction required to change the white sample of the painting into this specific pigment. The result also gives the image a neutral feature, and at the same time it gives some strength back to the different hues which have remained too dark further to the first methods (see color Figure 13). The yellow sleeves recover their radiance, as do the orangey-red brown shades of the path and hills. The final result shows that the darkening or the neutral density filter on the white area can apply to the entire image without defining a boundary between the various elements of the composition of the masterpiece. We can therefore consider applying this neutral density correction to the first methods.

4.3 Method 4: Indirect method

We presented the spectral reconstruction methods in the section about image processing. In this case, the indirect method has been used for specifically learning how to remove oxidized varnish. We apply an important database of known measurements without varnish and their corresponding measurements with aged varnish to build an inverse operator that allows the reflectance of *Mona Lisa* without influence of aged varnish from the original reflectance of *Mona Lisa* to be obtained. We used pseudo-inverse as a mathematical transformation. We did not have enough samples available to create a sufficiently defined system with our specific varnish target. In order to improve this method, we have been searching for a gelatin filter similar to the oxidized rosin. As regards transmittance, the filter with the closest features obtains a GFC of 0.9985. We thus applied on our learning targets a series of measures with the gelatin filter. The results obtained are slightly less satisfying, given that there is an identical dependence in the spectral reconstruction between the nature of the materials of the painting and the learning target. On the other hand, the filter was placed in wide width on a full-size print of the *Mona Lisa* with correction (method 2) compared with a print without correction. The visual correspondence under controlled lighting is extremely close and validates through this experimentation the color filter effect of the aging of the varnish and the binder of this masterpiece.

5. Conclusion

The results enable a better readability of the masterpiece with a restoration of the color ratios (sky, river, skin tone, dress), and the portrait and landscape thus recapture their full depth. The global modification must be considered as an intermediate phase prior to taking into account other effects in the paint layer such as the various thicknesses of the varnish and local interactions depending on the relevant materials. As regards chromatic and photometric aspects, we have defined the aging of part of the materials of the *Mona Lisa*. Two different functions define it – the first one is a color filter which may be corrected through knowledge of the features of our oxidized rosin or its synthetic copy (gelatin filter). The second one is a neutral density filter, the index of which would be 0.41 in the event of relevant existence in the layer of fresh lead white. The various results are extremely close as regards neutrality and make it possible to consider a common suggestion which will be used as a basis for complementary studies, such as pigment identification based on spectral signatures, which will be the topic of a future study.

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Biography

Pascal COTTE is the founder and President of various companies as Lumière Technology specializing in digital imaging since 1980 and has designed and developed numerous R&D systems in the field of electronic imaging. He has invented 6-band and 13-band multispectral cameras and obtained numerous patents in the field of multispectral imaging and lighting systems. Pascal received his bachelor's degree at the French Lycée in Sao Paulo, Brazil. He then received post-graduate education in computers and electronics followed by optics, light and color in Paris. France.

Damien Dupraz received his engineering degree in photography from the Ecole Nationale Supérieure Louis Lumière, France in 2002. After one year in the French Museum Research and Restoration Center as color engineer, he began a Ph.D. in spectral imaging with Lumière Technology company and Paris VI University.

Pascal COTTE (front), Damien DUPRAZ and Mona Lisa, 19th Oct, 2004