Under the lens of *ISLe*: Leonardo da Vinci’s "Landscape" drawing analysed by colourimetry

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ABSTRACT

On the occasion of the fifth centenary of his death, the Museo Leonardiano da Vinci celebrates its anniversary with the exhibition "Leonardo a Vinci. At the Origins of the Genius" which includes the exhibition of the drawing of *Landscape*, dated August 5, 1473, kept at the GDSU of the Uffizi Galleries in Florence. The University of Bologna has been asked to make a 3D rendering of the drawing that could be used as a substitute, capable of investigating, describing and communicating the drawing, its methods and contents, faithfully reproducing its form, characters and appearance. The answer was the *ISLe* application, a means of observing and understanding, interpreting and envisioning drawings and therefore able to penetrate the secrets of Leonardo's Landscape. Technically, *ISLe* aims to provide a unified answer to two distinct and complementary questions: the first is the creation of drawing archives that can accurately describe the information of the original analogical physical system; the second is related to the methods for the collection and rendering of 3D drawings, i.e those systems and techniques that allow for the reproduction and systematically show a perception of the form three-dimensionally thus creating a visual evaluation of the current state of conservation of the drawing, of the superimposed sedimentation and of any restorations received over time. This paper describes the experience and results.

KEYWORDS Leonardo da Vinci, Antique drawings, Colour analysis, 3D, Visualisation, MTF, LED light.

RECEIVED 09 October 2019; **REVISED** 23 November 2019; **ACCEPTED** 28 November 2019

1. Introduction

On the occasion of the fifth centenary of his death, the Museo Leonardiano da Vinci celebrates its anniversary with the exhibition "Leonardo a Vinci. At the Origins of the Genius" which includes the exhibition of the drawing *Landscape*, dated August 5, 1473, kept at the GDSU of the Uffizi Galleries in Florence (inv. 8P). It is a small representation written on a sheet of 196x287 mm, i.e. about an A4, in pen and iron gall ink of four different shades, red stone and lead tip on paper, which presents the famous depiction of landscape on the front and a series of figures on the back. A complex system of signs that has never allowed a definitive answer to a series of questions that still remain open today.

What is inside that tiny drawing, smaller than an A4 format and 50 cm away already concealing secrets to the human eye? What did Leonardo think when he drew the *Landscape*? What does the *Landscape* represent? The Valdarno as some people want it to be? Or the Marmore Falls as others want? And how did Leonardo manage to draw his subjects so quickly and so effectively, still today incredible to the vision? Was it the work of Leonardo alone, or, as some scholars claim, is the sheet an extraordinary example of dialogue between Andrea del Verrocchio's collaborators and perhaps Verrocchio himself?

In order to try and answer these questions on the occasion of the exhibition, the University of Bologna has created a three-dimensional digital communication artefact called *ISLe*, which allows the drawing to be reproduced with perceptual fidelity to the shape, characters, colour and appearance on a 55" 4K touch table, interacting with it as if it were in the hands (Fig. 1). *ISLe*, born from a series of experiences conducted over a decade (Gaiani et al. 2011; Gaiani et al. 2012, Apollonio, et al., 2015), using five photographs, reconstructs the three-dimensionality of the drawing, rendering it digitally as a computer graphics image under all conditions of lighting and observation, with perceptual fidelity of high colour and a resolution of 50 μm.

Fig. 1. Leonardo da Vinci's Landscape drawing seen through ISLe.

In order to faithfully reproduce the original *ISLe*, rather than use the traditional solutions based on 2D (i.e. very high resolution images) or 2D1/2 (e.g. Reflectance Transformation Imaging techniques (Malzbender et al., 2001)), it adopts a completely 3D paradigm, relying on the concept of 'total appearance' (Wilkie, et al., 2009). The developed solution aims to reconstruct the entire spatial reflectance of the artefacts in order to appreciate not only the graphic characters of the work (signs and traces), but also the undulations of the paper, as well as the critical conservation of the sheet due to corrosion of the acidity of the inks and other accidents, such as exposure to light and other atmospheric agents, which have affected the artefact over time. From an operational point of view, the solution consists in the evaluation of a Bidirectional Scattering Distribution Function (BSDF) and its rendering in real-time rendering (RTR), using a simple acquisition scheme and not harmful to the design.

The system follows in its entirety the one used in Leonardo's previous experience of *Vitruvian Man* (Gaiani, et al., 2015), introducing, however, countless innovations, starting from the same basic scheme, for the desire to improve some characters that already at the end of the previous experience had shown the possibility of improvements: the accurate reproduction of colour, the morphological configuration of the design, the reflection model of paper and ink.

From a technical point of view, *ISLe* is composed of six sub-systems:

a. An effective 48-bit colour capture, using an integrated camera-back scanning solution: the Rencay DiRECT Camera Systems 24k³. This camera features a Kodak KLI-8023 CCD sensor trilinear RGB with 8000 pixels per sensor, for a native resolution of 13000 x 8000 pixels and a maximum resolution of 39000 x 24000 pixels. The pixel pitch is 9 μm which allows a resolution limit of 55 lp/mm with 60% contrast. The lens used is a Rodenstock Apo-Macro-Sironar-Digital 120mm. f/5.6 72×96 performing excellent resolution even at the corners, limited distortion and uniformity of illumination;

b. A lighting system based on individual High Flux LEDs with white light Relio2 (https://www.relio.it/), an illuminator emitting continuous spectrum light at a CCT of 4000°K, a neutral white with high colour rendering, a brightness of 40,000 lux at 0.25 m and a CRI > 95%. It avoids the typical problems of fluorescent illuminators that do not allow the acquisition of information at certain wavelengths of light (Fig. 2) in addition to the presence of harmful ultraviolet (UV) and infrared (IR) rays;

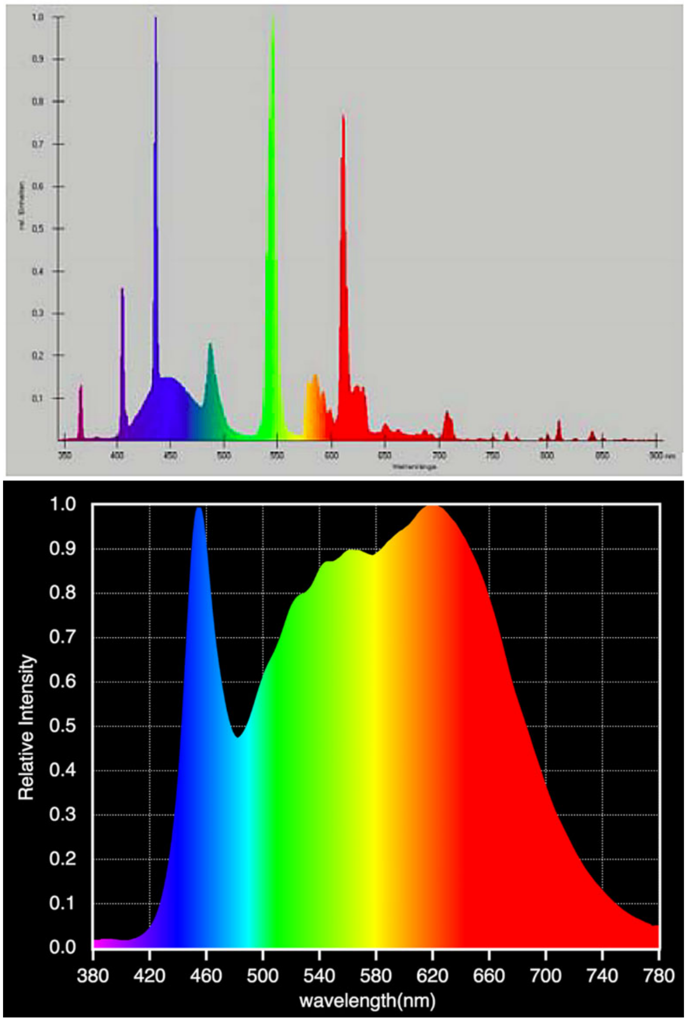

Fig. 2. Spectral Power Distribution of fluorescent light tubes for photographic use (left) compared to that of the Relio2 4000K lamp (right).

c. A computational model to give micro and macroscopic fidelity to the surface within a rendering window based on the OpenGL graphics libraries;

d. A software allowing an excellent Colour Correction from RAW images to faithfully reproduce the colour;

e. A solution to visualize the high-fidelity communication artefact using a rendering engine low-cost and portable on multiple devices (wall, monitor, PC, tablet, smartphones);

f. A visualization interface for visitors to museums and exhibitions based on touch and gestures usual because they are borrowed from those of smartphones.

Using *ISLe*, *Landscape* drawing has been examined as a graphic artefact through visual and colourimetric analysis. The paper shows the analysis results and a technical description of *ISLe* features more closely related to the type of analysis proposed.

2. Capture sharpness and resolution

The determination of the artist's tracing properties can be qualified only in the presence of an appropriate effective resolution of the images, in order to ensure the reproduction of all significant details present in the original document on the display device.

Two parameters must be measured to define the resolution: spatial detail and its preservation.

The necessary spatial detail can be established by a preliminary analysis of the document (MacDonald 2010). In this specific case, as already emerged from the analysis of other of his drawings, the trait of Leonardo's drawings is particularly challenging. The reference data reveal, in fact, sign values at a minimum of 90 μm thickness, while the wire rods making up the paper have a size of about 700 μm.

Following Shannon-Nyquist's sampling theorem, the resolution required to faithfully represent the structural characteristics of the *Landscape* is at minimum 565 ppi.

The measure of its conservation has been realized at different spatial frequencies through the measurement of the frequency transfer function (MTF - Modulation Transfer Function) (Jacobson, 1995), estimated by the spatial frequency response (SFR), i.e. the normalized module of the Fourier transform of a line diffusion function (LSF) (Ridler and Calvard 1978). The measurement of MTF is coded by the ISO 12233:2000-2017 (ISO 2017) standard, which provides for three metrological protocols, the most common of which is the one providing for the measurement of the slanted edge (Burns 2000). The method, which produces the Edge Spread Function (ESF) by scanning the image of an edge, has several advantages:

- The distance between camera and lens does not fit into the equation that converts the image to MTF response (it is invariant at scale);

- Inclined edges take up less space and are less sensitive to noise than sinusoidal models;

- MTF can be measured at Nyquist frequency (0.5 cycles / pixel) thanks to the binning/oversampling algorithm.

The characterization of the effective resolution was then carried out by measuring the MTF using an ISO 12233:2000 target size 200 x 356 mm and the software Imatest Studio version 4.5. The choice of the target defined in the 2000 standard has been made both because its defects do not particularly affect the results in the case in question, and because of the possibility of comparing the current results with those obtained in previous experiences with the same shooting system and similar subjects.

Base acquisition values		
	Venice	*Florence*
MTF50	0,099 Cy/Px	0,1425 Cy/Px
LW/PH	1600	2280
MTF10	0,26 Cy/Px	0,415 Cy/Pxl
MTF at Nyquist	0,00602	0,0545
10-90% rise	5,37 Px =1490 per PH	4,34 px =1845 per PH
Effective resolution	335 Px/inch	483 Px/inch

Acquisition values adding Unsharp Mask filter Venice [Intensity: 200; Radius: 1; Threshold: 6,00; Edge Offset: 0,00] Florence [Intensity: 150; Radius: 1; Threshold: 4,00; Edge Offset: 0,00]		
	Venice	*Florence*
MTF50	0,1699 Cy/Px	0,1791 cy/Px
LW/PH	2718	2865
MTF10	0,373 Cy/Px	0,452 Cy/Px
MTF at Nyquist	0,137	0,067
10-90% rise	4,99 Px =1604 per PH	4,76 Px =1682 per PH
Effective resolution	575 Px/inch	683 Px/inch

Tab. 1 - Vertical MTF. Comparison of MTF values in the two acquisitions: Vitruvian Man, 2014; Landscape, Uffizi, 2018.

The reference parameters were essentially two: MTF10 and MTF50. The MTF10, i.e. the frequency associated with the MTF response point of 10%, is used to evaluate the resolution capacity, i.e. the maximum resolution. The MTF50 is the most suitable parameter of image sharpness and to compare the sharpness of cameras and lenses.

In addition, the MTF technique has been used to evaluate the appropriate sharpening of image to remove the lens and sensor blur not achieved in-camera using an image editor and Unsharp Mask filter (UM). UM filter principle of operation is based on the fact that the contours of objects are locally areas of high contrast. In particular, an iterative system for finding the parameters of the UM was developed to minimize the phenomena of oversharpening and undersharpening, as proposed in (Williams and Burns, 2008). Ultimately, the response with respect to a slanted edge in terms of rising distance (rise 10-90%) and the MTF curve as function of the spatial frequency expressed in units of cycles per pixel, measured by the values of MTF50 and MTF10, were calculated. The average spatial resolution (horizontal and vertical) on an acquired image size of 13000 x 8000 pixels corresponding to a sampled area of 205.1 x 333.35 mm corrected with UM (values: Intensity: 150; Radius: 1.00; Threshold: 4.00; Edge Offset: 0.00), was for the rise 10-90% = 4.00 pixels; in the frequency domain was obtained an average MTF50 = 0.2445 Cycles/Pixels and an average MTF10 = 0.336 Cycles/Pixels, corresponding to an effective resolution of 740 px/inch (Tab. 1) capable of resolving details of 60 μm, finer than the minimum required.

Finally, the MTF values were compared with those recorded in 2014 on the occasion of the acquisition of the *Vitruvian Man* (Apollonio et al., 2015). The data resulting from the two experiences, despite the inevitable operational differences regarding some components of the equipment (such as the optical group of the target), confirmed the reliability of the procedure, and showed a slight improvement in the performance of the entire acquisition system in terms of quality of resolution, with an increase in the value of MTF50 and MTF10 and consequently of that of the actual resolution.

3. Colour Correction

A fundamental problem in the digital acquisition and reproduction of fine art drawings is the chromatic and tonal definition of the graphic work which, in our solution, must be framed within the more general topic of the complete definition of the material's properties, i.e. the Bidirectional Scattering Distribution Function (BSDF), so that it can be identified in the acquisition and reproduction of a colour map and a rendering algorithm.

Since the digital rendering of the reflection of a surface requires strong simplifications of the physical behaviour of light and its interactions with the surface in order to be calculable in a reasonable time, in the development of *ISLe* we have set ourselves the acceptable objective of restoring at least perceptual fidelity to the colour. For this reason, we followed a colourimetric approach based on the colour correction (CC) of the acquired RAW images, following a target-based technique, a particularly efficient solution when it is possible to define the requirements of the images and carry out the image under similar conditions of the target and of the subjects to be represented, exactly our case.

A fully automated CC solution developed by our team, so-called SHAFT (SAT & HUE Adaptive Fine Tuning) (Gaiani and Ballabeni 2018), was adopted for *ISLe*. It is based on an X-Rite ColorChecker Classic target (McCamy et al., 1976) (the expected values of which were obtained by measuring the patches of the ColorChecker used using a Minolta CM-2600 D ball spectrophotometer) and a two-stage CC process. A first correction is made using a per-channel polynomial fitting algorithm based on the MATLAB *Weigthed Polyfit (x,y,n)* function. The algorithm is explained in detail in (Gaiani, et al. 2017). A second correction is made using the actual SHAFT procedure *Weigthed Polyfit (x,y,n)*.

The process adopted follows the usual five rules of colourimetric imaging:

1. Correlated colour temperature (CCT) of the illumination 5000°K (D50 workflow);
2. Optimal exposure;
3. Colour profile based on ∆E minimisation with excellent brightness accuracy;
4. Target-independent validation used to create the camera profile;
5. Coding space capable of not cutting object colours.

As final encoding colour space we selected the sRGB-IEC 61966-2-1 whose values are defined with respect to CIE illuminant D65. Its potential contraindications (non-linearity, size smaller of the colour space perceived by humans) do not influence the colour quality of *ISLe* rendering. The *Landscape* not present badly representable colours by the sRGB colour space. In fact, iron gall ink, black chalk, red chalk and paper have colours completely inscribed in the sRGB colour space, without the need for colour clipping or remapping. On the other hand, the use of sRGB has a number of advantages including, mainly, full support from the 3D Graphic API used (OpenGL) and 100% displayability on today's monitors.

The CC workflow is instead completely realised in the linear space CIEXYZ. The reason is in the observation that, using this colour space, the errors calculated by the least squares fitting algorithms correspond very well to the deviations of the images corrected to the original, so fewer numerical deviations correspond to more visually accurate images (Lukac and Plataniotis 2007).

For the evaluation of the error in the correction both during the CC process and in the final validation, the colour metric issued by the CIE in 2000 (Sharma et al. 2005), calculated for each colour patch, was used.

As suggested e.g. in (Williams and Burns, 2016), a metric dispersion analysis was used in addition to the evaluation of the average ΔE_{00}.

The results show an average value of ΔE_{00} = 2.21, an average brightness accuracy of ΔL_{00} = 0.59 and an exposure error of 0.02 f-stop (Fig. 3).

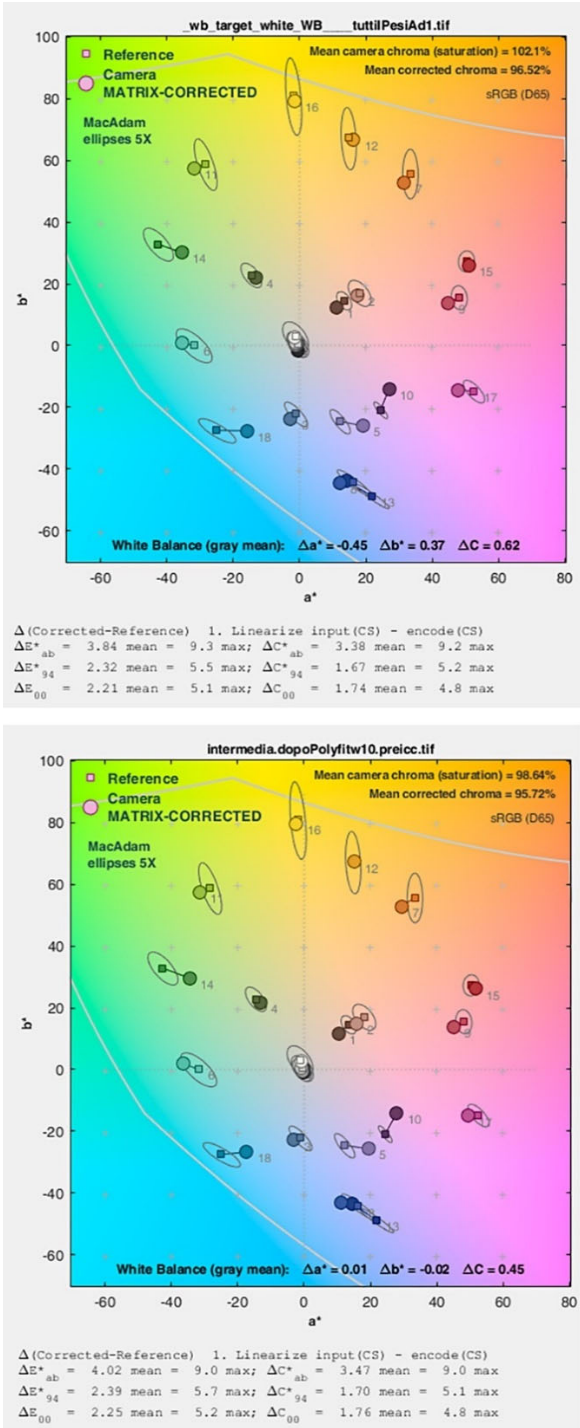

Fig. 3. Evaluation of the results of the CC using equal weights of all patches (above) and different weights between the various patches (below)

However, the evaluation of the ΔE_{00} error on the individual patches led to significant problems in the area of the yellow (for the D3 patch we reported a ΔE_{00mean} = 4.2) and partially of the red (for the C3 patch we reported a ΔE_{00mean} = 2.8), confirmed by direct and comparative observation of the correct images and the original drawing. This restates the observation of many authors that the CC procedure using standard colour targets is problematic when the object to be reproduced is characterized by a limited range of colours close to neutral colours, which is the typical case of the drawings (Berns et al. 2005, Trumpy 2010).

The experimentation of some solutions proposed in the literature, such as the construction of a personalized chromatic target with patches empirically chosen within the palette of colours present in the original (Williams and Burns, 2012), has shown a strong aleatory in the choice of candidate colours, as well as the verification using a different target from the original one has led to unsatisfactory results for the difficulty to reproduce measured distributions of colour not too dissimilar (Williams and Burns, 2016b).

A different procedure was therefore preferred:

A. From the images of the drawing (recto and verso) obtained from the standard CC process, corrected images were created manually using Adobe Photoshop on two different calibrated monitors (NEC Spectra View 2690 and Spectra View Reference 302) respectively at 5000°K and in sRGB colours for visual comparison with the original drawing placed next to the monitors and illuminated with the LED lamp used for the acquisitions until obtaining perceptively marginal differences at the prolonged observation of five expert users;

B. on a RAW image the CC process was carried out with SHAFT but giving different weights to the patches of the ColorChecker Classic emphasizing the neutral A4-F4 and those of the colours closest to those present in the drawing. This procedure has been repeated for various weights;

C. the images of the drawing thus obtained were compared by 20 expert subjects with respect to the original drawing illuminated with the LED lamp used for the acquisitions on the two NEC Spectra View monitors calibrated as above (5 people) and with respect to the correct image manually (20 people of which 5 on the two NEC Spectra View monitors, 15 people on the LaCie 526 monitor calibrated with respect to the sRGB colour space).

Considering that the changes in ambient light only affect the perception of absolute colour, but have no effect on the relative sensation of colour difference (Hao et al. 2011), the verification was held in two differently lit environments capable of allowing an observation as close as possible to that defined by the standard ISO 3664:2009 (ISO 2009).

All observers found perceptually marginal differences in the prolonged observation of the images in which was assigned a weight 2 to the patches A1, B1, A2, F2, C3, D3 and A4, and a weight 3 to the patch F4.

For this CC solution we achieved a ΔE_{00mean} = 2.25, a ΔL_{00mean} = 0.63 and an exposure error of 0.00 f-stop which corresponds to the indistinguishability from the real on a calibrated monitor. Moreover, for the D3 patch we obtained a ΔE_{00mean}= 2.88 and for the C3 patch a ΔE_{00mean}= 2.27 (Fig. 3).

4. The Landscape seen through *ISLe*

Here we briefly summarise only some of the main characters of the drawing compared with those of another drawing by Leonardo: the famous *Study of proportions of the human body*, previously acquired and analysed (Apollonio, et al., 2015). As main literary reference were used for the first drawing the Alessandro Nova's essay "*Addj 5 daghossto 1473*" (Nova 2015) and for the second one a paper by Loretta Salvador, the last restorer of the drawing (Salvador 2009).

The *Landscape* drawing has laid wires placed at regular intervals, horizontally, of a size of about 800 μm (13 lines per 10 mm approx.). These laid wires are well distinguishable on the front and are almost indistinguishable on the back, demonstrating that this was the part of the paper most treated, contrary to what happens in *Vitruvian Man* who shows the laid wires on the back, while they are not perceptible on the front. Chromatically, the paper is very similar to that of the drawing in Venice today, because it took three areas of 250 x 150 pixels in more parts of the drawing (front of both) blurred using a bilateral filter (Paris et al. 2009) and normalized the brightness, the average values read were for the *Landscape* L*a*b*= 87 4 11, for the *Vitruvian Man* L*a*b*= 87 4 13. The two drawings, on the other hand, have different average luminosity, for the *Landscape* L*= 82, for the *Vitruvian Man* L*= 87.

This last circumstance may be due to different causes, which may range from exposure to sunlight to the treatment of paper.

The comparison between the back of the 8P and the front of the *Vitruvian Man* shows identical colourimetric values. Taken three areas, as in the above analysis, the average values are L*a*b*= 87 4 15, supporting the hypothesis that the main face of the *Landscape* is the one that is currently commonly identified as verso.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9
L	55	54	54	47	45	44	41	42	47
a	12	12	16	12	12	13	13	11	10
b	26	24	26	16	14	14	16	13	14

Tab. 2 - Leonardo da Vinci, Landscape, colourimetric analysis of inks from images acquired, recto.

	Point 1	Point 2	Point 3	Point 4	Point 5
L	36	36	37	44	44
a	5	9	7	12	10
b	8	10	12	17	15

Tab. 3 - Leonardo da Vinci, Landscape, colourimetric analysis of the inks from the images acquired, towards

The colourimetric analysis of the inks identifies the use of two distinct substances that constitute two distinct graphic layers of the drawing. The first one includes the general layout of the composition, with what has been interpreted as the Fucecchio marshes, the hill on the right, the mountains in the background, the trees, and the layout of the hill on the left. The second instead includes the spur above the squared rocks, the waterfall, a series of retouches in the lower part, the confluence between the two rivers, and what has been recognized by some authors as the castle of Montevettolini. Table 2 shows the values in the L*a*b* scale for the samples extracted, located in the same table and Fig. 4 shows details extracted from the application that well show the realization with two different inks/instruments. Fig. 5 divides the traits of the drawing into two large families identified using the K-Means Clustering segmentation algorithm based on colour (Arthur and Vassilvitskii 2007).

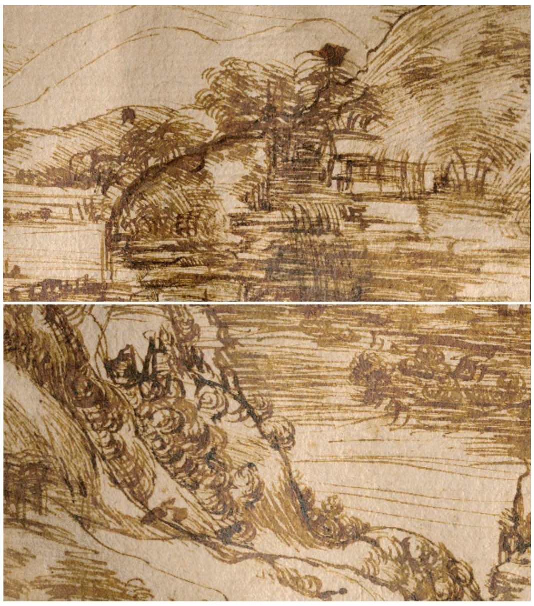

Fig. 4. Leonardo da Vinci, the Landscape seen through ISLe: different inks/instruments on the front of the drawing.

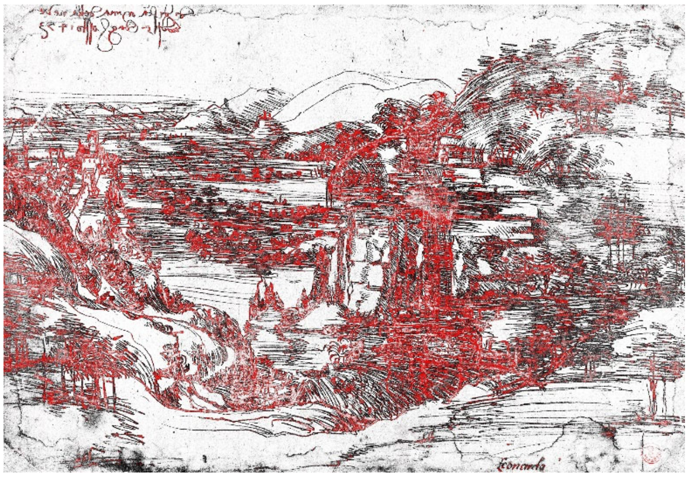

Fig. 5. Leonardo da Vinci, the Landscape seen through ISLe: different inks/instruments on the front of the drawing.

According to the colourimetric analysis, also the back of the drawing is made with two different inks. Their today colour is even different from those present on the front. An ink is used to draw the naked man in movement, the head in profile on his left and the words "*Jo Morando dant[oni]o sono chontento*". The second ink is used to sketch the mountainous landscape with the bridge over a stream and the foliage of the trees. Table 3 shows the values on the L*a*b* scale for the samples extracted.

Compared to *Vitruvian Man*, in whom two different ink are used to write and to draw the variation of chromaticity of the inks in the Landscape is much wider. This variation can be appreciated also by non-expert observers while the chromatic differences of inks used in the drawing today in Venice are much less evident and perceivable only by an expert observer.

As for the stroke, on the front of the 8P we can see the use of two different types of pens, one used for the background layer with a stroke width of 0.7-1.5 mm (and usually 1.2 mm), and one for the foreground layer with a width of 1.2-2 mm (and usually 1.7 mm).

It is a very different technique from the one used in the *Vitruvian Man* where the freehand strokes have an almost constant width of 0.3 mm and the straight strokes drawn on the groove have an almost constant width of 0.2 mm, as that drawing is without smudges, "perfect for a technical drawing that had to "prove" the proportions" (Salvador 2009).

5. Conclusion

The observation of the *Landscape* drawing through the colourimetric and the stroke analysis allowed to focus on features otherwise difficult to observe. It emerges, completely in line with the Alessandro Nova statement, that this drawing is a complex graphic system, certainly produced in several phases, a sort of work-in-progress that has generated various figurations, of which what appears today on the front is the most striking result for the character of completeness despite it is the result of at least two different tools each of which is used in a specific and homogeneous area of the drawing.

6. Conflict of interest declaration

The authors declare no conflict of interest.

7. Acknowledgment

We would thank the director of the Gallerie degli Uffizi in Florence Eike Schmidt, the director of the Museo Leonardiano in Vinci Roberta Barsanti that allowed this work. A special thanks to the members of the research group: Andrea Ballabeni, Giovanni Bacci, Marco Bozzola, Simone Garagnani, Roberto Palermo.

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