A Scientific Method for the Attribution of Paintings with application to Leonardo's Mona Lisa twins

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Introduction

The attribution of great paintings is one of the most important activities in modern museum work. The attribution of an artwork is the result of authentication – a procedure for the confirmation of its authenticity. The main task in authentication is to find material evidence by which it is possible to indisputably acknowledge the experts' conclusions about the authorship and the painting's time of creation. The author's signature, the dates and monograms left by artists on the front or back of the picture, as well as accompanying inscriptions and historical information on the provenance of the work are among such proofs. Unfortunately, the influence of the environment, adverse storage conditions and the consequences of radical restoration intervene in the structure of the painting and often lead to these proofs disappearing.

Furthermore, in many paintings, the artist's signature is actually absent. In such situations, it is necessary, in order to remain objective, to use natural-scientific approaches, including various optical and physical methods for studying the structure of the painting. However, despite the availability of a wide range of contemporary analytical research methods, they do not always prove to be effective enough to obtain the necessary information. In fact, the determination of the composition of the paint layers and the dating of a painting's support (by means of carbon dating and dendrochronological analyses), even combined with research results by art history experts, does not always allow for its attribution to the hand of a certain artist. Hence, the need to develop a new scientific method for studying paintings, which provides information that cannot be obtained with the use of traditional research methods, and which avoids subjective opinion.

In recent years, numerous computer methods based on the analysis of optical images obtained with the aid of digital photography have appeared in the field of the authentication of artworks. Most methods of computer analysis serve as a means for studying the visual characteristics of an artist's brushstrokes. Till now this information has been used to study paint layers and style. However, since in most cases the technique of applying the paint is highly individual for each artist, it can be considered as a "fingerprint". How to extract and analyse this "fingerprint"? The mathematical methods of processing a digital picture ("quantification") include the statistical method of a wavelet analysis, the support vector method, the fuzzy clustering method, etc., which are all used to analyze the brushwork technique [1] – [4]. In some cases, these methods are combined with analysis methods from other scientific fields, e.g. biometrics and medicine [5]. In this article, a scientific method for the comparative analysis of paintings is described, which employs intensity histograms of their digital optical images being the extraction of this "fingerprint". The possibilities provided by this method are illustrated by a case study of two paintings by Leonardo da Vinci.

Basic principles of histogram analyses in paintings

When creating a picture, an artist often applies a huge number of brushstrokes to a canvas , a panel or another support. The resulting painting surface thus acquires specific spatial and spectral characteristics that can be

identified for the analysis of the individual painting technique of the particular master. The brushstrokes of each artist, as a rule, have a certain length and direction, as well as a viscosity of the paint particular to this master. They result from the texture of the brushes, the speed of the hand movements, the particular features of the color palette, as well as from the pigment mixing techniques and the use of glazing.

In light of this, one of the possible ways of studying the properties of an artist's painting technique is to analyze the histograms from digital images of the paintings. Any amplitude histogram (another name for the intensity histogram) of a digital optical image is a function (graph) of the statistical distribution of the image elements of various intensities, in which the horizontal axis indicates the brightness level and where the relative number of pixels with a specified brightness value are plotted on the vertical axis (a typical histogram is shown in Figure 1).

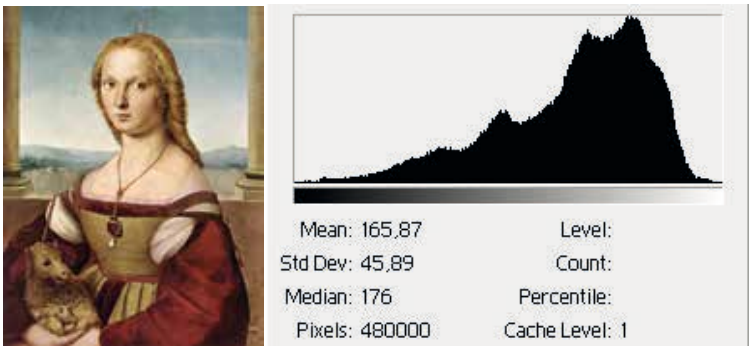

Fig. 1. **"**Young Woman with Unicorn" by Raphael (c. 1505-1506; Galleria Borghese in Rome) and **histogram of digitized image of face of woman**

The histograms from the digital images of paintings can be considered as the artists' "fingerprints", as mentioned above. This is connected with the fact that the histograms display a unique distribution of light and dark shading reflecting the style of each master. In fact, the analysis of pictures with the use of histograms is a quantification of their *chiaroscuro*, meaning "light and darkness", and it refers to the technique of painting that is characterized by a sharp contrast of light and dark tones. This technique serves to convey contrasts, often quite dramatic, in a painting. The term *chiaroscuro* should also be understood as the general character of the distribution of light and dark tones throughout any pictorial image. In the opinion of many art historians (including K. Clark and C. Pedretti [6], [7]), the analysis of the chiaroscuro feature plays the most important role when comparing the paintings of different great masters, since in the process of creating the works each artist develops the dance of "shadows" that is peculiar to him, and which is a unique individual characteristic of his painting technique. Thus the scientifically extracted histogram of the digital image of a painting is the identity of an individual artist's "fingerprint".

As a rule, chiaroscuro is a result of the blending of the color saturation and albedo from one region of a painting to the adjacent zones. Under the traditional subjective approach of the attribution of paintings, the art expert evaluates a picture visually (without any use of analytical methods). The properties of the spatial blending and contrasts of light and shade are the main features that are taken into consideration to establish the authorship of the artist's works and to determine forgeries or copies. This visual impression is correlated in the expert's mind with his memory of impressions of similar authenticated works by the same artist. As a result of this comparison, the expert gives his/her conclusion. Obviously, the analysis of the intensity histogram of the digital image of the picture, will allow the experts to conduct a more objective examination with the aid of mathematically precise data.

Method of the analysis of pictures through intensity histograms

Regarding the technical aspects of a histogram analysis, in all the typical formats of digital optical images, the pixels range over 256 intensity levels (their values can vary from 0 to 255). Currently, many computer digital image-processing programs incorporate special functions that allow us to obtain reliable histograms. Using the histogram "intensity" option, we can then count and plot the number of pixels (in the whole image or an individual region) for each of the 256 intensity levels. The graphical dependence of the quantification (the number of pixels) on the intensity level is known as an amplitude or intensity histogram.

When paint pigments are blended uniformly, the luminosity of the picture image can vary widely (from bright-light to very dark tones). In this case, the gradient in the luminosity distribution of the individual pixels from the highest to the lowest intensity values will be uniform (there will be no discontinuities or abrupt transitions in the distribution of the histogram). It should be added that each intensity histogram is characterized by two basic mathematical parameters: mathematical mean and standard (mean-square) deviation. When analyzing the artists' brushstrokes, the most important characteristic from these two parameters is the standard deviation. Therefore, when a painting is being examined by means of an analysis of the histogram of its digital image, one should not only compare the form of the distribution, but also take into account the value of this standard deviation. Paintings created by the same artist should obviously have a close similarity in terms of the painting technique, and consequently, their histograms should be similar to each other according to these two criteria. This is key to a comparative analysis of paintings based on a quantitative exposure of the artist's style through amplitude histograms.

In order to obtain more precise results when comparing histograms, it is advisable to convert the color image to a grayscale (that is, to a black and white image). The results can be more accurate if a comparative analysis of the histograms from color images is carried out in different spectral bands (separately in the red, blue, and green ranges).

It should be understood that histogram analysis is specifically a method of *comparative* analysis, i.e. comparing the painting under examination to others which have already accepted attributions. It is important to bear in mind that the painting techniques can change throughout an artist's life. Therefore, some differences in the characteristics revealed through histograms can be explained by the evolution of the artist's style and technique. It is also important to take into account that artists with little or no chiaroscuro technique may not manifest themselves in the individual histogram features of the digital images of their pictures.

As shown in research studies [8], [9], the works of those masters with a very delicate painting technique most often have very distinctive features in the histograms. An excellent example is Leonardo da Vinci. Leonardo is well known for being the first to apply the technique of sfumato (from the Italian *sfumare*, meaning "to evaporate like smoke"). This term denotes a manner of painting that is marked by fine shading which softens the outlines of figures and objects, and even allows the artist to convey the air that envelopes them. It was discovered in the course of recent research involving Leonardo's paintings that this effect was achieved by applying brushstrokes with a thickness of several micrometres, and that the total thickness of the paint layer often did not exceed 30-40 micrometres.

It is important to note that in portrait painting, analyses of histograms are the most effective when comparing facial characteristics. The subject of such a histogram analysis is best as a comparison of the parts of the paintings depicting human faces, for the face is the key element in the composition of a portrait. It is known that great masters often involved their assistants and apprentices in the performance of their work. However, the depictions of the faces in portraits were, as a rule, executed by the masters themselves. Consequently, a histogram

analysis of the facial images is the most reliable way to establish if works being compared belong to the hand of the same master.

Comparative analysis of the Leonardo paintings "Mona Lisa" and "Isleworth Mona Lisa"

As a clear illustration of what can be achieved by the histogram method, we present the results of a comparative analysis of the paintings Mona Lisa" and "Isleworth Mona Lisa". The composition of the "Isleworth Mona Lisa" is very similar to the famous "La Gioconda" displayed in the Louvre (Figure 2). According to many painting experts [10], [11], it is an earlier version of this subject, and it therefore is also often referred to as the "Earlier Mona Lisa".

Fig. 2. Left : Louvre "Mona Lisa"; Center: "Isleworth Mona Lisa"; Right: "Young Woman" (c. 1504) by Raphael

Like most Leonardo paintings, the certainty of its early provenance is not absolute, but historical documents lead us to conclude the existence of two original Mona Lisa paintings in the early 16th century – one in the French Royal Collection now in the Louvre Museum, and one with side columns that Raphael copied in a 1504 sketch (Figure 2) which was listed in the estate of his servant Salai. That latter painting is acknowledged by many experts today as the "Isleworth" or "Earlier Mona Lisa". This painting also fits Vasari's description of being unfinished and must be the seminal work which generated all the copies we have today with columns.

Most of the important detailed scientific research of the "Isleworth Mona Lisa" (including X-rays, UV- and IR-ray examinations, studies of the pigments with the aid of spectral methods, radiocarbon analysis and others (see the details in [12])) has been carried out during the last 10 years.

From this research, it was found out that all the pigments and the ground of the picture are identical to the materials used in the early 16th century by Italian artists and by Leonardo himself. Besides this, following carbon dating tests of the support, the approximate time of the creation of painting was determined to be between 1492 and 1652 with highest probability between 1493 and 1525. New studies were carried out by the authors of this article with the aid of a comparative analysis of the digital images of both paintings.

In 1989, following his extensive and successful work on the attributions of Rembrandt self-portraits, on the instigation of Dr. Kenneth Clark, one of the authors (John Asmus) received a special invitation to study in depth the Louvre "Mona Lisa" including a complete day alone with the famous artwork. He carried out a computer "restoration" of the Louvre "Mona Lisa", which revealed an idea of the original appearance of the portrait – without the dark yellow varnish and the craquelure webs that lie over the image [14]. This was soon followed by an

invitation to examine the "Isleworth Mona Lisa". As the results of these studies Asmus became widely known as a top scientific expert on brushtroke technique and identification.

During the first stage of the research on the detailed studies of digital images of both paintings and their comparisons were conducted. The proportions and arrangement of the key elements in the composition of both paintings showed that the "Earlier Mona Lisa" could not be a copy of the Louvre painting since the pictures differ significantly from each other in terms of the proportions of the images and in many other fundamental matters of construction. In addition, their main axes (the axes that can be aligned along the eye line (horizontally) and the hairlines section (vertically) do not coincide (see Figure 3) (for details, see [15]). When comparing the intensity histograms from the images of both paintings the very first results proved to be astonishing. The character of the distribution and the main parameters of the histograms (mathematical mean and standard deviation) in the areas of the face were almost identical in both pictures (Figure 4). Consequently, if the histograms of the digital images are the "fingerprints" of their authors as proven in the experience with the Rembrandt portraits, we can draw the conclusion on the basis of the experimental data that the faces of the "Isleworth Mona Lisa" and the Louvre "Mona Lisa" would most likely have been created by the same artist.

Fig. 3. Comparison of geometrical features of images of the Louvre "Mona Lisa" (left column) and "Isleworth Mona Lisa" (right column)

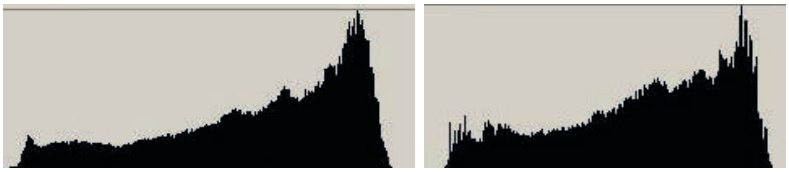

***Fig.4*. Histograms of digitised images of the Louvre "Mona Lisa" (*left*) and "Isleworth Mona Lisa" (right)**

To give such a conclusion a more solid ground, supportive analysis of the histograms of digital images from the most famous copies of "Mona Lisa" was undertaken. These include: 1. The "Mona Lisa" from the Prado Museum in Madrid (Spain) considered to be the earliest copy of the Louvre "Mona Lisa"; 2. The "Mona Lisa" from the Museum in Oslo (Norway) dating from the 17th Century; 3. The "Mona Lisa" from the Walters Art museum

(USA), attributed to Simon Vouet (1590-1649); 4. The Reynolds "Mona Lisa" (private collection, UK) and 5. The "Mona Lisa" Flemish school (private collection, UK) dating from the XVI and XVII centuries, respectively,

All of the portraits listed here are shown in Figure 5. The study of the histograms of their digital images showed that they all have significant differences that make them distinct from the histogram of the Louvre "Mona Lisa" (Figure 6 shows some of the histogram distribution characteristics).

Fig. 5. From left: Prado "Mona Lisa", Walters "Mona Lisa", Flemish "Mona Lisa", Reynolds **"**Mona Lisa" and Oslo "Mona Lisa"

In the data comparison shown in Figures 4 and 6, it is demonstrated that the histograms of the digital images of all the copies are distinctly different from the histograms of both the Louvre "Mona Lisa" and the "Isleworth Mona Lisa" (they differ not only in the distribution characteristics of the histograms, but also in their basic parameters). This significantly distinguishes the "Isleworth Mona Lisa" from the copies of "Mona Lisa". However, in order for the attribution to be even more accurate, we also compared the histograms of the individual features of the faces in all the portraits (eyebrows, eyes, nose, mouth, chin, etc.).

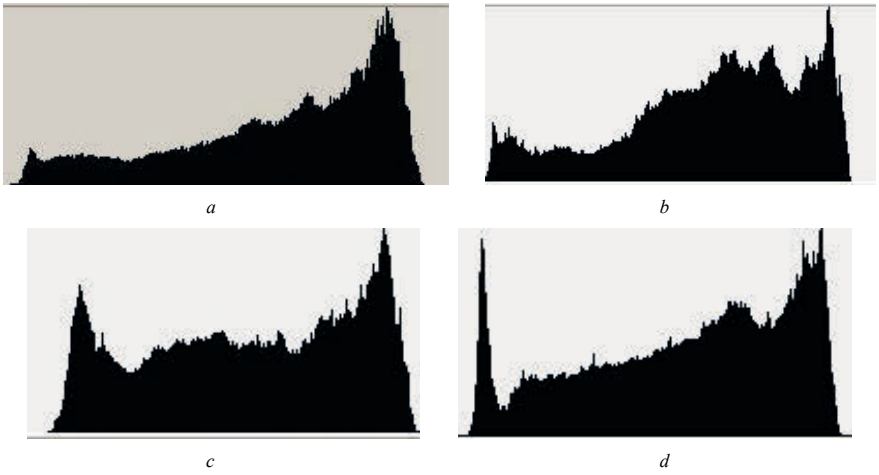

Fig. 6. Histograms of digitised images of the Louvre Mona Lisa (*a*) and its copies: with The National Gallery (Oslo) (*b*), with The Walters Art museum (*c*) and with Prado museum (*d*)

According to Morelli [16], studying the details of the art form allows us to reveal the specific character of the individual style of each master. Morelli was convinced that the artist's personality manifested itself in small details, since both the artist and the imitator displayed the individual features of their painting technique by a natural stroke, rather than in a neat signature which is applied consciously in both cases. This is due to the fact that while painting the details, the artist becomes relaxed and acts intuitively. Consequently, an analysis of the individual parts in paintings with a similar composition may reveal the distinctions in the techniques of different artists most clearly.

In addition, a comparison of the histograms of the images of all the above-mentioned works was carried out in different spectral bands (in the blue, green, and red ranges). Some of these histograms are shown in Figure 8.

a *b* *c*

Fig. 7. Histograms of digitised images of Reynolds Mona Lisa (*a*), Louvre Mona Lisa (*b*) and "Isleworth Mona Lisa" (*c*)

As can be seen from the graphs in Figures 4 and 7, in all cases, there is a very good correlation between the histograms of the "Isleworth Mona Lisa" and those of the Louvre "Mona Lisa". This similarity becomes particularly remarkable if the histograms of these two portraits are superimposed on each other (see Figure 9).

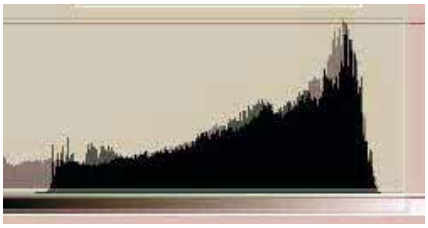

***Fig. 8*. Result of matching of histograms of digitized images of faces (in the field of nose) appeared on paintings "Isleworth Mona Lisa" and Louvre Mona Lisa** (background is histogram of "Islweworth Mona Lisa")

On the contrary, the comparisons of the histograms from the Louvre "La Gioconda" and its copies in similar studies indicate many apparent differences. The same result is demonstrated in a 3D-diagram (Figure 9). It shows the normalized values of the standard deviation of the histograms of the Louvre "Mona Lisa" (LML), the "Isleworth Mona Lisa" (EML), the copies from the Prado museums and the Oslo museum, and the copy executed by the Flemish painter. On the three axes in the diagram, the values of the standard deviation of the histograms from all these pictures in the regions of the nose, mouth and eyes are plotted. The graph clearly displays that the Louvre "La Gioconda" and the "Isleworth Mona Lisa" have the best correspondence in the standard deviation.

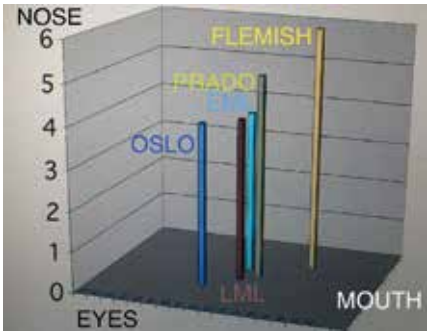

Fig. 9. 3-D plot of the statistical variances of three regions (eyes, noses, and mouths) of five *Mona Lisa* paintings (Louvre and Earlier/Isleworth versions as well as the Prado, Oslo, and Flemish copies)

Thus, based on the results of careful retracted studies of digital optical images of the Isleworth and Louvre "Mona Lisa" paintings, we can conclude that the faces in both works were created by the same artist.

Conclusion

In this article, a computer method for the comparative analysis of paintings is described, which could be useful for making the final decision on the attribution of paintings in those controversial situations when traditional methods of examination do not work or where there is a disparity in the subjective opinions of experts. It is worth mentioning that this approach was recently applied by the authors to the study of Rembrandt's self-portraits, where it showed the highest degree of efficacy. The results of that work will be published in a separate article, but it should be noted here that there is a clear correspondence between the results of the authors' research and the data on the attribution of Rembrandt's self-portraits, which were obtained in his paintings with the aid of technical and technological studies, and by an art examination conducted within the framework of the international Rembrandt Research Project [17].

Finally, it is important to say that the success and the further progress of this approach will depend entirely on the creation of an extensive histogram database of the properties and statistics of the most famous artists' works, which are recorded as a result of detailed studies. This may lead to more precise conclusions about the final attributions of the paintings on which art historians' opinions currently differ. It will provide a scientific method which may eventually be accepted as the most credible and popular way chosen by museums and collectors for the attribution of great artworks in light of its obvious objectivity.

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