Microchemical Journal 185 (2023) 108276

Contents lists available at ScienceDirect

Microchemical Journal

journal homepage: www.elsevier.com/locate/microc

Artomics: A holistic approach to the study of artworks integrating their compositional and formal characteristics. Application on the *Liber Feudorum Maior*

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ARTICLE INFO

Keywords:
Artomics
Multivariate techniques
XRF
PCA
Illuminated manuscripts

ABSTRACT

A novel analytical approach which combines the compositional and formal characteristics describing groups of artworks and their analysis using multivariate techniques is presented, under the title of *Artomics*. This approach aims to identify characteristics transferred, both voluntarily and involuntarily, to the objects due to the cultural, social and economic context of the time period they were created in. These characteristics are expressed through the material and iconographical choices made by the artists or artisans involved, and may include the materials used, the creative processes or techniques applied, decorative styles and calligraphy types amongst others. The suggested methodology has been applied to the study of the *Liber Feudorum Maior*, a medieval illuminated cartulary, extensively decorated with miniatures painted in two distinct styles and possibly created by more than two artisans. Data from X-ray Fluorescence (XRF) analysis is combined with the formal characteristics of the miniatures, previously parametrised using descriptive variables, in an effort to conjunctively classify the illustrations, study the possible participation of multiple artisans in the elaboration of the manuscript and observe how cultural criteria are projected on the objects. The combined analysis of the formal and compositional data revealed a classification which could be related to differences in the miniature execution. The joint classification prioritised stylistic variables over compositional ones, most likely because of the limited variety in the materials used for painting and the conventions for these representations during the Middle Ages. Nonetheless, compositional data provided interesting insights regarding execution, such as differences in the gilding techniques used.

1. Introduction

Cultural heritage objects can be considered time-capsules that allow an insight into the moment of their creation through their characteristics. These characteristics, intentional or not, are related with the art piece as a whole and emerge from the specific details, such as its form, decorative motifs, morphology, structure and material composition. These characteristics are determined not only by the artist, but also by the state of the society in the moment of the artwork's creation, which includes the availability of materials, the artisanal know-how, interactions with other cultures and artistic movements. This is especially relevant for artists of older times, when creative processes were limited by the technological advances of the times.

In many works there is a tendency to keep the stylistic and compositional study of artworks separate, a consequence of the traditional separation of scientific disciplines. However, the material characteristics of an art piece can greatly enrich its perception from a historical point of view, whereas it is impossible to truly comprehend compositional results if they are not contextualised. Based on this perspective, it becomes clear that an approach that combines information on content, style and materials is necessary in order to extract the largest amount of information regarding the object being studied. This combined study can help define the social, cultural, economic and ideological context in which the art piece was created in and determine the purpose of its existence.

A step towards the union of these disciplines is the simultaneous study of the parameters considered, in a way similar to hyphenated analytical techniques or data fusion methods already applied in Heritage Science [1,2]. With *Artomics*, we propose the combined study of the formal or stylistic and compositional characteristics of art objects, in an

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https://doi.org/10.1016/j.microc.2022.108276
Received 11 September 2022; Received in revised form 21 November 2022; Accepted 30 November 2022
Available online 1 December 2022

effort to correlate two aspects that are most often studied apart. The term *Artomics* has been previously used [3] in order to describe the application of -omics techniques to the study of archaeological findings and art objects. Conscious of the significance of the -omics suffix, deriving from Greek terms ending in -ώμα, which refers to the studying of a totality, we redefine the term and propose a metaphoric use of the definition, which would represent this holistic approximation when studying an art piece. The theoretical base of -omics in biological sciences is that by considering a complex system as a whole, a more thorough understanding of it can be achieved [4]. In this sense, and by drawing a parallelism with the definition of metabolomics offered by Daviss [5], as "the systematic study of the unique fingerprints that specific cellular processes leave behind", *Artomics* would represent the study of the "material fingerprints" left behind by creative processes, which in a way can be considered as fingerprints that a society transmits to the future through the artist and the object. These fingerprints would include both the formal and compositional characteristics of the objects, which should be studied jointly. The approach can be adjusted and complemented in each study case by including relevant information, such as the social or geographical context of the art piece.

Information regarding the process behind an artwork's elaboration or evolution and answers to matters regarding provenance and authorship or social activities can often be obtained through the compositional study of the object and the determination of the materials that make up the art piece. Significant advances have been accomplished in the field, in which a variety of analytical techniques are used in a complementary way, in many cases jointly [6–14]. Amongst these techniques, X-ray Fluorescence (XRF) is very commonly used for the analysis of illuminated manuscripts, as it is non-destructive, offers the advantage of providing information on the layers found immediately under the illustrations' surface, casting light on the creative techniques used, and also permits the collection of elemental distribution maps (Macro X-ray Fluorescence, MA-XRF), which can greatly facilitate interpretation [15,16].

The amount of data resulting from these multi-modal analyses or large-scale imaging techniques is very large and the data treatment can often become very complicated. For this reason, it has become almost the standard to introduce chemometrics tools in the data processing stage of the study. These multivariate techniques help to highlight the most important compositional characteristics of the samples, by reorganising the information and presenting only what is considered most relevant. The selected data treatment technique can vary depending on the necessities of the project and can be adapted to the technique used to achieve the maximum information possible. Such techniques include Principal Components Analysis (PCA) [17–20], Multivariate Curve Resolution – Alternating Least Square (MCR-ALS) [21,22] and Non-Negative Matrix Factorisation (NMF) [23], PLS-DA [2], Multivariate Image Analysis (MIA) [24] or Hierarchical Clustering [25] to name a few.

Nevertheless, multivariate analysis is not only applied to quantitative variables, but also to categorical or mixed data. Multiple Correspondence Analysis (MCA) is a technique used on exclusively categorical data [26], such as the formal characteristics of an artwork, whereas techniques such as Factor Analysis of Mixed Data (FAMD) [27] or Multiple Factor Analysis (MFA) [28], that in some way can be considered as expansions of the more traditionally used PCA and MCA, allow the simultaneous study of both categorical and numerical data. Although the introduction of statistical methods in stylistic analysis may hide certain difficulties, it can ultimately ensure the systematic analysis of the results and help reveal information and patterns that may not be immediately evident.

In the present article, *Artomics* is applied to a late-twelfth, early-thirteenth century Catalan illuminated manuscript, the *Liber Feudorum Maior* (*LFM*), an exception among decorated manuscripts of that time period, as it is not of ecclesiastical nature [29]. The manuscript also stands out for its decoration, containing miniatures painted in two different styles, associated to the artistic transition occurring at that time period in many regions of Western Europe, including Catalonia. The *Artomics* approximation, as established previously, combines the compositional and stylistic information using chemometrics techniques, in order to help with the contextualisation of results and achieve insight into the sociological circumstances of the manuscript's elaboration. In order to achieve this, the results from the compositional analysis of the LFM [30] are studied using PCA, whereas for the formal analysis, multiple variables that adequately describe the miniatures are established and MCA is applied in order to see how they contribute to their classification. Ultimately, the two data types – compositional and stylistic – are studied simultaneously, using FAMD, as a first attempt to implement the *Artomics* approach.

Table 1
Example of the categories established for the category of "Book Decoration" in the Romanesque miniatures.

Variable value	Examples		Variable value	Examples
Golden with red border			Golden with red lines	
Golden with white details			Golden with red double frame and circle	
Golden with red circles				

2. Materials and methods

2.1. Samples

A total of 76 miniatures decorate the *LFM*. As mentioned in the Introduction, these miniatures are painted in two different decorative styles: one closer to a Romanesque style and the second one with Gothic influences, belonging to the "Year 1200" style. To avoid nomenclature misunderstandings, miniatures from the first style shall be referenced to as Style A and from the second style as Style B, as has been done previously in the literature [31].

Twenty-three of the miniatures are painted in Style A, while 51 are painted in Style B. Two miniatures present a mixed style, with parts pertaining to each of the two aforementioned styles. A representative selection of the illustrations was analysed, which includes 4 Style A (folios 74v, 110r, 114r and 56v), 10 Style B (folios 1r, 3r, 37v, 45v, 61r, 82v, 93r, 94r, 95r and 99r) and 1 mixed (folio 109r) miniature, that represent both styles' palettes.

Apart from the miniatures, the manuscript's text was also studied. Letters were chosen from different text sections, presenting varying visual aspects, such as calligraphy and colour. In total, 17 black and 4 red letters were studied.

2.2. Data collection

2.2.1. Compositional data

X-ray Fluorescence was applied in order to obtain all compositional data. The portable XRF spectrometer Elio (by XGLAB Srl) was used for the XRF measurements. It is equipped with a Rh anode X-ray tube, a 12.5 μm thick Be window and a 25 mm^2 active area Silicon Drift Detector with an energy resolution of 135 eV at the Mn Kα line. Both single point analyses and maps were obtained, always maintaining a voltage of

Fig. 1. The two decorative styles present in the *LFM*. Left: Style A, Middle: Style B and Right: Mixed-style.

50 kV and a current of 80 μA. The data used for the analysis of the miniatures derive from maps, which were obtained by fixing the spectrometer onto an XY motorized stage. Consecutive spectra corresponding to 1 mm^2 areas are obtained, by moving the head 1 mm at every measurement. The analyses have a duration of one second and correspond to a pixel of the generated map.

In order to avoid interferences from lower folios, a 2 cm thick methacrylate plate was placed under the folio analysed at the time. Additionally, an effort was made to avoid regions with drawings or text on the reverse side of the folio, to further limit unwanted interferences.

2.2.2. Formal data

The selection of the formal data was based on a procedure involving the close inspection of all miniatures by the researcher and the determination of similarities and differences between them. Once a characteristic was considered representative for the description of all miniatures, the categories of the variable were established, keeping in mind that they had to be specific enough so as to correctly describe the miniature, but also generic enough to include multiple miniatures. An example can be seen in Table 1, where the categories of a variable characterising Style A miniatures is presented. After establishing the variables and the categories, each one of the miniatures was assigned to a category, thus recompiling all the information in a systematic way.

2.3. Data treatment

The XRF measurements used are obtained by selecting a group of pixels from each elemental distribution map that correspond to the colour that is analysed each time, from which, in continuation, the average spectrum is calculated and used for comparison.

For the multivariate analysis of the compositional data, the XRF spectra are used after conducting the appropriate pre-treatment. The technique used is Principal Components Analysis (PCA), where one colour is analysed at a time, comparing the spectra of all miniatures analysed. In certain cases where it is considered relevant multiple measurements from one miniature are included.

For the analysis of the formal data Multiple Correspondence Analysis (MCA) is the selected technique. This method can be considered as a "generalization of PCA", where instead of quantitative data, categorical variables are used [28]. The miniatures of the two styles are studied separately and the tables established following the process described in Section 2.2.2 are used. With MCA, these tables are converted into indicator matrices, in which the values 0 and 1 are used to represent the absence or presence, correspondingly, of a characteristic, and onto which a standard correspondence analysis is carried out [28]. As a result, new dimensions are defined (equivalent to the Principal Components of PCA) and are used to represent the reorganised information.

Following the application of MCA, Hierarchical Clustering on Principal Components (HCPC) is applied on the generated data, which is based on the combination of "principal component methods, hierarchical clustering and partitional clustering to better highlight and better describe the resemblances between individuals" [32].

The most relevant results from MCA and HCPC are presented in the Supplementary Material. These include the hierarchical tree, the cluster plot without figures, bigger images of each miniature organised by the cluster they fall into, the categories graph and bar plots displaying the contribution of the 15 most relevant variables for each dimension are provided in the Supplementary Material. It must be noted that the clusters in the dendrograms and cluster plots may differ slightly, due to the final step of the HCPC algorithm, in which the initial partition obtained from hierarchical clustering is improved with the performance of K-means clustering [32].

Finally, for the combined study of the compositional and stylistic data Factor Analysis of Mixed Data (FAMD) is used. In this case, for the compositional data, the peak areas for a group of relevant elements are calculated and are used as variables. These areas are calculated using the software PyMca [33], which allows the deconvolution of peaks, avoiding in this way problems occurring from overlapping peaks corresponding to different elements. A table including all morphological and compositional (in peak area form) data is created and used. The main principle of this technique is the conversion of quantitative variables into categorical ones, by establishing classes made up by variation intervals, allowing a posterior Multiple Correspondence Analysis [34].

Regarding the software used, PCA was carried out using the PLS toolbox for MATLAB while MCA, HCPC and FAMD were carried out using the FactoMineR package for R [35].

3. Results and discussion

3.1. The Liber Feudorum Maior: Decorative characteristics

As mentioned in the Introduction, one of the most characteristic features of the LFM is the presence of two different decorative styles that accompany the text (Fig. 1).

The first style of decoration (Style A) is found in 25 miniatures and can be classified as Romanesque. It is characterised by an absence of volume, geometricizing figures and a stylistic and content homogeneity among all miniatures, which represent only two types of scenes:

vassalage (in 22 miniatures) and agreements between two royal figures (in 3 miniatures). In both types, the lords are dressed in heavy tunics decorated with red and golden details and sit on thrones in front of quadrangular or polylobed blue backgrounds, decorated with white details. In the vassalage scenes, the vassals, painted with fewer details, are always placed kneeling outside of the throne frame. The chromatic range and the use of colour in these miniatures is very limited, as the artists involved often take advantage of the parchment's colour to give shape to the figures. Finally, another characteristic of these miniatures is their lack of naturalism and the symbolic representation of events, something especially visible in vassalage scenes, in which the three stages that make up the process can be found in the same figure: (1) the kneeling of the vassal, (2) the oath, represented by the book and (3) the investiture, represented by the flower held by the king [31].

The second style (Style B) is found in 53 miniatures and is more difficult to assign to a specific art style, showing elements from the stylistic transition from Romanesque to Gothic. It has been categorised by several art historians into the "Year 1200 style" [31,36]. It presents a more extensive chromatic palette, with colours that do not appear in the Romanesque miniatures, such as green, different hues of blue, orange and pink among others. Furthermore, the dresses and backgrounds featured in these miniatures are decorated with elaborated patterns, figures are represented more realistically, and their faces are more expressive than their Romanesque equivalents, especially in the occasions where coloured brush strokes are used to enhance facial features. These miniatures also show a larger variation when it comes to the content displayed. Although a majority of them depict vassalage scenes, others show money exchanges, a wedding or the concession of two castles, while there are also two miniatures, occupying the whole folio, representing the compilation of the manuscript in one and a portrait of two crowned and enthroned figures in the second. Several of the second style miniatures are incomplete, some only decorated with golden and silver leaf, others showing painted regions, but no details and others seemingly finished, but with all figures lacking facial details. There are also certain miniatures initially painted in Style A and in continuation complemented with Style B characteristics.

There is an uncertainty among art historians regarding the number of artisans involved in the decoration of the manuscript [31,36,37]. With respect to Style A, most authors suggest that one artist is responsible for all miniatures. However, Proust claims that this artist only made the sketches using ink, while the coloured details were added by another artist, more specifically the same one who decorated the capital letters in the documents' headings, which have the same white details in the blue areas [36]. Wearing suggests that the miniatures are product of one artist, but also expresses a hypothesis regarding the existence of a second miniaturist adding the finishing touches on some unfinished images [31].

The plurality of artisans involved is more obvious in the case of the second type of miniatures, due to the multiple formal differences detected between certain groups. Wearing differentiates between two illustrators: one responsible for the miniatures with more elaborated decoration (including the two full-page images) and the other, possibly-one of the first artist's pupils or assistants, responsible for the simpler ones [31]. This hypothesis is based on the repetitiveness and lack of detail of the miniatures of the second artist, as well as the presence of some annotations next to certain miniatures of this group, which could be instructions left by the principal artist to his student. Proust talks about a "Master" artist responsible for the current manuscript's cover and the sketches of some others, while his disciples were reproducing miniatures following his style [36]. Finally, it is worth mentioning a possible retouching of the miniatures by artists not involved in the initial decoration phase is a possibility which has not been considered.

As can be deduced, these characteristics of the *LFM* make it an excellent case study for the application of *Artomics*, as the plurality of styles and artists may be associated to a differentiation in material choices. The majority of these parameters are eventually associated with the formal analysis of the illustrations, which includes the establishment of the variables that are relevant for the description of the miniatures and the application of MCA to this data. The composition study is carried out taking into account the findings of MCA in order to explore the differentiation of the miniatures based on changes in material composition and the simultaneous contribution of all colours. Finally, the two types of information are integrated in order to juxtapose their contribution in the final classification.

3.2. Considerations before the application of Artomics

The purpose of *Artomics*, as previously mentioned, is the unification of the compositional and formal characteristics of art objects with the purpose of obtaining a more thorough understanding of them, in a way which could eventually contribute to their sociological and historical contextualization.

In order to obtain meaningful results, a step of significant importance is the determination of the categorical variables, due to the fact that their selection depends entirely on the investigator and can easily include a subjective perspective. The formal characteristics chosen must be relevant and make sense for the majority of the samples included in the study, as a perpetual lack of classification for certain variables can also greatly condition the results. Due to this requisite, in the case of this work, Style A and Style B miniatures were studied apart, as variables that would describe one set of samples, could be not appropriate enough for the description of the other. Furthermore, the selection of variables must be such, so as to avoid placing excessive importance on certain aspects of the object and leaving others unconsidered.

Regarding the compositional characteristics, their influence on the results can strongly be affected by the quality and preciseness of the measurements. Furthermore, in the case of using quantitative data, results can also be affected by the calibration procedure used to obtain them.

Due to the difficulties regarding the two data types, it is important to conduct a study of how they affect classification of the samples separately. The results obtained from these separate studies can help to better explain conjunctive results and also to avoid the inclusion of variables that may cause confusion.

A final point that should be addressed is the possibility to extend *Artomics* by directly including a wider range of information from the set-up of the application. In this way, available data regarding the social or historical context of the artworks can be included as variables that help classify the results. Such data could be related to the destination, or the function of the object studied, the iconographic characteristics of the representations, or the structure or the execution of the art piece. This type of information, especially relevant to art historians, as shown by the approach of Marie-Madeleine Gauthier, can greatly help to better understand the object [38]. Gauthier focuses on eight variables: destination, function, structure, execution, iconography, ornamentation, composition, and style. In the case of the *LFM*'s miniatures, a variable such as the object's structure, which would make reference to the geometry and anatomy of the object, is not significant when studying two dimensional depictions on parchments. On the other hand, variables such as destination and function would have the same expression for all miniatures.

For this reason, it must be noted that the variables considered depend entirely on the purposes of the study, which can in some cases mean that a greater amount of information does not necessarily lead to more significative results.

3.3. Formal study of the miniatures

3.3.1. Selection of variables

With all previous considerations in mind, the formal variables were established based on the common characteristics found on all miniatures of each style. All variables represent formal details of the figures that

Table 2
Variables used to define the Style A Romanesque miniatures based on their formal characteristics.

Category	Variables		Variable values
Ensemble	Framing	Profile	(1) Quadrangular, (2) Polylobed
		Throne Type	(1) Podium throne, (2) X-shaped throne
	Content	Scene Type	(1) Vassalage scene, (2) Agreement scene
Details	Figures	Hands	(1) Book with flat hand, (2) Book with forward-facing hand, (3) Book with up-pointing finger, (4) Holding hands with other lord
		Beard	(1) No beard, (2) With Beard
	Decoration	Sceptre	(1) Red and white, (2) Red with gold details, (3) Golden with red frame, (4) Golden balls, (5) None
		Book	(1) Simple, (2) Red frame and red spot, (3) Red spots, (4) Red lines, (5) White details
		Sceptre and book position	(1) Right: book, left: sceptre, (2) Right: sceptre, left: book
		Arrows	(1) With red arrows, (2) Without red arrows
		Crown	(1) Serrated type – simple, (2) Serrated type – red or white line, (3) Serrated type – black details, (4) Floriated type – simple, (5) Floriated type – with details, (6) Two crown types
		Cushion	(1) Golden with red lines, (2) Golden with red frame, (3) red with white details
		Profile	(1) Quadrangular with decorative points, (2) Quadrangular without decorative points, (3) Arches with decorative points, (4) Arches without decorative points
		Background	(1) With white flowers, (2) Without white flowers
	Clothing	Belt	(1) Simple border, (2) Double border – one side, (3) Double border – two sides, (4) Red line – belt middle
		Tunic	(1) Falls to the right, (2) Falls in the middle, (3) Falls to the left, (4) Two kings – tunics fall symmetrically
		Upper tunic decoration	(1) Simple border, (2) Double border – one side, (3) Double border – two sides, (4) Red line – Middle
		Lower tunic decoration	(1) Golden, (2) Red, (3) Yellow, (4) No decoration

Table 3
Variables used to define the Style B miniatures based on their formal characteristics.

Category	Variables		Variable values
Ensemble	Framing	Frame	(1) Straight, (2) Curved, (3) Other
		Towers	(1) With towers, (2) No towers
		Arches	(1) One arch, (2) Two arches, (3) Three arches, (4) Four arches, (5) Five arches, (6) Six arches, (7) No arches
	Content	Scene Type	(1) Vassalage, (2) Agreement, (3) Other
		Number of figures	(1) Two figures, (2) More than two figures
		Presence of court	(1) No court, (2) Court behind lord
		Royal figure positioning	(1) Right, (2) Left, (3) Other
		Seated figures direction	(1) Forward, (2) Sideways
Details	Figures	Faces	(1) White faces with black details, (2) White faces with no details, (3) Faces with coloured details
		Hair	(1) Black hair, (2) Brown hair, (3) White hair, (4) Two hair colours
	Decoration	Background	(1) With decorative motifs, (2) Single colour, (3) Unfinished
		Arch colour	(1) Red/Orange, (2) Green, (3) Yellow, (4) Golden, (5) No arches
		Arch and column decoration	(1) Black details, (2) Black details and white spots, (3) White details, (4) White details and white spots, (5) White spots, (6) No decoration, (7) No arches or columns
		Gold in column capitals	(1) With gold, (2) Deteriorated capital, (3) No gold, (4) No columns
		Crown	(1) No decoration, (2) Simple decoration – black line, (3) Detailed decoration, (4) No crown, (5) Deteriorated crown
		Bricks	(1) With bricks, (2) No bricks
	Clothing	Clothes decoration	(1) Black lines (folds), (2) Simple decoration, (3) Elaborated decoration
		Shoes decoration	(1) Black shoes – no decoration, (2) Black shoes – white details, (3) Decoration not visible

have indisputable values, such as the colour or the quantity of an element appearing in the illustration. The variables can be sorted into two categories: those that offer a global description of the miniature (ensemble), such as the type of scene or the shape of the frame; and those that represent details, such as the figures' hands and hair or the decoration of the clothes and backgrounds. The selected variables are organised into these two categories and can be found in Tables 2 and 3, along with all the values these variables can take. An example of one of these variables is displayed in Table 1. The same weight was given to every variable in absence of prioritization criteria. In the cases where the miniatures were unfinished, or a specific detail could not be observed, the condition of Not Available (NA) was used.

3.3.2. Style A miniatures

Using the above established variables, MCA is applied to the data, starting with the miniatures painted in Style A. The results are posteriorly analysed with HCPC in order to establish clusters containing similar miniatures, which are represented in Fig. 2. For a better understanding of the results, an image of each miniature is presented next to the equivalent plot point.

The Style A miniatures show a limited classification and the HCPC results organise the illustrations into three categories, of which two have a slight overlap. The biggest difference is found for the three miniatures on folios 19r, 15v and 88v, which appear separated from the rest on the right side of the plot (Yellow Cluster).

The study of the categories and contributions plots make it clear that Dimension 1, which determines the position of the scores on the × axis, attributes most of the weight to the scene type, the tunic and the sceptre type. This occurs because all agreement scenes present characteristics distinct from the vassalage scenes, leading to a concentration of these scenes in the right side of the graph, while all vassalage scenes belong to the Red and Blue Clusters situated on the plot's left side.

Dimension 2, which affects the score position on the y axis, attributes most of the weight to the frame type, the use of red arrows and the crown decoration. As is apparent from the graph, the contribution of these variables is not strong enough to obtain a clear classification. However, the close inspection of the miniatures corresponding to each cluster shows that all illustrations with red arrows occupy the blue cluster, while all but one miniatures with polylobed frames belong to the red cluster.

As a general observation, the MCA results do not offer a clear distinction between miniatures, except for the separation of the agreement scenes. This result confirms the stylistic homogeneity of these miniatures, which would be a reflection of the established patterns for these representations and the limited margin for the creativity of the

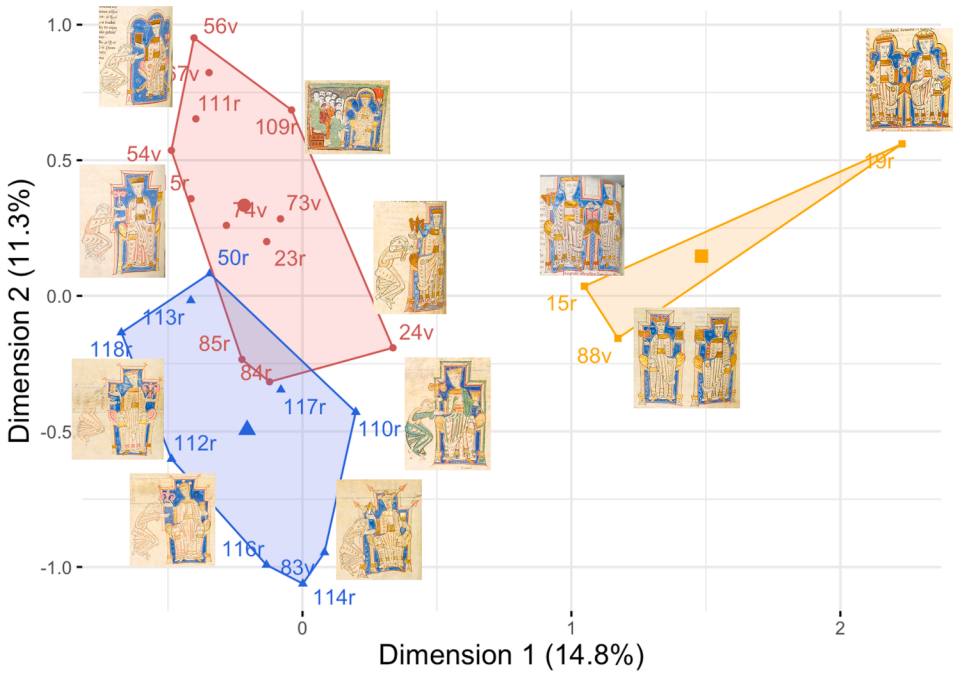

Fig. 2. Results of MCA and HCPC applied to the Style A miniatures. Yellow Cluster: Miniatures on folios 15r, 19r, 88v. Red Cluster: 23r, 24v, 54v, 56v, 67v, 73v, 74v, 84r, 85r, 109r, 111r, 115r. Blue Cluster: 50r, 83v, 110r, 112r, 113r, 114r, 116r, 117r, 118r.

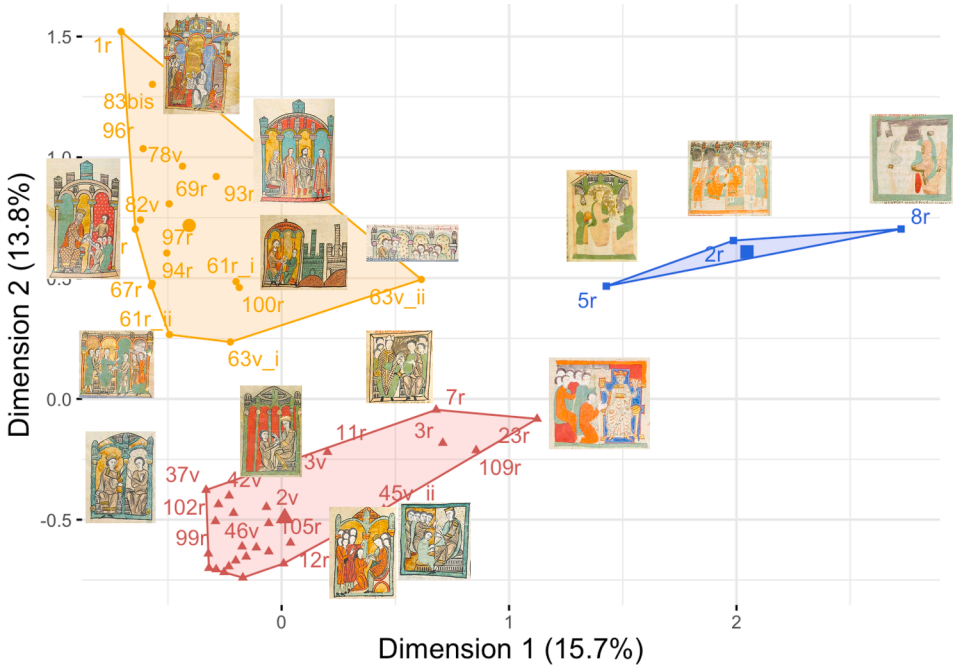

Fig. 3. Results of MCA applied to the Style B miniatures. Yellow Cluster: Miniatures on folios 1r, 61r, 63v, 67r, 69r, 78v, 82v, 83bis r, 93r, 94r, 95r, 96r, 97r, 100r. Red Cluster: 2v, 3r, 7r, 11r, 12r, 13v, 23r, 35r, 36r, 37v, 41r, 42v, 44v, 45v, 46v, 98r, 99r, 101r – 109r. Blue Cluster: 2r, 5r, 8r.

artisans.

3.3.3. *Style B miniatures*

The same procedure is applied to the miniatures painted in Style B and as can be seen in the individuals plot in Fig. 3, three distinct clusters can be observed. In the case of Style B miniatures, both dimensions attribute weight to certain details such as the decoration of faces, shoes and clothes, but also structural characteristics of the illustration, such as the position of the lord on the left or right side of the miniature. Through the study of the contribution of each variable to the dimensions, it can be deduced that Dimension 1 gives more weight to the characteristics of unfinished miniatures, where information on certain details is lacking, while the variables contributing more to Dimension 2 are related with elaborated decorative details, such as the faces and the clothes.

The miniatures belonging to the Yellow Cluster include vassalage scenes as well as other types and are all described by a more detailed decoration both in the faces and the clothes the figures are wearing. The miniatures appearing in the lower part represent only vassalage scenes, while the ones in the upper part represent other types of scenes. All the miniatures that appear in the Red Cluster represent vassalage scenes and

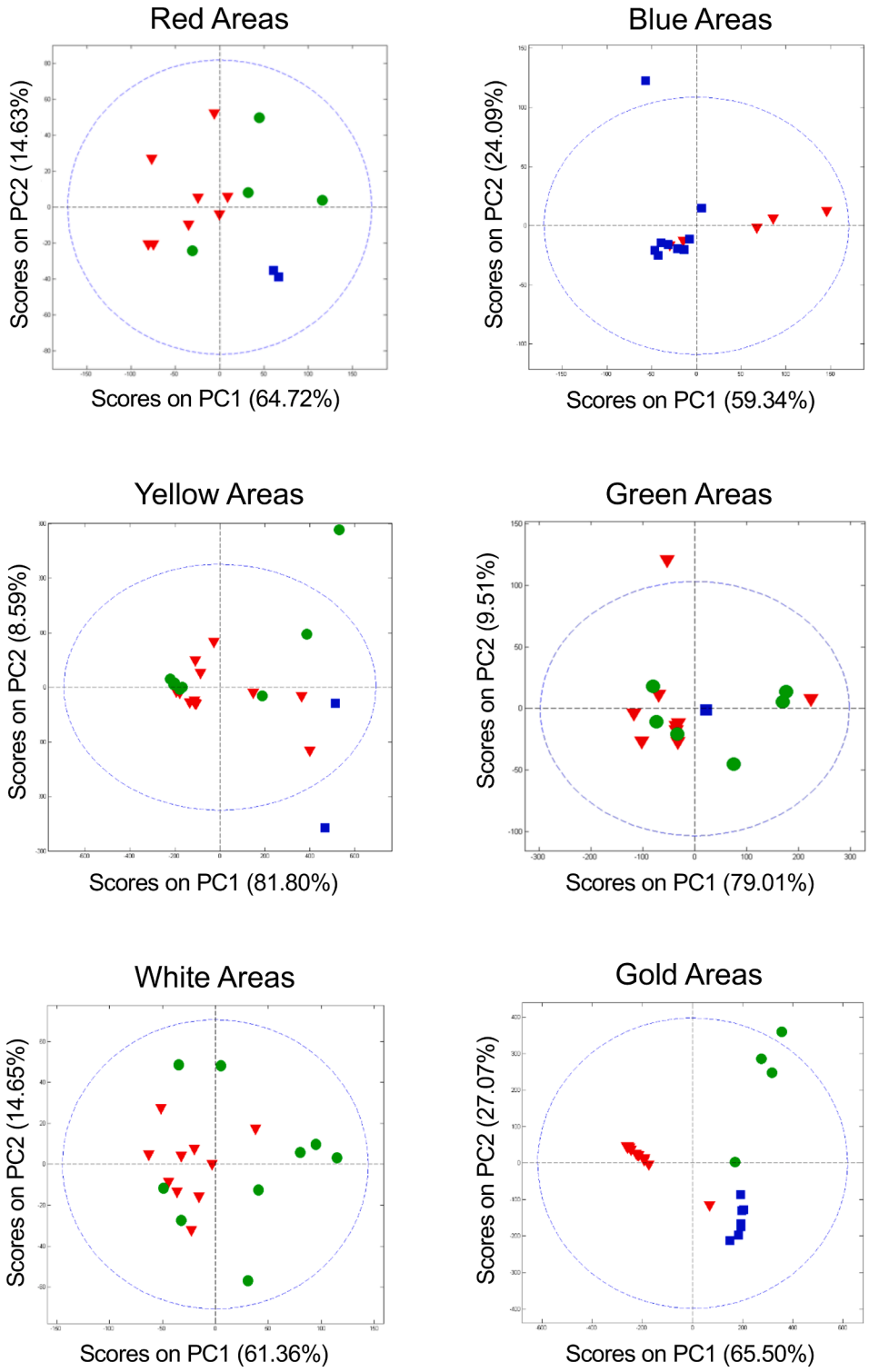

Fig. 4. Results of the application of PCA to the compositional data of the different coloured regions of the miniatures found in the *LFM*. The Style A miniatures are represented with a blue square, the decorated Style B miniatures with a red triangle and the simple Style B ones with a green circle.

are plainly decorated. The figures' facial characteristics are drawn using only a black pigment, while the backgrounds and the figures' clothing are simply decorated, without any motifs. The cluster also contains the two mixed miniatures present in the manuscript and some miniatures where green is the predominant colour, an even simpler decoration that is not found in the other miniatures and mostly faces with no facial features. Finally, the Blue Cluster is made up by the manuscript's unfinished miniatures and one that was cut in half, a fact that means that not all its characteristics could be distinguished.

The fact that the miniatures are grouped in this way is an indication that characteristics such as the decoration of faces and clothes are relevant in the differentiation of the miniatures and that the unsupervised multivariate approximation can effectively help in their discrimination which could ultimately be associated with the content and execution of the miniature, but also with the participation of multiple illuminators. An interesting observation regarding the results is related

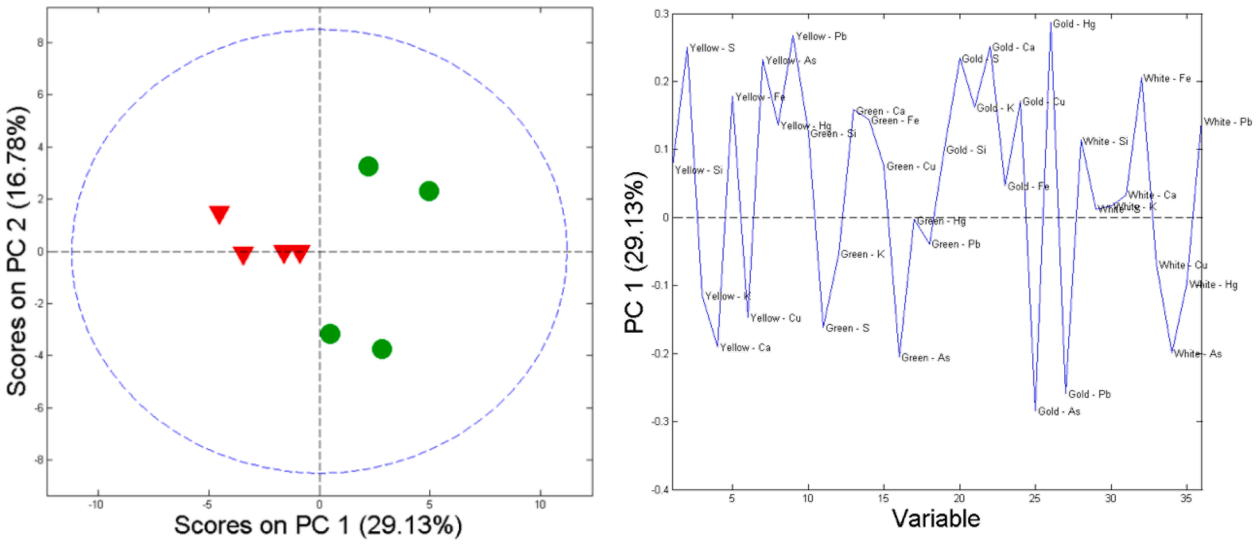

Fig. 5. Results of the application of PCA to 8 Style B miniatures considering the simultaneous contribution of all colours.

to the iconographical representations of the miniatures. The only illustrations that do not represent vassalage scenes all belong to the Yellow Cluster, which is characterised by a more elaborated decoration scheme. This could mean that in the case that these were carried out by a different artisan, they were the one commissioned to depict the more diverse and possibly more sociologically important scenes. These would include the two full-page illustrations situated on the covers of the two volumes of the manuscript, the marriage agreement scene and also more detailed vassalage scenes that deviate from the repetitiveness that characterizes the majority of the others.

It is interesting to correlate the results obtained from the application of MCA with the results of Wearing's art-historical research, who makes a case for the participation of two artists, which are refered to as B1, the master; and B2, the student/assistant [31]. The clusters formed after the application of HCPC coincide nearly perfectly with the classification of Wearing, as the Yellow Cluster miniatures correspond to those attributed to the master (B1), whereas the Red Cluster coincides with the student miniatures (B2). The only exception would be the inclusion of miniatures 2v, 3r, 7r, 11r and 12r into the Red Cluster, which Wearing has not classified, due to their unfinished state. This would mean that the application of MCA using carefully selected variables can lead to a possible identification of multiple artists.

In total, the *LFM*'s miniatures display a high homogeneity, possibly due to the limitations and conventions established for miniature representations during the Middle Ages, which would in turn reflect the structure of the social organization.

3.4. Compositional study of the miniatures

As has been mentioned in the Introduction, works of art present characteristics that can be intentional or unintentional. The formal characteristics presented in the previous section are a clear example of intentional attributes that, in these miniatures, could be more related to the patrons than to the creative choices made by the artist. A complementary observation to this thought could be that certain characteristics can be considered unintentional, such as the ones originating from values unconsciously interiorised by the society of that moment, or some technical limitations, due to the experience or artistic capabilities of the painter.

In the case of compositional characteristics, an intentionality exists in the choice of the material or pigment used by the artisan, even though they are selected from a finite number of resources. The exact composition of these materials, including the minor elements that may make them up are not relevant at the moment of the artist's choice, as what matters to them is their visual aspect. Thus, small differences in the composition of one type of pigment are something that is out of the miniaturist's grasp, meaning that they represent an unintentional parameter, whereas the choice of different pigments for the obtaining of varying visual effects would represent an intentional parameter.

For this reason, it is thought that by comparing the composition of one colour across a number of miniatures decorating the manuscript, information can be achieved regarding this intentional or unintentional choice of materials that ultimately may yield information about the execution process.

The compositional data collected is analysed using PCA, first by focusing on each colour separately (Fig. 4) and then by integrating data from all colours (Fig. 5). The components attribute weight to different parts of the spectrum that correspond to the constituents of the pigment. The detected signal and weight given to each component depend on the composition of the pigment, but also on the structure of the illustration, such as the stratigraphy and the position of each material in the miniature. The loadings plots that demonstrate the weight attributed to each of the components have not been included, but have been used to interpret the results.

According to the findings from the formal study, the *LFM*'s miniatures are highly homogeneous. Differences in the composition and structure of the miniatures could reveal some minor trends related to changes in the conventions, materials and technologies involved in the execution procedure, or the individuals involved in the task.

For a better understanding of the results and in order for them to be contextualised based on the findings in the previous section, the 15 miniatures analysed using XRF have been classified into 3 categories based on their decorative style and the results of the stylistic study presented in section 3.3.3. These categories, the miniatures they include and the symbols used to represent them in the following graphs (between brackets) are:

- Style A: 56v, 74v, 109r, 110r and 114r (blue squares)
- Style B - Simple: 3r, 37v, 45v, 99r and 109r (green circles)
- Style B - Decorated: 1r, 61r, 82v, 93r, 94r and 95r (red triangles)

The "Style B - Simple" category includes miniatures belonging to the Red Cluster established in 3.3.3, while the "Style B - Decorated" category is formed by miniatures belonging to the Yellow Cluster (as seen in Fig. 3). Miniature 109r, which is a mixed-style illustration, presenting characteristics from both styles is classified according to the colour

Table 4
List of pigments used for the decoration of the two styles of miniatures.

Style A Detected elements		Pigment	Style B Detected elements		Pigment
Blue	Si, S, K, Ca, Fe	Ultramarine Blue	**Blue**	Si, S, K, Ca, Fe	Ultramarine Blue
Red	Hg, S	Cinnabar	**Red**	Hg, S	Cinnabar
White	Pb	Lead White	**White**	Pb	Lead White
Gold	Au	Gold leaf	**Gold I**	Au, Pb	Gold leaf – Lead preparation layer
			Gold II	Au, Ca	Gold leaf – Calcium preparation layer
Green	Cu	Unidentified copper-based pigment	**Green I**	Cu, S, Cl, K	Unidentified copper-based pigment (with chloride)
			Green II	Cu, S, K	Unidentified copper-based pigment (without chloride)
Black (Ink)	Fe	Unidentified iron-based ink	**Black I**	Ca, K	Organic carbon-based ink / pigment
			Black II	Fe, K	Iron gall ink
Yellow	Ca, K	Unidentified organic colourant	**Yellow I**	As, S	Orpiment
			Yellow II	Ca, K	Unidentified organic colourant
			Yellow III	Pb, K, Ca	Lead-based yellow pigment or lead white mixed with yellow colourant
			Orange	Pb	Minium or lead white mixed with red pigment
			Brown	Pb	Unidentified lead-based pigment mixture
			Silver I	Ag, Pb	Silver leaf – Lead preparation layer
			Silver II	Ag, Ca	Silver leaf – Calcium preparation layer

region studied in every case.

3.4.1. *Study of each colour separately for all miniatures*

Before moving on to the interpretation of the PCA results, it should be mentioned that the palettes used for the miniatures of both styles have previously been characterised and are representative of the time period [30]. The identified pigments and the detected elements for each colour are presented in Table 4.

Starting with the **red pigment**, which has been identified as cinnabar (HgS) in both styles, the scores corresponding to the spectra of this colour display a limited tendency of separation according to the type of miniature they come from. All Style B miniatures appear close to each other on the graph, independently of the degree of decoration, whereas the two points corresponding to the same Style A miniature are situated together in a short distance from the rest. The greatest part of the variability is expressed in the first Principal Component (PC), which corresponds to the graph's × axis. In this component a positive weight is given to the Ca and K peaks, while a negative weight is attributed to Hg. In the second PC, Hg is once again weighed negatively, while a positive weight is assigned to Pb, which can be explained due to the composition of neighbouring areas. Considering that the Hg peak originates from the pigment and the Ca and K peaks correspond to the signals emitted by the parchment, a more intense signal of Ca and K would mean that the pigment layer is thinner, information which is relevant to the miniature's structure.

Regarding the **blue areas**, structural information can be deduced by studying the PCA plot. The pigment used is ultramarine blue and there is again a slight tendency of separation amongst the miniatures, although it does not strictly coincide with the two different style types, as some points coincide in the central part of the graph. The first PC assigns most of the weight to Pb, while the second one assigns it to Hg. In both cases, the discriminatory elements are not related with the composition of the pigment, but with the structure of the paintings, as both elements are related to painted zones on the other side of the folio. Although these separations do not help in the miniature classification based on the artisan participation or composition differentiation, they are evidence of the procedure's capability to yield structural information.

Lead is a highly relevant element regarding the discrimination of the **yellow** pigments, as PC1 is strongly correlated to its presence. This is due to the use of two different yellow pigments, with and without lead, for the decoration of Style B miniatures. Both pigments are used for both types of miniatures – simple and elaborated decoration –, and in some instances appear together in the same miniature, which means that discrimination for yellow is not made based on decoration. In Style A miniatures only the pigment without lead was detected.

Regarding the **green** areas, the only information provided by the existing slight separation is probably related to the conservation state of these regions, or the thickness of the copper based coloured layer.

In the case of the **white** areas, no significant difference is detected between the two types of Style B miniatures. Style A miniatures could not be added to this classification due to the limited use of white in this type of decoration.

The most interesting information regarding the technical aspects of the miniatures' elaboration are related to the **gold areas**, where the three categories are separated in a well-defined way. In this case, the differences are due to the preparatory layer found under the golden leaf. In the case of the Style A miniatures, there is no preparation, in the simple Style B ones, a preparation layer characterised by Ca can be observed, while in the ones with a more elaborate decoration, a red lead-based layer can be found under the golden leaf. There are two easily observable deviations in this pattern. One comes from the miniature found on folio 82v, where all golden areas show a red preparation layer except for one area where curiously no preparation seems to have been placed. The other is related with the miniature on folio 45v, a simply decorated Style B illustration, in which, as the golden leaf is intact, the preparation layer cannot be appreciated. The grouping of the miniatures based on the golden preparation confirms how certain stylistic choices are accompanied by different compositional/structural characteristics, as the groups formed on this occasion correspond to the groups created during the stylistic study.

3.4.2. *Study of effects of all colours simultaneously*

Apart from studying how the pigments' compositions contribute to the miniatures' classification individually, an attempt was made to evaluate the contribution of each colour when their effect is studied conjunctively. In order to achieve this, the peak areas for 9 elements considered relevant in regards to the pigments' composition were calculated and used as variables. Due to the fact that not all colours are present in every miniature, or that in some occasions there is no information about a certain colour, for this approach not all miniatures were included; instead, a selection of 8 miniatures presenting the four common colours was made. The miniatures selected are 1r, 3r, 37v, 45v, 82v, 93r, 94r and 99r, all decorated in Style B and in which there are yellow, green, gold and white areas.

The application of PCA on this dataset demonstrates how the two types of Style B can clearly be classified based on their global composition, with all more elaborately decorated miniatures appearing concentrated to the left side of the plot and the simpler ones to the right side (Fig. 5). The study of the loadings plots for the two PCs shows that

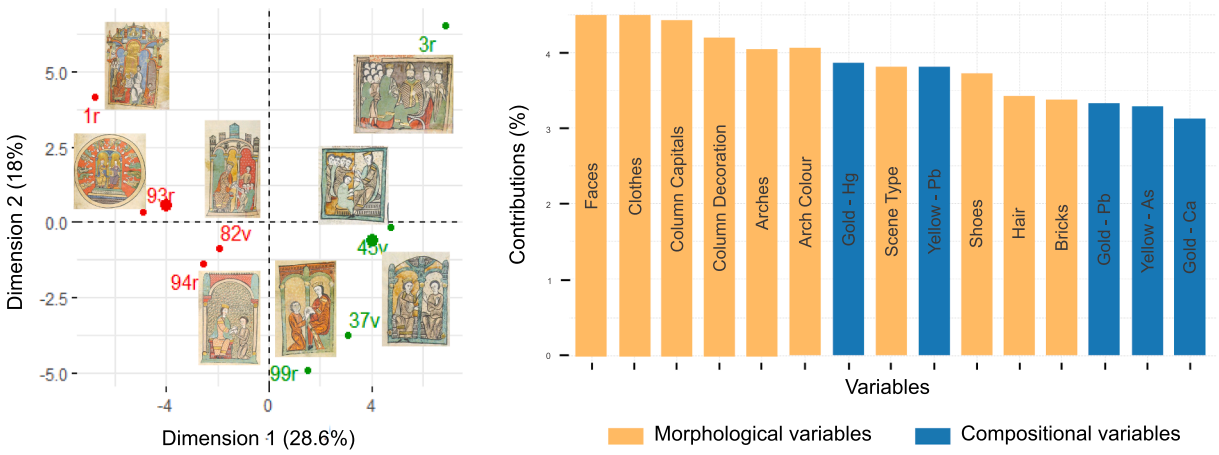

Fig. 6. Results of the application of FAMD to 8 Style B miniatures. Left: Classification of the miniatures, the decorated Style B miniatures are represented in red and the simple ones in green Right: Contribution of variables to the first dimension (x axis), the qualitative variables are represented in yellow and the quantitative in blue.

the main classifying variables are the ones related to gold, and more specifically the ones describing the contents in Hg, Pb and As. Even though the strong classification effect of the golden areas had been determined in the individual colour analyses, it is encouraging to see how the two decorative types confirm their differences based on a more global perspective, thus indicating a link between morphological and compositional characteristics.

3.5. Combined study of the miniatures

The final step in the study of the miniatures is the combination of all the data that has been used so far in this work, which means a study of both formal and compositional variables, in what is a first attempt to evaluate the *Artomics* approach. In addition, this step shows the difficulties related to the treatment of qualitative and quantitative variables at the same time. A multivariate technique which allows this procedure is Factor Analysis of Mixed Data (FAMD). The basis of this technique is the transformation of quantitative data into qualitative, by creating range classes based on the numerical data, to which each sample is assigned accordingly.

The results observed for the Style A miniatures are not presented as they show very limited discrimination. This behaviour could be related to the small variation in the colours used in the miniatures, but also to the stricter stylistic conventions related to their earlier fabrication. In a way, these become the main force defining the representations and causing other aspects involved to obtain a secondary role.

The combined analysis study on the Style B miniatures include the eight miniatures where the four common pigments have been used.

The effect the joint contribution of form and composition (qualitative and quantitative variables) has on the discrimination of the miniatures can be appreciated in Fig. 6. The Style B miniatures are once again differentiated according to the level of decoration of the miniature, in a very similar way to when the formal and compositional studies are performed separately. Due to the fact that the miniature types are separated along the X axis it is worth studying the contribution of the distinct variables to the first Dimension. As can be seen in the graph, 10 out of the 15 top variables are related to the formal characteristics of the miniatures, meaning that they are the ones principally contributing towards the obtained results. The qualitative variables regarded most important are the ones related to basic decorative features, such as the figures' faces, or the decoration of their clothes, as well as the decoration of the architectural elements of the illustration. In respect to the compositional data, once again the golden areas are the most discriminatory factors.

The repeated presence of the most relevant characteristics in each of the two groups is a further indication of the participation of two artists responsible for the Style B miniatures, consolidating the discrimination established by MCA, as each illustrator apart from a characteristic artistic vocabulary, also uses a different gilding technique.

The fact that the miniatures are differentiated in a similar way in both the stylistic and compositional analysis but also when both aspects are considered together means that in this case study the two components are directly correlated. This result corroborates that, for this manuscript, both the morphological characteristics and the pigments used by the artists were determined and limited by the social criteria present during the Middle Ages. For instance, the pigment availability of the time period the LFM was elaborated in is fairly limited, so artistic choices and initiatives were also restricted by such technical issues.

3.6. Ink

The *Artomics* approach can also be used to study the text found in manuscripts. In this case, the formal characteristics would be related to the palaeographic differences between different sections of the manuscript. By combining the two types of information, it may be possible to get more information about the writing process of the manuscript (i.e, identify the participation of different scribes or changes in ink preparation procedures).

In the case of the *LFM*, the approach begins with the classification of samples based on their composition, taking into account results from previously realized paleographic studies, in which parts of the text had been attributed to a scribe called Ramón de Sitges [39]. This approach is more similar to the traditional application of chemometric techniques to compositional data. However, with the collaboration of a paleographer who could establish specific variables for the morphological discrimination of letters, the approach could be brought to the same level of complexity as the case presented regarding the miniatures.

The study of the elemental distribution maps of certain letters has demonstrated the presence of up to six different inks used in the manuscript, based on their chemical composition [30]. During the Middle Ages it may have been possible that each scribe prepared their own ink using a different recipe, but also that differences in the composition could be related to different materials being used for every ink batch. Furthermore, it is possible that multiple scribes working in the same scriptorium may have used the same ink, or that each scribe had access to multiple inks, choosing the most adequate one for each occasion. Therefore, although it is not possible to determine the exact number of scribes through differences in ink composition, what can be asserted is that each ink indicates a different stage of the completion of the manuscript that could be related to any change in the writing

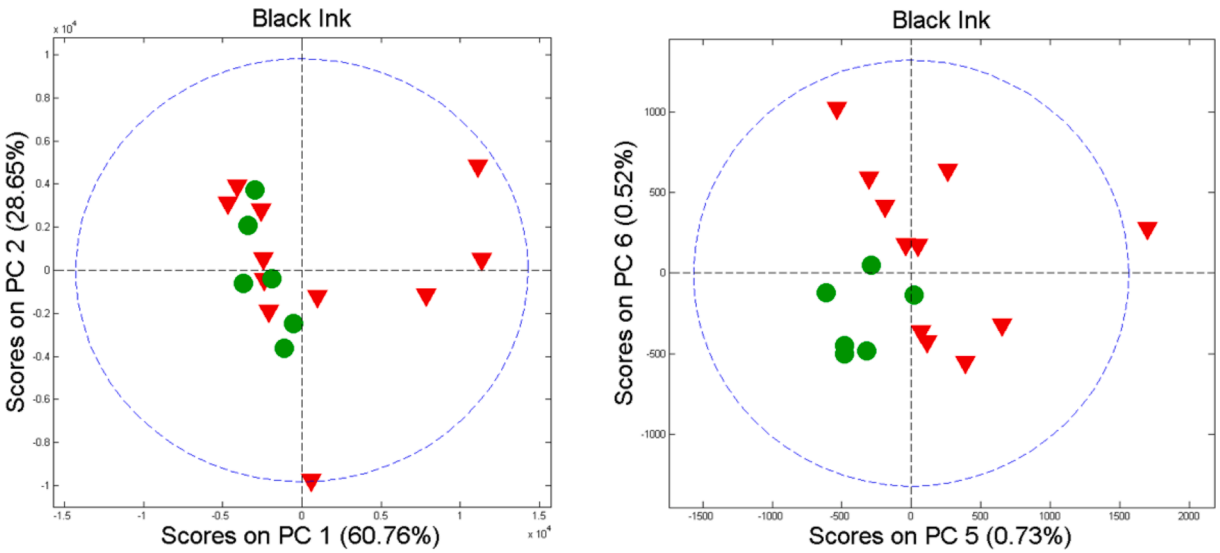

Fig. 7. Results of the application of PCA to the compositional data of the inks found in the *LFM*. Letters attributed to Ramon de Sitges are represented with a green circle, while all others are represented with a red triangle.

process, be that the participation of a different scribe or the use of a different ink.

PCA was once again applied to the compositional data and the results are represented in Fig. 7. The letters attributed to Ramon de Sitges [39] are displayed with a green circle, whereas all the rest are represented with a red triangle. In contrast to the results related to the coloured regions, the most relevant information is not represented in the first two Principal Components. These are mostly related to the two main constituents of the ink and the parchment, giving the most weight to Fe and Ca respectively, which means that all inks used throughout the manuscript are similar in composition. However, the inks' minor constituents, represented in Principal Components 5 and 6, lead to a clearer differentiation between the unattributed letters and the ones attributed to Ramon de Sitges. The variability they represent is very low compared to PCs 1 and 2, however, the loadings plots correspond to spectra with visible peaks, and not just background noise. The elements the weight is given to are Cu and Zn, which are most probably related with the composition of the vitriol used in the ink preparation, and K, which in other works has been attributed to gum Arabic but could also be related to the parchment.

Although in the case of this study the number of samples is limited, the results seem to indicate that it is a promising method in order to differentiate, at the very least, the different elaboration phases of the manuscript, be that related to the participation of different scribes, or simply a change in the ink being used. This approach can best be used as complementary to paleographic studies that may be able to differentiate between hands involved in the manuscript's preparation. The fact that this occurs in the case of the *LFM*, makes it easier to ascertain the veracity of the results, which only seem to show a clear separation in Principal Components that represent a small part of the results' variability. Multiple measurements from each text's section would help to form groups of letters that have a common composition, thus enhancing the differentiation capacities of the method.

4. Conclusions

A new methodology for the transdisciplinary study of cultural heritage objects, named *Artomics*, has been developed, which unites their formal and compositional characteristics. The classification of the objects based on their similarities, as well as the understanding of the variables responsible for such classification, allows us to obtain information on them that may not be immediately obvious when analysing each aspect of the artworks separately. The application of the methodology on a medieval illuminated manuscript has revealed that it is possible to differentiate miniatures based on their formal parameters, with certain compositional characteristics agreeing with such separation, indicating the possible participation of multiple artists. The joint use of the two data types revealed a strong predominance of the stylistic variables, most probably due to stylistic conventions and the limited colour palette used in the period of the manuscript's fabrication, in combination with XRF's inability to identify organic colourants and the small variety in techniques and in the source of the materials used. In fact, style and composition separately yield similar results which would indicate that the social criteria affecting these cartulary representations conditioned both aspects of the execution. Future work could allow for additional revelatory results by applying the technique on artwork groups where a wider range of materials may have been used, a factor majorly related to the time period the art piece was created in.

CRediT authorship contribution statement

G. Magkanas: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **H. Bagán:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – review & editing, Supervision, Project administration. **M.C. Sistach:** Conceptualization, Investigation, Resources, Writing – review & editing, Supervision. **J.F. García:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank the University of Barcelona for the economic support, under RTI2018-099990-B-I00, and the Catalan Agència de

Gestió d'Ajuts Uiversitaris i de Recerca (AGAUR) for financial support, under 2017-SGR907, while G. Magkanas also thanks the University of Barcelona for the APIF grant. The authors would also like to thank S. Wearing for her remarks on the manuscript and, finally, the former director of the Arxiu de la Corona d'Aragó, Sr. Carlos López Rodríguez, and the current director, Sr. Alberto Torra Pérez, for their collaboration in the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.microc.2022.108276.

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