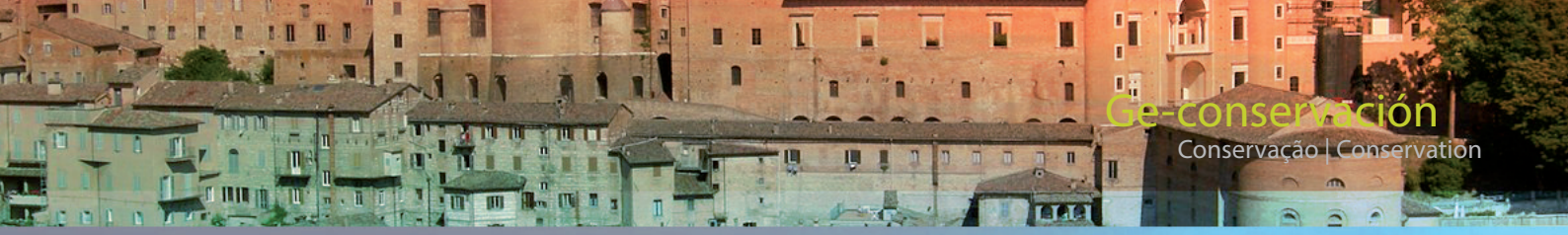

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5TH EDITION OF THE INTERNATIONAL MEETING ON RETOUCHING OF CULTURAL HERITAGE
UNIVERSITÀ DEGLI STUDI DI URBINO "CARLO BO"
SCUOLA DI CONSERVAZIONE E RESTAURO DEI BENI CULTURALI
18TH - 19TH OCTOBER 2019

Image processing methods integrated to imaging and material characterisation for the study of incunabula illustrations: an innovative multi-analytical approach on a case-study

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Abstract: This study focuses on the application of a multi-analytical approach combining image processing techniques, imaging studies and material characterisation of a French late fifteen-early sixteen century *incunabulum* – the BPE, Inc.438. The first study goal was to verify the potential of computational methods in NIR imaging to retrieve accurate reconstructions of the engraving printings by Germain Hardouyn. For this aspect, two representative scenes were chosen: *Trinity, f.8r; Saint Anthony the Abbot, f.61v.* The applied methodology allowed faster creation of digital reconstructions while the material analysis proved the use of azurite, malachite, vermilion, lead white and ochres, and their NIR response was assessed in the context of the digital processing. The second goal was to make a comparison between chosen illuminations and engraved references of the same representations from two incunabula of the British Library, unravelling the illuminator's intentional iconographic alteration based on visual and theological criteria.

Keywords: incunabula, illumination, IR-reflectography, image processing, material characterisation

Métodos de procesamiento de imágen integrados hacia la caracterización de imágenes y materiales para el estudio de ilustraciones de incunables: un enfoque multianalítico innovador no estudio de un caso

Resumen: Este estudio se centra en la aplicación de un enfoque multianalítico que combina técnicas de procesamiento de imágenes, estudios de imágenes y caracterización de materiales en un incunable francés de finales del siglo XV y principio del XVI: el BPE, Inc.438. El primer objetivo del estudio fue verificar el potencial de los métodos computacionales en imágenes NIC para recuperar reconstrucciones precisas de las impresiones de grabado por Germain Hardouyn. Para esto, se eligieron as *Trindade, f.8r; San Antonio Abad, f.61v*. La metodología aplicada permitió la creación más rápida de reconstrucciones digitales, mientras que el análisis material demostró el uso de azurita, malaquita, bermellón, plomo blanco y ocres, y su respuesta NIR se evaluó en el contexto del procesamiento digital. El segundo objetivo fue hacer una comparación entre las iluminaciones elegidas y las referencias grabadas de las mismas representaciones de dos incunables de la British Library, desentrañando un plan de alteración previsto seguido por el iluminador insistiendo en criterios visuales y teológicos.

Palabras clave: incunabula, Iluminación, IR-reflectografía, Image Processing, Caracterización de materiales

Métodos de image processing integrados à análise de imagens e caracterização material nos estudos sobre as ilustrações aplicadas aos incunábulos: o inovador exame multi-analítico de um caso

Resumo: Este estudo concentra-se na aplicação de uma abordagem multianalítica que combina técnicas de processamento de imagens, estudos de imagem e caracterização de materiais num Incunábulo francês do final do século XV e princípio do século XVI: o BPE, Inc. 438. O primeiro objetivo do estudo foi verificar o potencial dos métodos computacionais em imagens de NIC para recuperar reconstruções precisas de impressões de gravura por Germain Hardouyn. Para isso, como *Trindade, f.8r; San Antonio Abad, f.61v*. A metodologia aplicada permitiu a criação mais rápida de reconstruções digitais, enquanto a análise do material demonstrou o uso de azurite, malaquite, vermelhão, chumbo branco e ocre, e sua resposta NIR foi avaliada no contexto do processamento digital. O segundo objetivo era fazer uma comparação entre as iluminações escolhidas e as referências registradas das mesmas representações de dois incunábulos da Biblioteca Britânica, desenrolando um plano de alteração planejado seguido pelo iluminador insistindo em critérios visuais e teológicos.

Palavras-chave: incunábulos, Iluminação, IR-reflectografia, Processamento de Imagem, Caracterização de materiais

Introduction

The beginning of the press in Europe in 1450 was a technically relevant phenomenon. Prior to the start of such a productive system, the manuscript enjoyed centuries of respect as a multi-faceted object, mostly as a trademark of prestige and wealth. Early printed books or *incunabula* were issued while ateliers retained the long-established creation of these luxurious manuscripts (Majeski 2012). Therefore, the producers of the new book had the task of competing with the magnificence and prestige of the old product elaborating effective strategies to attract clientele (Macfarlane 1900). A possible solution to fulfil the task would be to upgrade the books' layout by imitating the features of illuminated manuscripts, trying to achieve the general reference of quality of art patrons. As a result, some incunabula would closely resemble their model and be sumptuously decorated with colour (Wieck 1997). Another solution would be to elaborate the printed media to deliver a full black-and-white product yet not less admirable (Zöhl 2004). Due to the existence of such a variety, each early printed book is unique (Reinburg 2012). Today, the incunabula are of interest in the fields of technical art history, heritage science and book sociology to unravel the effective differences between manuscripts and incunabula, especially as for their decoration.

One of the places where the industry of printed books expressed its full complexity is Paris, that was a leading printing centre already before the 16th century. This city witnessed the emergence of numerous workshops that rapidly emerged under the lead of local and foreign printers. These professionals published books of any kind, most of which were prayer books or service books. In most cases, these items were commercialised as Books of Hours, that are books of daily prayer (Reinburg 2012).

The decoration of printed Hours was sometimes remarkable for lavishness. To create it, printers preferred the adoption of long-established artistic techniques like illumination since they were acquainted with the more traditional manuscript. As a result, the procedure employed to decorate these early printed books was somehow comparable to manuscripts. Nevertheless, printed Hours diverge from manuscripts, for engraving and illumination were coupled to create illustrations (Duplessis 1861; Renouvier 1862).

The visuals from the two stages of the creative process – engraving and illumination – were sometimes not fully comparable. A case is an *incunabulum* held by the Biblioteca Pública de Évora, the Inc.438, from which a comparison between the underprintings and the illuminations has been presented for the first time (Miguel *et al* 2019). Its maker was the printer-bookseller Germain Hardouyn, that was especially prolific in the exclusive edition and creation of printed Hours (Winn 2009). According to Miguel et al (2019), there were three different sizes, corresponding to different formats for the representations. In this case, the chosen case-studies were *Adoration of the Magi* (acquired painted area of 60 x 84 mm), *Pietá* (acquired painted area of 31 x 52 mm) and Pentecost (acquired painted area of 34 x 47 mm). However, the process followed by the authors for the digital reconstructions of these underprintings from IR reflectographies was a hard and extremely time-consuming task: around 12 hours were spent to hand-draw the digital reconstruction from the IR reflectogram of the hugest format, sizing approximately 60 mm × 84 mm. In this sense, the use of digital tools combined with diagnostical images becomes a powerful tool to optimize the building of the digital reconstructions.

In addition to this study, previous cases of technical examination on materials and techniques applied to illuminated manuscripts are abundant, some of which concern specifically French Books of Hours (Melo *et al* 2014; Araujo et al 2015). Unfortunately, Hours on the printed format did not enjoy comparable interest to date (Miguel *et al* 2019). In these cases, the applied *modus operandi* involved multi-analytical approaches consisting of optical, elemental, spectroscopic and chemometric techniques (Burgio *et al* 1997; Burgio *et al* 2010; Miguel *et al* 2008; Miguel *et al* 2012; Pessanha *et al* 2012; Manso *et al* 2013).

Digital Image Processing also proved to be very useful when applied to diagnostic imaging because it allows retrieval of very useful information of documentary objects. In palimpsests and ancient papyri, UV-Vis-NIR (ultraviolet-visible-near infrared) multispectral cameras were used to recover underlying scratched texts or lost writings (Sparavigna 2009; Easton *et al* 2003). In painted objects, IR (infrared) reflectography in the NIR region (also called IRR) is often applied for recovering underdrawings of paintings (Faries 2000). In books, IRR response depends both on the transparency of the painting materials used for the illuminations to the radiation, and on the reflectivity of the inks used for the printing process (Gargano *et al* 2004).

However, as not all areas of an image can respond positively to the technique, reflectographies could not be entirely legible. Although digital tools could be applied, they have not been explored in relation to IRR yet. To bridge this need, this work has the aim of offering an innovative approach combining the techniques of chemical characterisation to other analytical methods from computer science. In this view, it is here proposed an optimized approach to study the iconographical alterations occurred in the passage from the original engraving to the final illustration in an early-16th-century Parisian incunabulum, the BPE (Biblioteca Pública de Évora), Inc.438. From this, two representative illustrations - the *Trinity (f.8r) and Saint Anthony the Abbot* (*f.61v*) [Figure 1] – were analysed with a multi-analytical approach aimed at accomplishing both recovering the underprintings and evaluating imaging efficiency to offer a possible art historic interpretation of the changes that occurred between the initially engraved illustration and the final illumination.

Figure 1.- Full-size images of the selected folia from Inc.438 (170 mm × 103 mm). From left to right, the *Trinity (f.8r) and Saint Anthony the Abbot (f.61v)*. Photo ©HERCULES Lab and BPE.

Methodology

The viability of computational methods was explored to create a holistic approach crossing natural sciences, social sciences, and computer science. The purpose of the study was twofold, to manipulate digitally the original images to offer a support to the well-established techniques of technical examination of the illuminations of the case-study, and to feed new material to art historical research on the illustration-making process of printed books.

With this purpose, several goals were established. The first specific goal of the study was to justify the adequacy of computing tools in diagnosing the artistic creative process' stages. This first task consisted of three phases, namely capturing diagnostic images of the chosen representations, processing in the computational environment, and getting material information through analytical techniques that are routinely applied. The comparison among the two batches of data, those digitally processed and the material results, allowed to assess the quality of the proposed method as acceptable.

As for diagnostic images, Vis photographs were taken from two representative illuminations, while NIR imaging had the goal of recovering information of the original printed designs, or underprintings [Figure 2]. To gain information on the behaviour of the paints to the IR reflectography analysis, colour maps for the two representations were extracted digitally from their Vis images [Figure 3], which were later used to assess the paints' behaviour to the NIR source (as reflective or attenuating). Then, an Image Processing software was employed to identify the underprintings from the NIR images.

For the evaluation of the artist's palette and technique, some areas representative for each employed colourant were selected and analysed with non-invasive spectroscopic techniques, or Raman microscopy and RS (Reflectance Spectroscopy) and looked at closely with stereomicroscopy. These results and the NIR response of the material were compared to justify the reliability of IRR in the underprinting detection.

The digital reconstructions were used as a source to retrieve personally unpainted illustrations, or carvings, from other books issued by the same workshop and available in other public libraries. The engravings served as a reference for the last stage of the research, that is to propose a possible explanation to the discrepancies between the original engraved illustration and the later illuminations.

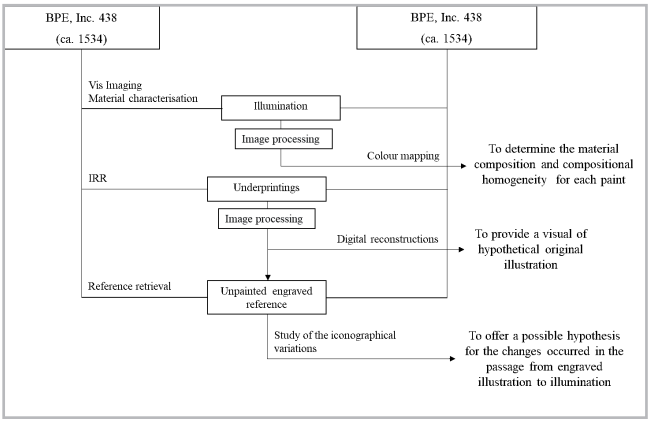


Figure 2.- Experimental design followed in the study of the iconographical alterations in the passage from the original engraving and final illustration of two representative illustrations from Inc.438.

—The selected representative illustrations and reference images

The developed approach for recovering the underprintings in incunabula was based on two representative representations from the Inc.438: the *Trinity* (f.8r, 47 mm x 62 mm, H x W) and *Saint Anthony the Abbot* (f.61v, 32 mm x 32 mm) [Figure 1]. Both representations are devotional images flanking a dedicated prayer for each celestial being (Brown 1994: 119). For the comparison with original printed representations by Germain Hardouyn, two unpainted representations were found in British Library incunabula.

— Analytical conditions

• *Vis-NIR imaging*: a Nikon Camera D3400 coupled to an 18-55 mm, VR AF-P, Multi-CAM 1000 11-point focus objective by Nikkor was used. The diaphragm aperture, shooting time, ISO, focal distance and working distance were always maintained respectively at f/1.8, 1/33 sec, 100, 55 mm and 15 cm.

• *NIR imaging:* the reflectograms were acquired with an OSIRIS camera equipped with an InGaAs detector (sensitivity: 900-1700 nm), and PhaseOne 120 mm macro lens [Figure 3]. The working distance and diaphragm aperture were maintained respectively at 6.5 cm and f/8 during all scans, done in slow acquisition mode (10 min/scan). The tile system for the acquisition is as follows: for the *Trinity* (f.8r), 130 mosaic sections (10 x 13, H x W), reflectography dimension 3593 x 4494 pixels; for the *Saint Anthony the Abbot* (f.61v), 49 mosaic sections (7 × 7), reflectography dimension 3072 x 3072 pixels.

• *Lighting*: 2 bulbs of Tungsten-Halogen VC–1000Q Quartz light system (3200 K), 1000 W power, were positioned at the left and right at an angle of incidence of ~50° (light-book-camera). These working settings were adopted to avoid mirror-like reflection. The lighting-object distance was ~2 m, and a lux-meter was adopted to ensure uniform illumination. A surface thermometer was adopted to make sure that no raise > 5% of the initial temperature would occur.

• *Reconstructions creation*: MATLAB® R2019b software with Image Processing Toolbox™ 11.0 was applied. To create them, the reflectographies were segmented multiple times with thresholding algorithms based on L (levels of grey) values. Since the original bit depth of the reflectographies was 8, the magnitude of the dynamic range consisted of 256 levels. Thresholding filtering was done on single or multiple Ls chosen with local histograms extracted from representative regions of the image. Through this step, a series of binary masks representative of either individual or extensive underprinting features were extracted and combined until creation of an overall reconstruction. Upon completion, each mask was converted to 8-bit arrays and finally filtered with a gaussian filter (1σ) to return visually appealing images [Figure 5].

• *Colour maps*: The MATLAB-Colour Threshold App was applied on each Vis image and the boundaries of the obtained maps were later superimposed on the unmodified reflectographies [figure 4]. After this, histograms were extracted from the ROIs (regions of interest) of the reflectographies in the areas defined with the extracted colour maps, to calculate the weighted mean for the L of each of these regions. The averages were calculated as L-weighted values to calibrate each mean on both pixel intensity and L level (number of pixels of the image raster having that L). Finally, the obtained data were compared singularly against the weighted L of the parchment. To also consider the effect of both surface roughness and non-flatness of the parchment substrate, the mean for the ground was averaged from several areas located on the top, bottom, and sides of each illustration. The comparison between the L-weighted (w-L) means of the ROIs and the parchment had the purpose of assessing the behaviour of the paints at the NIR irradiation. If the outcome of the two weighted means (ROI corresponding to a single paint and parchment) was equal in value, the paint would be transparent. If the ROI's weighted mean was lower than the parchment's (the ROI appears darker than the parchment), the coloured paint would attenuate the radiation. Finally, if the weighted mean of the ROI is higher than the parchment (the ROI appears brighter than the parchment), the paint would be reflective.

• *Magnified images*: Magnified images of selected spots were acquired under a LEICA M205C stereomicroscope equipped with a Leica DFC295 camera and external illumination in the 0.74×-8× zoom range.

• *Raman microscopy*: a HORIBA XPlora spectrometer equipped with a diode laser of 10.3 mW operating at 785 nm and 633 nm, coupled to an Olympus microscope was used for the analysis of selected spots. Raman spectra were acquired in extended mode in the 100–2000 cm^{-1} region, using the LabSPEC5 software. The laser was focused with an Olympus 50× lens, 1–10% of the laser power on the sample surface (10 s of exposure, 10 cycles of accumulation). Only for illumination in f.61v it was possible to inspect the following paints with Raman spectroscopy: blue, blue light, red, red light, brown, grey [Figure 3].

• *RS*: Site-specific diffuse reflectance spectra of spot were collected using a Vis-FORS (Vis-Fiber optic-Reflectance Spectroscopy) instrument (i-Spec® 25) operating from 450-1000 nm with spectral sampling 1.4 nm. The collection spot at the surface was ~5 mm in diameter and working distance ~5 mm from the sample. Data acquisition was performed as follows: 95 ms integration time, single accumulation. The spectra were calculated as ratios of the light incident on a Halon G-50 white reference with iSpec® 4 software. RS spectroscopy was applied to inspect the artist's palette in both illuminations. For f.8r, blue, blue light, red, red light, green, brown, white paints were investigated. In f.61v, RS was applied to the same coloured areas except for grey, that was investigated instead of white areas [Figure 3].

Figure 3.- Maps of the analysed coloured areas. From left to right, the Trinity (f.8r) and Saint Anthony the Abbot (f.61v). Photo ©HERCULES Lab and BPE

Results and discussion

— Material characterisation

The operation of colour mapping on both images allowed to notice that blue and red paints cover a major portion of the two images being investigated [Table 1]. Red paints are used lavishly for clothing in both illustrations, while blue tint is also used to colour garments and to support the background [Figure 4].

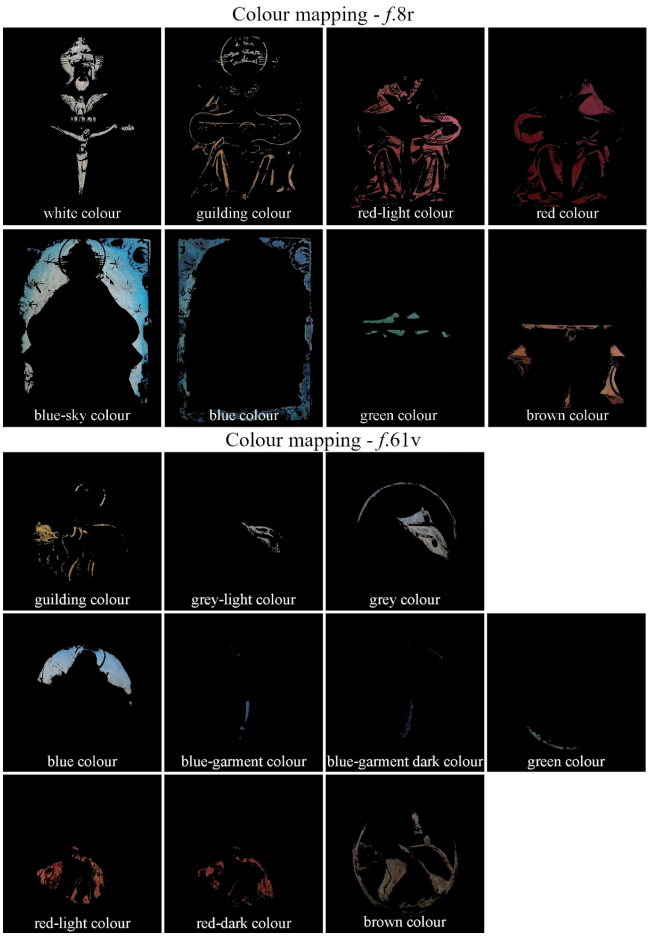


Figure 4.- Colour maps distribution for the *Trinity* (upper) and the *Saint Anthony the Abbot* (bellow) in BPE, Inc.438 (f.8r and f.61v, respectively). Photo ©HERCULES Lab and BPE

The visual inspection of the reflectographies for both representations touches upon two remarkable elements. One is the strong positivity of the black backing to the NIR source, while the other is the locally differing NIR attenuation and reflection. Through this effect, the radiation is prevented from interacting with the black materials of the underprintings, with the result of returning a partially readable image [Figure 5].

The Raman analysis made on f.61v (left side of Saint Anthony's red robe) [table 1, red and red light spots] suggests that red paints were produced with vermilion

Figure 5.- Vis, NIR images and MATLAB reconstruction for the Trinity (upper) and the Saint Anthony the Abbot (bellow) in BPE, Inc. 438 (f.8r and f.61v, respectively). Photo ©HERCULES Lab and BPE.

(HgS), due to the characteristic bands at 263, 295 and 353 cm-1 Raman shifts from the stretching vibrations of the crystalline lattice (v-HgS) [figure 6, red spot spectra]. This detection finds confirmation in the characteristic inflection point of vermilion at ~600 nm of RS spectra, corresponding to the electronic transition of the medium-gap band semiconductor (Cosentino 2014). Additionally, RS spectra suggests in both f.8r and f.61v illumination also the presence of further colouring agents, that might be ochres. These are identified with the absorption bands observed at ~550, 700 and 930 nm, together with the S-shape of the spectrum (Cosentino 2014). The first band (~550 nm) is of interest because it corresponds to the typical λ_m (inflection point) of red and brown ochres. The absorption arises after ligand-to-metal charge transfers, d-d transfers of the O^{2-}, OH-, and Fe-ions of the crystalline lattice as reported in previous studies (Sherman and Waite 1985; Torrent and Barron 2002; Elias *et al* 2006). These features could be related to darker pigments added to the main red colorant whenever a darker shade was necessary, and which are revealed by stereomicroscopic images of f.8r [Table 1, red dark spot]. Unfortunately, the assignment of dark ochres to red paints is tentative. As for the Raman analysis, vermilion provides a strong Raman fluorescence that might easily cover the signal from other pigments used in admixture to adulterate the vermillion brilliance or as neighbouring colouring matter, like ochres. As for FORS analysis, the very large dimension of the spot in comparison to the coloured areas (max 2.4 mm) and to the brown contour applied thoroughly both illuminations can partly hinder the signal from ochres. Therefore, the signal in RS spectra could also come from neighbouring areas. With the MATLAB calculations, red paints were found to be reflective. Generally, both vermilion and ochres are observed to be quite NIR-transparent (Gargano et al 2004). If a white, NIR-reflective pigments is admitted being added for brightening and matting, in the brightest areas and in overlaps

the underdrawing is slightly less clear and the L value darker. However, this NIR-reflecting effect does not affect seriously the readability of the underprintings.

Blue paints (f.8r, upper-right corner of and both sky; f.61v, sky and blue garment of Saint Anthony's clothing) [Table 1, blue and blue light spots] might have been produced using the mineral azurite ($2CuCO_3.Cu(OH)_2$, basic copper carbonate) as the blue pigment. The mineral is primarily identified through the Raman bands corresponding to the diagnostic symmetric stretching modes (s-v), asymmetric stretching modes (a-v) and bending vibrations (δ) of the functional groups of the mineral (-CO, -CO_3) at 1095, 1389, 834, 816 and 741 cm^{-1} Raman shifts (only the last one being well resolved). The FORS results confirmed this tentative attribution through the characteristic reflectance peak at 450-480 nm of the d-d electronic transition of the idiochromatic colour centre Cu^{2+} of azurite, followed by a reflectance minimum at 640-660 nm (Cosentino 2014). At the same time, the steep rise of reflectance at the broadest wavelengths (750-900 nm) in both illuminations in f.8r and f.61v suggests the presence of another scattering agent, such as a filler. Indeed, the stereomicroscopy images of the lighter spots in both f.8r and f.61v [Table 1, blue light] display a denser, thicker layer in the regions where the paste appears visually paler and differing in texture from deep blue paints [table 1, blue and blue light spots]. The Raman spectra for the blue spot in f.61v display a series of weak vibrations, the most eminent of which is a peak centred at 1052 cm^{-1} [Table 1, Raman results] and which can be interpreted as the stretching vibration of the carbonate anions (v_1-CO_3) of lead white ($2PbCO_3.Pb(OH)_2$, basic lead carbonate). Such identification is historically justified, for lead white is known as a main white pigment already in this period (Martens et al 2004). Then, lead white could have been supplemented also to these paints similarly to the red colourants. The calculations of the w-L ROIs defined with MATLAB allowed to define all blue paints as NIR-attenuating and indeed, previous researches described azurite as a NIR-attenuating pigment (Gargano *et al* 2004).

The study of the brown colourants (f.8r, right corner of God's throne; f.61v, Saint Anthony's hair) was more troublesome. In the Raman spectra of the spot, the parchment influence was very strong and could have masked the mineral signal with the result that this information was not fully conclusive. With the stereomicroscopy images, instead, two totally different kinds of composition were revealed among f.8r and f.61v [Table 1, brown spots]. The brown paint of f.8r is a dense mass containing red and black pigment, while f.61v brown appears thinner and rougher, including more abundant black pigment and sporadic, huger crystals of red pigment. In both cases, the red and darker pigments could be some ochre (weak bands in 300-400 cm^{-1} region in Raman, light depression ~550 nm and at 800-900 nm in FORS) (Tomasini *et al* 2011). Also, there could be little lead white in f.8r brown, thanks to the usual peak at 1052 cm^{-1} from the Raman spectra. Finally, MATLAB calculations proved f.8r brown to be strongly NIR-reflective, for the underdrawings of the swine and Saint Anthony's head get completely hidden. This effect could be due to the white pigment or the lavish gilding (that is NIR-reflective) and a possible black pigment.

The grey paints in f.61v (Saint Anthony's cloak), could be made of blue, white and black pigments mixed together [Table 1, grey spot], that could be respectively azurite because of the same RS band at 490 nm (Cu^{2+} transition) and absorption bands at 660 nm in FORS spectra), lead white (Raman band at 1052 cm^{-1}) and ochres (Raman band in the 150-350 cm^{-1} region, typical S-shape and the mentioned absorption bands in RS spectra). Magnified images do not display dominance of any pigment, that seems to be applied in thin layers and indeed, in these overlaps (grey light on grey), the underdrawing is slightly less clear and the L value darker.

The green pigment (f.8r, God's sleeve; f.61v, bottom grass) could be malachite. FORS spectra of both f.8r and f.61v displayed a reflectance band (λ_{refl}) at 540 nm, which is traditionally assigned to the idiochromatic coloration arising from the Cu^{2+} d-d electronic transitions of malachite ($CuCO_3.Cu(OH)_2$, acid copper carbonate) (Cosentino 2014). In literature, the position of λ_{refl} shifted to longer wavelengths than azurite is explained as a consequence of the crystalline lattice expansion, where the oxidation of the Cu^{2+} ions is more advanced than azurite (malachite possesses a $Cu(OH)_2$-to-$CuCO_3$ ratio of 1:1 for malachite, while the same parameter is 1:2 for azurite). Accordingly, Cu in malachite minerals coordinates the anions more closely in an octahedron, with the result that its transitions have shorter wavelengths (Klein *et al* 2007). Unfortunately, Raman results from the green spot cannot support fully this hypothesis: no spectrum could not be acquired because of the very strong influence of the parchment. But the MATLAB results for green paints in both illustrations showed that they were strongly absorbing, and this behaviour agrees with the literature (Gargano *et al* 2004).

No Raman spectra could also be taken for the white spot while the RS spectra (f.8r, God's beard) were quite inconclusive since the signal was strongly influenced by the signal from neighbouring colorants. However, the MATLAB calculation was able to define all areas painted in white as strongly reflective. Probably, the white pigment used to make lighter tones is the same as the other colorants.

The reconstructions built on the reflectograms with MATLAB allowed to notice striking differences between the original engravings and the final illuminations [Figure 7]. Both created reconstructions were found to have a visual match with illustrations found in unpainted incunables made in the same workshop of the British Library [Figure 7], and their comparison is discussed below.

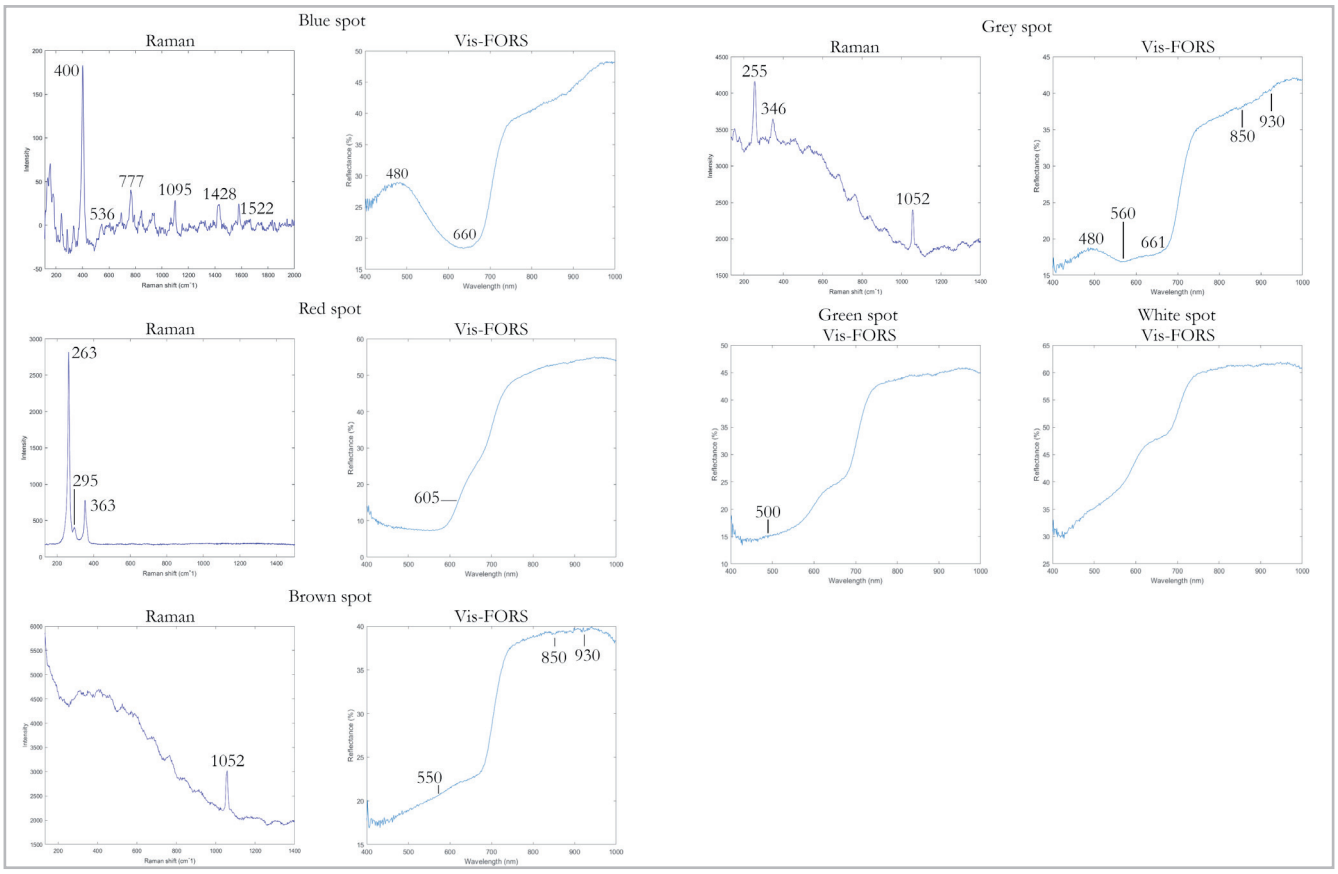


Figure 6.- Representative spectra for the studied spots among f.8r and f.61v ©HERCULES Laboratory

Table 1.- Table of the results of the material analysis for each spot in f.8r and f.61v Photo ©HERCULES Lab and BPE.

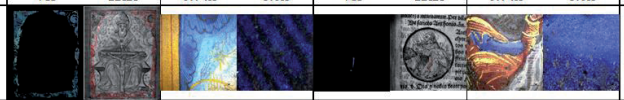
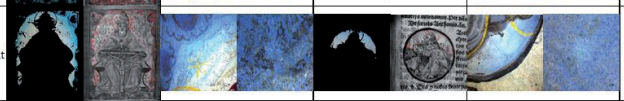
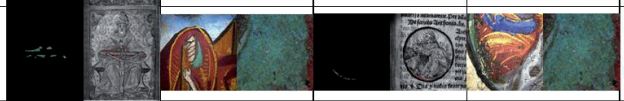
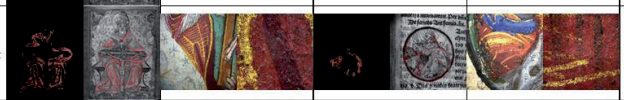
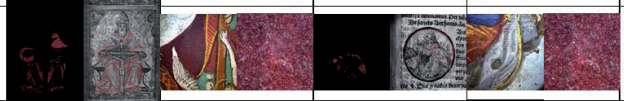
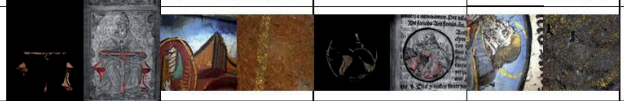
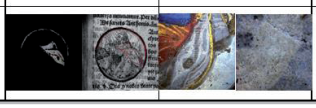
Paint	f.8r				f.61v				MATLAB assessment		FORS (nm)		Raman (cm^{-1})		Pigment
	Vis	IRR	0.74x	8.0x	Vis	IRR	0.74x	8.0x	f.8r	f.61v	f.8r	f.61v	f.8r	f.61v	
Blue									NIR-attenuating	NIR-attenuating	refl: 470; abs: 650.	refl: 480; abs: 650.	-	400, 1095, 1434, 1581.	azurite
Blue Light									NIR-reflective	NIR-reflective	refl: 470; abs: 650.	azurite lead white	-	400, 1095, 1434, 1581; 1052.	azurite lead white
Green									NIR-attenuating	NIR-attenuating	refl: 500.	refl: 500.	-	-	malachite (?)
Red light									NIR-reflective	NIR-reflective	infl: 608; refl: 740; abs: 680, 850, 930.	infl: 610; refl: 740; abs: 680, 850, 930.	-	263, 295, 353.	vermilion ochres
Red									NIR-reflective	NIR-reflective	infl: 608; refl: 740; abs: 680, 850, 930.	infl: 608; refl: 740; abs: 680, 850, 930.	-	263, 295, 353.	vermilion ochres
Brown									NIR-reflective	NIR-attenuating	refl: 740; abs: 680, 850, 930.	refl: 740; abs: 680, 850, 930.	-	215, 274, 1357, 1358; 305, 411.	ochres
White					-	-	-	-	NIR-reflective	-	undefineable	-	-	-	
Grey	-	-	-	-					-	NIR-reflective	-	refl: 490, abs: 660; abs: 550, 930.	-	215, 274, 1357, 1358; 1052; 400, 1095, 1434, 1581.	ochres lead white azurite

Figure 7.- Digital reconstructions and engraved references, from left to right. On the top: the *Trinity* in BPE, Inc.438 (f.8r), in BL, C.29.f.10 (f.F4v). Down: *Saint Anthony the Abbot* in BPE, Inc.438 (f.61v), in BL, C.29.g.5 (f.L4v). Photo ©HERCULES Lab, BPE and British Library Board, C.29.f.10 and C.29.g.5.

— *Iconographical considerations*

Both the illustration in f.8r in BPE, Inc.438 and another recovered from f.F4v in BL, C.29.f.10 (Hours with Roman Mass rite, printed in 1528 in Paris by Germain Hardouyn) portray the Trinity as the *Mercy Seat* [Figure 7]. In this version, the Almighty Father sits on his throne and supports a "slumped crucified" Son (Schiller 1972: 219). The Father as an aged man could be connected with the *Ancient of Days*, as described in the Book of Daniel (7:9, 13, 22): "I beheld till the thrones were cast down, and the *Ancient of Days* did sit, whose garment was white as snow, and the hair of his head like the pure wool: his throne was like the fiery flame, and his wheels as burning fire". In this regard, the representation of the elderly Father could be interpreted as a mention of God's eternity (Schiller 1972). Above or between them, the Holy Spirit hovers in the shape of Dove, accordingly to the custom of the late medieval-Renaissance Western Christianity (Didron and Stokes 1886: 535).

The engraved illustration shows distinctive features: God the Father's cap, the Holy Spirit's *nimbus* and the two angels in prayer. Firstly, the Father wears a three-crown tiara in the engraving. Such a headpiece resembles a *triregnum*, the three-circlets papal tiara that signifies both the spiritual and temporal nature of the papal power, and its superiority to any earthly authority, imperial or royal (Cross and Livingstone 2005: 378-379, 1632). The reason this choice may not be casual. In this merit, Didron suggests that when the Almighty dresses this cap and a plain robe, he is narrowly associated with the papacy (Didron and Stokes 1886: 224), as a sign of affection towards the papal stewardship and of authority approval.

The Holy Spirit's *nimbus*, that is the halo surrounding the celestial beings' head, extends towards three directions. This feature is typical in the depiction of the three joint and separate identities of the Trinity (Didron and Stokes 1886: 540).

The two angels flanking the Father lament Christ's pain (Didron and Stokes 1886: 530) and their function could be to emphasise the Father's glory.

In the illumination, many original details underwent either elimination or alteration. One of the most striking is the Father's tiara: the illuminator featured it as a bishop's mitre, probably to connect the pope and the celestial master. A possible explanation to this connection could be in Jesus' his confession to Peter, where he says: "And I tell you that you are Peter, and on this rock, I will build My church, and the gates of Hades will not prevail against it. I will give you the keys of the kingdom of heaven. Whatever you bind on earth will be bound in heaven, and whatever you lose on earth will be loosed in heaven" (Matthew 13:18-19). After these words, Peter is entrusted with the responsibility of the spiritual salvation of mankind and, becoming the first bishop of the Christendom settled in Rome, he is the first Roman bishop. Accordingly, that the ultimate intention of the artist could be to interpret the nature of pontificate as solely spiritual, abstracted from any secular implication.

The other pair of illustrations regarding Saint Anthony the Abbot - a Christian monk from Egypt that is credited to be the founder of monasticism -, is established between BPE, Inc.438 and an engraved print from f.L4v from BL, C.29.g.5 (Hours with Roman Mass rite, printed in 1534 in Paris by Germain Hardouyn). The distinctive features of his iconography are as follows: the hog at his feet, his black robe and stick, flames of a fire and surrounding desert.

Most of the described features are included in the engraving but not in the illumination (Guiley 2001). The first attribute is the black cloth. Probably, it refers to the medieval order of the *Hospital Brothers of Saint Anthony*, in charge of curing skin diseases and the *fire of Saint Anthony*, or ergotism (Classen 2017: 23). The order's popularity creates a sturdy connection between the saint and the hospital brothers, with the possible result in the common belief that the saint could protect from rashes and similar maladies (Guiley 2001). Granting the link, two attributes could be explained: one is the black cloth with the blue Greek Tau sewed on the shoulder as the members' robe, the second is the black pork. In this case, the pig could refer to the historical event of the special permission that the order was granted to breed pigs freely in cities (Guiley 2001).

The pig deserves further interest. Some authors are positive that the swine could be a "demon of gluttony and sensuality" and that prevailing over the animal, the saint affirms its "triumph […] over sin" (Earls 1987: 20). The swine or hog could be therefore intended metaphorically. This iconographical use find justification in the biblical references to pigs and boars. The Deuteronomy mentions pigs as unclean animals (Deuteronomy 14:7-8): "they are unclean for you, as well as the pig; […] You must not eat its meat or touch its carcass". The uncleanliness of the pig has important consequences, for "if a person touches anything unclean […] even if he is unaware of it, he is unclean and guilty" (Leviticus 5:2). However, the biblical boar is referred to as a picture of sadness, impurity (Psalms 80:13), or repetition of sin, for it eats its own vomit (Peter 2:22). More specific is the Christian reinterpretation, as the boar is found as a personified-vice representation of Gula (Gluttony) or Luxuria (Lust or Lechery) in Italian 15th-century Franciscan paintings (Cristoforo Cortese, ca. 1399 – 1445, and Sassetta, ca. 1392-1450). (Cohen 2008: 174). But the depictions of the sinful swine are not exclusively Franciscan. In France, Bernard Silvestris of Tours wrote in a 12th-century commentary to the Aeneid that "beasts signified the nature of man transformed by vice" (Silvester 1924: 62), and that the boar embodies men's wrathful nature, while the pig represents their lustful essence (Cohen 2010: 193). In central Europe, several paintings of the Dutch painter Hieronymus Bosch connect boar and lust (Bloomfield 1952: 138). In conclusion, during Middle ages, either representation of boar or pig could be related to a specific sin.

This dualism persisted: Renaissance engravings of the saint are numerous, and the hog is maintained as the invariable feature of his iconography. Off his feet there is always a pig, or sometimes a boar. One of these cases is a 1525-1550 woodcut of the Dutch Master S featuring Saint Anthony in full size with a boar peering out from behind his legs (British Museum, Inv. No 1853,1008.28). Another instance is an etching of the *Holy Family with Saints John the Baptist* by the Italian Agostino Carracci (ca. 1582), with a Saint Anthony and a boar on the lower part of the illustration (Harvard Museum, Inv. No S1.9) [figure 8]. In conclusion, this allegorical interpretation of the illustration could add a symbolic character to early Renaissance imagery and the opinions debating its full channelling in the neat realism of later representations could be supported (Cohen 2014).

The last three elements in the representation of Saint Antony the Abbot worth discussing are the stick, fire and the desert. The first represents the ability to chase the evil away, the second the two-fold reference to ergotism and to the saint's vision of hellish fire that quenched his flesh call (Earls 1987: 20), and the third his Egyptian origins. In the illumination, the iconography undergoes extreme simplification.

The most noticeable changes among the two versions occur in the Saint's clothing and the background building.

Figure 8.- Representations of personified vices. On the left: Sassetta, *St Francis in Glory*, panel of the Borgo Sansepolcro Altarpiece, 1437-44, Berenson Collection, Villa I Tatti, Settignano (source Wikimedia Commons); centre: Master S, *Saint Anthony Abbot*, Netherlandish school of engraving, 1525-1550, printed on paper, British Museum, museum no. 1853,1008.28 © The Trustees of the British Museum; right: Agostino Carracci, *Holy Family with Saints John the Baptist*, Catherine, and Anthony Abbot, Italian school of engraving, 1582, printed on paper, Harvard Art Museums, Alpheus Hyatt Purchasing Fund, Acc. no. S1.9 © President and Fellows of Harvard College.

As for clothing, the vestment is rendered colourfully in the illumination, and the Tau of the Hospital Brothers of Saint Anthony gets completely hidden. However, the adaptation to a rich palette does not simplify the holy nature of Saint Anthony: the lavish blue and red are two central colours in medieval symbolism (Gage 1999: 71-76). Blue was the colour of heaven and purity that the Roman Church often associated to Marian imagery (Jacobs and Jacobs 1958); red is the colour of power and martyrdom (Gage 1999: 71-73). Obscuring the Hospitallers' attributes is suppressing their patron. Historically, this choice could find an explanation in the 16th-century decadence of the order. During the Reformation, the wealth of the order's monasteries and hospitals could be a sign of corruption of the Roman Church, which the Protestant reformers condemned. As a result, several priories were closed or absorbed in private properties of central and northern Europe. For instance, the Antonian Mårkær Monastery in Southern Schleswig (Denmark) was closed in 1520 (Jørgensen 1899), and the Tempzin Hospital in Mecklenburg-Vorpommern (northern-eastern Germany) was closed to pass on Ulrich, Duke of Mecklenburg (1555-1603). Even so, no serious damnatio memoriae should have occurred here, for the colossal statue of Saint Anthony was still there during the Lutheran rages (Chadwick 2001: 20). At the same time, other factors would contribute in compromising the order's importance. One was the increasing competition with the Military Hospitaller Order of Saint John of Jerusalem (Chadwick 2001: 21), and another could be the affirmation of innovative medical approaches, such as the surgery of Ambroise Paré of the Parisian Hospital in the Hôtel Dieu (Drucker 2008). The other important divergence is the swine, that was shifted from boar to black pig. According to the previous interpretation, the pig could be interpreted as a general marker of sin, and the furious and lascivious dimension of the boar had been simplified.

— Relations between engraved underprintings and illuminations

Both images reveal important differences among the original engravings and final illuminations. Such alterations have a strong visual impact since the final images appear neater than their originals. Indeed, many iconographic features are removed from both engravings: the two angels in prayer (Trinity, f.8r); or the rear building on illustration background, as a likely hospital if related to the Hospital Brothers, the desert and holy rays (Saint Anthony the Abbot, f.61v). The choice is more radical in the second illustration, but surely the iconography of Saint Anthony the Abbot is traditionally more convoluted than the Mercy Seat Trinity.

One of the possible reasons could lay in final rendering. Engravings are structured with monochromatic, black lines, and use the background tone as a backbone to provide contrast. On the contrary, illuminations rely exclusively on colours, that also add psychological effects, evoking in the observer a feeling depending on hue selection and matching. Painting each feature of the original version could therefore introduce the delicate problem of skilful colour matching to avoid visual overload, which would eventually leave a displeasing effect on the observer. Removing unnecessary details, the final image would maintain an easier balance.

Hence it follows that there could be criteria to process the selection. The Trinity's flanking angels do not appear to cover an important capacity as for a correct interpretation of the illustration content. The essence of the dogma is already expressed by the three identities of the Trinity, that are represented as the Ancient of Days, the crucified Son and the Dove consistently to the custom. Therefore, their recognition is straightforward. The two angels do not help other sublevels of interpretation and they could be removed without compromising the purposes of the illustration itself. As for Saint Anthony, the elements that are removed appear to be related with the connection of the saint with the Hospital Brothers.

In this second case, a more interesting scenario can be proposed: the separation of Saint Anthony from the order is proved to have historical bases, some of them relate to the growing criticism against the secularisation of the Roman Church. When the Father is identified as the bishop of Rome and Saint Anthony is reduced to the initial dimension of father of monasticism, the artist could distance himself from any Reformation bias. Commercially speaking, maintaining impartiality would be a clever strategy, especially in the eye of the close Council of Trent. Maintaining theological fairness, the seller of a printed prayer book would accordingly meet a broader audience.

— Comparison between analytical results and iconographic considerations

Speaking of the applied materials, the Raman analyses revealed a consistent use of lead white as the whitening agent. Although the usage extent varies among pigments, the white mineral has a relevant influence on final appearance for all paints. As a filler, this scattering agent adds visually to the overall reflectance and shades endmembers towards brightest tones (i.e. blue and blue light paints, red and red light paints). Among the identified minerals, vermilion is known as a brilliant red pigment with excellent body and hiding power (Gettens and Stout 1966: 172), and that is still the case for the blue mineral azurite. And indeed, RS spectra of blue and blue light, red and red light spots reveal that the reflectance maximum and minimum are located approximately at the same positions, and that only the overall reflectance differs [Table 1]. Adding a filler also enhances the amount of light scattered by poorly diffusive minerals, like some ochres. Indeed, natural iron-containing oxides, hydroxides and oxy-hydroxides could have poor hiding power (Gettens and Stout: 134).

Not just the wise addition of filler, but the same way of processing pigments reveals the artist's skill in manipulating artistic materials. The mentioned azurite is surely a pigment with good hiding power, but its strength depends largely on the way it is ground: previous studies reveal that the particle size plays a significant role in the final appearance of a pigment. When the mineral is poorly ground and its grain is coarser, the resulting colour is a strong blue masstone (Gueli *et al* 2017). As a matter of fact, the low-magnified stereomicroscopy images (8.0 x) reveal coarse particles with indented surface [Table 1]. Similarly, the green mineral malachite requires equal attention [Table 1]: the artist had not to grind this pigment too finely or otherwise, it would appear dingy and ashy (Cennini 1899: 42). At both a visual and a magnified inspection, the pigment appears brilliant and covering the bottom design. At IRR imaging, the paint was proved to be attenuating, which fact might suggest that it was used mostly as alone.

However, other visual effects arise. A secondary, yet not less important feature is that paints appear dense in texture. As a result, they easily cover the underlying printed pattern, that is not perceivable at a naked eye, only slightly at a magnified view at the stereomicroscope, completely with IRR-digitally improved.

Therefore, the applied colouring materials seem to be of fair-to-good quality and including luxury pigments like vermilion, malachite, and lead white. The fact reveals that beyond these images there was a talented artist, that knew how to use artistic materials, how to combine them to obtain certain visual effects, how to work on distinguished objects. This artist knew efficient strategies to hide unwanted features speaking religious preferences, especially in Saint Anthony's illumination. Additionally, the artist proved his capability in clearing unnecessary features from the final image. In the *Trinity*, the relieving the image from the angels was previously argued as a visual easing, that reveals itself the personal artistic preferences of the customer.

Although the artistic materials were carefully selected, the illustration making is not similarly elaborate. In fact, the stereomicroscopy images suggest that the materials are applied mostly as a monolayer, with brighter or darker paints superimposed with the sole purpose of lining up or adding light to single areas. There is no trace of glazes, multiple overlayers, *chiaroscuros* or any technique applied in the finest illuminations. The relative simplicity of the paints' features denotes a fast execution, like a workshop order from a regular customer.

Conclusions

This study touched upon the match of computational methods and spectroscopic characterisation to analyse two illustrations of the Parisian mid-16th-century *incunabulum* from Germain Hardouyn through a cross-disciplinary approach between technical examination, social sciences, and computational methods. In a first phase, the investigation made use of a multi-analytical approach relying of Vis-NIR diagnostic images to feed a well-known software and computing language in Image Processing. The use of the software allowed to extract detailed reconstructions of the underprintings and to elaborate on the NIR reflectivity and NIR absorptivity of the single painted areas. Also, the chemical palette of the artist was determined to provide further support to the explanation of the NIR material responsiveness. The used pigments are azurite, vermilion, lead white, ochres and malachite. These results are consistent with the observed behaviour of the pigments in NIR-reflectographies.

The reconstructions of the underprintings acted for an important tool to retrieve other unpainted engravings in other Hardouyn's *incunabula* from the BL in order to appoint a reference for the original appearance of the illustration. A similar, non-automatised approach to create reference reconstructions of the original print was used in a previous study on Inc.438 (Miguel *et al* 2019) and that proved to be time-consuming (12 hours were spent to create the large-format reconstruction). Through the MATLAB automatization, it was possible to get a significant gain of time, for the computation of both the studied digital reconstructions required less than one hour. The unpainted engraving and the illuminated illustration were compared, with the result of highlighting important iconographic differences in both illustrations. The interest in this visual shift consists in the fact that since these books were commercial items, one of the possible causes for the major differences observed in their illustrations could lay in the business patterns of printed books of prayer where the client could potentially play an important role. The material studies assisted by the computational methods also support the hypothesis of a gifted, intentional use of high-quality artistic materials to translate the religious, artistic identity of the contracting customer into a coloured visual. The results further suggest that the manufacture is hasty, ensuing that the illumination was one instance of a largely demanded market.

Acknowledgements

This work is supported from Portuguese national funds through the FCT – Fundação para a Ciência e a Tecnologia, I.P., within the projects UID/EAT/04042/2019, DL 57/2016/CP1372/CT0012 and HERITAS program (PD/297/2017). The authors express a special thanks to the BPE for making Inc.438 available for this study and to the BL for granting permission of reproducing the illustrations from C.29.f.10 and C.29.g.5. Silvia Bottura Scardina also thanks the University of Lisbon for financial support with the doctoral scholarship BD-2017. A special thanks goes also to Sónia Costa for providing technical support and to John Boneham (British Library), Manuel Peters (Politecnico di Torino) and Roy Bayot (Universidade de Évora) for their assistance.

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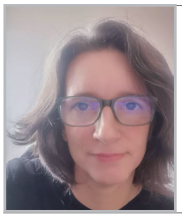
Filipe Themudo Barata is a Portuguese researcher of the Centro Interdisciplinar de História, Cultura e Sociedades at the University of Évora. Previously Full Professor and Vice-President of the same university, he completed a degree in History at the University of Lisbon and a PhD in the same subject at the University of Évora. Since then, he has been specialising in Medieval History, Mediterranean Cultures, Museology and Intangible Heritage. He is also responsible of UNESCO Chart of Intangible Heritage, member of the Scientific Council of the University of Évora, director of the TPTI- Erasmus Mundus Master course and collaborates in numerous international projects.



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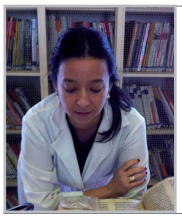
Alice Nogueira Alves is a Conservator-Restorer. Since the beginning of her academic training, issues related with the history and theory of restoration and the way different cultures see the artistic object gained fundamental importance in her academic interests, which culminated in the completion of a PhD in Art History, Cultural Heritage and Theory of Restoration, at the School of Arts and Humanities of the University of Lisbon, in 2009. Currently, she is a Guest Assistant Professor at the Faculty of Fine Arts of the University of Lisbon.



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Catarina Miguel is an integrated researcher at the HERCULES Laboratory (HERança CULtural Estudos e Salvaguarda) at the University of Évora. She holds a degree in Chemical Engineering from Instituto Superior Técnico and a PhD in Conservation Sciences from the NOVA University of Lisbon. Specialist vibrational spectroscopy, Catarina Miguel has been working for more than a decade in the study of materials and techniques used in the production of illumination. Catarina Miguel is the author of more than two dozen publications with international circulation, and has supervised several master's and doctoral theses.

https://doi.org/10.37558/gec.v18i1.825