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COMPARATIVE STUDY OF TWO MULTISPECTRAL IMAGING SYSTEMS ON THE 'ARXIU VALENCIÀ DEL DISSENY' INTERIOR DESIGN SAMPLES

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Abstract

Cultural heritage analysis using Multispectral (MSI) and Hyperspectral Imaging (HSI) has grown significantly since the early 21st century. This boom has been related to the development of digital imaging, with the appearance of cheaper and easier-to-use tools. This paper presents a comparative study between two multispectral imaging systems applied to interior design watercolours from the Arxiu Valencià del Disseny (AVD) at the Universitat de València (UV). For the comparison, the samples were registered with these two systems: one based on an adapted digital DSLR camera and another dedicated hyperspectral camera. One of the systems made it possible to combine multiband technical photography (TP) with MSI (405–920nm, 18 bands) and open-source software processing. The second, based on HSI in the VNIR region (400–1000nm, 204 bands), even though it was not preferable for art photographic registration, favoured the data acquisition and processing thanks to the proprietary software automatization mechanisms. Therefore, it was observed that spectral information, calibration, and data processing were more limited in one system than in the other. Finally, this comparison aims to expose considerations to take into account when purchasing this equipment, rating issues such as affordability, versatility of use, and obtaining data.

***Keywords**: MSI; HSI; Watercolour; Design collections; Technical documentation; Conservation; Cultural heritage*

Introduction

The technological revolution that the development of digital imaging has brought about in many science fields has had a considerable impact on cultural heritage studies, largely due to the instrumental contribution of lightweight equipment such as digital DSLR cameras, multispectral cameras, and smartphones [1–3]. Currently, this type of equipment is widespread in research and industry areas, as it is relatively cheap and easy to use. This has led to the market making available equipment with a variety of characteristics and properties of use that can lead to confusion due to its nomenclature when talking about multiband, multispectral, or hyperspectral technologies [4,5].

To compare two (multi)spectral imaging equipments, samples of interior design (furniture sampler) watercolour paintings belonging to the *Arxiu Valencià del Disseny* of the Universitat de València [6] were analysed. The AVD is an archive made up of mainly documentary collections donated by companies and professionals in the design sector of the Valencian Community. Created in 2018, this archive that keeps a variety of cultural artefacts aims to document, preserve,

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and disseminate the local and national design heritage, emphasising that this legacy should have an impact on the creative industries. On this wise, these watercolours and other artefacts' characterization is one of the most compelling steps for the AVD project, as the documentation of the composition materials is essential for their conservation and will be integrated into a searchable and interoperable semantic web of the Design legacies.

Multispectral imaging was developed for different remote sensing scientific applications [7, 8], and it has been widespread since the beginning of the 21st century. Its use covers fields such as biomedicine, the food industry and agriculture, geography, and astronomy [9–11]. Spectral imaging techniques provide information on the radiation emitted in a scene and its reflectance spectrum for each registered pixel [12]. In multispectral imaging techniques, this information must be acquired well enough to form a continuous spectrum. As a rule, spectral imaging is built into a digital camera with a photosensitive sensor and several bandpass filters with different spectral ranges. In fact, and explained in a simplified way, digital photography simulates the trichromatic vision of the human eye by conforming to three wavelength measurements corresponding to pixels of the RGB channels in the visible region (400–700nm). When spectral systems are built from tens or with a few spectral filters, for example, 7, 9, 12, or 18, it is called multispectral imaging, while with hundreds, that is, 100 or 200 records, it is considered hyperspectral imaging [13].

When incident radiation interacts with the surface of a material, the physicochemical processes of reflection, absorption, or transmission of that energy flux can occur [14]. In this context, each compound has particular reflectance properties that are linked to different electronic transition processes. For example, dye substances are considered to absorb visible light through mechanisms such as charge transfer, transitions of valence-conduction bands, or transitions in d-d orbitals [15, 16]. Definitely, these reflectance properties, graphically translated into reflectance curves or spectra, are the ones that provide the greatest information about the composition of materials and are very relevant to cultural heritage studies.

Multi- and hyperspectral imaging has been widely used in artwork studies, both for authentication, documentation, and classification of materials. In the conservation research area, it has been a support tool for the identification of pigments [17–19] and assistance in restoration processes, thanks to its capability for deterioration and other alterations monitoring [20, 21]. It has also been used for mapping regions of interest (ROI) and carrying out image analysis in the ultraviolet (UV) and infrared (IR) non-visible areas [22, 23]. The versatility of the information obtained has been a real achievement for better heritage understanding since it allows combining reflectance spectroscopy with the acquisition of processable technical images. In this line and with the Principal Component Analysis (PCA) and multivariate analyses [24], the non-invasive documentation of cultural heritage has been significantly improved [25].

On the other hand, the mainly qualitative nature of the technique and the difficulty of standardising the acquisition and data processing have been distantly and critically observed by the scientific community [26]. On occasion, the validity of the results obtained has been called into question for various reasons, including: 1) the lack of reflectance databases that contemplate the complexity and diversity of historical-artistic materials, including mixtures; 2) the variability shown by spectral patterns for the same materials according to the acquisition method, incident radiation, or type of instrumentation; and 3) the high dependence on the investigator's criteria in the processing, comparison, and interpretation of the data.

In some cases, scientific criticism has focused on analytical chemistry research carried out in the area of cultural heritage [27], whether from conservation or art history, aiming at the lack of specific knowledge on topics such as experimental design development, analysis methods, and equipment operation. Conversely, the trend towards multi-analytical approaches in recent years has not been a notable milestone in the study of cultural artefacts either, since they become general protocols where the objects lose their unique character and significant economic and human resources are consumed without a specific criterion.

Within this context, multi- and hyperspectral imaging techniques based on compact and portable equipment become ideal tools for a non-invasive and non-destructive approach to cultural heritage. These are resolved as fundamental axes in conservation and research processes in the sense that they help to optimally manage daily work, from planning and developing specific experimental phases, working in situ or remotely, to digital documentation, in a single process. Instead, the market availability of these instruments and the usual nomenclature can create confusion. For example, some equipment is suitable for obtaining excellent-quality images but has a lower resolution or is limited in the number of bands. On the contrary, others with enhanced spectral resolution may not be suitable for acquiring high-definition images. Finally, the general objective of this research is to generate knowledge about hyperspectral imaging systems uses, methodologies, and equipment in a practical sense, comparing some of their possibilities, benefits, and limitations for the study of cultural heritage.

Experimental part

Materials

For this study, four samples from the *Hijos de Mariano García* collection belonging to the AVD were selected. The collection is made up of an assortment of administrative documents, sketches, books, photographs, and commercial samples of interior design for furniture sales, which were made with different techniques. In the collection, it finds handmade samples with charcoal, through watercolour, pastel drawing, and printing techniques such as lithography and offset, to the photographic album (Fig. 1).

Fig. 1. An historical photograph of Mariano García's furniture factory and exposition (left) and two laminae made with charcoal pen (up-right) and watercolour-pastel drawing mixed technique (down-right), AVD photographies licenced

The illustrated sheets that make up the samplers are made by various authors and photographic studios, building an essential memory of the furniture industry and national design. The four watercolours studied belong to a historical period prior to the Spanish Civil War, between 1930 and 1936, and represent different rooms such as bedrooms, dining rooms, or living rooms (Table 1). At a structural level, they are all composed of a paper primary support adhered to a secondary support of thicker cardboard.

Table 1. Technical information of the four laminae analysed in this study. Artefacts were painted in paper support adhered to cardboard, possibly to form part of a sampler book for furniture sales.

Sample ID	Size (mm)	Technique	Colours	Condition
Numero 132 (MG_132)	266 x 440	Watercolour	Blue, lavender, ochres, orange, brown, purple, green, carmine red	Ref. 128 in pencil. Paper acidification, colour fading, stains, fingerprints
N° 145 (MG_145)	281 x 455	Watercolour	Brown, bronze, blue shades, violet, green, carmine red	Ref. 228 in pencil. Paper acidification, foxing, fingerprints, material loss
Numero 147 (MG_147)	270 x 465	Watercolour	Brown, blue shades, purple, ochres, carmine red	Ref. 230 in pencil. Paper acidification, foxing, material loss, colour fading
Número 148 (MG_148)	275 x 455	Watercolour	Brown, blue shades, ochres, yellow, green shades, purple, carmine red	Ref: 122 in pencil. MARIANO GARCIA MUEBLES-VALENCIA sealed. Paper acidification, adhesive stains, foxing

Fig. 2. Sample MG_148 sealed with the Mariano García company stamp. The capture shows the lamina conservation condition, with some areas of foxing and grease stains. Photography by the authors, AVD licensed

One of the peculiarities in the representation of furniture is the incorporation, for example, of mirrored glasses in wardrobes, an innovation that Mariano García's company introduced around 1929 under the influence of the Franco-Belgian industry. In watercolours, glass and mirrors are painted with different shades of blue, simulating the irregular reflections of incident light. Similarly, shiny or metallic surfaces, such as ceramic objects, glass vases, marbles, and copper finishes, are represented with special mastery and attention to detail, thus creating a set of scenes of great artistic quality. Although the authorship of laminae is unknown, they have two types of non-consecutive numbering, one done in pencil and the other with a pencil nib (India ink), while only one (MC_148) appears sealed with the stamp of the company (Fig. 2). All artworks show a stable conservation condition with alterations derived from paper acidification, colour fading, foxing, and fingerprint stains. In order to compare colours, Pigments Checker v.5 provided by *chsopensource.org* [28] was used. This card is made up of a collection of traditional pigments in art history, all in acrylic binder applied on pure cellulose watercolour paper, acids and lignin-free, compounds chemically tested and stable.

Methods

Two lightweight and portable Multispectral (MSI) and Hyperspectral Imaging (HSI) devices were used to study the laminae. Table 2 summarises some of the relevant technical features in this comparison. In addition, the works were documented through Technical Photography (TP), a set of high-quality multiband images that combine the use of light radiation in the ultraviolet, visible, and infrared ranges (UV-Vis-NIR) and bandpass filters. Acquiring this set of scientific images is a methodology widely used by conservators and artwork photographers that allows the visual and digital analysis of the object in different bands of the electromagnetic spectrum, from which information such as the presence of underlying drawings, non-visible alterations, or retouching, as well as different materials according to their fluorescence, can be obtained.

Table 2. Equipment technical features for two Multispectral and Hyperspectral Imaging systems used. Both tools have differences regarding spatial and spectral resolution, respectively

Features	MSI	HSI
Equipment	Adapted DSLR camera (Nikon D850)	Dedicated hyperspectral camera (Specim IQ)
Sensor	CMOS FX	CMOS
Wavelength band	360-1000nm	400-1000nm
Spectral resolution	---	7nm
Spatial sampling	8256 x 5504pix (FX image zone)	512 x 512pix
Spectral bands	18 bandpass filters	204
Object distance	450 – ∞mm	150 – ∞mm
Size	146 x 124 x 78,5mm	207 x 91 x 74mm (125,5 mm depth with lens)

Multiband TP

Technical photography was performed with a Nikon 850 FX DSLR camera (45.4MP, CMOS sensor) modified to have a complete sensitivity between 360 and 1000nm, eliminating the internal filtering or 'hot mirror' (dielectric Bragg mirror) that commercial cameras incorporate to avoid undesired IR signals in traditional photography. A Nikon Nikkor 50mm AF f/1.8D lens and three scientific filters (UV, Vis, and IR) were used for image acquisition. For UV photography, a UV LED lamp was used with 14250mW of radiation power, a 60° focusing lens angle, and an emission at 365nm UVA standard. Vis and IR photography was performed with a set of two 150-watt halogen lamps (220–240V) with a colour temperature of 2800–3200°K, each one located at a 45° angle to the object. The images obtained were edited as overlapping layers in a single file, to which others of false colour (IR-FC) were added to favour their fast analysis, observation, and comparison.

MSI imaging

From the registration of 18 images, a DSLR camera, and 18 bandpass filters obtained, the respective sample data cubes were built. To obtain images, the 18 records were made without moving the camera, with the two halogen lights, and manually changing the filters. Filters cover a spectral range of 405–920nm (Fig. 3), with a 10nm bandwidth for each one. Although the filter set is not evenly spaced (405, 430, 450, 467, 480, 500, 532, 506, 580, 610, 640, 671, 700, 730, 760, 840, 860 and 920nm), they represent the spectral characteristics of some historical pigments in terms of absorption and specific inflection points [29]. Calibration colour was carried out with an in-scene card composed of a reference of white, black, and four greys and applying a multi-point 3rd-degree polynomial curve to the images. As a result, the data cube shows normalised reflectance (0:1) for each channel pixel on a 256-colour scale (0:255). Thus, white, grey, and black represent 100, 80, 60, 40, 20, and 5% of the material's reflectance, respectively. In brief, the data cube was built following these steps: 1) decompose and split into native components in B/W mode (*ImageJ*); 2) align and scale the images to overlap (*Registration App*); 3) calibrate the white, grey, and black scales (*ImageJ*); and finally, 4) build the data cube with Hypercube (US Army Geospatial Centre, v. 11.52) software [30–32].

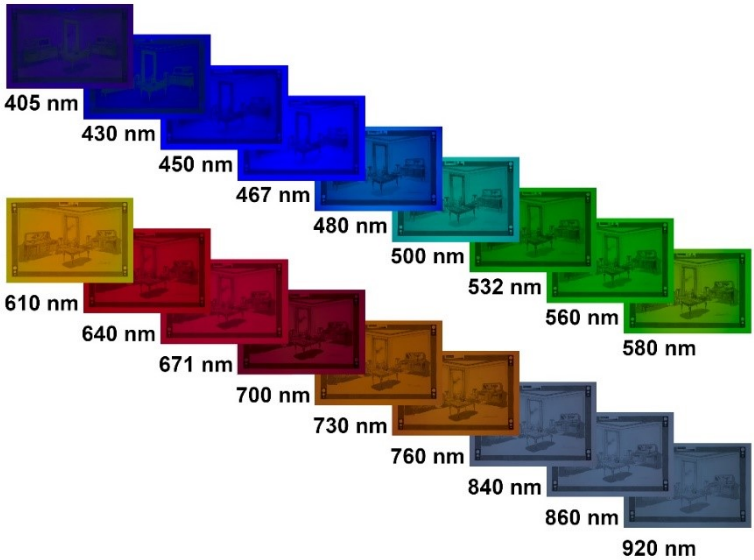

Fig. 3. Eighteen images of each lamina were captured with the adapted DSLR camera and then processed for building the spectral datacube. The filter set has been selected to represent historical pigment absorption or inflection points.

HSI Imaging

HSI data were acquired with a Specim IQ hyperspectral camera (Spectral Imaging Ltd., Finland, Konica Minolta) with a spectral range of 400–1000nm and a resolution of 7nm for a total of 204 bands in 3.5nm steps [33]. The camera acquires the data in three files, or data cubes. The datacube is a three-dimensional array of values formed with the information from the X and Y axes of the two-dimensional image (512x512pixels) and a third Z axis corresponding to the wavelength (λ) where the spectral information is registered [34]. The file set is formed by three data cubes: the raw reflectance data, a white reference, and a dark frame or black reference. With all these data, a normalisation process is carried out to obtain reflectance curves, which at a graphic level result in a continuous line formed by 204 points that represents the spectral, and a white reference panel for calibration provided by Specim is used. Spectral information is recorded in three data cubes: 1) raw data, 2) dark frame, and 3) white reference. With these data, the camera software performs an automatic normalisation process called 'Reflectance transformation'. This reflectance normalisation (0:1) is appropriate for spectral curve comparison. For data cube processing, Specim IQ Studio, Envi v.5.4, and OriginPro v.9 software were used. Reflectance spectra were compared with several libraries (U.S. Geological Survey, CAMEO, COLOURLEX) for qualitative interpretation of the curves' shapes and features [35–37] and colour-mapped both in multispectral and hyperspectral images with a Vector Angle (VA) classification method. VA is an automated Hypercube method that calculates the spectral angle between a selected pixel and similar ones, showing an image with the best pixels matched.

Results and discussion

Multiband Technical Photography (MTP)

Technical photography allowed the recording and high-resolution digitalization of the AVD's laminae. The photographs taken with the DSLR camera in the visible region (Figure 4) are calibrated to be colorimetrically accurate to the human eye's visual perception depending on the conditions (incident radiation, geometry, shutter speed, f/number) in which registration is made. The file was stored in raw format and processed in other image formats (TIFF, JPEG, and PNG) following UNESCO document archiving standards and for website publication. A full set of multiband images (Fig. 4a) consisted of registers made with raking light in the visible bands (RAK-Vis) and the spectrum non-visible bands as fluorescence ultraviolet (UVF), reflected ultraviolet (UVR), infrared (IR), raking infrared (RAK-IR), and infrared false colour (IRFC), for a total of 7 captures. This multiband set allowed us to document the laminae conservation condition, better determining the presence of organic residues and fingerprints through ultraviolet fluorescence images (Fig. 4b). One feature to take into account with multispectral imaging techniques is the compromise established between spatial and spectral resolution in the different equipment. In general, larger sensors with high megapixel resolution lack good spectral resolution as measured by band numbers, while dedicated sensors with high spectral resolution obtain lower resolution and smaller images (Fig. 4c).

Fig. 4. A multiband approach gives us information about the laminae condition (*a*), e.g., materials loss, paper topography, or surface fingerprints in the UVF capture for the sample MG_145 (*b*). For comparison, a small RGB 512-pixel image (*c*) was processed using a band interval selection as channels from the MG_132 hypercube

Multispectral and Hyperspectral Imaging (MSI & HSI)

The paper support of the four samples shows yellowing due to oxidation processes during natural ageing. Figure 5a shows the reflectance spectra of five contiguous points selected from the pixels line from the lightest to the darkest shades in the MG_132 lamina. Although the spectrum has no characteristic features beyond a progressive increase in reflectance, it shows its highest absorption in the violet region [16]. Mainly, yellow pigments and dyes absorb in this short-wave region and reflect on the rest of the spectrum; moreover, paper is a highly reflective near-white material due to the presence of charges such as calcium carbonate, barium sulphate, or titanium dioxide [38]. Likewise, the cellulose and other compounds, such as resins and adhesives, degradation processes present in the paper produce the support's yellowing due to acidification. Fig. 5b shows the primary support reflectance curves acquired using MSI. These curves were selected with the same criteria as HSI and in approximately the same image area. In comparison, the same spectral behaviour of the material can be observed, with the exception of slight variations in the intensity of the reflectance.

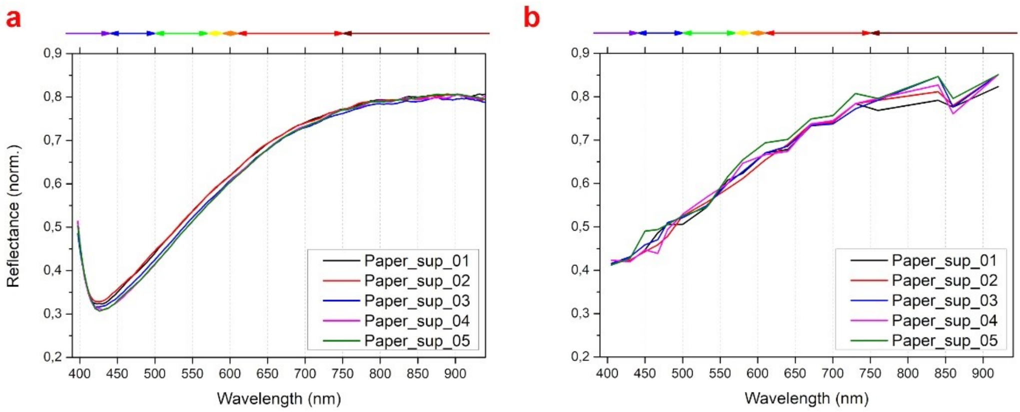

Fig. 5. HSI (*a*) and MSI (*b*) reflectance spectra of five points, lighter to darker pixels, from the sample MG_132 paper support. Both present similar spectral behaviour with a flat shape with an increasing reflectance.

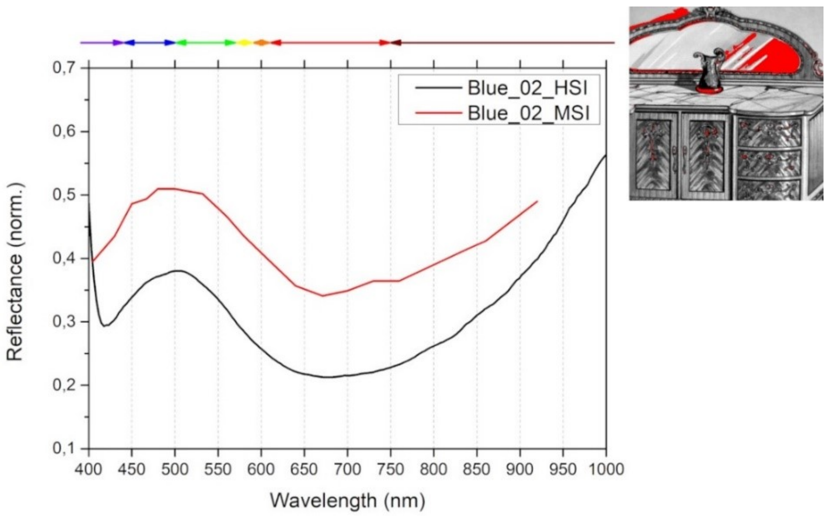

Fig. 6. HSI and MSI reflectance spectra of two blue points on sample MG_145. Spectral features in both techniques are useful to understand the material behaviour and, hence, their hypothetical classification with comparison methods. Blue_02 was mapped (in red) on a hyperspectral image with a Vector Angle (VA) classification method

In the same way, a distinctive variation of the reflectance intensity is observed on two blue-coloured analysed points of the sample MG_145 (Fig. 6). Changes in intensity were not attributed so much to the selected analysis points as to the white calibration carried out using different target cards. On the other hand, the spectra show the same behaviour, with absorption bands at 405–420nm and 670nm and a maximum reflectance at 460–480nm in the blue region. Curve prolongation in the green region (ca. 500nm) may be characteristic of this hue, as in the case of phthalocyanine blue (green shade), a synthetic organic pigment used since the early 1930s [39]. Another distinctive feature of some blue pigments is the appearance of an inflection point or a progressive increase in reflectance in the IR region, observed in both spectra from 730–750nm.

Two red points of the MG_145 lamina were compared in Figure 7. The HSI spectral curves of points 02 and 05 show the same behaviour regarding absorption bands and inflection points. The changes in intensity correspond to the apparent luminosity, one pixel lighter and one pixel darker, respectively. The absorption bands are observed in the short wave of the spectrum, between 400 and 550nm, with an inflection point at 580nm and a reflectance increase in the red and near-infrared regions. In comparison, the MSI curves follow the same pattern, with absorption bands at the beginning of the spectrum and a coincident inflection with the 580 and 610nm bandpass filters. The reflectance is also increased with the 640 and 671nm filters. In general, the maximum reflectance is indicative of the colour of the sample or, in this case, of the analysed points. It is considered that some organic red colours, such as madder lake or alizarin, have inflection points around 600nm [40, 41].

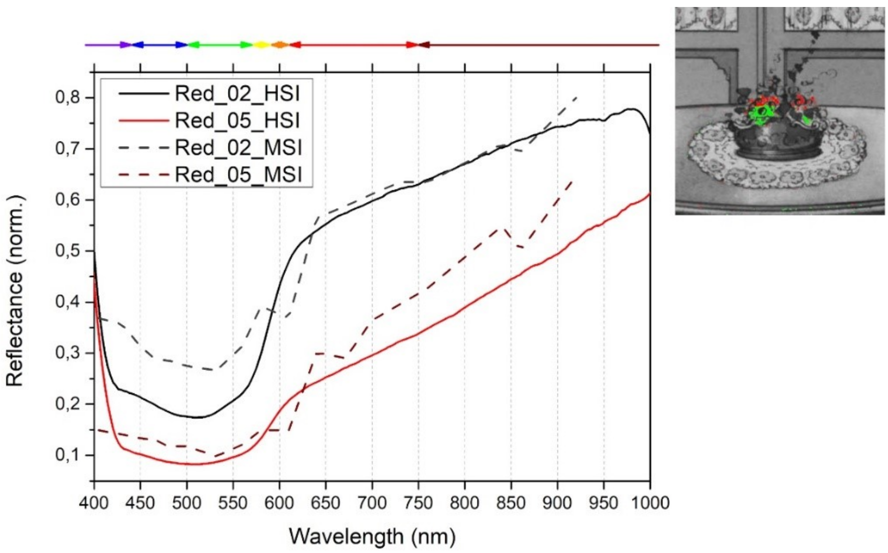

Fig. 7. HSI and MSI reflectance spectra of two red points (Red_02 and 05) on sample MG_145. Spectral features of the red colour were identified for the sigmoid shape of the curve around 600 nm and a reflectance increase at 640 nm. Red_02 (in green) and Red_05 (in red) were mapped on a multispectral image with VA classification method.

Conclusions

Multispectral imaging techniques used in this study on heritage design artefacts, although they show similar features and capabilities, have fundamental differences depending on the instrumentation. Multispectral equipment, a digital DSLR camera, and a set of bandpass filters for reflectance curve processing are extremely useful for image analysis, while dedicated hyperspectral equipment shows excellent performance in terms of spectral resolution. One of the most important characteristics when working with reflectance spectra is standardising the capture method and data processing, something that is achieved more appropriately with one piece of equipment than with another.

Multispectral data cube capture from 18 filters is complex, slow, and, in a certain sense, difficult to control due to variables such as the incident radiation, the lens optical and chromatic aberration, or the processing through multiple software packages that can condition the interpretation of the final result. On the other hand, the ability to create a set of high-resolution multiband technical images makes this equipment a fundamental tool that any conservator, archive, or museum professionally dedicated to heritage conservation should have.

Conversely, hyperspectral equipment is more limited in image resolution but is very powerful in acquiring spectral information. This is done semi-automatically, in a few minutes or seconds, and the data obtained is easy to extract and process. The system also allows the customization of the analysis by being able to load applications or capture modes in which the identification of materials occurs instantly and can be manipulated on the equipment's screen. In conclusion, the results shown in this work reinforce the idea that although both devices are lightweight, portable, and economically affordable, they stand out for having different capacities concerning spatial and spectral resolution and data acquisition and processing.

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