Colourimetric Characterisation of Digital Sensors and Application in Heritage Documentation of Prehistoric Rock Art

Introduction

Documenting heritage is no trivial task and must be addressed as rigorously as possible.

Comprehensive, complete and accurate cultural documentation is required in order to carry out specific and optimal actions to preserve the heritage items. Thus, such documentation must reflect the current state of the cultural artefact. This is particularly true for highly vulnerable heritage emplacements, especially those which suffer short- or long-term degradation, such as the prehistoric rock art shelters. Most of these sites are located in open enclosures exposed to numerous environmental or natural factors, in addition to progressive degradation arising from human activity (Giesen *et al.*, 2014: 49).

Documentation work is no longer restricted to archaeologists and these days more often involves coordinated action by technicians, researchers and professionals spanning multiple disciplines. This collaboration entails introducing the use of new technologies to effectively meet the high demands required in this type of work, such as European guidelines. We can leverage digital imaging and photogrammetric techniques to obtain metric, photorealistic and accurate 3D models relatively easily, quickly and cheaply (Balletti *et al.*, 2015: 215-222; Domingo *et al.*, 2013: 1879-1889).

Although the use of these novel techniques has resolved technical issues like geometry, some aspects, particularly colour, remain to be addressed with more rigour. Colour is a basic descriptive attribute providing significant information on the state of an object and is crucial in heritage documentation, especially conservation and preservation work (Boochs *et al.*, 2014: 13; Korytkowski, and Olejnik-Krugly, 2017: 333; Ruiz, and Pereira, 2014: 338).

The fundamental problem is that colour is a matter of perception and, to some extent, subjective interpretation. The same object can be perceived differently depending on the lighting and observer. The classical methodology used to record colour in documentation was often restricted to subjective processes involving colour charts and dependent on the observer's expertise, limiting the outputs obtained (Ruiz, and Pereira, 2014: 344). Although the use of digital images represents a new approach to colour recording, their use alone is not enough.

This article aims to measure colour as rigorously, precisely and close to reality as possible through the colourimetric characterisation of digital sensors. The purpose of such a characterisation is to convert the sensor-dependent signal into colour spaces independent of the device, adapting the process to the recommendations of the International Commission on Illumination (CIE). Thus, a camera can be used to operate as if it were a colourimeter (Martínez-Verdú *et al.*, 2003: 279-295). As a fundamental and novel aspect of this study, particular mention should be made of the development of a software package for colourimetric data processing and sensor characterisation, known as pyColourimetry (Molada-Tebar *et al.*, 2017: 48-53).

Finally, we would note that the methodology has been successfully applied to different scenes of Levantine rock art in Barranc de la Valltorta (Ares del Maestrat, Castellón, Spain), undoubtedly one of the most unique pictorial ensembles of the Iberian Mediterranean Basin, declared a World Heritage Site by UNESCO in 1998.

Digital sensor characterisation

The incorporation of digital images constitutes a methodological advance in the tasks of capturing, archiving and analysing heritage documentation. However, data recorded directly by camera sensors cannot be considered strictly colourimetric. Although most digital cameras today work in colour spaces based on the RGB system, this name is a generic framework and in reality, the RGB space is not unique but sensor-dependent (Chang-Rak, and Maeng-Sub, 1999: 585). Different cameras record different signals, even for identical scenes captured under the same exposure or illuminant conditions.

One approach to the problem of accurate colour recording consists of using International Color Consortium (ICC) profiles during raw digital image development, usually referred to as camera profiles (Pereira Uzal, 2013; Iturbi *et al.*, 2018: 61-62). A suitable alternative to using colour profiles is the colourimetric characterisation of digital sensors which makes it possible to obtain colourimetrically accurate results. Characterisation is an objective method since the results do not depend on the observer, therefore no subjective interpretation is involved (Molada-Tebar *et al.*, 2018: 56).

Characterisation establishes the mathematical relationship between the information from the digital image containing the colour chart used as a reference and their previously measured CIE colourimetric data (Barnard, and Funt, 2002: 154-157; Pointer *et al.*, 2001: 67). From the different models used in characterisation, previous experiences show that good outcomes are obtained from a second-order polynomial adjustment (Hong *et al.*, 2001: 76). These models offer similar results to the use of other, more complex techniques such as neural networks, with the advantage of lessening model processing and training time (Chang-Rak, and Maeng-Sub, 1999: 586; Cheung *et al.*, 2004: 25; Finlayson *et al.*, 2015: 1460).

Schematically, characterisation can be considered as the result of combining two methods: direct and indirect (figure 1). There are two datasets in the process, the CIE XYZ colourimetric data obtained using specific instruments (colourimeter or preferably spectrophotometer) of the reference colour chart (“direct measurement”), together with the RGB digital levels recorded by the camera sensor (“indirect measurement”). Characterisation allows users to obtain transformation equations between the RGB input data referring to a sensor-dependent colour space and an independent, physically-based space such as the CIE XYZ. Finally, since most modern viewing devices are configured to display images in the sRGB space, a final transformation is required to obtain the final output image in this colour space.

The use of characterised cameras offers numerous advantages in heritage documentation. After characterisation, a conventional digital photographic camera can be used for accurate colour recording, simulating a colourimeter (Martínez-Verdú *et al.*, 2003: 293). This enables not only a considerable reduction in time and cost, but also the colour recording of complete pictorial scenes and their comparison with scenes obtained by different sensors, periods or lighting conditions, since they are recorded in the same colour space regardless of the device.

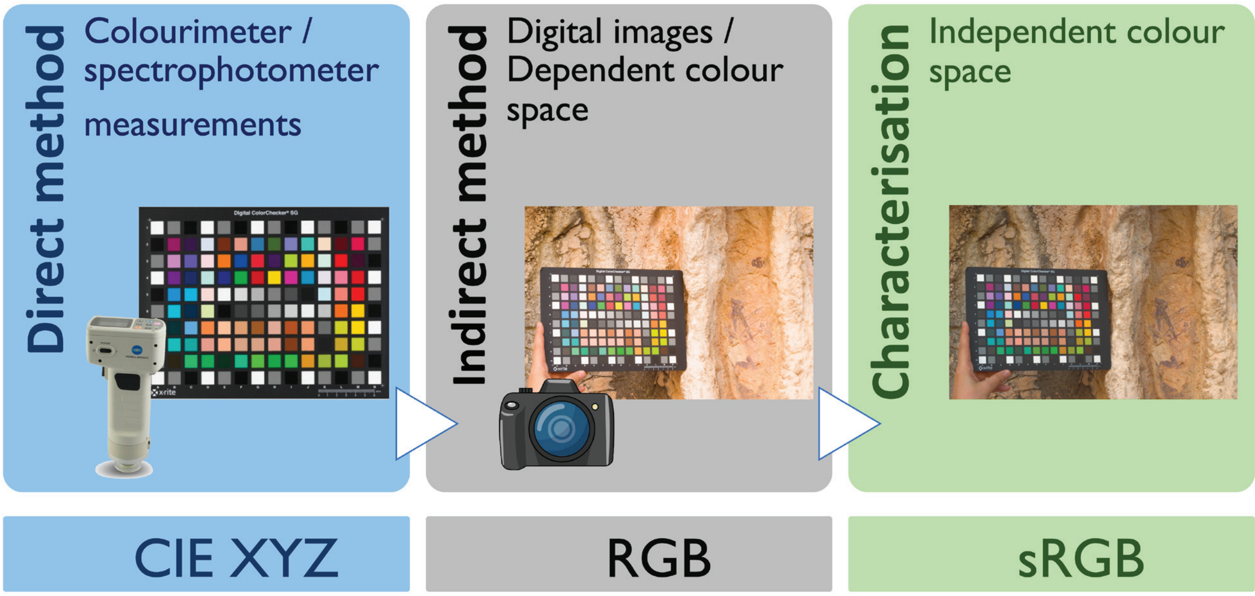

Figure 1. Digital camera characterisation procedure. Combination of the direct and indirect method.

Characterisation should not be confused with image improvement or visual enhancement processes. While characterisation seeks to accurately record colour, improvement and enhancement techniques aim to highlight or enhance pictorial figures, or detect specimens that escape the naked eye, such as through multi-spectral imaging. The key objective of enhancement techniques is to facilitate the creation of digital "tracings," sacrificing rigorous colourimetric information (Domingo *et al*., 2015: 84; Fernández-Lozano *et al*., 2017: 161-164).

Colourimetric data processing and sensor characterisation software: pyColourimetry

Sensor characterisation requires dedicated software to work simultaneously with colourimetric data and digital images. Colourimetric data processing is usually approached with proprietary software of the instrument manufacturer. The options are much more extensive for digital image processing. However, especially in Adobe Photoshop or GIMP-type image editing software, despite their great versatility and functionality, colour processing is based on profiles as the most advanced method, thereby not allowing users full control or access to computation internals during the different methodological stages. User intervention is also limited to selecting the most appropriate image enhancement option under a subjective criterion.

This technological shortcoming was addressed by developing a software package called pyColourimetry for colourimetric data processing and sensor characterisation, which also makes it possible to work with raw images (Molada-Tebar *et al*., 2017: 48-53). The programming language used was Python, a multiplatform language that is open source, intuitive, easy to implement and widely used across all types of scientific applications (Python Software Foundation, 2010).

The system consists of a set of modules – Python source files with a .py extension – that users can execute through the graphical user interface (GUI), the software centrepiece (figure 2). The current version allows users to obtain direct colourimetric measurements by means of the Konica Minolta CS-100A colourimeter (*serialPort.py*); process colourimetric data and transform between colour spaces (*myColour.py*); extract raw RGB data from the image; calculate transformation equations for camera characterisation with statistics (*characterisation.py*); apply transformation equations to the original image and finally create the output image in the sRGB colour space ready for visualisation with maximum quality on any device compatible with this colour space.

The GUI was designed to make it attractive, simple and intuitive to use but without losing functionality, giving the user full control over the workflow during camera characterisation. By way of example, figure 3 features a screenshot of the graphical interface, in particular the RGB raw data extraction from the input image, where we can see some of the main menu options implemented.

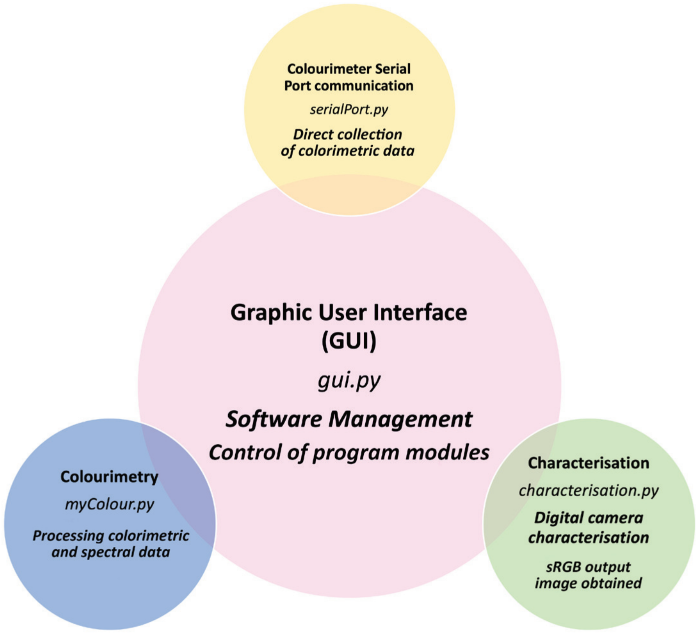

Figure 2. Main modules of the pyColourimetry software.

To ensure colourimetric rigour, the recommendations published in the technical report released by the CIE in 2004 were fully considered. Key aspects such as the illuminant, observer, reflectance reference standards, viewing conditions, lighting, equations for tristimulus value calculation, chromaticity coordinates, colour spaces, colour differences and auxiliary formulas were included (CIE 2004).

All these features make pyColurimetry a rigorous and versatile software with wide-ranging functionalities to process colourimetric and spectral data and to process raw images. The user has full control during the characterisation process, powering the analysis and management of the outputs obtained in each stage of the process, which can be leveraged in heritage documentation work.

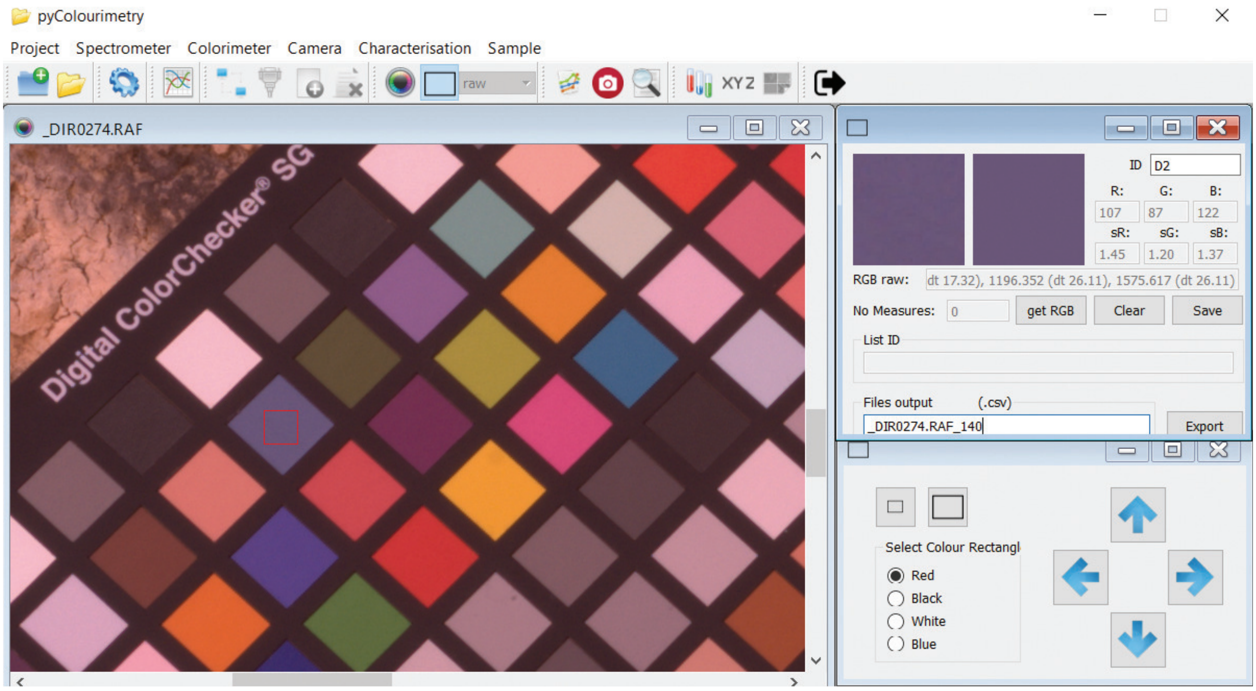

Figure 3. pyColourimetry GUI example. Extraction of raw RGB data.

Case study: Cova dels Cavalls

The digital camera characterisation methodology was applied to a series of images taken at Cova dels Cavalls. The cave is part of one of the most distinctive Levantine rock art ensembles in the Iberian Mediterranean Basin, located at Barranc de La Valltorta in the municipality of Tírig, Castellón, Spain (Martínez, and Villaverde, 2002). It is therefore an ideal sphere of application for analysing characterisation behaviour in this type of prehistoric art scenario.

A Fujifilm IS Pro SLR digital camera was used to capture the images. This camera has a high-sensitivity, low-noise integrated CCD sensor with a depth of 14 bits/pixel, enabling work in raw mode (RAF extension).

In colourimetry, it is preferred to work with raw images, instead of using processed RGB data. In a typical workflow with raw data ('raw developing' in photographic terminology), the original RGB data are converted by applying a number of complex operations such as white balance, pixel restoration (demosaicing) and colour transformations using colour filters arrays (CFA), the most common being those known as Bayer filters (Ramanath *et al.*, 2005: 35). These operations are generally applied automatically, so that the user is not aware of which corrections or in what exact manner they have been applied.

It is important to remember that the application of these automatic corrections is intended to obtain visually appealing images from a purely photographic perspective, where colourimetric values are not a priority. Since the purpose of camera colourimetric characterisation is the rigour of the colour recording, we decided to work with raw data which is the closest information to the signal recorded by the sensor.

Figure 4. Set of original images: a) 0272 (1 s); b) 0273 (1/2 s); c) 0274 (1/5 s); d) 0275 (1/10 s).

In this case study we had a total of four raw images for the same pictorial rock art scene, taken in a short period of time, and with the ISO setting at 100, the focal length at 60 mm and the camera aperture at f/22. The only parameter we changed was the exposure time, to simulate different light conditions.

The four images are 0272 (figure 4a), 0273 (figure 4b), 0274 (figure 4c) and 0275 (figure 4d), with exposure times of 1, 1/2, 1/5 and 1/10 seconds respectively. The effect that the change in exposure has on the colour recordings can be clearly seen. Processing the four images makes it possible to assess characterisation behaviour for scenes under different lighting conditions.

Images used in colour characterisation must contain a colour chart as a colourimetric reference, with a set of colour patches with known tristimulus values. The X-Rite Digital ColorChecker SG colour chart, often used in digital image processing, was chosen. It contains a total of 140 patches that broadly cover the colour range in the visible spectrum.

The manufacturer of each colour chart typically provides patch information, although this information is not always easily accessible. Furthermore, it is not common practice to specify under which particular conditions the measurement was performed. Therefore, to avoid errors we collected our own CIE XYZ data of the X-Rite colour patches, with a Konica Minolta CM-600d spectrophotometer, using the standard two-degree observer and D65 illuminant.

Workflow: methodological stages for camera characterisation

Most digital trichromatic cameras capture colour in some variant of the RGB space. The problem is that this space is not unique, so the signal recorded by a particular camera is dependent on the built-in sensor. This means that RGB camera values are not strictly colourimetric data; in other words, they do not correspond to the tristimulus coordinates based on the standard CIE observer (Chang-Rak, and Maeng-Sub, 1999: 585).

For the procedure of camera characterisation, we need an input image (preferably in raw format), the CIE XYZ coordinates of the colour chart used as reference, and the RGB data extracted from the selected patches. These two datasets, i.e., the RGB data and corresponding CIE XYZ coordinates, will be used to determine the transformation parameters between the two colour spaces (Molada-Tebar *et al.*, 2018: 49-50; Westland *et al.*, 2012: 143-157).

We can split the characterisation process into four phases: extraction of RGB data from the digital image; computation of transformation equations; statistical analysis of the adjustment, and creation of the sRGB output image (figure 5). Below we summarise the main aspects of each of the methodological phases.

— Stage A: Extraction of raw RGB data from the image containing the colour chart. pyColourimetry provides access to raw values stored directly by the camera sensor without interpolation using the DCRAW tool.

— Stage B: Computation of transformation equations (characterisation). While raw RGB data tends to be linear, better results are obtained from applying second-order polynomials by means of a least squares adjustment. The use of polynomials of a greater order is not recommended, even if the residuals decrease as the polynomial degree increases, due to colour saturation in the converted RGB data, whose origin is the overfitting of the polynomial model (Molada-Tebar *et al.*, 2018: 56).

— Stage C: Analysis of post-adjustment results. The quality of the adjustment will be determined by statistically evaluating the CIE XYZ residuals and the root-mean-square error (RMSE). Since the CIE XYZ colour space is by definition not visually uniform (the differences perceived for colour stimuli over the entire chromatic domain are not equal), it is

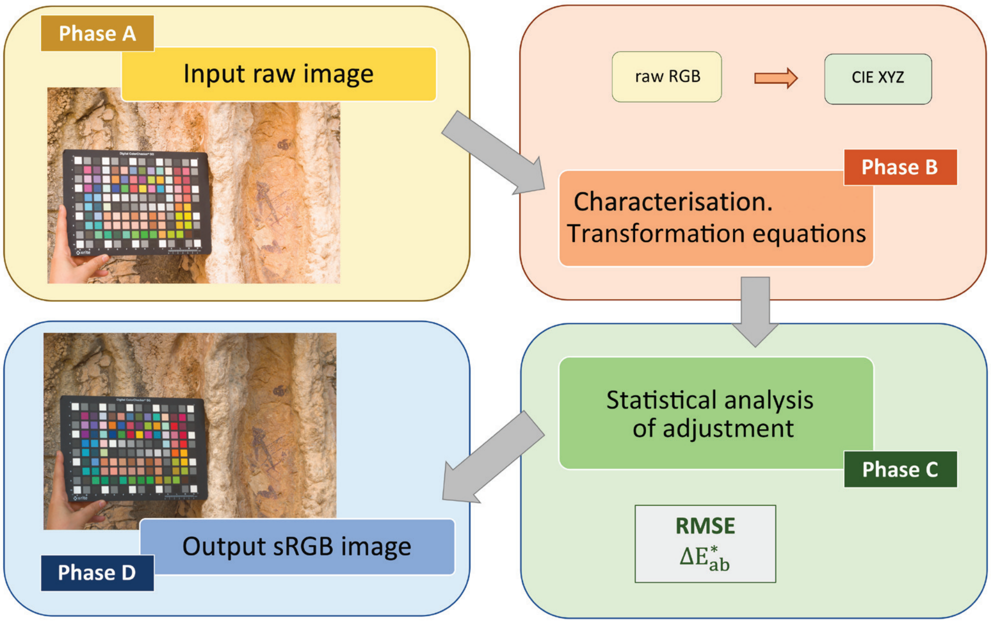

Figure 5. Methodological stages for the digital camera colourimetric characterisation.

also necessary to examine the colour differences between the theoretical tristimulus values and their predictions after adjustment. In basic colourimetry, colour differences are obtained in the CIELAB space, since they are perceptually more uniform. From the multiple formulas available to calculate colour differences, we opted for ΔE^*_{ab} CIE76 (CIE, 2004: 18), as it better matches the data and measurement conditions at archaeological sites.

— Stage D: Application of transformation equations to obtain the characterised image in the sRGB colour space. We applied the transformation coefficients to the input image and obtained the CIE XYZ tristimulus values of all pixels in the input image. Since most visualisation devices are not prepared to work with images in this colour space, we decided to convert the coordinates to the sRGB space that is compatible with most devices.

The proposed workflow was rigorous from a colourimetric viewpoint as it is a methodology that does not involve observer subjectivity. Instead, it works directly with raw data, thus avoiding any previous processing of the data from the camera. Furthermore, the statistical analysis of the residuals and colour differences helps the user select the right adjustment to apply for each particular case.

By using the colourimetric characterisation of digital cameras, we were able to convert sensor-dependent RGB input data to a CIE XYZ independent colour space. Thus, we obtained an accurate and rigorous colour record in a physically-based, device independent space for complete scenes of rock art.

Results

The transformation equations between the camera-dependent RGB space and the theoretical CIE XYZ patch values were calculated using a least squares adjustment with a second-order polynomial model. A preliminary analysis was conducted by evaluating the root-mean-square errors (RMSE) of the residuals in CIE XYZ units together with the values for the colour differences ΔE^*_{ab} after the adjustment (Table 1). The lowest residual values were obtained in image 0274 (around 2 CIE XYZ units), while the highest values were obtained in image 0272 which were around 4 CIE units for the Y and Z coordinates (table 1).

Table 1. RMSE Values and Colour Differences

Image	*Time Exposure*	*CIE RMSE*			*Average ΔE_ab^* (CIE76)*
		X	*Y*	*Z*	
0272	1 sec	3 187	3 929	3 972	5.48
0273	1/2 secs	2 479	2 443	2 825	3.67
0274	1/5 secs	2 185	2 096	2 308	3.26
0275	1/10 secs	2 651	2 649	3 075	3.70

If we compare the two images, the values obtained for the residuals make sense from a colourimetric point of view and are the expected results. Image 0272 is clearly overexposed (figure 4a), while the exposure for 0274 is close to normal exposure values (figure 4c).

Moreover, the values of the ΔE^*_{ab} colour differences obtained follow this same trend. The lowest mean ΔE^*_{ab} was for image 0274, with a value of 3.26, while the value of image 0272 was over 5 units. The worst result was obtained in the overexposed photo, whereas the best result was obtained in the picture with normal exposure. Values above 4 CIELAB units for ΔE^*_{ab} indicate that results are not satisfactory for characterising this photo (Molada-Tebar *et al.,* 2018: 49).

After analysing the residual values and the ΔE^*_{ab} colour differences achieved, we could conduct a visual analysis of the output sRGB images obtained after characterisation (figures 6a, 6b, 6c and 6d). The results were clearly satisfactory. Regardless of lighting conditions, colour differences between the images were virtually imperceptible by eye, even for the overexposed image.

Figure 6. sRGB images obtained after characterisation: a) 0272c; b) 0273c; c) 0274c; d) 0275c.

Discussion

The use of digital images has considerably contributed to the improvement in works connected with the documentation, conservation and preservation of cultural heritage. However, their use alone without a colour pipeline does not guarantee correct colour recording. Rigorous techniques are required to provide accurate results that record colour as close as possible to reality (Balletti *et al.*, 2015: 215-222).

The results obtained through the colourimetric characterisation of digital cameras by means of second-order polynomials show that this is a suitable method for recording colour in rock art documentation. It is a rigorous and objective method from a colourimetric perspective since it dispenses with observer subjectivity by combining direct and indirect techniques (Molada-Tebar *et al.*, 2018: 47-57).

RMS errors tend to decrease in images as we approach appropriate exposure values (table 1). We would therefore emphasise the importance of good exposure when taking pictures. Colour depends, among other factors, on the illuminant, the intrinsic characteristics of the object itself, the effect of the contour and geometry. Illuminant is definitely a determining factor. In fact, for overexposed images, there would be a loss of chromaticity for the colour patches used for model training (figure 4a), and consequently a worst polynomial model adjustment.

Similarly, we reached the same conclusion based on colour difference values ΔE^*_{ab}. Again, the effect of the illuminant on the characterised images could be clearly seen. The ΔE^*_{ab} values achieved assume the non acceptance of the characterised image 0272c – with a value of 5.48 CIELAB units –; while the best result was obtained with 0274.

We can compare the original images (figure 4) with their corresponding post-characterisation counterparts (figure 6). Regardless of the different forced illuminant conditions when changing camera exposure, we saw that all the characterised images were successfully converted to the same chromatic range, with almost imperceptible visual differences, in one of the typical CIE colour spaces defined for the standard two-degree observer and illuminant D65. Only image 0272c had a slight saturation, greater than in the rest of the pictures, due to the extreme overexposure of the original data. It is precisely in this image where the polynomial model is worst adjusted and the greatest colour differences were obtained ΔE^*_{ab}.

Given the critical role of lighting during the characterisation process, it is clear that if the best results are to be achieved, the exposure time, together with the other camera parameters, must be considered at the time of taking the pictures.

Conclusion

The importance of colour in heritage documentation is undeniable. Accurate colour recording provides basic descriptive information that enables, among other aspects, correct discrimination between pigment and support, as well as an analysis of its condition in a specific period and its degradation over time. Given its importance, the measurement and treatment of colour cannot be performed in a trivial fashion, but rather requires being addressed through rigorous procedures from a colourimetric perspective. In view of the results obtained, the methodology set out in this article for sensor characterisation complies with the rigour required for colour processing, although it is essential to pay special attention to the correct exposure of each photo.

The procedure provides correct, accurate and objective colour recording as close as possible to reality. By characterising RGB images from a conventional digital camera we obtained images in an sRGB colour space independent of the sensor, calculated from colourimetric tristimulus values.

Digital camera characterisation can be used in combination with other heritage study and conservation techniques such as laser scanning, photogrammetry and augmented reality.

The pyColourimetry software, in constant process of improvement and optimisation, offsets the shortcoming of commercial programs that do not enable colourimetric data and raw images to be processed together. It is a versatile tool of intuitive handling where the user has full control during each of the methodological stages. It facilitates data acquisition, colourimetric coordinate measurement, polynomial adjustment for characterisation and final creation of sRGB images. This makes it a high-performance software that can be successfully applied to cultural heritage documentation, conservation and preservation, both in production and research work.

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