Accuracy in Colour Reproduction: Using a ColorChecker Chart to Assess the Usefulness and Comparability of Data Acquired with Two Hyper-Spectral Systems

Tatiana Vitorino[1](✉), Andrea Casini[1], Costanza Cucci[1], Ana Gebejes[2],
Jouni Hiltunen[2], Markku Hauta-Kasari[2], Marcello Picollo[1], Lorenzo Stefani[1]

[1] Istituto di Fisica Applicata "Nello Carrara" - Consiglio Nazionale delle
Ricerche (IFAC-CNR), Florence, Italy
tatianamfv@gmail.com,
{a.casini,c.cucci,m.picollo,l.stefani}@ifac.cnr.it
[2] Institute of Photonics, University of Eastern Finland, Joensuu, Finland
{ana.gebejes,jouni.hiltunen,markku.hauta-kasari}@uef.fi

Abstract. Hyper-spectral imaging has been applied as an *in situ* technique for the study and accurate digital documentation of coloured artworks. Providing spectral and colorimetric characterisation across the entire surface of an object, it can be used to identify the coloured materials, measure colour changes, and document it with high fidelity. However, depending on the system used, data accuracy and reliability may vary. In this work, developed within the Round Robin Test being carried out by COSCH Working Group 1, an X-Rite® ColorChecker Classic chart was analysed with two push-broom hyper-spectral systems developed by different groups (IFAC-CNR and IP-UEF), in the 400-1000 nm range, and the data obtained were compared. This comparison allowed to assess the accuracy of colour reproduction processes performed by the two systems. The results obtained are satisfactory in terms of spectral and colorimetric accuracy for some colours, but show differences at both ends of the visible range.

Keywords: Hyper-spectral imaging · Spectral and spatial resolution · Accuracy · Colour reproduction · ColorChecker · CIELAB colorimetric values · COSCH

1 Introduction

We are not only inheriting cultural heritage from our ancestors, but we are also borrowing it from our children. Starting from this premise, curators and conservators realise that the study and documentation of the artworks that constitute our cultural heritage is important to preserve them and to increase accessibility and possibilities for our and for future generations [1]. For either of these purposes - study and documentation -, accuracy and high quality are very important features concerning the data that is acquired and kept [2]. These records have to be true and accurate representations that show the required information, without anything added to or taken away from the original artwork [3]. This is particularly important when coloured materials are concerned.

A. Trémeau et al. (Eds.): CCIW 2015, LNCS 9016, pp. 225–235, 2015.
DOI: 10.1007/978-3-319-15979-9_21

Colour is an essential language of cultural heritage that often needs more decoding than what was originally intended by the artist. Coloured materials are generally prone to changes, leading to alterations in the artworks visual appearance and, consequently the objects are interpreted differently from the artists' intention. Often conservators need to go beyond what is seen, and to successfully conserve the artworks, they need to identify and document colours with as much accuracy as possible.

The study of colour in artworks using *in situ* spectral imaging techniques, therefore avoiding that colour measurement is restricted to a limited number of points on the surface of the object, is of great importance [4,5]. These techniques provide a highly accurate way to measure colour across the entire surface of the object, and may indeed be crucial to guarantee a high-quality colorimetric reproduction [2], [5]. They allow to acquire the objects' spectral reflectance, which is a physical quantity characteristic of the material [6,7]. In other words, for each spatial pixel (picture element), a reflectance spectrum is acquired in a determined spectral region. This is obtained by recording a collection of reflectographic images of the same area at almost contiguous spectral bands (hundreds in the case of hyper-spectral systems). From the acquired data-set it is therefore possible to extract the spectral reflectance of each pixel, which has several advantages such as: the possibility to reconstruct it in the CIE colour space with any choice of illuminant and of the colour matching functions; the possibility to monitor the conservation state of the object since a change in the spectral reflectance evidences the alterations of the material; and the possibility to reliably identify and discriminate the coloured materials used by the artists [6,7,8,9,10].

In the context of the promotion of research, development and application of spectral imaging techniques towards the study and documentation of cultural heritage, COSCH[1] Working Group 1 (WG1) aims to identify and explore important characteristics of different spectral imaging systems and understand how they influence data accuracy and information reliability with respect to the various types of studied artworks [11]. As a matter of fact, several different types of devices have been developed to implement spectral imaging techniques for applications in cultural heritage [12]. These devices are commonly categorised according to the portion of the file-cube (the complete dataset formed by the three dimensions - two spatial and one spectral - over which data is collected) that is acquired in a single detector readout [13]. They can consist in cameras equipped with filtering systems for the optical selection of the wavelengths, or they can be constituted by scanners equipped with dispersive systems for the selection of the spectral bands (such as push-broom spectrometers), or they can also be based on snap-shot imaging systems, which collect the entire 3D file-cube in a single integration period without scanning [4], [13]. However, in practical terms, for the same object the acquired information can be significantly influenced by the method of data collection, the system used, and any other parameters influencing the general experimental setup. As such, WG1 is performing a Round Robin Test (RRT) with four objects of distinct characteristics, to explore different spectral imaging systems, identify the impact of each instrumentation on the results obtained, and ensure the usefulness, accuracy and comparability of the data. Colour being such an

---

[1] COST Action TD120: Colour and Space in Cultural Heritage (COSCH, www.cosch.info).

important issue, one of the objects that integrates the RRT is a ColorChecker reference chart.

ColorChecker charts are used as a colour reference, and are very important when colour image processing is concerned [6], [14]. Constituted by several standard coloured patches, these charts allow to assess the accuracy of the colour reproduction processes of the systems used, to guarantee that the information obtained is valuable and represents the true colours of the object that has to be studied and documented [3], [5], [15].

This contribution presents the comparison between data acquired from the ColorChecker chart used in the RRT with two hyper-spectral devices from different research groups that are part of the COSCH WG1 RRT: the “Nello Carrara” Institute of Applied Physics of the National Research Council (IFAC-CNR), in Florence, Italy; and the Institute of Photonics - University of Eastern Finland (IP-UEF), in Joensuu, Finland. Both groups measured the ColorChecker in their own laboratory with push-broom hyper-spectral systems that collect data with a 2D array detector at all wavelengths simultaneously for one spatial line of the object so that only one spatial dimension needs to be scanned to fill out the file-cube [13]. However, even though both systems are based on the same working principle, they were designed and optimised in different ways depending on the purpose of analysis of each group (for example, if they are seeking for high spatial or spectral resolution, or high colour accuracy). For this contribution, the data acquired with IFAC-CNR and IP-UEF systems were first used to confirm the homogeneity of the ColorChecker coloured patches. Afterwards, both set of data were compared with respect to the spectral reflectance curves, and, finally, colorimetric CIELAB values were calculated for a standard illuminant (D65) and observer (10°) and also compared.

2 Experimental Design

2.1 X-Rite® ColorChecker Classic

The X-Rite® ColorChecker Classic target is a matt chart with dimensions 279.4 mm x 215.9 mm. It has twenty-four coloured square patches, each with 40 mm of side, displayed in a 4 by 6 array, that include the representation of true colours of natural matter (such as skin, foliage and sky), additive and subtractive primary colours, various steps of grey, and black and white [15,16].

2.2 Methodology

The X-Rite® ColorChecker was analysed by the two different groups using their own push-broom hyper-spectral system. In each case, the working conditions and technical parameters were not predetermined, since the point was that each group used the setup commonly used in their laboratories. However, for treatment of the hyper-spectral file-cube (that contains both spatial and spectral information, and can easily reach several tens of megabytes), the participants were asked to follow a few guidelines.

The reflectance spectrum of ten selected coloured patches (Blue Sky 03, Foliage 04, Orange 07, Purple 10, Blue 13, Green 14, Red 15, Yellow 16, Magenta 17, Cyan 18) were extracted from centred squares with 35 mm of side, to represent the average of each patch. Reflectance spectra were also extracted from five different small areas (squares with 1 mm of side) of each patch (in the middle and in the four corners), to see if the colour within each coloured patch is uniform. Reflectance data were extracted as well from centred squares with 8 mm of side in order to resemble the common area of analysis of a contact colorimeter. The spectra extracted from each coloured patch were then used to calculate the colorimetric values of the same areas, using the CIELAB system with the CIE illuminant D65 (natural daylight) and the CIE 1964 standard observer (10°). From the L*, a* and b* coordinates, the colour-difference parameter, ΔE, was also calculated using the CIEDE2000 formula [17].

2.3 Apparatus

IFAC-CNR's hyper-spectral imaging spectroscopic measurements were carried out in the 400-960 nm range with the hyper-spectral scanner designed and assembled at IFAC-CNR. The system is based on a prism-grating-prism line-spectrograph ImSpector^{TM} V10E (SpecIm Ltd), with a 30 μm slit, which is connected to a high sensitivity CCD camera (Hamamatsu ORCA-ERG). The line-segment analysed is focused on the entrance slit of the spectrograph by means of a telecentric lens (Opto-Engineering Srl), which performs a parallel projection of the points falling within its working distance (3 cm deep at 23 cm from the lens), thus avoiding perspective displacements when the imaged points lie on a not perfectly planar surface. Illumination of the line-segment is made by two Schott-Fostec fibre-optic line-lights equipped with focusing lenses that are fixed to the scan-head and symmetrically project their beams at 45° angles with respect to the normal direction at the imaged surface (0°/2x45° observation/illumination geometry). Light is supplied by a QTH-lamp. The mechanical system can scan a maximum area of about 1 x 1 m^2, with 20 vertical line-scan stripes. The spatial sampling rate guarantees a spatial sampling of ~ 11 points/mm (~ 279 ppi) and resolution better than 2 lines/mm at 50% of contrast reduction. The system's spectral sampling is about ~ 1.2 nm and resolution is ~ 2.5 nm at half maximum. The scan is carried out in the "free-run" mode: the vertical movement runs freely at a constant speed of 1.5 mm/sec, while the acquisition of the camera images proceeds independently at a constant rate of 15 frames/sec. [18,19,20]

IP-UEF's hyper-spectral imaging spectroscopic measurements were carried with IP-UEF line scanning based spectral imaging system that uses a SpecIm VNIR camera (with a sCMOS detector) working in the 400-1000 nm range. The system consists of moving the camera and illumination unit together while the sample lies over a table with adjustable height. Illumination is carried out by QTH lamps on both sides of the camera, with a 0°/2x45° observation/illumination geometry. 240 spectral bands were recorded with a 2.8 nm nominal spectral resolution. The spatial resolution used is of 0.2 mm. 1032 spatial pixels were recorded with every line leading to about 0.23 mm resolution in spatial direction. Reflectance data were extracted in the 400-1000 nm range, with a 5 nm step. Colour calculations were performed in the 400-780 range, also with a 5 nm step. [21].

3 Results and Discussion

With respect to handing and organisation of data, the guide-lines provided to each group were of high significance since they allowed to compare information extracted from areas of the same size (considering size in millimetres, and not in pixels) and with approximate positions. Moreover, since each group has its own software to handle data, it was also important to prepare the information in a way easily accessible for the two research groups.

Both hyper-spectral systems provided high-quality RGB images of the ColorChecker (Fig. 1). To discuss the results obtained, in terms of spectral and colorimetric data, five coloured patches are presented: Blue 13, Green 14, Red 15, Yellow 16 and Magenta 17 (patches are numbered from left to right, and from up to bottom in the ColorChecker chart).

Fig. 1. RGB colour images of the X-Rite® ColorChecker chart reconstructed from the hyper-spectral file-cube from IFAC-CNR (left) and IP-UEF (right)

To check the uniformity of the colours in the chart, the comparison between reflectance spectra extracted from 1 mm x 1 mm areas at different places of each coloured patch showed that, although not completely homogenous, there is a satisfactory degree of uniformity within the respective patch (Fig. 2). Not only that, spectra from such a small area present fairly good resolution. This was observed for both hyper-spectral systems. When comparing the data obtained with the different systems, spectra are similar with the exception of the lower and higher wavelengths that show differences in intensity (*ca.* 0.08 in reflectance factor) and shape.

The colorimetric values are also in agreement between the different areas of each patch, apart from some small variations of 1-2 units in the L*, a* and b* coordinates that can be observed and which indicate that colours are not totally homogenous. On the other hand, when comparing the colorimetric values between the two hyper-spectral systems, L* and a* values are similar but significant differences are observed for the b* coordinate (Table 1). In fact, for the blue colour, an average b* value of -41.8 was obtained with IFAC-CNR's system, while an average b* value of -46.8 was obtained with IP-UEF's system. A similar difference was observed with the red colour that presents average b* values of 26.5 and 19.0, respectively.

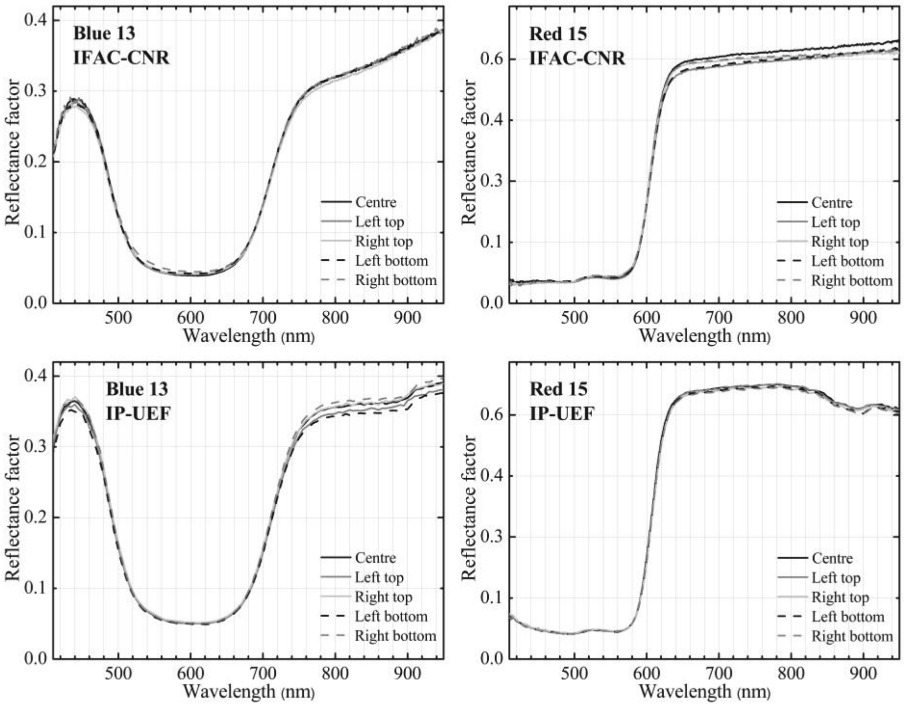

Fig. 2. Reflectance spectra from 1 mm x 1 mm areas of coloured patches Blue 13 and Red 15 from the X-Rite® ColorChecker chart extracted from the hyper-spectral file-cube from IFAC-CNR and IP-UEF

Within the same coloured patch, reflectance spectra extracted from areas of different size are the same. As a matter of fact, the spectral resolution of spectra extracted from areas of 8 mm x 8 mm and 1 mm x 1mm (high spatial resolution) was proved to be as good as that of spectra extracted from the average areas of 35 mm x 35 mm, showing that there is a good compromise between spectral and spatial resolution for both systems (Figs. 3 and 4). However, the increase of spatial resolution to 1 pixel had an obvious influence in the spectral resolution, particularly in the case of IFAC-CNR's system, for which spectra present more noise probably due to the higher rate of spectral acquisition step and spatial resolution (than that of IP-UEF system). When comparing between systems, as was already noticed, spectra are identical with the exception of differences in intensity (*ca.* 0.07 in reflectance factor for the magenta colour, and 0.04 for the green and yellow colours) and shape observed at the lower and higher wavelengths.

Table 1. Colour coordinates from 1 mm x 1 mm areas of patches Blue 13 and Red 15 from the X-Rite® ColorChecker chart extracted from the hyper-spectral file-cube from IFAC-CNR and IP-UEF

	Blue 13			Red 15		
	*L**	*a**	*b**	*L**	*a**	*b**
IFAC-CNR	32,3	12,3	-42,4	41,9	42,5	26,1
	32,4	11,6	-41,4	42,8	42,2	28,1
	32,7	11,7	-41,7	42,3	42,0	24,8
	33,7	10,6	-40,9	43,0	42,0	27,8
IP-UEF	36,4	12,6	-46,5	43,8	44,4	18,5
	37,0	12,6	-47,0	43,9	44,1	18,3
	36,1	12,7	-46,3	43,8	44,8	19,4
	36,7	12,8	-47,2	43,8	44,7	19,4

Regarding the colorimetric values, they are also constant within the same coloured patch (only some small variations of 1-2 units in the L*, a* and b* coordinates can be observed), regardless of the area size (Table 2). However, when comparing the L*, a* and b* values from both systems, again the most notable difference is observed for the b* coordinate and especially for the magenta colour (together with the blue and red ones, already discussed). Indeed, considering the 35 mm x 35 mm area, for the magenta colour, a b* value of -13.9 was obtained with IFAC-CNR's system, while a b* value of -20.2 was obtained with IP-UEF's system. It is possible to conclude that the colours presenting bigger differences for the b* coordinate are the magenta, bluish and reddish ones (ΔE 3.7, 3.8 and 5.1, respectively), which are at both ends of the visible range, where the reflectance spectra also present variations. On the other hand, colours as green and yellow present a higher similarity between the values obtained with the different systems, with only variations of 2-3 units in the L*, a* and b* coordinates (ΔE 3.3 and 2.5, respectively).

Table 2. Colour coordinates of patches Green 14, Yellow 16 and Magenta 17 from the X-Rite® ColorChecker chart extracted from the hyper-spectral file-cube from IFAC-CNR and IP-UEF

	Size of square side	**Green 14**			**Yellow 16**			**Magenta 17**		
		*L**	*a**	*b**	*L**	*a**	*b**	*L**	*a**	*b**
IFAC-CNR	35 mm	55,5	-35,5	32,4	80,5	4,0	78,4	52,6	44,2	-13,9
	8 mm	55,7	-35,9	32,6	80,7	4,0	79,0	52,6	44,4	-14,0
	1 mm	55,6	-35,8	32,6	80,6	4,1	78,7	52,6	44,5	-14,1
	1 px	55,5	-36,1	33,6	80,7	3,7	81,6	52,4	44,0	-12,2
IP-UEF	35 mm	59,1	-33,2	30,3	82,6	6,9	75,8	54,6	45,1	-20,2
	8 mm	59,1	-33,3	30,3	82,7	6,8	75,6	54,7	45,1	-20,3
	1 mm	59,0	-33,3	30,2	82,5	6,9	75,3	54,6	45,0	-20,3
	1 px	59,1	-33,2	30,1	82,5	6,9	75,6	54,7	44,9	-20,0

The differences observed at the lower and higher wavelengths can be due to the different ways in which each system was designed, as well as to their sensitivities and distinct technical features. The optical module of IFAC-CNR's scanner has been optimised to reduce internal stray-light through the use of additional optical filters. Thus, the spectral variations observed near the 400 nm end are very likely due to differences in the method used to compensate for the internal stray-light. Moreover, at the higher wavelengths of the spectrographs small errors can arise when blue targets are measured due to the insufficient rejection of the SpecIm filter that blocks the second order visible spectrum. However, for a better understating of these differences, further work is needed, which goes beyond the scope of the present contribution.

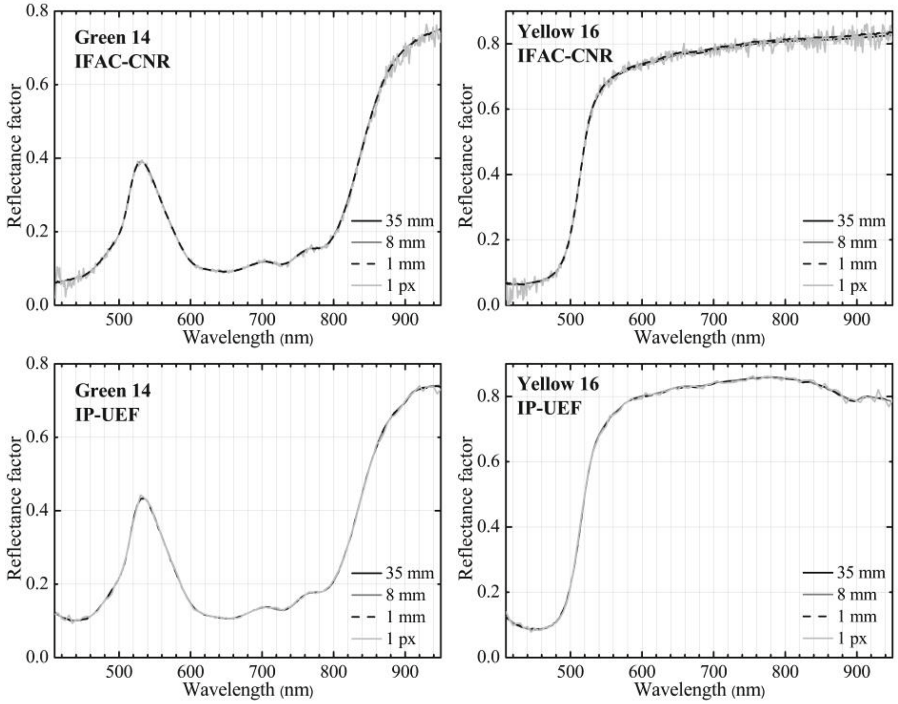

Fig. 3. Reflectance spectra from coloured patches Green 14 and Yellow 16 from the X-Rite® ColorChecker chart extracted from the hyper-spectral file-cube from IFAC-CNR and IP-UEF (data in millimetres correspond to the size of side of the squares of analysis)

In general, the results obtained indicate that the colorimetric data acquired with the two hyper-spectral systems have to be carefully used, and they should be always reported together with the specification of the instrumentation and experimental setup used, mostly if it will be necessary to compare results from both systems and for the same objects. On the other hand, the differences obtained between the two colour reproduction processes can be relevant to provide information about the way the human observer would see colour in pictures imaged by each system. Considering that magenta, blue and red colours show the most significant differences, if colours such as green, orange and yellow, which show small unnoticeable changes, are imaged with each system they should look like the same to the human eye. In this case, both hyper-spectral systems would be equally useful to image an artwork.

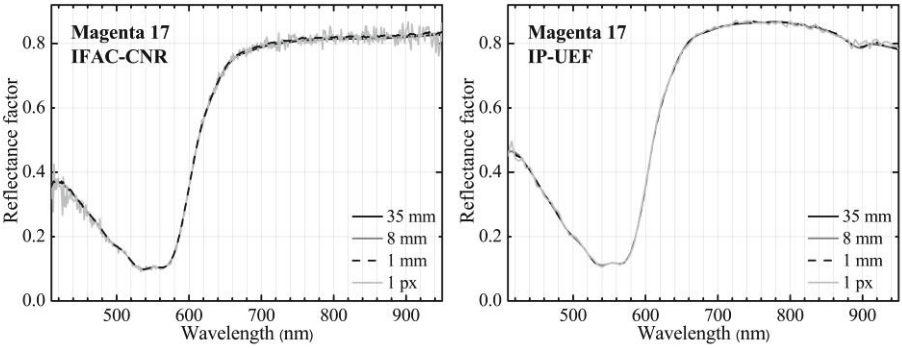

Fig. 4. Reflectance spectra from coloured patch Magenta 17 from the X-Rite® ColorChecker chart extracted from the hyper-spectral file-cube from IFAC-CNR and IP-UEF (data in millimetres correspond to the size of side of the squares of analysis)

4 Conclusions and Future Research

This paper presents the preliminary results obtained from the comparison of data from an X-Rite® ColorChecker chart acquired with different hyper-spectral systems developed by two different groups that are participating in the COSCH WG1 Round Robin Test. Both systems showed very good spectral and spatial resolution, being able to acquire information from areas as small as 1 mm x 1 mm and obtain spectra of high quality. Moreover, the spectral results from the different systems were in agreement, with the exception of information at the lower and higher wavelengths that show some variations. Consequently, colorimetric values can be comparable for colours such as green and yellow, but are not so accurate for the magenta, bluish and reddish hues that present more significant differences with respect to the b* coordinate. In order to further understand these differences and which system, or if both, is reproducing colour in a more accurate way, after the Round Robin Test is finished, the results obtained from the different participants will be all compared and further analysed. Future calculations should be performed as well, to provide numerical results for the comparison between the spectral shapes obtained with the two systems, to assess which range of wavelengths is the most comparable or different. Also, this approach to the use of an X-Rite® ColorChecker chart as a form of evaluating colour accuracy of hyper-spectral systems revealed that each coloured patch is not completely homogenous. In fact, data extracted from sub-areas in different places within the same patch showed small variations. This is an important aspect to take into consideration whenever the ColorChecker chart is used to assess the accuracy of a system's colour reproduction process.

Acknowledgements. Part of this work was supported by the European Cooperation in Science and Technology, COST Action TD120: Colour and Space in Cultural Heritage (COSCH, www.cosch.info). Tatiana Vitorino is sincerely grateful to the COST Action TD1201 Management Committee for approving the short-term mission COST-STSM-ECOST-STSM-TD1201-310814-048809, and to Vanessa Otero and Cristina Montagner for essential support.

References

1. Bianchi, C.: Making online monuments more accessible through interface design. In: MacDonald, L. (ed.) Digital Heritage – Applying Digital Imaging to Cultural Heritage, pp. 445–466. Butterworth-Heinemann (2006)
2. Saunders, D.: High-quality Imaging at the National Gallery: Origins, Implementation and Applications. Computers and the Humanities **31**, 153–167 (1998)
3. Beckett, N. et al.: Imaging historical architectural sites for conservation. In: MacDonald, L. (ed.) Digital Heritage – Applying Digital Imaging to Cultural Heritage, pp. 377–410. Butterworth-Heinemann (2006)
4. Cucci, C. et al.: A hyper-spectral scanner for high quality image spectroscopy: Digital documentation and spectroscopic characterization of polychrome surfaces. In: ART 2011 - 10th International Conference on Non-destructive Investigations and Microanalysis for the Diagnostics and Conservation of Cultural and Environmental Heritage (2011)
5. Martinez, K. et al.: Ten years of art imaging research. In: Proceedings of the IEEE, vol. 90(1), pp. 28–41 (2002)
6. Antonioli, G. et al.: Spectrophotometric scanner for imaging of paintings and other works of art. In: Proceedings of CGIV 2004, pp. 219–224 (2004)
7. Liang, H.: Advances in Multispectral and Hyperspectral Imaging for Archaeology and Art Conservation. Applied Physics A **106**, 309–323 (2012)
8. Colantoni, P.: Analysis of multispectral images of paintings. In: 14th European Signal Processing Conference (EUSIPCO 2006), Florence, Italy (2006)
9. Burns, P.D., et al.: Error Propagation Analysis in Color Measurement and Imaging. Color Research and Application **22**(4), 280–289 (1997)
10. Kubik, M.: Hyperspectral imaging: A new technique for the non-invasive study of artworks. In: Creagh, D., Bradley, D. (eds.) Physical Techniques in the Study of Art, Archaeology and Cultural Heritage, pp. 199–259. Elsevier (2007)
11. Boochs, F. et al.: Towards optimal spectral and spatial documentation of cultural heritage. COSCH – An interdisciplinary action in the cost framework. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XL-5/W2, pp. 109–113 (2013)
12. Fischer, C., Kakoulli, I.: Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications. Reviews in Conservation **7**, 3–16 (2006)
13. Hagen, N. et al.: Snapshot Advantage: A Review of the Light Collection Improvement for Parallel High-dimensional Measurement Systems. Optical Engineering **51**(11), 111702. 1–111702.7 (2012)
14. Berns, R.S.: The Science of Digitizing Paintings for Color-Accurate Image Archives: A Review. Journal of Imaging Science and Technology **45**(4), 305–325 (2001)
15. McCamy, C.S., et al.: A Color-Rendition Chart. Journal of Applied Photographic Engineering **2**(3), 95–99 (1976)

16. ColorChecker Classic for Image Reproduction - X-Rite. http://xritephoto.com/ph_product_overview.aspx?ID=1192
17. Sharma, G., et al.: The CIEDE2000 Color-Difference Formula: Implementation Notes, Supplementary Test Data, and Mathematical Observations. Color Research and Application **30**(1), 21–30 (2005)
18. Cucci, C. et al.: Open issues in hyperspectral imaging for diagnostics on paintings: when high spectral and spatial resolution turns into data redundancy. In: Salimbeni, R., Pezzati, L. (eds.) Proc. of SPIE, vol. 8084, O3A: Optics for Arts, Architecture, and Archaeology III, 739106, pp. 80848.1–80848.10 (2011)
19. Cucci, C. et al.: Extending hyper-spectral imaging from vis to nir spectral regions: a novel scanner for the in-depth analysis of polychrome surfaces. In: Pezzati, L., Targowski, P. (eds.) Proc. of SPIE, vol. 8790, O3A: Optics for Arts, Architecture, and Archaeology IV, pp. 879009-1– 879009-9 (2013)
20. Vitorino, T., Casini, A., Cucci, C., Melo, M.J., Picollo, M., Stefani, L.: Hyper-spectral acquisition on historically accurate reconstructions of red organic lakes. In: Elmoataz, A., Lezoray, O., Nouboud, F., Mammass, D. (eds.) ICISP 2014. LNCS, vol. 8509, pp. 257–264. Springer, Heidelberg (2014)
21. Hirvonen, T., et al.: A Wide Spectral Range Reflectance and Luminescence Imaging System. Sensors **13**, 14500–14510 (2013)