Application of a hyperspectral camera for colorimetric and spectroscopic measurements under natural light on outdoors artistic polychrome surfaces.

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ABSTRACT

The aim of this study is to define the parameters of accuracy of data acquired with the Specim IQ hyperspectral camera for CIE colorimetric measurements of polychrome surfaces in outdoor architectural settings with natural light. Furthermore, the study aims to compare the data obtained by the Specim IQ camera with those acquired by a contact colorimeter (Konica-Minolta CM-700d). CIE colorimetric measurements are generally acquired with dedicated instruments, such as tristimulus method colorimeters and spectrophotometric method, which require contact with the surface and coverage areas on the order of tens of mm2. The characteristics of requiring contact and analyzing very small areas can severely limit the study of artistic polychrome surfaces. This is because it may not always be possible to touch the analyzed surface and the measured areas may not necessarily be representative of a wider area of the same color. To overcome these limitations, one possible alternative is to use imaging techniques to acquire measurements from a distance while covering larger areas of the analyzed artifact. To calculate the colorimetric values as defined by the CIE and to also have the possibility to acquire spectroscopic data it was used the Specim IQ compact hyperspectral camera. This camera acquires 204 bands with a spectral resolution of 7 nm and an acquisition step of 3.5 nm in the 400-1000 nm operating range.

Colorimetric data were initially acquired on eight different color targets and two color palettes using a spectrocolorimeter. Subsequently, outdoor tests were conducted on the same samples under natural light using the Specim IQ hyperspectral camera. As a result, the operating characteristics of the hyperspectral camera for outdoor measurements aimed at studying the color of polychrome surfaces were defined.

KEYWORDS Hyperspectral imaging, polychromatic surfaces, natural light, Specim IQ, colorimetric analysis.

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1. Introduction

In the 1980s, a new technology called Imaging Spectroscopy (IS) was introduced, which has effectively revolutionized scientific research in the field of remote sensing of the Earth's surface (Goetz et al., 1985; Green et al., 1998). Specifically, the hyperspectral imaging (HSI) version of this technology allows for the acquisition of a nearly continuous sequence of spectroscopic images in contiguous, narrow spectral bands (bandwidth <10 nm) over an extended spectral range, generally from the visible (VIS, 400-750 nm) to the near-infrared (NIR, 750-2500 nm) (Cucci et al., 2016).

In recent years, the field of application of this technology has expanded into other areas, particularly in the field of cultural heritage, where it has been utilized for analyzing decorative elements, easel and wall paintings and even building facades (Casini et al., 2005; Kubik et al., 2007; Delaney et al., 2010; Ricciardi et al., 2012; Mounier et al., 2015; Cucci et al., 2016; Cucci et al., 2018a; Cucci et al., 2018b; Picollo et al., 2018; Amigo, 2019; Striova et al., 2020).

The HSI dataset, commonly referred to as a "cube-image" or "file-cube," contains a high level of information and can be processed using various algorithms depending on the desired final information (Nielsen 2015; Cucci et al., 2016, Luo et al., 2016; Deborah et al., 2019; Bai et al., 2019; Kleynhans et al., 2020; Cucci et al., 2021). This cube is a sequence of spectroscopic images that can provide the information typically given by traditional imaging techniques, such as infrared false color (IRFC), ratios between selected spectral images, and more. Additionally, the file-cube allows for the extraction of a reflectance spectrum from each pixel of the dataset, providing spectroscopic information that can be used to identify pigments and painting materials to some extent (Cucci et al., 2016). However, the potential of this technique is often limited by the complexity and cost of the instrumentation, software and hardware required to process the data, as well as the need for qualified technical personnel to interpret the data. Moreover, the equipment used in cultural heritage applications is often bulky and not suitable for outdoor use, making it difficult to adapt to different work environments.

In recent years, advancements in technology have made it possible to extend the use of hyperspectral technology outdoors, reducing and compensating for its previous limitations. The Specim IQ hyperspectral camera, developed by SPECIM Spectral Imaging Ltd. (Oulu, Finland, www.specim.fi), is one of the new imaging spectroscopy systems available for these applications, as presented in this work.

2. Specim IQ camera technical information

The Specim IQ is a hyperspectral imaging system designed to be used in various environments (Behmann et al., 2018). It differs from other hyperspectral imaging devices by its integration of color cameras, interchangeable data storage and batteries, data acquisition and processing electronics, and optimized operating system and user interface into a single portable housing.

The integrated RGB camera in the Specim IQ system permits to point the camera using a standard viewfinder image and manually adjust the focus of the hyperspectral camera. In addition, it is possible to check and process the acquired data using the camera back screen (like for common RGB cameras) and the processed data are storage in SD cards. This eliminates the need for additional computers, cabling, and power supplies making it easier for users to take advantage of this innovative technology.

The Specim IQ operates in the 400 – 1000 nm range recording spectra with 7 nm spectral resolution and 204 bands. The camera spatial resolution is of 512 x 512 pixels and from each pixel is possible to extract a spectrum. It saves both unprocessed and processed data, and the dimension of a single measurement is about 300 MB.

The operating system is user-friendly and guides the user through camera adjustments and data quality validations, eliminating the need for in-depth knowledge of hyperspectral imaging technology. The goal of the system design is to make hyperspectral imaging accessible to users who may not be familiar with it, enabling them to use it successfully in their applications.

Similar to most hyperspectral cameras, the Specim IQ data are acquired by performing a line scan over the target area. The camera is equipped with internal mechanisms for image scanning. However, since the process involves scanning to collect the image, it may take seconds or longer under normal conditions. Therefore, it is recommended to use Specim IQ with a standard tripod.

The Specim IQ allows for hyperspectral data acquisition under both outdoor and indoor conditions (Cucci et al., 2017; Behmann et al., 2018, Sciuto ed al., 2022), using either sunlight or artificial, broadband illumination souces. To calibrate the raw data the system is provided with a reflectance standard made of Spectralon®.

The Specim IQ camera allows for immediate visualization of hyperspectral data after the measurements, and users have the option to add metadata to them. The camera can be operated via PC with the Specim IQ Studio software. It can be used to control the camera and at the same time to process the IQ data as well as to create functions and models for processing the hyperspectral data. These models can be installed as applications to the Specim IQ camera to process the data and provide visualizations of the processing results for the user in real time without the need of a PC. The hyperspectral image data format is also compatible with most other hyperspectral data processing software available in the market.

The Specim IQ hyperspectral camera requires a white reference target to calibrate the data and obtain accurate reflectance spectra from the scene being measured. The white reference target should be a material with known diffuse reflectance, as spectrally constant as possible and close to 100%. The normalization operation can be performed in two ways:

- The white reference can be analyzed only once before all the other measurements (custom white reference). However, this approach requires that all the measurements are made under the same experimental conditions as that on the white reference.
- Alternatively, the white reference can be analyzed at the same time as the sample (concurrent white reference).

In addition, the camera allows to calibrate the data on the emission spectrum of a factory defined halogen light source.

After the reference target data have been obtained, each pixel data are normalized by referencing them to the white reference target. This normalization operation allows for accurate comparison of reflectance values between different pixels and different scenes.

3. Reasons for the research and definition of experimental parameters.

The Specim IQ camera offers significant advantages in terms of portability and versatility in comparison with most of the HSI devices available, making it a valuable analytical tool for various applications in the field of Cultural Heritage. Despite its usefulness, there are still some aspects that require clarification, particularly with regard to the use of quantitative measurements. In 2018 and 2019, two outdoor tests were conducted to evaluate the efficacy of the Specim IQ camera for colorimetric analysis in the architectural field.

During the analysis of the first test (Cucci et al., 2018), which was carried out at the minor historic village of Brozzi in Florence, problems emerged with the use of the camera in the presence of direct light. The second test (Cherubini et al., 2019), carried out at Piazza Santa Croce, aimed to compare different methodologies of color analysis in architecture, including RGB camera, spectrocolorimeter, color maquette, and Specim IQ hyperspectral camera. The obtained results were promising.

Finally, in 2021 (Cherubini et al., 2021), a test was also carried out in a controlled environment with a well-defined instrumental setup and artificial lighting, but issues still emerged with the type of setup used.

Despite this, all the tests performed have confirmed that this instrument can be used for colorimetric analysis in the architectural field. However, it is important to note that sufficient tests have not yet been conducted in an outdoor environment under natural light.

The motivation behind this research is to confirm the accuracy of data acquired by the Specim IQ camera for colorimetric calculations of polychromatic surfaces in outdoor architectural settings with natural light, such as building facades.

The polychromatic surfaces used for this study included:

- Eight certified Spectralon® Color Standards (Labsphere, New Hampshire, USA) with an approximate diameter of 3cm;
- Two mockups painted on a plaster support measuring 40x25x3cm, using colors from the Sikkens 4041 Color Concept Palette paints (https://www.sikkens.ch/it/colori/4041_color_concept), with chromes D6.10.30, F2.03.88, D6.35.55, E8.30.60, H2.03.82, and SN.02.77 (Figure 1a);
- Four samples of different stone materials commonly used in Florentine architecture, such as *pietra serena*, Carrara marble (Figure 1b), *pietra bigia*, and travertine, each of them measuring 25x25x5 cm.

These materials were arranged on an iron grid to be positioned on different wall backgrounds, as shown in figure 2. The results of the HSI analysis were then compared to data obtained from a Konica-Minolta CM700d spectrocolorimeter.

The acquisition setup for the data analysis campaign was configured as follows:

- The Specim IQ camera was mounted on a tripod at a distance of approximately 300 cm from the surface being analyzed (as shown in Figure 2).
- A set of eight Spectralon® Color Standards color samples, including nominal colors of red, orange, yellow, green, cyan, blue, violet, and purple, were used.
- Two mockups were created with the six different Sikkens paints, as previously reported.

- Four stone fragments made of materials commonly used in Florentine architecture were included.
- Measurement were performed with natural diffuse daylight between 09:00-11:00, with the polychrome samples arranged in the shade.
- A single operator was responsible for acquiring measurements at defined times.

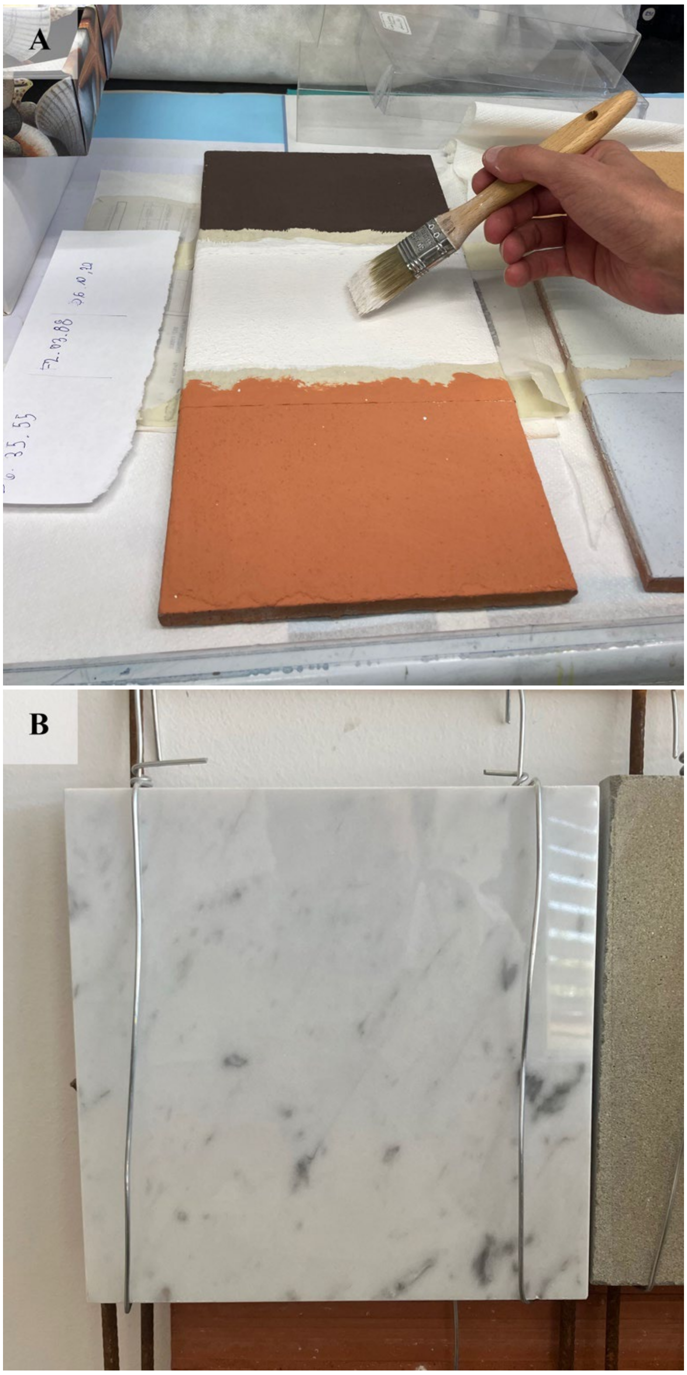

Fig. 1 – a)One of the two color palettes made using colors D6.10.30, F2.03.88, D6.35.55 from the Sikkens 4041 Color Concept palette. b) One stone sample of Carrara Marble.

Fig. 2 - Specim IQ camera arranged on a tripod at a distance of about 300 cm from the analysis surface.

All mockups and Spectralon® Color Standards color samples were arranged in the grid as shown in Figure 3.

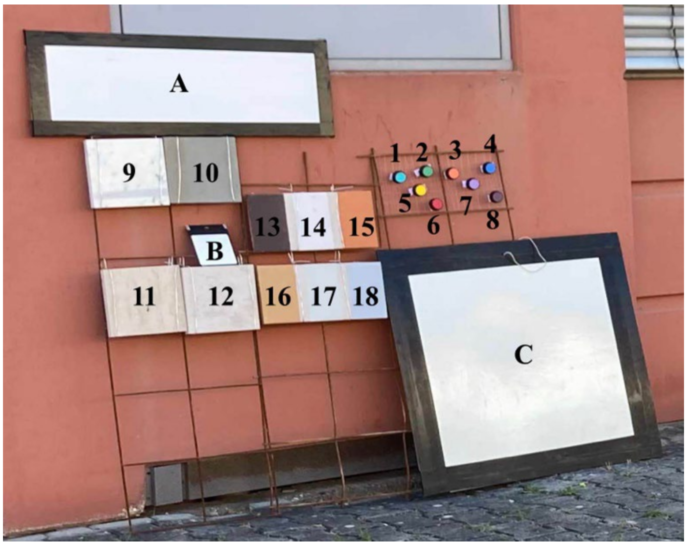

Fig. 3 – Mockups, stones and Spectralon® Color Standards arranged in the grid.

Legend: 1- Spectralon Cyan; 2- Spectralon Green; 3- Spectralon Orange; 4- Spectralon Blue; 5- Spectralon Yellow; 6- Spectralon Red; 7- Spectralon Violet; 8- Spectralon Purple; 9- Carrara Marble; 10-Pietra Serena; 11-Pietra Bigia; 12- Travertine; 13- Sikkens D6.10.30 Color ; 14- Sikkens F2.03.88 Color ;15- Sikkens E8.30.60 Color ;16- Sikkens D6.35.55 Color ;17- Sikkens H2.03.82 Color ;18- Sikkens SN.02.77 Color; A- Custom made white paint "Maimeri acrilico 018 - bianco di titanio" reference (not used for this test); B- White Spectralon reference; C- Custom made rutile titanium dioxide paint (not used for this test).

4. Data analysis

First, the samples were analyzed by using the Konica-Minolta CM-700d spectrocolorimeter. This instrumentation is equipped with an integrating sphere with a d/8° measurement geometry and works in the 400-700 nm range with an acquisition step of 10 nm. The light source and detector are a pulsed xenon lamp with a UV filter and silicon photodiodes, respectively. The instrument has its reference for white calibration (100% reflective) and a 'trap' for black calibration (0% reference). Measurements were taken using the 8-mm diameter measurement area accessory (MAV configuration) in diffuse reflectance configuration (SCE) excluding the specular component.

Due to the lack of homogeneous surface color in both the stone samples and the mockups, colorimetric analysis was conducted on five different points for each, as illustrated in Figure 4.

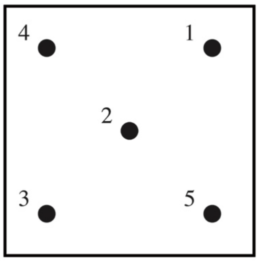

Fig. 4 – Scheme of the contact color measurements for the mockups and the stone samples.

Subsequently, an arithmetic average of the measured data was calculated to obtain a colorimetric average value for each sample. The L*a*b* values of the Sikkens paints on the mockups, and of the stone fragments are reported in Table 1 and 2, respectively.

	F2.03.88	m.e.	D6.10.30	m.e.	D6.35.55	m.e.	E8.30.60	m.e.	SN.02.77	m.e.	H2.03.82	m.e.
L*	93,27	±0,52	38,24	±1,4	61,53	±1,05	66,31	±0,3	80,74	±0,69	85,18	±0,35
a*	0,91	±0,33	4,95	±0,03	23,9	±0,35	9,82	±0,2	-0,83	±0,03	-1,66	±0,04
b*	4,17	±0,53	5,61	±0,18	31,57	±0,08	30,32	±0,34	-2,54	±0,12	5,25	±0,26

*Table 1 – Sikkens paints on the mockups L*a*b* values with the maximum error.*

	PIETRA SERENA	m.e.	MARBLE	m.e.	PIETRA BIGIA	m.e.	TRAVERTINE	m.e.
L*	60,71	±3,5	77,88	±1,81	82,42	±4,77	80,87	±0,78
a*	-0,53	±0,6	-0,76	±0,32	1,35	±0,68	2,23	±1,42
b*	10,13	±5,11	-1,83	±1,05	9,83	±2,82	13,41	±0,94

*Table 2 – Stone samples L*a*b* values with the maximum error.*

Then, "the maximum error" (m.e.) for each set of measurement was calculated. In this context, the "maximum deviation" or "maximum error" refers to the largest difference between the calculated average and each measured value of the set of data, indicating the maximum deviation found between the collected data and the reference value under consideration. If these data are carefully analyzed, it becomes evident that the paints applied on a plastered surface exhibit a more homogeneous distribution throughout the area. The maximum error found is approximately ±1.4, with an average value below ±0.5 for all L*a*b* coordinates. Instead, for the stones the value of the maximum error is significantly higher, reaching a maximum of ±5.11, with an average value of approximately ±2. This fact indicates that the stones have a less homogeneous surface than the paints under the chromatic aspect. This element is important to be considered when the colorimetric data are analyzed.

Regarding the data acquired with the IQ camera, they were recorded with an integration time of 20 milliseconds per band using the simultaneous white reference mode (concurrent white reference). Lastly, in order to apply the formulas of the International Commission on Illumination (Commission Internationale de l'Éclairage, CIE) using the data generated by the IQ camera for the analyzed objects, it was necessary to interpolate the spectral sampling interval of the hyperspectral data from 3.5 nm to 1 nm. This was achieved using a program developed specifically at IFAC-CNR, which, upon completion of the process, provides gray-scale TIF images of the three L*, a*, and b* coordinates (CIELab76 color space) for the standard observer 2° and illuminant D65.

The L*a*b* values calculated for the Labsphere color targets, painted mockups, and stone samples, contained in the TIF format files, were managed and processed using the Adobe Photoshop® program. The 'eyedropper' tool was used to acquire the L*a*b* values of the TIF files. The 'eyedropper' tool in Photoshop is used for color sampling and color picking. this tool allows you to click on any pixel within an image and it will sample the color of that pixel. Due to the low resolution of the image, the 'eyedropper' tool was used with the 'medium' mode to obtain the L*, a*, and b* values by selecting a square of 3x3 pixels in the sample.

when we use the 'eyedropper' tool with a 3x3 pixel area means that when we click on a pixel in the image, Photoshop will not only sample the color of that exact pixel but also include the colors of the surrounding 9 pixels (3x3 square area) in the average calculation. By considering a 3x3 pixel area, the tool helps reduce the impact of isolated color outliers and provides a more accurate representation of the color within that small region of the image. The 'medium' mode refers to the way Photoshop calculates the color average. In this mode, Photoshop calculates the median value for each color channel (L*, a*, b*) within the 3x3 pixel area. The median value is the middle value when all the values are arranged in numerical order. This method helps minimize the impact of extreme color values and produces a more balanced color representation. Using the 'eyedropper' tool with a 3x3 pixel area and medium mode is particularly useful in situations where you want to obtain a more stable and representative color reading, especially in images with noise or small color variations. It's worth noting that when using the 'eyedropper' tool in Photoshop, there are significant limitations imposed on the L*, a*, and b* values: Photoshop displays these values only as integers, eliminating any decimal points (Figure 5).

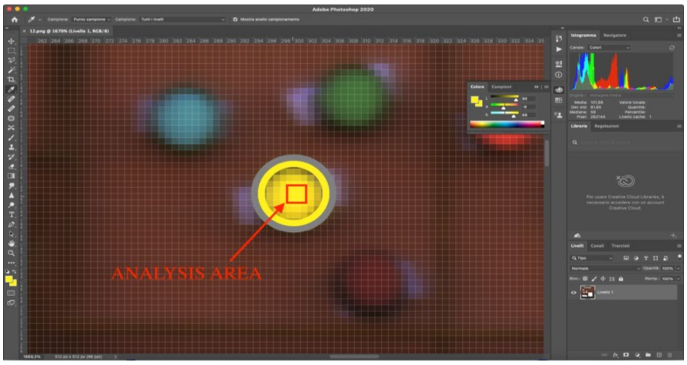

Fig. 5 – Measurement IQ-925. Colorimetric values for targets calculated with Adobe Photoshop® software.

However, this work mainly focused on defining the accuracy of the measurement system, Specim IQ hyperspectral camera, under daylight measurement conditions. The primary objective was to verify the accuracy of measurements by calculating colorimetric parameters.

The data obtained were reported in Table 3.

	CM700d	**IQ-923**	**IQ-924**	**IQ-925**
Analysis area in px	*	3x3	3x3	3x3
Degrees	*	0	0	0
Distance in cm	*	300	300	300
Violet	63.77, 18.45, -22.42	62, 17, -15	62, 17, -15	62, 17, -15
Purple	43.78, 14.94, -5.05	44, 15, 0	44, 15, 0	44, 15, 0
Yellow	87.39, 3.02, 84.67	85, 6, 81	85, 7, 82	85, 6, 81
Orange	69.77, 45.35, 40	68, 45, 40	68, 45, 40	69, 46, 40
Cyan	71.95, -27.92, -11.38	68, -24, -6	68, -24, -5	68, -25, -5
Blue	57.61, 3.06, -43.06	56, 2 ,-35	56, 2 ,-35	56, 2 ,-35
Red	49.65, 50.88, 23.95	51, 48, 23	51, 49, 23	51, 48, 22
Green	62.76, -30.42, 15.52	61, -25, 17	61, -25, 17	61, -25, 17
D6.10.30	36, 6, 9	40, 5, 7	40, 5, 7	40, 5, 7
F2.03.88	94, 1 ,6	93, 1, 8	93, 1, 8	93, 1, 8
D6.35.55	61, 26, 35	62, 24 ,33	62, 24 ,33	62, 24 ,33
E8.30.60	66, 13, 34	66, 10, 31	67, 10, 31	66, 10, 31
H2.03.82	88, -1, 4	84, 0, 8	85, 0, 8	84, 0, 8
SN.02.77	83, -1, -2	80, 0, 0	81, 0, 0	81, 0, 0
Pietra serena	60.71, -0.53, 10.13	62, 0, 12	63, 0, 11	63, 0, 11
Carrara Marble	77.88, -0.76, -1.83	83, 0, 6	83, 0, 6	83, 0, 6
Pietra bigia	82.42, 1.35, 9.83	81, 2 ,13	82, 3 ,14	81, 2 ,13
Travertine	80.87, 2.23, 13.41	79, 3, 16	79, 4, 17	80, 4, 17

*Table 3 - L*a*b* values calculated from measurements acquired with the Specim IQ camera*

The data obtained were divided into three homogeneous groups, namely Spectralon® Color Standards, mockups, and stone samples and the following results can be highlighted:

- All eight certified Spectralon® Color Standards were strongly influenced by the spatial resolution of the acquired data due to the distance of the camera (300 cm); in fact, the external pixels of the targets are partially affected by the background wall color that resulted to be mixed with the targets' colors (Figure 6).
- The mockups showed a sufficient agreement with the expected colorimetric values except the dark brown D6.10.30 and the light gray H2.03.82 paints;
- The stone materials presented the most critical issues, as expected, due to their natural surface variability. The lack of chromatic homogeneity of the surface made the colorimetric analysis challenging. However, for the more homogeneous samples such as *pietra serena*, *pietra bigia* and travertine, results comparable to those obtained with contact instrumentation were achieved. Carrara marble, on the other hand, showed greater chromatic dissimilarities.

It should be remembered, however, that the Adobe Photoshop® program displays only integer values for the L*a*b* color space. This introduces an additional factor of error that has to be considered when analyzing the data.

The software Adobe Photoshop® was selected due to its extensive usage and popularity as a commercial software that ensures accurate analysis of L*a*b* values without introducing errors. According to the research reported in the paper "Application of a hyperspectral camera for colorimetric measurements on polychrome surfaces in a controlled environment and evaluation of three image processing software for displaying colorimetric data: Pros and cons of the methodology presented" (Cherubini et al., 2023), other freely available software, such as GIMP, demonstrated inconsistent value, particularly regarding the b* parameter.

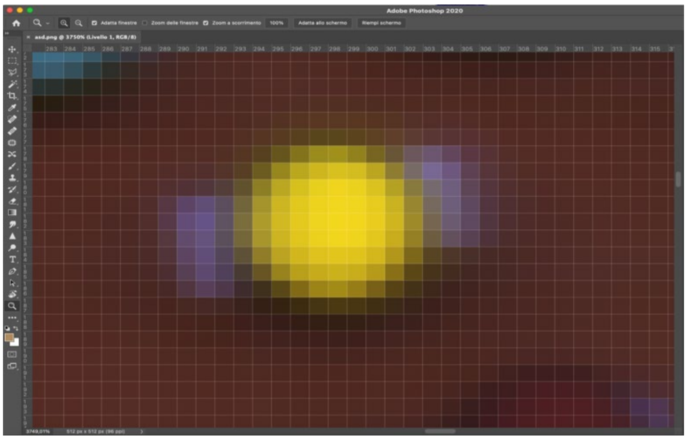

Fig. 6 - The external pixels of the Yellow target affected by the background wall color

5. Conclusion

From what emerged in this preliminary study designed to verify the characteristics of the Specim IQ hyperspectral camera applied in an outdoor environment for colorimetric analysis of non-self-luminous objects, it can be said that the system has interesting properties for this application.

Considering the instrumental setup and the adopted lighting conditions, the Specim IQ camera, as described in the data analysis, exhibited a good response in terms of colorimetric calculation for painted surfaces on mockups. However, the colorimetric calculation of the stones presented more critical issues. In conclusion, we can affirm that the Specim IQ camera demonstrated a positive response.

However, further testing under more challenging measurement conditions and in the presence of more environmental variables will be required to fully evaluate its capabilities.

6. Conflict of interest declaration

All authors of the Color Culture and Science Journal (CCSJ) are requested to disclose any actual or potential conflict of interest including financial, personal, or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work. The Conflict of interest declaration must be included in the paper and states if no financial/personal interests have affected the author's objectivity(s) or, if there are, the source and nature of the potential conflicts. Authors must state explicitly whether potential conflicts do or do not exist.

7. Funding source declaration

All authors are requested to provide a declaration of any funding or research grants (and their source) received in the study, research, or assembly of the manuscript. Authors are requested to identify who provided financial support for the research and/or preparation of the article and briefly describe the sponsor's role(s) if any. If the funding source(s) had no such involvement, then this should be stated.

8. Short biography of the author(s)

Filippo Cherubini - Filippo Cherubini is a technician at the Sabec group. He has a Bachelor of Science degree in Architecture and two postgraduate course at the University of Florence. His interests include environmental restoration and architectural color studies.

Andrea Casini - Andrea Casini, MSc graduated in Physics from the University of Florence on 1968, has worked extensively on the digital processing of both biomedical and non destructive testing images as a researcher at IFAC-CNR. Since 1990, he has been working on optical hyperspectral imaging equipment in the Cultural Heritage field, mainly on paintings, and on the processing of their data. After retirement, he maintains an external collaboration with IFAC-CNR.

Costanza Cucci - Costanza Cucci graduated in Physics and got her PhD in Conservation Science from the University of Florence (Italy). She is permanent researcher at the Institute of Applied Physics "Nello Carrara" of the Italian National Research Council (IFAC-CNR) of Florence, where she has carried on her research activity since 2000 in different applicative areas of photonic and applied spectroscopy (cultural heritage, environmental monitoring, safety/quality controls in foods, optical sensors). Her current research interests are mainly in hyperspectral imaging with a focus on applications on Cultural Heritage; spectroscopic data-analysis and processing with a focus on multivariate/statistical techniques; museum lighting (monitoring, preventive conservation, and guidelines)

Marcello Picollo - Marcello Picollo, PhD in Photonics from the University of Eastern Finland (UEF), Faculty of Science and Forestry, Joensuu (Finland) and graduated in geology from the University of Florence, is a researcher at the Institute of Applied Physics "Nello Carrara" of the National Research Council of Italy (IFAC-CNR), Florence. He has been working on spectroscopic investigations of works of art since 1991 and his main research focus is on artists' material characterization using non-invasive spectroscopic and imaging techniques

Lorenzo Stefani - Lorenzo Stefani is a technician in telecommunications at IFAC-CNR. He is in charge of the development of hardware and software for computer-controlled instrumentation for the non-invasive and in situ study of artworks.

Maruzio De Vita - Maurizio De Vita is a Full Professor at the University of Florence department of Architecture, and the Director of the School of Specialization in Architectural and Landscape Heritage at the Department of Architecture, at the same university. He has taught at Columbia University in New York, Syracuse University, IUAV Faculty of Architecture in Venice, Beijing University of Civil Engineering and Architecture in Beijing, and South-East University in Nanjing. Additionally, he is a co-owner of Studio De Vita & Schulze Architetti, an architectural firm based in Florence and Beijing. De Vita has been involved in the design and supervision of numerous restoration projects worldwide, encompassing historic and artistic buildings, monumental complexes, city walls, historic parks, and gardens, both in Italy and abroad.

Licensing terms

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