2. Digital color acquisition and management of cultural heritage: from spectrophotometry to digital imaging

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Abstract

Color plays a fundamental role in cultural heritage applications. From frescoes to statues, from paintings to architectures, from photography to films, color is used to engage the public, communicate a message, and as a mean of expression of the artists. Although, the color sensation and perception derived from an object of cultural importance depend on the properties of the materials composing it, together with the spatial arrangement in which the colors are inserted and observed. When thinking about real objects, color is not just an esthetical element or only a mean of expression, but it is the consequence of the radiation-matter interaction, which is strictly related to the physical and chemical properties of the material. In this context, modern colorimetry became a fundamental science since the beginning of the last century, when it was first applied to industrial aims.

Moreover, since Human-Computer Interaction and computational power are becoming more and more essential in our daily lives, greater importance is given to the digital color representation and to the digital color imaging. In this way the development of instruments, measurement strategies, and tools that can correctly reproduce and represent materials, contrast, and colors as faithful as possible to the original objects is fundamental. The correct reproduction of the color of an object of cultural importance is necessary for many applications (e.g., the analysis of physical color, the light design study, etc.) besides the restoration, preservation, and valorization of the artwork itself.

In this essay, we will analyze the main limits of colorimetry as well as the current analytical techniques employed to digitally acquire the color information of physical objects for cultural heritage applications. We will focus on digital color reproduction issues, describing the importance and the difficulty of a correct illumination, and showing some practical examples of problems encountered in the color digitization workflow of physical color.

2.1 Introduction

The color of objects exists because of the interaction of three factors: the light source illuminating the object, the physical and chemical properties of the material composing the object itself, and the response of the Human Visual System (HVS) (Oleari, 2015). In this triangle, the objects are visible because of the wavelengths they absorb, reflect, or transmit depending on their chemical and optical properties. Then, color is created by our vision system through two mechanisms: the photons capture by cones (also known as quanta catch) and the spatial computation of the receptors' responses. Finally, the light source not only interacts with the object but also with the HVS, as it plays a vital role in the color appearance of objects through adaptation.

The science attempting to physically describe the human color perception with an objective numerical system is colorimetry. It was first introduced by Maxwell in 1862 and from the beginning of the current century it has played an important role in all areas that involve color generation, perception, and rendition. This is even true in the field of cultural heritage, where the introduction of colorimetry has allowed a multiplicity of applications.

Over time, if on one hand the spread of interest in the study of cultural heritage has led to the development of new non-invasive and non-destructive technologies for the analysis of materials, on the other hand this was not the case for color analysis. The colorimetric approach is still stuck to the traditional analysis since the beginning of the twenty-first century: conservation scientists exploit it only to assess the color of the materials studying their optical properties and without considering the psycho-physical aspects of color vision. In this way, color science still presents numerous open issues that have not been resolved yet.

The spread of the wide variety of digital technologies deeply contributes to increasing the application of colorimetry in the field of cultural heritage as well. The digital color reproduction of the objects of cultural interest to enable their preservation and valorization is the most common purpose in this context. The digitization of the archives is also becoming more and more prevalent and is highlighted by various national and international digitization campaigns. In this field, the complexities of a correct color acquisition and reproduction are largely well-known, but this becomes particularly dangerous and challenging in the case of cultural heritage.

Starting from the above considerations and aiming to grow awareness on the readers of this book, we organized the chapter into three sections: the first one presents a concise critical overview of some open problems in color characterization and measurements, the second part briefly presents the variety of color acquisition technologies and recording system; the third part introduces the most common problems encountered during digitizing cultural objects, describing the importance of instrument calibration, the difficulty of a correct acquisition due to several open issues (such as glare phenomenon, the impossibility to obtain a uniform illumination, the complexity of a real scene and its bidimensional representation), and the difficulty of proper color management.

2.2 Color formation and colorimetry

The concept of color is often entangled with colorimetry. To better understand how a correct description, measurement, and evaluation of color is achieved, it is necessary to briefly introduce the principles of colorimetry and color formation.

Two clear and complete critical overviews about these topics are (Rizzi, 2021a) and (Rizzi, 2021b).

In his works, Rizzi underlines that the HVS generates color sensation with two mechanisms: the photons capture by cones (i.e., the spectral radiance of a stimulus) and the spatial computation of the receptors’ stimulation (i.e., the spatial arrangement of all the spectral radiances in our field of view). This means that color is not the unique product of retinal cone responses, since the local structures, such as edges and gradients, in the content of a scene change the final color sensation.

Since the high complexity of the HVS, color science has simplified the color sensation characterization limiting the effect of spatial mechanism. As a result, colorimetry works under the strong basic constraint of *aperture mode*, where a small color stimulus is isolated, and it is observed in a darkroom with no light. Based on this assumption, CIE XYZ is a pointwise colorimetric model in which the light responses of several stimuli do not interact with each other. This is deeply far from real situations and the contribution of the illuminant source and the objects are not distinguishable (see the scheme of Fig. 2.1).

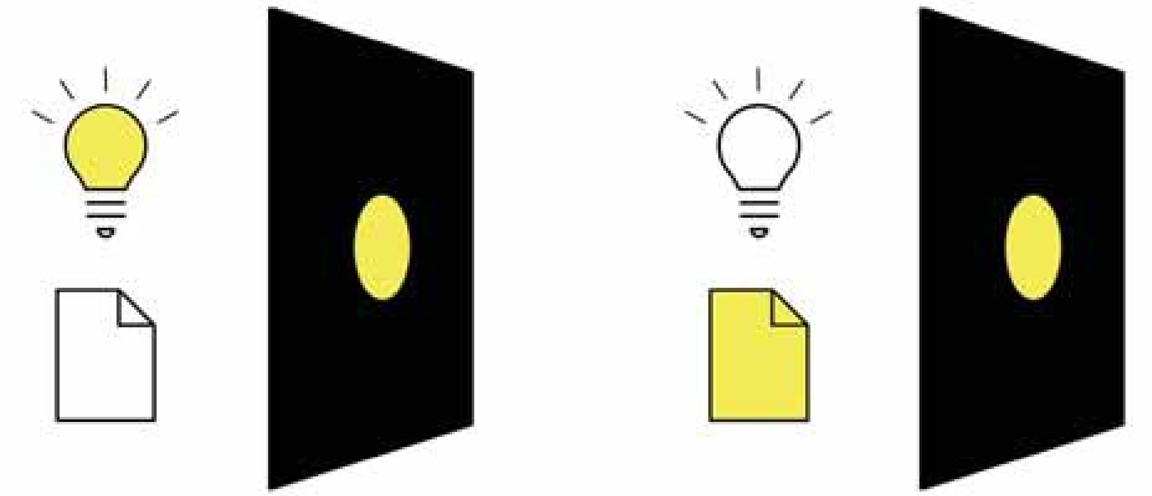

Fig. 2.1 - Aperture mode constraint: a white source illuminating a yellow paper (left) and a yellow source illuminating a white paper (right) generate the same color signal (Rizzi, 2021b).

This ambiguity is solved with the so-called “perceptual uniform spaces”: CIE L*a*b* and CIE L*u*v*, which work in *object mode* (or *surface mode*), with the introduction of a reference illuminant. In this way it is possible to distinguish the exact color of a surface from the lighting source. Nevertheless, the color is still evaluated pointwise since spatial interaction is still not considered.

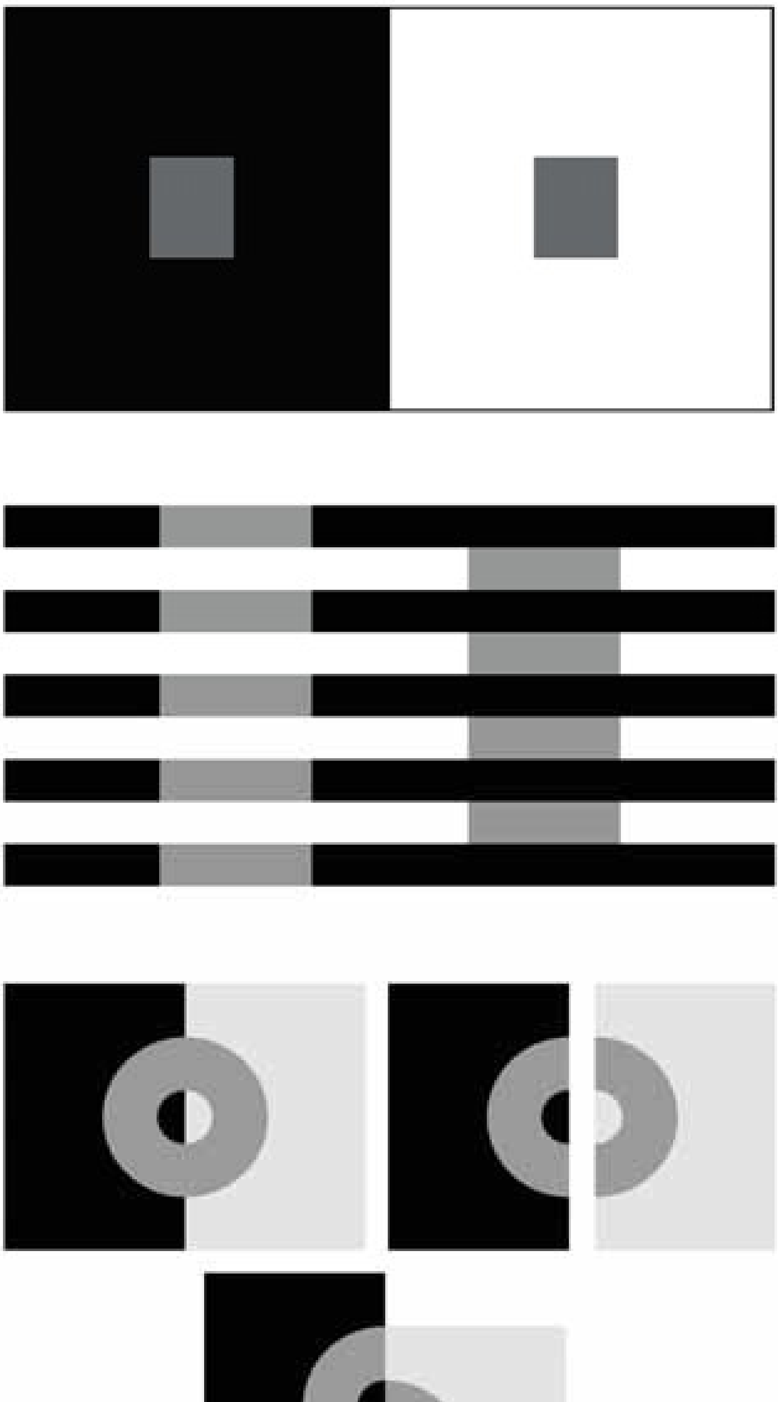

Fig. 2.2 – Example of visual illusions determined by the spatial interaction mechanism: simultaneous contrast (top), assimilation (center) and Kofka ring (bottom). (Rizzi, 2021a; Rizzi, 2021b; Koffka, 1935).

Fig. 2.2 shows some visual illusions that Rizzi presents in (Rizzi, 2021a) and (Rizzi, 2021b) as examples of the effects of spatial arrangement on color perception. On the top, the simultaneous contrast phenomenon, that changes the perceived brightness of the color in the center in conflict with the surrounding (the darker the background the lighter the center will appear and vice versa). In the center the assimilation phenomenon, that changes the perceived brightness of the color in the center accordingly to the surrounding (the darker the background the darker the center will appear and vice versa). Finally, on the bottom, the Kofka ring (Koffka, 1935), where the perceived brightness of each color changes according to the different edges. Even though the gray patches look different, their colorimetric values are always the same in every color system. This is because the difference in appearance is not caused by different stimuli but depends on different spatial arrangements of the scene.

Outside the *aperture mode* and *object mode* configurations, colorimetry has not been defined yet. A nowadays open issue is clearly the need to develop a model that includes the entire contribution of the HVS mechanisms, able to objectively describe the color from different fields of view and spatial arrangements.

2.3 Color recording systems

Systems for color information recording include both color measurement instrumentation useful for uniform areas of color and image capture devices designed to capture spatially varying color information.

Hereafter, the main technologies for color acquisition are introduced. For their technical operating principles, the readers may refer to the book (Sharma and Bala, 2017).

2.3.1 Spectroradiometer and spectrophotometer

The most direct and complete method for recording color information is to sample the spectral distribution. A spectroradiometer is a punctual device for sample surface inspection. It measures the power distribution of optical radiation (SPD) or the reflectance as a function of wavelength. Spectroradiometers employed for color recording usually operate in the visible region of wavelengths (ca. 360-780 nm) and have a spectral resolution of 1 to 2 nm.

A spectrophotometer is a punctual tool for measuring the spectral reflectance of an object as well, and, unlike spectroradiometers, it does not measure self-luminous objects since it features an inbuilt internal light source that illuminates the sample under measurement.

Both devices are useful for the color calibration of printers and scanners as well as for determining the color characteristics of objects. In the field of cultural heritage, they are usually employed for the identification of organic and inorganic materials like dyes and pigments (Bruni *et al.*, 2002; Bacci *et al.*, 2003), especially when a database of frequently used pigments is available.

2.3.2 Colorimeter and photometer

A colorimeter is a punctual device that exploits trichromacy as color values in CIE XYZ, CIELAB, or other color spaces. Some colorimeters have an inbuilt light source (sometimes few different illuminants are available) for the acquisition of color of reflective objects, whereas others measure only self-luminous or externally illuminated objects. This type of instrument is less expensive than spectrophotometers and spectroradiometers since it does not provide detailed spectral information. It is less accurate and measures only color tristimuli offering an acceptable color performance and significant speed advantage in addition to lower cost.

In the field of cultural heritage colorimeters are widely used in many applications, e.g., the study of color aging and degradation in relation to different parameters such as temperature, humidity (La Gennusa *et al.*, 2005), illumination (Zhao *et al.*, 2019), (Dang *et al.*, 2018), and/or microorganisms presence (Rosado *et al.*, 2019); the production and testing of new protective and cleaning products, which do not cause a chromatic alteration of the surfaces (Giorgi *et al.*, 2002), (Bartoletti *et al.*, 2020); the color matching for restoration purposes; and so on.

Photometers are single-channel devices that provide a measurement of the luminance of a self-luminous or externally illuminated object. It is usually employed to inspect the power spectral distribution of illuminant sources.

2.3.3 Digital color cameras and color scanner

Color recording devices such as digital color cameras and color scanners work on similar principles, but their intended uses are somewhat different. Both tools capture color data by acquiring the picture through a series of color filters having a different spectral transmittance and sampling the colored resulting images with electronic sensors. Digital color cameras are meant to take color photos of the real-world scene in the same way that traditional cameras do, with the exception that the images are captured electronically rather than on film. The lack of control over scene illumination is one of the issues of color capture that color cameras face more than scanners and colorimeters.

Scanners are usually designed to scan images printed on paper or transparencies (like documents, photographs, and films), and they feature an inbuilt light source. These devices do not need to capture the complete image in a single exposure like digital cameras do, thus a single sensor per channel is scanned across the image to enable spatial sampling. The use of a single sensor simplifies and improves the performance of the device, as well as allowing the use of more expensive and precise sensors.

2.3.4 Multispectral and hyperspectral imaging

Multispectral imaging is a technology that acquires an image in which each pixel has several channels carrying spectral information. Multispectral images cover a wide range of image types, from the common three-channel color images to hyperspectral imaging with hundreds of bands. Thus, the data provided by the hyperspectral imaging technique are the so-called *datacube* or *hypercube*, which contain data represented in three dimensions: two dimensions describing the spatial location, and a third spectral dimension representing a continuous spectrum (in the case of multispectral images, the third dimension represents a discrete function). Thus, hyperspectral imaging mixes the power of spectrophotometry whit the power of imaging technology. It is a non-invasive and non-destructive technology that allows us to obtain in a single shot thousands of radiance spectra of the object under analysis, one for each pixel of the image. These devices are not limited to the visible range of the electromagnetic spectrum, and they commonly operate from the UV to the infrared regions, usually ranging from 400 to 1000 nm.

Traditionally, multiband sensors were born for remote sensing applications, and only in the last twenty years they have been employed for the analysis of historical and cultural objects, e.g., for the exploitation of underdrawings in paintings (Walmsley *et al.*, 1994); the characterization and mapping of pigments and inks in painted artifacts and drawings (Casini *et al.*, 1999; Baronti, Casini and Porcinai, 1998); the studying of unreadable scrips revealed (Bearman and Spiro, 1996); the digitization purposes (Lahanier *et al.*, 2002; MacDonald *et al.*, 2017); and many others.

For further details, the readers may refer to (Fischer and Kakoulli, 2006).

2.4 Digital color reproduction issues

In order to process digital color images or 3D reconstruction, the object must be sampled both spatially and spectrally, acquiring their spectral radiance or reflectance distributions. To achieve this purpose, defining a standard acquisition protocol is mandatory not to run into wrong sampling, affected measures or bias. This is also true in the field of historical and cultural heritage and especially for photographic and audiovisual materials. Nowadays museums, libraries, and archives (where this type of material is usually stored) are indeed promoting digitization campaigns to allow wider access and fruition to the public to their collections.

Despite the existence of many regulations provided by national and international institutions, like the Italian ICCD (Istituto Centrale per il Catalogo e la Documentazione) (MiBACT ICCD, 1998) or the European FADGI (FADGI, 2015) and Metamorfoze (van Dormolen, 2012), the guidelines are usually not enough to carry out a correct and accurate digitization. Most of the problems, usually resolvable by simple precautions, are rarely mentioned in the regulations. Furthermore, the operators that perform the digitization are often not aware of all the risks of wrong color reproduction and an evaluation of instruments performance is rarely considered, as well as an objective evaluation of the quality of the results. As a consequence, an uncontrolled application of automatic operations without an accurate knowledge of the algorithms and corrections introduced can indeed produce errors in the acquisition, which can lead to issues in managing data.

Hereafter, in the next subsections we list a set of the most common issues that can be found along the digital color reproduction workflow. There are no solutions to overcome the presented problems; instead, the focus is on describing issues and the questions they raise.

2.4.1 Calibration of the instruments

One of the main open issues is the calibration of the instruments. Scanners and monitors are quite always not sold with adequate calibration tools, like for example the IT8 targets. Furthermore, most of the time calibration operations are not included in the acquisition process described by the national or international protocols, and all results in a high risk of scanning materials without any calibration.

2.4.2 Optical veiling glare

Another fundamental problem is instrumentation errors such as the transmission of frequencies, the aberration, and the formation of glare. These errors are caused by the presence of lenses inside the acquisition instruments themselves, which alter the information reaching the sensors. Optical veiling glare is indeed a light reflection-based phenomenon that consists of an unwanted light-spread on the imaging sensors. As a result, it produces a loss of information and a decrease of the dynamic range of the image acquired, so that the resulting digital image always has a different contrast from the original one. Even though the glare problem is well known in the field of lens design optics, it is much less studied and considered in the imaging field. Measures and tests of glare in image acquisition systems started indeed only some years ago (Signoroni *et al.*, 2020). Unfortunately, glare is not just noise but is a systematic distortion of the acquired data. The values at each point of the scene are affected according to their spatial arrangement and magnitude, making this phenomenon scene-dependent and exposure time-independent. (Gianini *et al.*, 2019) discusses the main reasons why glare cannot be easily removed in the image acquisition process.

An example of application in the field of cultural heritage is the assessment of the presence of glare also in hyperspectral imaging techniques (Sarti, Plutino and Rizzi, 2020).

Glare also affects our vision since human eyes are equipped with lenses as well. Despite the loss of contrast in the retina can be severe, spatial comparisons counteract the glare phenomenon. As a result, the HVS is much more robust than any color recording system based on traditional colorimetric approach due to the spatial mechanism of vision. Therefore, the pointwise colorimetry cannot overcome the limits imposed by the instruments and the problem of a correct image acquisition is still open.

More detailed information on glare can be found in (McCann, Vonikakis and Rizzi, 2017).

2.4.3 Non-uniform illumination

Colorimetric pointwise approaches for predicting color appearances are not applicable in complex-scene with non-uniform illumination. Unfortunately, uniform lighting distribution does not exist. Every point in a scene is likely to have different levels of illumination, which can have a big impact on the color signal and appearance. Moreover, while the human eye adapts to the scene, providing a visual appearance that is mostly independent of the scene illumination, cameras lack these adaptation mechanisms, resulting in imaging with significant color casts and shifts.

This is a very complex open issue that in the field of cultural heritage, is not only concerned with digital color acquisition purposes, but it is also a well-known problem in the definition of an optimal illumination for the valorization and the fruition of the works of art, especially for museums and collections. Every exhibition needs a trade-off among three factors: the visitors, the cultural assets, and the architecture of the building that hosts the event (Berns and Grum, 1987; La Gennusa *et al.*, 2005). First of all, the contribution of the light must be specifically designed for the exhibit since it can affect the experience of the public. Nevertheless, the illumination system must not damage the work of art. Because of this, the museum personnel must also consider the specific national and international regulations that define the condition of the range of intensities and the amount of light per year the historical material can tolerate – as an example see Italian regulations for museums in (MiBACT, 2000). Unfortunately, due to the nature of the buildings within which the museum is located, the lighting conditions cannot always be controlled. The buildings themselves can be considered historical monuments under the Cultural Heritage regulations. This means that they are not allowed to be changed or modified as well as the windows cannot be obscured by curtains or shutters to not modify their architectural appearance. For instance, many exhibition rooms are hosted inside ancient buildings such as old castles, monasteries, or factories, which may have large windows that provide natural light to the entire room. As a result, the light variation during the day can significantly affect the design of the exhibition and cause sensitive materials to fade and degrade more quickly (Gunde, Krašovec and Platzer, 2005).

In this unstable balance, the adequate assessment of the color rendering of the work of art is effectively hard to manage. This is also aggravated by the lack of guidelines and objective metrics related both to the final color perception of an object in a complex spatial arrangement and to the spatial distribution of the illumination. A light source is indeed characterized only by its spectral power distribution (SPD), which provides no information about its spatial arrangement. The other important metric is the Color Rendering Index (CRI) (CIE, 1987), which tries to objectively define the quality of a light source by comparing its SPD with an ideal reference illuminant. Even though different rendering indexes have been introduced during the years, CRI still presents some criticism, especially for lighting systems with spiky emission spectra such as LEDs. The computed colorimetric value of CRI is indeed not always in line with the perceived final color evaluation. As a result, the chromatic rendering decision is usually left to the subjectivity of the curator of the museum or the light designer.

2.4.4 Complex real scene

Several parameters can affect the final color perception of a complex scene, such as the illuminant spectral and spatial distribution, the geometry of illumination, the observer's point of view, and, above all, the shape and the size of the objects. The non-correspondence between computed and perceived color can be observed using different color recording systems. Data acquisition tasks can indeed have some criticisms like the inappropriate measurement conditions. As already said, the colorimetric approaches of *aperture mode* and *object mode*, constrain the acquisitions to precise standard parameters of geometry of illumination, direction of observation and light source. Outside these conditions, traditional colorimetry will usually fail. This is the case of complex 3D real scenes.

For instance, an application that remarks the limits of pointwise colorimetric measurements is the color evaluation of gemstones (De Meo, Plutino and Rizzi, 2020). Even though their color assessment is a key factor for determining the market price of a gem, defined standards and guidelines for their color evaluation still have not been introduced yet. Furthermore, the lack of a commonly shared protocol, the refractive properties of these materials make the task even harder because of the extremely complex measure condition. The objective colorimetric measures have indeed provided different results compared to the subjective human eye evaluation, which instead reached the highest precisions. As a result, the color assessment of gemstones is still visually performed by experts.

Other applications in which the human eye evaluation still provides better results are, for instance, the color assessment of materials under LEDs illumination; the hair color evaluation; the variation assessment of color after restoration work. In all these cases pointwise approach fails because it tries to compute a color evaluation of a complex contest without considering the spatial processing of vision.

2.4.5 Bidimensional representation of real scenes

All the problems mentioned above are valid not only for image or film digitization but also for 3D reconstruction purposes. The creation of the 3D digital model consists of acquiring images or scans of the object under analysis from various points of view and then merging the information into a single digital model consisting of a dense cloud of points or a set of triangles. Thus, 3D acquisition consists of the creation of a three-dimensional digital model that faithfully represents the shape and color characteristics of an object. In practice, the 3D digital model is an accurate description of the surface of the object under examination. Since the starting point of this technique are still images, the targets and tools available for calibration, contrast correction, and color management are the same. However, there is also another important complexity to deal with: when acquiring an image, a 3-D object scene is projected into a 2-D representation, but a bidimensional representation of a real scene is not the same as looking directly at the 3-D object (Rizzi, 2021b).

2.4.6 Color management

Once images are acquired, colors are a fundamental parameter during data processing since they influence the results of the algorithms. Usually, a color image processing pipeline follow the following steps: (a) exposure estimation, (b) pre-processing (e.g., noise removal), (c) linearisation, (d) dark current compensation, (e) flare compensation, (f) white balance, (g) demosaicing, (h) color transformation (in unrendered and rendered color spaces), (i) post-processing (Plutino and Simone, 2021; Ramanath *et al.*, 2005).

While the pipeline structure is generally standardized, each step can be carried out using a variety of algorithms, metrics, and measurements based on several reference targets, like the ColorChecker, the SFR, or the IT8. In addition, the quality of several features, such as color reproduction, noise reduction and edge preservation, can be assessed by the system performance evaluation. As a result, each pipeline is unique for its specific application field.

The ColorChecker is one of the most common targets for image correction in image processing and photogrammetric pipelines. This chart, which was first introduced in 1976, is nowadays employed in photography, scanning, and object acquisition to check color stability. However, several color reproduction errors may occur, and several studies proved the ColorChecker to be insufficient to ensure color reproduction robustness. As a result, the entire photogrammetric process, as well as object digital reconstruction, may be biased and not faithful (Gaiani *et al.*, 2017).

Cultural heritage digitization differs from other imaging applications because aiming at future repurposing and durability. Therefore, in this domain it is crucial not to lose information, and the digitization process must provide digital images perceptually faithful to the original object, rather than pleasant. As a result, contrast and color reproduction cannot be approximated, and inaccuracies must be kept to a minimum and constantly monitored. Several image quality assessment methods and many difference/quality measures have been introduced to achieve a faithful digital image, but they are still dependent on pointwise colorimetry (Barricelli *et al.*, 2020). As already underlined, pointwise-based colorimetry has been proven to be still unable to reproduce colors accurately and fails in complex scenes with non-standard expositions and with different light sources. The digital acquisition system and technologies at current reading are still not sufficient to guarantee a faithful reproduction of the historical and cultural assets, thus new solutions are required.

2.5 Conclusions

In this chapter we have underlined and recalled the assumptions and constraints beyond colorimetry, which are often not considered or even not truly understood. Their description can help in comprehending possible mismatches between computed and perceived color sensations in many applications.

The description of the current analytical technologies employed to analyze color information was meant to show the wide applications in which colorimetry can support the study of historical and cultural object, as well as to facilitate the explanation of the most prevalent and challenging issues among all the color digitization pipeline.

Color analysis and reproduction work fine in *aperture mode*, but still fail outside pointwise colorimetry constraints and are often substituted with subjective assessment. There is the need to develop new methods for computing color mechanisms in complex scenes, that is, considering spatial interactions, and not just input signal of cones.

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