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RESEARCH PAPER

Real-time identification and visualization of Egyptian blue using modified night vision goggles

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Abstract

The possibility to use light in the visible spectrum to induce near-infrared luminescence in some materials, particularly Egyptian blue and related pigments, offers a significant advantage in terms of their detection. Since 2008, this property has been exploited to reveal the presence of those pigments even in tiny amounts on ancient and decayed surfaces, using a technical-photography method. This paper presents a new type of imaging device that enables real-time, easy, and inexpensive identification and mapping of Egyptian blue and related materials. The potential of the new tool is demonstrated by its effectiveness in detecting Egyptian blue within some prestigious sites: (a) Egyptian findings at Museo Egizio, Turin; (b) underground Roman frescoes at *Domus Aurea*, Rome; and (c) Renaissance frescoes by Raphael, *Triumph of Galatea* and *Loggia of Cupid and Psyche,* at Villa Farnesina, Rome. The device is based on night vision technology and allows an unprecedented fast, versatile, and user-friendly approach. It is employable by professionals including archeologists, conservators, and conservation scientists, as well as by untrained individuals such as students or tourists at museums and sites. The overall aim is not to replace existing photographic techniques but to develop a tool that enables rapid preliminary recognition, useful for planning the work to be carried out with conventional methods. The ability to immediately track Egyptian blue and related pigments, through real-time vision, photos, and videos, also provides a new kind of immersive experience (Blue Vision) and can foster the modern use of these materials in innovative applications and future technologies.

Keywords Night vision · Egyptian blue · Visible-induced luminescence imaging · Conservation science · Education · Immersive experience

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1 Introduction

Night vision technologies have experienced an outstanding technology transfer from the military sector to other uses in recent decades. They gained traction first in law enforcement, then in security, and finally spread into civilian applications. In addition to hunting (where when combined with weapons, they are banned in many countries), their civil uses include recreation, astronomy, and improvements in many fields of science (Chrzanowski 2015).

However, if we exclude the use of thermal imaging cameras (Moropoulou et al. 2013), night vision technology uses in conservation science seem still surprisingly limited. A notable exception is represented by the interesting 2009 pioneering work by Smith et al., illustrating the use of a modified night vision Visible/Near-InfraRed (Vis/NIR) webcam, for educational purposes in chemistry-of-art courses (Smith et al. 2009). Despite that study, this technology seems not to have spread into conservation science even though 15 years have passed and even though in the meantime high-performing devices such as digital Vis/NIR Night Vision Goggles (NVG) have become widely available. The use of digital NVGs seems, in fact, to have never been documented within conservation science, not even for educational purposes. The present study aims to address this gap by exploring the potential of a small, inexpensive commercial NVG for specific prototypical applications.

This NVG will be used to improve some aspects of Near-InfraRed (NIR) imaging and to make it available to a wider audience. It has to be said, however, that there has been at least another recent attempt in this direction, albeit not directly involving night vision technologies. It is the adaptation of the camera of some smartphones (Torres and Floyd 2019). The very limited availability of suitable cameras in smartphones seems to have currently prevented the spread of these modified devices, nevertheless, a similar approach has been followed with the consumer-adapted technology presented in this paper. To this regard, it has to be noted that even if some smartphones expressly equipped with night vision cameras are now available, commercial NVGs have been preferred since, due to their nature, they are able to perform better in the middle-long range. They are thus in general expected to perform much better than the night vision camera of a smartphone of comparable price.

Digital NVGs are essentially Vis/NIR cameras that can operate at a distance, in low-light illumination, and can switch easily from visible to NIR. Simply adding an inexpensive NIR long-pass filter in front of the ocular immediately turns a digital NVG into a pure low-light NIR goggle, which can be referred to as a modified night vision goggle (MNVG). Such an MNVG can directly be used in conservation science as a practical and low-cost tool to quickly obtain useful data in the NIR spectral region. Indeed, with a total price that can be as low as USD100–150 or even less, MNVGs can be used to acquire digital images and record videos of NIR reflection, NIR transmission, and NIR luminescence working from quite close distances up to a long range (even tens of meters away). It may be worth noting that MNVGs can detect NIR roughly up to 1000–1100 nm (Smith et al. 2009) which is the same range exploited by the most common NIR imaging techniques used by professionals in conservation science (Cosentino 2016).

Even if it is only a part of the potential of an MNVG, in this work, we will focus on the ability to effectively acquire NIR photoluminescence of Egyptian blue (EB), de facto using the MNVG as a visible-induced luminescence (VIL) imager. The sensitivity to low levels of light, the possibility to visualize luminescent materials in real time and even if far away, and the enhancing effect due to algorithms present within the NVGs, seem, indeed, promising features for an effectively improved detection of EB and other photoluminescent materials. In the present study, the potential of MNVG has been tested in different setups such as the museum environment in Museo Egizio, underground monumental archeological sites at *Domus Aurea*, and Raphael's frescoes on the ground floor of Villa Farnesina. The results obtained are discussed, also comparing them with those obtainable with traditional VIL imaging. The overall purpose is to identify possible attractive applications of NVGs in conservation science, including the potential to enhance education and visitor experience. More specifically, this paper aims to highlight the potential of NVGs in improving the visualization of EB and other photoluminescent materials.

1.1 Night vision

Night vision is the ability to see in low-light conditions either naturally (scotopic vision) or through a device that uses night vision technology. NVGs are night vision devices that use a combination of optical and electronic components to amplify available light and make it visible to the human eye (Raghatate et al. 2013). The first attempts to develop a technology to obtain night vision date back to the late 1920s when Holst and Hades Boer, who worked for Philips Inc., pioneered the development of an imaging device that utilized the infrared spectrum (Mahmood et al. 2018). However, the earliest practical uses of NVGs emerged as military technology only during World War II, and their widespread adoption occurred during the Vietnam War (Junedul and Muntjir 2017). Intensively perfected in the following years, NVGs have been fashioned in many shapes to variously fit military equipment. NVGs are generally based on the use of image intensifier tubes (IITs), i.e., vacuum tubes that amplify a low-light-level image to observable levels (Chrzanowski 2015). Many different types of NVGs were developed and they are traditionally grouped into four generations numbered from 0 to 3. Generation 0 includes the early night vision systems, the only using active NIR illumination. They were soon abandoned because the NIR illuminators were easily detected by enemies. Generations 1–3 include passive NVGs, with IITs more and more sophisticated (Chrzanowski 2015; Junedul and Muntjir 2017). At the same time, many new technologies emerged, thus improving night vision. Thermal imaging was developed in the 1970s, and Vis/NIR cameras (up to roughly 1000–1100 nm) based on modern solid-state technology were established in the 1980s paving the way to digital NVGs (Chrzanowski 2015). These latter are based on charge-coupled device (CCD) and complementary metal-oxide semiconductor (CMOS) technologies. Low-light Vis/NIR cameras gained then traction, using sensors ICCD/ICMOS (intensified CCD and intensified CMOS) and since the 2000s EMCCD (electron multiplying CCD) and EBCMOS (electro bombarded CMOS). Other improved sensors were also developed such as MicroChannel plate CMOS, and overall, the so-called scientific grade sensors (sCCD and sCMOS). The scientific grade sensors have reduced internal noise and improved image resolution at the expense of a price that can be up to 100 times higher than that of typical CCD/CMOS (Chrzanowski 2015). Other high-price NVGs are the Short-Wave InfraRed imagers (SWIR imagers) based on InGaAs sensors and working up to 1700 nm (Rutz et al. 2019). The use of combined technologies to enhance the performances of NVGs is a vivid research field. Examples are the attempts to fuse improved CCD/CMOS and thermal imaging (Mahmood et al. 2018) or to fuse visible and NIR images (Li et al. 2020). They are based on the use of more and more performing algorithms (Chrzanowski 2015) and are soon expected to be greatly improved by the use of artificial intelligence and related technologies (Li et al. 2020).

Although commercial digital NVGs generally are less performing than traditional military NVGs, some Vis/NIR cameras offer similar sensitivity to classic NVGs. Despite that, digital NVGs have some advantages in comparison with traditional ones, *e.g.,* in terms of data availability, image processing, storing, ability for electronic communication, etc. Perhaps, the main advantage of commercial digital NVGs, however, is their very low price combined with ease of use and durability. Based mainly on CMOS technology, they generally offer the ability to experience automatic image enhancement and optimization through algorithms, making them an interesting tool for any application requiring NIR sensors (Chrzanowski 2015).

1.2 Egyptian blue

Egyptian blue (EB) is a multi-component material credited as being the first properly synthetic pigment produced by humans (Corcoran 2016). It is a glass–ceramic material with a structure constituted by a limited vitreous matrix embedding tiny crystals of its main component, i.e., $CaCuSi_4O_{10}$, a layered silicate analogous to the rare mineral cuprorivaite (Nicola et al. 2023). Traditionally obtained through melt-flux synthesis methods (Warner 2011), EB was made by heating for many hours to around 850–950 °C, a mixture of silica together with sources of calcium and copper, e.g., calcium carbonates and bronze filings. Typically, a flux containing sodium or potassium was added to decrease the melting point of the mixture. EB was first used in ancient Egypt around 3300–3200 BCE as an alternative to the precious lapis lazuli stone (Shortland 2012). Due to its durability and its bright blue colors, it quickly gained widespread popularity, becoming the main blue pigment used for millennia in the Mediterranean and Western Asian regions (Kovalev et al. 2023). Very popular in Rome as *caeruleum*, EB was widely used in Roman frescoes, reaching possibly its highest diffusion at the end of the first century CE (Nicola et al. 2023). However, during the Middle Ages, the knowledge of its production was lost (Nicola et al. 2018a, 2019), and only sporadic occurrences of EB were reported (Nicola et al. 2023). Surprisingly, during the Renaissance, EB reemerged in a very limited number of works of art within a restricted group of Italian artists (de Vivo et al. 2019). Notably among those rare paintings, there are two frescoes by Raphael, both located at Villa Farnesina in Rome, *Triumph of Galatea* (Anselmi et al. 2020) and, as will be shown, *Loggia of Cupid and Psyche*. If we exclude these few exceptions, it seems that EB only reappeared in the nineteenth century when it was rediscovered by a group of scientists including Chaptal and Davy (Warner 2011). During the twentieth century, EB and related materials garnered attention primarily within the fields of archeology and mineralogy, with researchers examining their chemical, mineralogical, and crystallographic properties (Nicola et al. 2023). Interestingly, in the last part of the century, also emerged the existence of two ancient pigments closely related to EB, namely Chinese purple (main component $BaCuSi_2O_6$) and Chinese blue (main component $BaCuSi_4O_{10}$) (FitzHugh and Zycherman 1983, 1992). They were developed independently and have been utilized as pigments in Ancient China roughly in the period 770 BCE–220 CE (Nicola et al. 2023). EB and related pigments feature copper ions (Cu^{2+}) as chromophores. Cu^{2+} is in square-planar coordination and determines an overall color that is influenced also by the effects of the internal electric field created by the entire crystal (García-Fernández et al. 2015). However, particle size, synthesis route, raw materials, impurities, binders, decaying processes, and other factors also play a significant role in determining the specific color of each pigment sample (Nicola et al. 2023).

A breakthrough in the study of EB and related pigments emerged at the turn of the new millennium with the discovery of their very strong NIR photoluminescence centered at 900–1000 nm. The NIR photoluminescence can be triggered by the absorption of visible light in the red region (overall between 600 and 630 nm) and, to a lesser extent, in the green (~550 nm) and the NIR (~800 nm) (Ajò et al. 1996; Pozza et al. 2000; Martinelli et al. 2023). It can be induced also by the absorptions of UV (excitation peak ~250 nm) (Binet et al. 2021). The luminescence seems correlated with the fact that despite their high concentration in the host matrix, Cu^{2+} ions behave as independent centers and release the accumulated excitation energy mainly via radiative decay and not through non-radiative pathways (Nicola et al. 2023, 2024). The discovery of the exceptional NIR luminescence of EB and related materials has sparked renewed interest in them, opening the way to applications in a wide range of rapidly expanding research fields. These extend well beyond the widespread applications in archeometry (Verri 2009a; Kriss et al. 2016) and include forensic science (Shahbazi et al. 2020), sensors (Borisov et al. 2013), energy-saving pigments (Berdahl et al. 2018), luminescent solar concentrators (Rajaramanan et al. 2023), nanotechnology (Johnson-Mcdaniel et al. 2012; Selvaggio and Kruss 2022), security inks (Salguero et al. 2014), biological imaging (Selvaggio et al. 2020), and many others.

1.3 Visible-induced luminescence imaging

Visible-induced luminescence (VIL) imaging (Verri 2009a) is a multispectral imaging technique (Dyer et al. 2013) that falls within the methods of technical infrared photography (Bridgman and Lou Gibson 1963; Cosentino 2016). VIL exploits the phenomenon of photoluminescence that occurs in some materials which, when irradiated with visible light, exhibit luminescence at a longer wavelength (typically NIR fluorescence or phosphorescence). Overall, EB exhibits exceptionally strong (and relatively long-lasting) NIR luminescence when irradiated with visible light (Accorsi et al. 2009; Comelli et al. 2016; Nicola et al. 2024) and therefore it is particularly suitable to be studied with this technique. However, good results can be obtained also for Chinese blue, Chinese purple, cadmium-based pigments, and, to a minor extent, a few other materials (Bridgman and Lou Gibson 1963; Verri 2009a). To acquire VIL images, CMOS or CCD sensors are generally used since they are sensitive to NIR with wavelengths up to approximately 1000–1100 nm (Dyer et al. 2013; Cosentino 2016). Since such sensors are commonly present in commercial digital cameras, VIL cameras are generally made by modifying commercial cameras. The modification consists of removing the standard filter that prevents the NIR radiation from reaching the sensor. A NIR long-pass filter is then added in front of the camera (typically 800–850 nm) to eliminate visible light and allow only NIR light to pass to the sensor (Chiari 2018). The modified camera can then be used to acquire VIL images. However, the light source plays a key role in the whole process (Verri 2009a). To allow for a VIL image to be acquired, the environment should be as free as possible of any source of NIR different from the photoluminescent material. Interference can come from NIR-containing light, such as natural light, incandescent light bulbs, and security NIR illuminators. Vivid illumination must then be provided using NIR-free sources such as white, green, or red LED light (Verri 2009a), or camera flashes properly filtered to remove the NIR component (Verri and Saunders 2014; Chiari 2018). With such a setup, the only NIR light that can reach the sensor should be the one emitted by photoluminescent materials. However, some stray NIR light is often present in the environment or the light source. When its presence can be misleading, its contribution can be eliminated through mathematical procedures by inserting a 99% reflectance standard into the VIL image (Verri 2009b). Filtered camera flashes can also be used to obtain VIL images in the presence of a limited amount of NIR such as in diffuse daylight (Verri and Saunders 2014; Chiari 2018).

VIL is a non-invasive imaging technique extremely safe and can be used to analyze artifacts without damaging and not even touching them and without the use of any harmful radiation. It is particularly useful for analyzing EB, which, being a very stable and widespread pigment, can be found still sound and luminescing in many artifacts even if thousands of years old (Verri 2009b). VIL can be used for a multitude of purposes. For instance, it can identify lost decorative patterns that cannot be seen with the naked eye, it can help conservators to recognize previous conservation treatments (Kriss et al. 2016), and it can be used in authentication studies (Nicola et al. 2018b). VIL is a versatile technique and can be used for a variety of applications far beyond conservation science, including fingermarks detection (Errington et al. 2016) and biomedical imaging (Selvaggio et al. 2020).

VIL has been applied to cultural heritage since at least 1963 (Bridgman and Lou Gibson 1963) and it has been used elsewhere also previously, e.g., to detect if any mineral in the entire study collection of the U.S. National Museum emitted luminescence in the NIR when excited by either visible or UV (Barnes 1958).

However, it was only thanks to the efforts of Verri in 2008 and 2009 that VIL began to be used to study EB, Chinese blue, and Chinese purple (Verri 2008, 2009a, b). This gap of about 50 years is due to at least the following three unfortunate coincidences:

a. The phenomenon of NIR luminescence in EB, Chinese blue, and Chinese purple had been reported only in the years 1996–2000 (Ajò et al. 1996; Pozza et al. 2000).
b. In the collection of the U.S. National Museum, there were no samples of the then recently discovered cuprorivaite mineral (Minguzzi 1938), nor of the at the time unknown effenbergerite (Chinese blue) or colinowensite (Chinese purple) (Barnes 1958; Giester and Rieck 1994; Rieck et al. 2015).
c. The EB pigment was simply not considered in Bridgman and Lou Gibson's 1963 study nor in the subsequent ones, thus de facto limiting VIL to the study of cadmium pigments (Chinese blue and Chinese purple were unknown at that time).

All of these factors prevented the VIL technique from establishing itself in archeological science until Verri's studies in 2008–2009 (Verri 2008, 2009a, b). However, since then, within a few years, VIL imaging of EB and related materials has become a popular approach (Daveri et al. 2016; Kriss et al. 2016) and currently VIL is a widely used method in archeometry (Sgamellotti and Anselmi 2022).

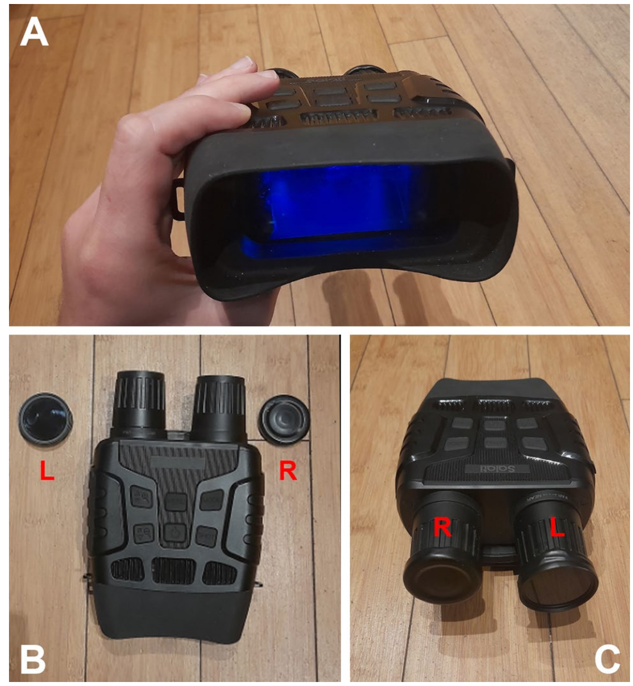

Fig. 1 Night vision goggles (**A**) with highlighted modifications on the left and right oculars

2 Experimental

2.1 Modified night vision goggle (MNVG)

MNVG has been developed starting from a Salati digital NVG (price roughly 90-100USD, purchased through Amazon). The NIR illuminator (right ocular) has been excluded by covering it with a standard 43 mm twist-off lid shown in Fig. 1 as R (recyclable from many commercial glass containers or on sale for less than 1 USD each). To prevent visible light from reaching the sensor, a dHD Digital 43 mm long-pass ir850 filter has been used (price roughly 30USD, purchased through Amazon). The filter has simply been placed in front of the objective (left ocular) and, to facilitate an easy attachment and removal, it has been fixed with a black electrical tape on a cut 43 mm twist-off lid analogous to the one used on the right ocular (see also L in Fig. 1). Contrary to what happens with other commercial devices used to acquire VIL images (e.g., cameras), in NVGs, there is no need to remove any internal filter nor is there any need to open their shell to modify them. An NVG becomes able to detect EB luminescence by simply adding the two lids L and R as shown in Fig. 1. When they are off, it fully turns back to its original function.

The Salati NVG employed is based on CMOS technology and has a 960P resolution (1280 × 960). It has manual focus and 4X digital zoom. An included 32 GB SD card offers the ability to save photos and videos. The device has a built-in 2.31-inch LED screen that can be used for real-time visualization and for the display of saved photos and videos. The MNVG has been used without the need for any additional illumination within the Museo Egizio exposition, and mainly without any external light in the *Domus Aurea*. The acquisition at Villa Farnesina took place at night, taking advantage of the illumination setup for conventional VIL (see next paragraph). Even if unnecessary for real-time visualization, a tripod has been used during the acquisition of all the photos to minimize blur effects.

2.2 Conventional VIL

A modified digital camera (Nikon D3200, sensor CMOS DX, 24.7) with the inner IR and UV filter removed was used to acquire traditional VIL and reflected NIR images. The camera has a range of up to 1000–1100 nm. To remove visible light (VIS) from the recorded images, an external B + W IR pas 830 filter was used. For VIL imaging, an LED lamp with low emission in the infrared (IR) range was used (i.e., NEEWER CB60B 70W LED Video Light with 2.4G/APP Control). To enhance the differences in the intensity of luminescence and to take into account the differences in the reflectance/absorption of NIR and visible light, a false-color approach was used (Seymour et al. 2020). VIL false color images have been obtained blending VIL red channel with green and blue visible channels.

3 Results and discussion

3.1 General considerations

The MNVG approach for detecting EB luminescence has shown many advantages over the conventional VIL technique. The main one is that the detailed and real-time visualization provided by an MNVG greatly improves the ability to quickly inspect an object or site and identify the presence and distribution of EB. Other strengths of the MNVG include its greater versatility, its light weight and ability to work at long distances (even tens of meters) without the need for any scaffolding, its ability to work in low-light conditions, its extreme speed, its very low cost, and its ease of use. It has to be noted that the final quality of the images acquired can be lower than the one obtainable with optimized and postprocessed conventional VIL. Another drawback found is that a direct comparison of luminescence intensities between different images is generally not possible due to the instrument's autotuning feature. In addition, working with non-standardized lighting conditions can also lead to a lack of reproducibility in the results. However, MNVG limitations can be easily overcome by combining it with traditional techniques. It is of paramount importance to highlight that, even if the explorative results obtained with MNVGs are impressive and very useful, a careful and more in-depth analysis has always to be recommended using the best conditions and established tools available. In the following, the results obtained in each specific location are presented and discussed.

3.2 Museo Egizio of Turin

Hosting one of the largest collections of Egyptian antiquities outside Egypt, the Museo Egizio of Turin is among the most important archeological museums in Italy and the world. It was founded in 1824 and its collection has grown over the years, now numbering more than 40,000 objects. The museum's collection includes several objects containing EB from all periods of ancient Egyptian history and provides an important resource for scholars studying this material.

The images acquired within the collections of Museo Egizio with MNVG are useful to illustrate the potential of this technology within a museum environment. In this regard, it should be noted that all the images acquired have been collected in different places within the museum and in a very short time, i.e., roughly an hour, a time analogous to a quick visit. A second edge is that a photographic set is not required. The objects, indeed, can be adequately observed directly within their showcases, limiting the costs, time-consuming procedures, and risks associated with handling the pieces. A third advantage is that NVGs, and thus MNVGs, automatically adapt to the amount of light present, thus generating good results even simply using the artificial LED light normally present in a standard museum exhibition. The images of the findings in the museum have, indeed, all been acquired without the help of any external light source different from the museum's standard illumination. They are presented in Figs. 2, 3, 4, 5, 6, and 7 within the case studies below.

3.2.1 Case study #1—Ahmoses Nefertari's statuettes: detecting discolored EB

The two statuettes shown in Fig. 2A and B depict the deified queen Ahmose Nefertari, reflecting her divine status in the period following her death. They are crafted from wood and date back to the New Kingdom, specifically the 19th–20th Dynasties (1292–1076 BCE). Originating from Deir el-Medina, they are part of the Drovetti collection, acquired in 1824, and are numbered C. 1369 and C. 1388.

The first application case presented deals with them and shows the potential of MNVG as a tool to immediately

Fig. 2 The wigs of Ahmoses Nefertari's statuettes (ME—C. 1369 and C. 1388). Visible image (**A** and **B**). MNVG visible image (**C**) and MNVG NIR image (**D**)

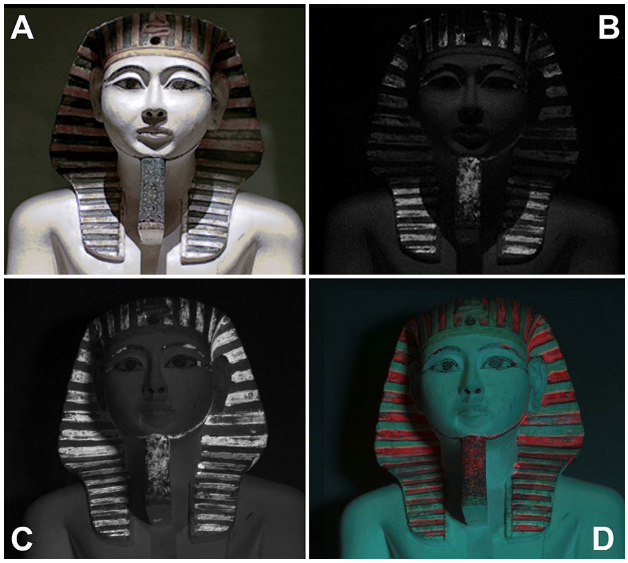

Fig. 3 Head of the cult statue of Amenhotep I (ME—C.1372). MNVG visible image (**A**), MNVG NIR image (**B**), VIL image (**C**), and VIL false color image (**D**)

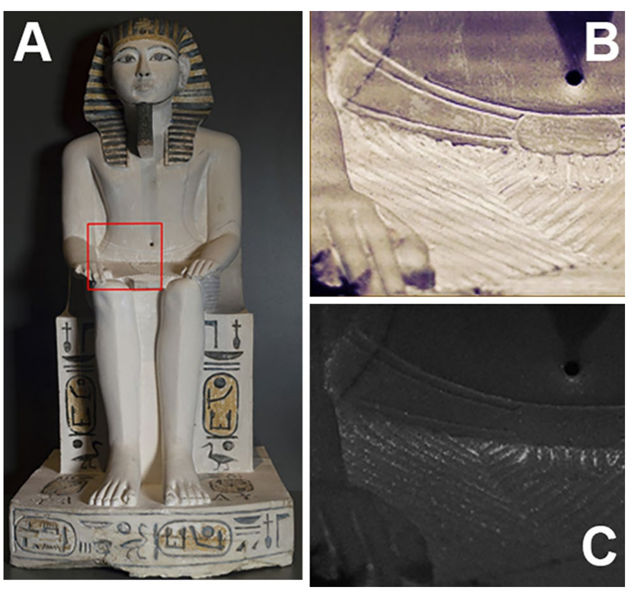

Fig. 4 The cult statue of Amenhotep I (ME—C.1372). Visible image with detail area highlighted in red (**A**). MNVG visible image of the detail (**B**), MNVG NIR image (**C**) (color figure online)

Fig. 5 A cosmetic spoon with floral decoration (ME—C. 6442). Visible image (**A**). MNVG visible image (**B**) and MNVG NIR image (**C**)

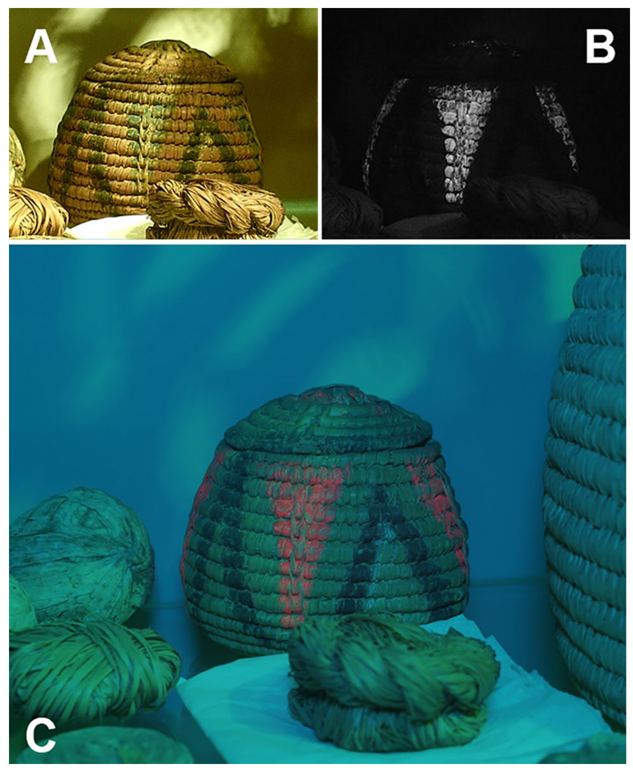

Fig. 6 A painted basket made of vegetable fibers (ME—C. 6499). MNVG visible image (**A**), MNVG NIR image (**B**), and conventional VIL false color image (**C**) (color figure online)

identify EB blackened due to degradation, which is a very frequent occurrence on archeological finds in museums (Daniels et al. 2004).

The wigs of the two statues seem very similar when observed in visible light (Fig. 2A and B); however, the use of MNVG instantly unveils that they were reliably produced in different ways. The wig on the left statue was originally blue and was produced with EB, while the one on the right was arguably produced without EB and using black pigments. MNVG images can not only be useful for quickly identifying blackened EB, but upon closer inspection, they can also reveal further details such as construction features or the presence of damage and repairs. In Fig. 2D, for example, the asymmetric shape of the EB silhouette on the top of the wig can be easily detected. It can then be further investigated to provide archeologists with important data to reconstruct

Fig. 7 MNVG visible image (**A**) and MNVG NIR image (**B**) of the two scarabs (ME—C. 6016, C. 6037)

the vicissitudes of the statue. Students and visitors may be surprised and interested by these details and the view with MNVG can act as a means to illustrate these features and make them aware of general concepts, for instance the high stability of EB and its degradation mechanisms in archeological times.

3.2.2 Case study #2—the cult statue of Amenhotep I: unveiling hidden EB residues

The limestone cult statue of Amenhotep I is shown in Figs. 3A and 4A. Hailing from Deir el-Medina, it belongs to the 19th Dynasty of the New Kingdom (1292–1190 BCE) and is part of the Drovetti collection acquired in 1824 and numbered C. 1372. This statue stands as a noteworthy example of ancient Egyptian art, capturing the ceremonial and sacred representation of the kingship.

The statue can be used as a second application case. EB can be easily detected on the wig even by an unexperienced user (Fig. 3B), but great attention should be placed on the intensities of the tones since the uneven illumination commonly present in the showcases within the museums can produce shadows in the acquired images that can be misleading. While such a general view can be adequate for visitors and students, professionals, in this case, face one of the limits of the MNVG approach and should use a better setup of illumination and acquisition to have a true vision of EB mapping. A traditional VIL with specific illumination (although still with the object within the showcase) is shown for comparison in Fig. 3C. The mapping of EB is highlighted in red in Fig. 3D using the false color technique postprocessing on conventional VIL images. As already stated, this demonstrates how it is important to be careful in EB luminescence imaging, and how it is of paramount importance to use conventional techniques for a correct display of EB spatial distribution, possibly also making use of appropriate internal reference standards (Dyer et al. 2013). Nevertheless, the use of MNVG allows a preliminary detection of EB without requiring a photographic set, making the operator aware of the need for more careful and in-depth image acquisition. Notably, in this case study, MNVG's advantages have been exploited to identify hidden residues of EB. As shown in Fig. 4C, MNVG readily unveils traces of EB present on the statue's skirt. Before this discovery, these traces had remained undetected, and now they enable us to hypothesize for the first time that the statue's skirt once sported yellow and blue stripes, mirroring the wig.

As shown, the possibility of quickly and accurately observing the details of the statue in the round made it possible to immediately identify very important clues that can be of great use to archeologists and conservation scientists (i.e., residues, discolored or hidden EB decoration, etc.). Further in-depth study using conventional VIL will allow for an exact mapping of the minute residues present. However, it is evident that the image provided by MNVG is by far enough to immediately unveil the presence of hidden traces of EB.

3.2.3 Case study #3—a spoon, a basket, and two scarabs: unexpected EB

EB can be present even in places that may seem odd and where it is not easy to figure it out. This is the case of the spoon in Fig. 5A which contains EB residues that pass completely unspotted at first sight. It is a cosmetic spoon with floral decoration (ME—C. 6442) that dates back to the New Kingdom, spanning the 18th to the 20th Dynasties (1550–1070 BCE). This delicate item features an intricate floral design, showcasing the elegance and esthetic attention characteristic of the art of that period.

As clearly shown by the MNVG NIR image (Fig. 5C), its intricate carving should once be filled or covered by EB. The use of MNVG can readily identify such kind of unexpected uses, helping archeologists to better understand ancient features of the finds and compare them among different objects.

A similar case is that of the object in Fig. 6A. It is a basket with a lid (ME—C. 6499), originating from the Late

Pe-riod of Ancient Egypt (722–332 BCE). Embellished with paint, it is crafted from vegetable fibers. The use of EB on a non-rigid material, such as plant fibers, is a rare occurrence compared to its more common applications on rigid supports such as wood, stone, and stucco. As can be seen by the preliminary MNVG image (Fig. 6B), EB is contained mainly in the upper triangular segments, adjacent to the lid of the basket, and at a minor extent on the top of the lid itself. The combined use of conventional VIL and in particular of the image using false color VIL (Fig. 6C) allows in this case to obtain further information on the decoration. The inverted V decorations in the lower part of the basket (and the border of the lid) seem visually similar to EB from an esthetic point of view but are made with other pigments, possibly with Egyptian green.

The last case we report within the Museo Egizio is that of the two scarabs (ME—C. 6016, C. 6037) visible in Fig. 7A. They are dated to the New Kingdom (1550–1070 BCE) and their massive EB nature was already known (Masic and Nicola 2021); however in this case, what is interesting is how their composition becomes immediately evident as soon as they are visualized by the MNVG. They remain the only two luminous objects inside the dark showcase that contains hundreds of other objects, mostly made of faience and other vitreous materials other than EB. What is also surprising is the detail that can be achieved despite the inclined position of the scarabs, and being inside a showcase, among other objects, and in a low-light environment. Even some of the finest surface details seem remarkably clear in the image, with a freshness that is surprising considering the simplicity of the MNVG used. Even if their imaging can be for sure improved using conventional VIL and a proper photographic setting, as far as we know, this is the most detailed NIR image available of these two rare objects.

3.3 Domus Aurea in Rome

The archeological site of the *Domus Aurea* is what remains of Nero's prestigious residence built in 64–68 CE. The site also includes the superstructures that were built on it in the centuries that followed its destruction in 105 CE. What can be seen today is an extraordinary complex of structures that unfold in a sensational labyrinth of underground rooms, variously frescoed, that can partially be visited. They were accidentally discovered at the end of the fifteenth century and were visited by, among others, Raphael and Michelangelo. The decorations found in the underground rooms were so impressive that the term "grottesche" decorations was coined from their sight, which means decorations "of the caves" in relation to the cave-like appearance of the discovered rooms. Notably, around 1815, Sir Humphry Davy and his assistant Michael Faraday studied many samples of EB from the *Bath of Titus* (Davy 1815; Moshenska 2015), a structure built over the private bath of Nero's *Domus Aurea.* Their study represents one of the first-ever modern chemistry analyses of EB and more in general of any ancient artistic material (Nadolny 2003).

The *Domus Aurea* is an amazing example of an underground archeological site. The possibility of using MNVG technology to explore the frescoes within it is intriguing not only for scholars but also for any visitor including students. The two case studies presented below showcase some of the potential of MNVG technology, specifically its ability to immediately identify EB in paintings even when it is mixed with other pigments. They also demonstrate the ability to work at long distances even with poor lighting (the vault is approximately 12 m high) and the ability to detect even limited amounts of EB residues. However, the most impressive result is the ability to reveal completely hidden or lost paintings. Also, for *Domus Aurea*, it has to be said that the total time used to acquire all the images has been around 1–2 h, a time comparable to a quick explorative visit. By far, better results can be expected for systematic studies.

3.3.1 Case study #4—Colle Oppio pavilion, Room 53: unveiling EB in complex mixtures of pigments

EB was a versatile pigment used by ancient artists not only for its vibrant blue color but also due to its ability to create a wide range of other hues and effects through various techniques (Nicola et al. 2023). *Colle Oppio pavilion, Room 53*, is a clear example of these uses. It is a rectangular room with a barrel vault, characterized by frescoes with scenographic architectures on the south and west walls. A female figure is centrally located on the south wall.

The presence of EB within the south wall paintings can be seen in Fig. 8. The room is dimly lit, and the visible light view of the room is shown in Fig. 8A. Figure 8B instead shows the mapping of the EB distribution (the reddish areas are those containing EB). The mapping has been obtained through conventional VIL using the false color technique (see also Sect. 2.2).

A careful comparison of Fig. 8A and B immediately shows how EB is present in many areas that are not blue.

The most straightforward method to obtain other hues using EB was to mix it with other pigments. It is known that this has been used to produce greens, for example, by mixing EB with yellow pigments such as orpiment or iron-based yellows (Scott 2016). EB was also commonly used to enhance the tone of existing soft green pigments such as green earth or Egyptian green (Mazzocchin et al. 2003; Perez-Rodriguez et al. 2015; Bracci et al. 2022). Adding EB to iron oxides or cinnabar (i.e., vermilion), many other colors were produced such as purples, grays, browns, ochres, and even skin tones (Edreira et al. 2003; Aliatis et al. 2010; Fermo et al. 2013; Osanna and Rescigno 2022). EB was

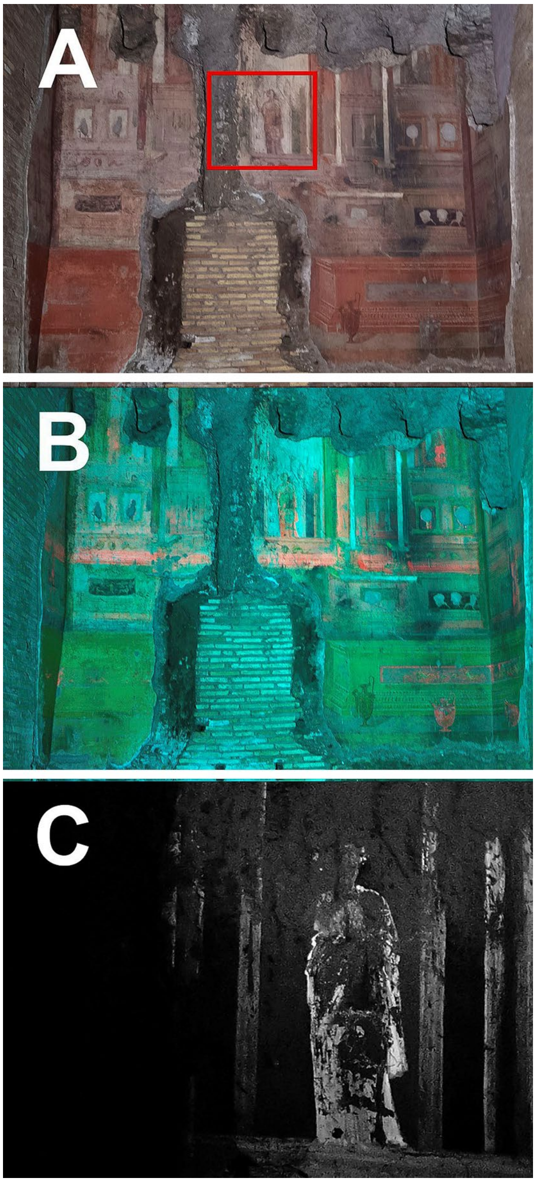

Fig. 8 *Colle Oppio pavilion, Room 53*: fresco on the front wall. Visible image with detail area highlighted in red (**A**). EB mapping obtained through conventional VIL false color image (**B**). MNVG NIR image of the detail area shown in A (**C**) (color figure online)

generally available in a range of blue shades depending on the production procedure (e.g., grain size, furnace conditions, etc.). However, its blue color could be lightened by also adding white pigments such as calcium carbonate or lead white. A peculiar use of EB was as a brightener of subdued white pigments. For this purpose, small amounts of EB were added to white pigments to "optically achieve" a brighter white (Nicola et al. 2023). A typical (but not exclusive) use for this kind of brightened white in classic antiquity was in painting the white of the eyes (Verri et al. 2010). This use likely inspired also Raphael as will be seen in the following paragraph about Villa Farnesina (Anselmi et al. 2020). Other specific optical effects were produced by layering EB on top of other pigments since the partial transparency of EB allowed for creating depth and color variations through thin layers (Osanna and Rescigno 2022). EB was used also in sketches and underdrawings, indicating that it should have been quite an inexpensive pigment (Baraldi et al. 2016; Skovmøller et al. 2016; Nicola et al. 2023).

The use of EB as a pure pigment and to modify and enhance other colors has been observed in various historical periods since Ancient Egypt (Scott 2016). However, its most extensive and varied use was probably reached exactly during the first century CE (Blümich et al. 2021; Bracci et al. 2021; Falzone et al. 2021). Studying a Roman fresco of the first century CE, like the one in *Room 53,* is thus an extraordinary opportunity for archeologists to improve their understanding of ancient artistic techniques.

As shown in Fig. 8C, the use of MNVG allows to immediately detect if and where EB is present in the fresco. MNVG has been used as a preliminary approach to direct the subsequent mapping shown in Fig. 8B. The MNVG image is also relatively high in quality taking into account that the fresco is far from the viewer and is not possible to reach it since is in an inaccessible and low-lightened area. The comparison with the visible image allows archeologists to readily detect pigment mixtures and unveil also faint drawings and profiles that are currently hard to be seen.

3.3.2 Case study #5—Colle Oppio pavilion, Grande Criptoportico 92: long-range detection of hidden decorations and paintings

One of the most impressive underground chambers within the complex of the *Domus Aurea* is undoubtedly the majestic *Grande Criptoportico 92*. It is a 59-m-long service corridor that winds through the eastern sector of the *Domus Aurea*, connected through rooms and corridors to both the *Golden Vault Room (Room 80)* and the *Octagonal Room* complex. The room is crossed by an arch, which hides the water pipe that fed the *nymphaeum* of the *Octagonal Room* from the upper floor and can be identified as a direct connecting path between the first and second pentagonal courtyards. The *Grande Criptoportico* is an ideal place to showcase the potential of the MNVG viewer. The vault, approximately 12 m high, is adorned with various types of decorations (see Fig. 9A, C, and E), which are barely lit and are difficult to access and observe in detail. Thanks to MNVG, it is possible to quickly screen different areas of the vault without the need to build scaffolding or use large lighting systems. The decorations containing EB can thus be quickly highlighted to allow for the study of their execution techniques (see Fig. 9B, D, F). The images can also be very useful in the preparation procedures of conservation projects, as they

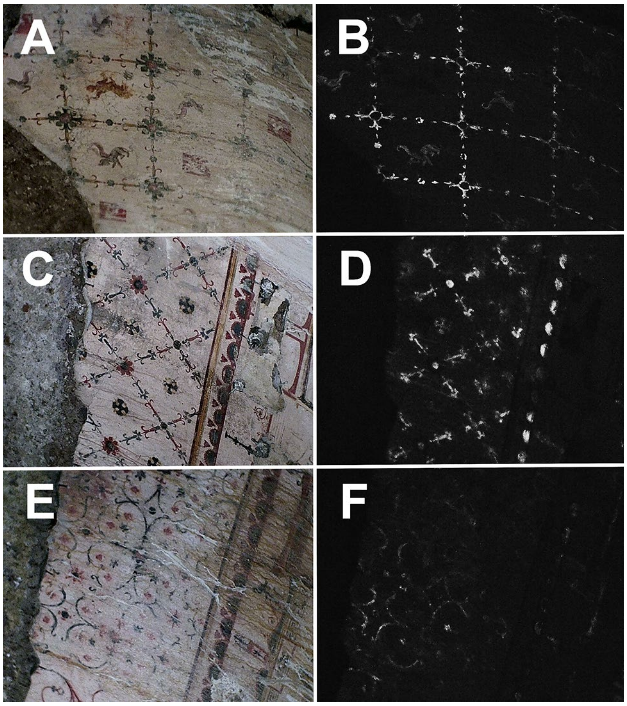

Fig. 9 Different types of decorations on the surface of the vault. MNVG visible image (**A**, **C**, and **E**) and corresponding MNVG NIR image (**B**, **D**, and **F**)

can facilitate the drafting of the graphic documentation of the decay.

The most surprising results, however, can be obtained in the case of decorations or paintings that are completely hidden or lost. Situations of this type are common in the *Grande Criptoportico*. As shown for example in Fig. 10A

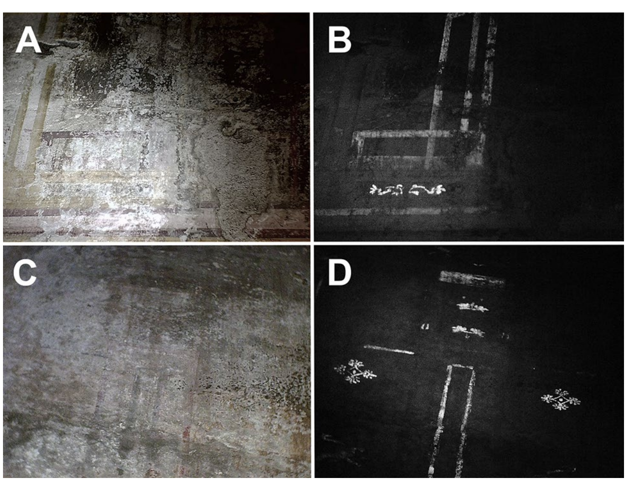

Fig. 10 Two examples of hidden decorations on the wall of the *Grande Criptoportico.* Due to the presence of a thick layer of carbonation, they are practically invisible. MNVG visible image (**A** and **C**) and corresponding MNVG NIR image (**B** and **C**)

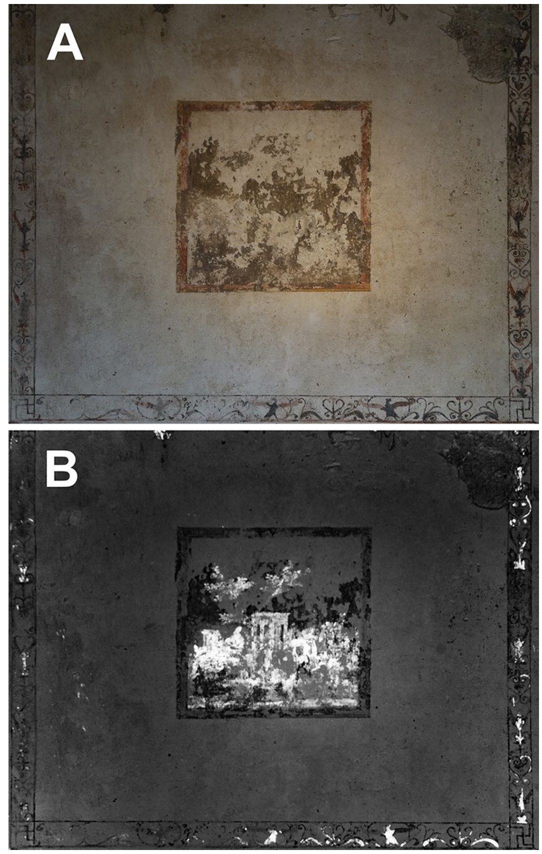

Fig. 11 An example of degraded painting in *Grande Criptoportico*. Visible image (**A**) and conventional VIL NIR image (**B**)

and C in many areas the presence of thick layers of superficial carbonation and dirt makes it difficult or even impossible to read the underlying images. Since these layers are semi-transparent, a certain amount of light can reach the surface below while the re-emitted NIR can easily pass back through them. For this reason, as shown in Figs. 10B and D, the MNVG can readily detect the presence of even completely hidden frescoes and to a certain extent can also be useful to evaluate their state of conservation.

In other areas, the pictorial layers, degraded over centuries, have collapsed and only residues remain. To recover precious information on apparently lost paintings, it is possible to use MNVG to screen the surface in search of residues and if found follow with conventional VIL. In Fig. 11, the final example from the *Domus Aurea* shows how a scene that seems to represent trees and architecture has emerged in this way from a square wall painting of difficult or impossible interpretation.

3.4 Villa Farnesina

To test the versatility of MNVG technology in contexts other than archeological sites and proper museum environments (*i.e.,* areas specifically designed to conserve and display works of art), it was used in a place that was originally a private home, and only later did it become a museum of itself. The difference is substantial because the structural requirements and conservation conditions of a building not originally designed to be a museum are generally more difficult to control. When adapting them, it is necessary to preserve the existing structure, which, being itself a complete work of art, cannot undergo more than small modifications. The building in question is Villa Farnesina, in Rome, the representative seat of the Accademia Nazionale dei Lincei. It was built in the early 1500s by the Sienese banker Agostino Chigi who entrusted its design to the architect Baldassarre Peruzzi and the interior decoration to Peruzzi himself and some of the greatest artists of the Renaissance. Among them were Sebastiano del Piombo, Giovanni Antonio Bazzi, known as Sodoma, and Raphael.

In this explorative campaign with MNVG, the frescoes by Raphael have been screened in search for EB. Given the impossibility of avoiding the entry of natural light inside the building, the images were acquired after sunset and using a single portable source of artificial light placed at floor level as lighting (see also Sect. 2.2).

3.4.1 Case study #6—Triumph of Galatea by Raphael: studying the artistic technique of a master

The fresco *Triumph of Galatea* painted by Raphael in the years 1511/12 is depicted in Fig. 12A, and it is certainly the most representative artwork in the villa. Recently, the presence of EB has been surprisingly identified extensively on this fresco throughout the surface during non-invasive measurements: the sky, the sea, and numerous details, such as the eyes of many characters, resulted painted using EB (Anselmi et al. 2020). Of the few cases known so far of EB use in the Renaissance, *Triumph of Galatea* is the earliest one, dating from around 15–20 years before the findings in Ferrara (Bredal-Jørgensen et al. 2011; de Vivo et al. 2019; Spring et al. 2019). The 295 × 225 cm fresco, located in the homonym *Loggia of Galatea* on the ground floor of the villa, starts from approximately 3 m above the flooring and belongs to a wide range of artworks that are characterized by their immovability, large dimensions, and locations that are not easily accessible, such as ceilings or entire walls. It should be pointed out that the previous analyses conducted on *Triumph of Galatea*, including the 2019–2020 non-invasive campaign which allowed the use of EB to be detected, were only possible with the support of bulky structures such as scaffoldings. They were used to allow the instruments, and therefore the operators, to get close enough to the surface to analyze it. Given the challenges of using scaffolding and structures when analyzing ancient wall paintings, tools that eliminate such needs are particularly valuable. These tools simplify diagnostic procedures while enabling preventive screening of surfaces. This is especially true for detecting pigments with unique chemical–physical properties like EB and its structural analogs (Nicola et al. 2023). Since they present discontinuities in use over time, tracing the occurrences of these pigments over the centuries is crucial for understanding their transformations and spread.

The images obtained on *The Triumph of Galatea* using MNVG show the different areas of the fresco with satisfactory sharpness. Although the traditional VIL technique shows some advantages in terms of resolution and material differentiation (see Fig. 13), the handy MNVG proved capable of highlighting in real time and from a distance of several

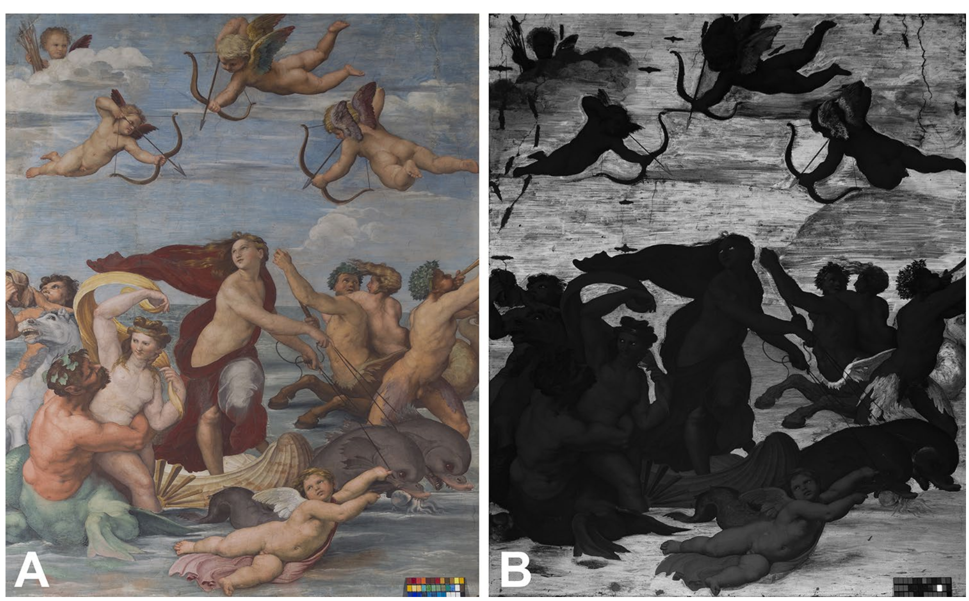

Fig. 12 The *Triumph of Galatea.* Overall visible image (**A**) and corresponding conventional VIL image (**B**), collected after MNVG screening

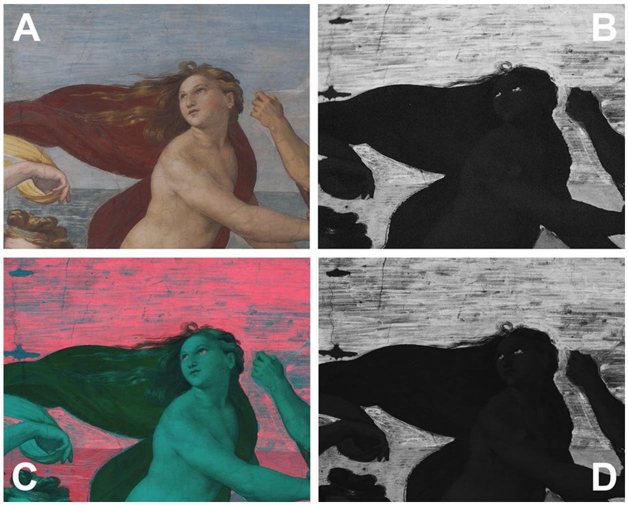

Fig. 13 Detail of *Triumph of Galatea.* Visible image (**A**), MNVG NIR image (**B**), EB mapping obtained through conventional VIL false color image, where EB appears in pinkish color (**C**), and conventional VIL image (**D**) (color figure online)

meters, the areas where EB has been used alone, in mixtures or confined to certain details. Below are some examples of the results obtained.

A. Sky and Sea

Using the MNVG, it is possible to appreciate Raphael's extensive use of EB in the sky and sea. It has to be noted that, as shown in Fig. 13D, the conventional VIL technique can provide some advantages in terms of improved resolution, i.e., the brush strokes used to apply EB across the sky are better defined. However, the Fig. 13B shows that also using simply MNVG, the quality of the images is sufficient to identify the strokes, with thin, irregular layers evident where the clouds appear. In terms of drafting, the sea appears far more uniform, albeit with a more attenuated luminescence than the sky. This is indicative of the use of EB in a mixture and not alone. The MNVG is able to distinguish to a certain extent the areas where EB is used alone or in a mixture depending on the different luminescence intensities. Nevertheless, as shown in Fig. 13C, the combination with the VIL false color image allows for better differentiation of EB when it is used in a mixture with other materials.

B. Eyes

One of the most interesting details of the fresco is the presence of a mixture of EB and a white pigment, used for the sclera of the eyes of all the characters looking toward the observer (see Fig. 14). The MNVG can reveal this particularity with great sharpness and not only in the groups where the composition of the incarnations is to provide a

Fig. 14 Detail of MNVG NIR image of *Triumph of Galatea* showing EB in the eyes of the characters

sharp contrast to the luminescence of the eyes but also where the contrast is less, as in the case of *Palemon*'s incarnation shown in Fig. 14B.

C. Wings

The MNVG image (see Fig. 15) shows how EB is used in mixtures to achieve different final color tones. In the upper angel's details, EB is used in a homogeneous mixture, while

Fig. 15 MNVG NIR image of a detail of *Triumph of Galatea* (central upper area)

in the other, EB is present on the superficial layer as a finishing touch to the color of the wings. The difference between these two uses can be seen in the different intensities of the luminescence as recorded by MNVG. In the former, in fact, the luminescence is uniform but weakened compared to the latter, where EB remains mostly on the surface.

3.4.2 Case study #7—The Loggia of Cupid and Psyche: an extraordinary discovery

After testing the potential of the MNVG on *Triumph of Galatea* where the presence of EB was already known, it was decided to try to use it to detect the possible presence of EB in other frescoes inside Villa Farnesina and in particular in the *Loggia of Cupid and Psyche*. The *Loggia of Cupid and Psyche* is located on the ground floor, adjacent to the *Loggia of Galatea*, with five arches that are currently closed by protective glass windows. The room takes its name from the fresco decoration painted in 1518 on the vault by Raphael and his workshop, based on designs by the master, depicting episodes inspired by the fable of Cupid and Psyche, taken from *Apuleius' Golden Ass*.

Loggia of Cupid and Psyche has been chosen not only because it is close to *Loggia of Galatea* and was created by Raphael and his workshop, but also because there was circumstantial evidence of a possible presence of EB.

In fact, following the disclosure of the discovery of EB on *Triumph of Galatea* in 2019–2020 (Anselmi et al. 2020) and his discussion in 2021, Sidoti et al. undertook a study aimed at the search for EB on residual old samples coming from some Raphael frescoes. The samples were available within the archives of the Istituto Centrale per il Restauro in Rome (ICR) and had been historically taken, generally in conjunction with restoration interventions, and then embedded in resin for observation in thin and/or polished section (Sidoti et al. 2022). This study, which essentially focuses on the application of VIL to samples in cross-section (Aramini et al. 2013), was then published in the ICR Bulletin in Italian in 2022 (note that, despite this, the study is included in issue 37, 2018). The study concerned 38 sections, of which 1 came from *Triumph of Galatea* (sampled in 1971) and 14 from *Loggia of Cupid and Psyche* (sampled in 1990–1993). Of all the 38 sections analyzed, only two had a positive result for the presence of EB: the sample from *Triumph of Galatea* and one of the 14 from *Loggia of Cupid and Psyche* (*i.e.,* section number 4838). This specific section was produced in the occurrence of the restoration intervention that took place in 1990 and consisted of several microfragments all embedded together in the same lump of resin and with different orientations. The sampling point was difficult to reconstruct as it was only indicated as "Vela con Amore che si punge un ditino, angolo superiore-unghia" ("Spandrel with Cupid pricking his finger, upper corner") and, in the words of the authors themselves, without any other information that allows for a more precise location.

However, this study was useful to hypothesize that EB was possibly present in some way on the *Loggia of Cupid and Psyche*, even if the available information did not provide elements to say where it was present or how widespread its presence was, nor, ultimately, could it guarantee with certainty that the fragmentary section produced more than 30 years ago was truly representative of the *Loggia of Cupid and Psyche*.

The use of MNVG in the *Loggia of Cupid and Psyche* yielded an impressive and unexpected result: not only EB was present and immediately visualized, but it has also been detected in a large part of the frescoed vault. Aiming the MNVG at the 8-m-high ceiling, it was possible to map the significant extent of the areas where EB is present, *i.e.,* in the background skies of approximately half of the entire ceiling, as schematized in Fig. 16C. This fact is highly significant because it opens up a new discussion on the phases of the work's creation and its restoration. Particularly Fig. 16B, for instance, helps to better visualize the transformation that occurred in Venus' hair as a result of an ancient restoration intervention. In Fig. 16B, it is in fact possible to clearly see the original shape of the goddess's hair as a ponytail.

As a final remark, it is worth noting that one limitation of using MNVG is the inability to immediately acquire a global image of large artifacts. This is especially true in contexts where there is not enough distance to observe the surfaces in

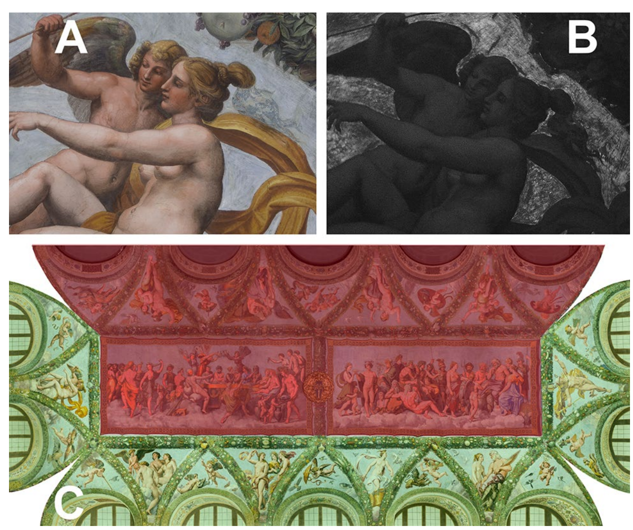

Fig. 16 The *Loggia of Cupid and Psyche*. Visible image of the detail showing Cupid and Venus (**A**), corresponding MNVG NIR image (**B**), and scheme of EB distribution obtained by using MNVG. In the latter, green area corresponds to the zone where EB is present within the skies and red area corresponds to the zone where EB is absent. The starting image used to create **C** belongs to the Archivio Accademia Nazionale dei Lincei. (Photograph by Federico Di Iorio) (color figure online)

their entirety with a single view. However, it must be noted that the MNVG function, and the purpose for which it was developed, is to obtain a real-time screening to highlight the use of EB in practically any type of artwork.

3.5 Considerations on the use in education and for museums and sites

The new and exciting possibilities offered by MNVG technology also concern education and visitor experience in museums and cultural sites. MNVGs provide a perfect platform for students to engage their individual attitudes. As part of conservation science, EB luminescence imaging lies at a fascinating multidisciplinary intersection between humanities (namely art, history, and archeology) and STEM (namely science, technology, engineering, and mathematics). There is a wide consensus about the fact that interdisciplinary courses that combine science and art can provide students with a more comprehensive understanding of complex concepts in chemistry and physics (Smith et al. 2009; Torres and Floyd 2019). Thanks to their charm, their simplicity of use, and the possibility of being used directly by each individual, MNVGs can therefore help the students to approach and delve into disciplines outside their comfort zone, improving their attention and comprehension. Furthermore, the experience with MNVGs in museums and sites can be combined also with other EB-related experiences. The synthesis of EB directly at school is a straightforward and easily achievable goal for high school classes. This is because it can be done using widely available ceramic kilns (Johnson-McDaniel and Salguero 2014; Nicola et al. 2019). Another easy task that can be accomplished during art lessons is the use of EB (whether purchased on the market or self-produced) to create surprising NIR luminescent paintings. The students can thus visualize their NIR luminescent paintings or verify the effective production of EB at their school by checking its luminescence with the MNVGs and then have an experience at the local museum or in an archeological site searching for ancient EB.

The possibilities offered by MNVGs are also very attractive for improving visitors' experience in museums and sites. Carrying out specific routes equipped with an MNVG can allow a visitor to live an extraordinary experience in contact with objects and literally see them in a different light, thus identifying themselves with the activities of archeologists and conservation scientists. Modern-produced EB and related materials can be used by the museum or site staff to set up dedicated visit itineraries, adding exclusive physical contents, such as writings, explanations, real objects, and images, immediately or exclusively visible for users equipped with MNVGs. It is a new kind of immersive experience, which we can call Blue Vision, and which offers new opportunities. It is not meant to replace, but to improve similar approaches such as the ones by augmented reality, virtual reality, and related technologies (Trunfio et al. 2022; Cheng et al. 2023). EB can, in fact, not only provide more content but also be useful to create luminescent and/or invisible targets that can be effectively used by other technologies. However, Blue Vision can be more vivid and real in comparison with other immersive experiences as it is not based on fictional content but is linked to real physical materials, objects, and graphics that are simply highlighted or unveiled smoothly and naturally by the MNVGs. This technology can also pave the way for customized user experiences and gamification to engage even younger visitors (Hutson and Hutson 2024) such as treasure hunts or escape rooms in specifically equipped areas of the museums and sites.

4 Conclusions and outlook

The MNVG technology is still in its early stages of development, but its potential applications are vast and promise rapid diffusion in multiple sectors. Its expected introduction as Blue Vision for museums and educational and recreational purposes is just the tip of the iceberg. In synergy with the advancement of computer science and the production of new types of EB, MNVG technology can find fertile ground in applications within security and tags, plastics (including 3D printing), textiles, nanotechnologies, and possibly in medicine within bioimaging devices. Added to this is the evolution of night vision technology itself, increasingly affordable and with high performance, integrated into cell phones and commonly used video cameras. The expectations of improvement in this field are tangible, and a transfer of advanced night vision technologies and devices from sectors such as the military or astronomical observation could lead to revolutionary results in conservation science. Particularly promising are the applications such as NVG that can combine the image acquired through different sources to produce automatic VIL FC view, or combine VIL data with hyperspectral imaging dataset. Another improvement soon expected is the development of a method using NIR-NIR luminescence. The latter uses light sources emitting in the NIR at around 780 nm as the excitation system. NIR light at 780 nm is invisible and is more penetrating. A NIR-NIR luminescence device is thus expected to be able to see deeper-hidden EB in comparison with conventional visible-NIR systems.

The study conducted within the specific case studies here presented highlights the need for further research in different directions. For example, on residues of lost decorations in objects within museums, since as highlighted in the case studies within the Museo Egizio, such an approach opens up new possibilities for the rediscovery of otherwise invisible details of artistic and historic relevance. Systematic mapping of hidden or lost decorations in archeological sites is another aim. It is illustrated for the *Domus Aurea,* but similar situations can be found in many sites and the perspective of analog applications covers a huge number of possible sites in particular in a large part of the Mediterranean and Asia, representing an emblematic example of the application of MNVG technology on a large scale. In this regard, it is worth noting that the use of EB alone and in mixtures, in Roman times (and probably even earlier), was so widespread and systematic, that VIL images, and therefore MNVG, have the potential to become as routine and fundamental for antique mural paintings as radiographic images are for paintings on canvas and panels.

The in-depth study of the specific cases of *Loggia of Cupid and Psyche* offers insights for the analysis of complex and stratified artistic artifacts and has the potential to deeply impact the history of art related to Raphael or perhaps to the whole Renaissance. It should finally be said that the use of MNVG as a means to detect EB or, more generally, NIR luminescence is just a fraction of its potential. It is evident that the use of MNVG in conservation science as a versatile means to visualize and quickly acquire also the other NIR images (i.e., reflected NIR images or transmitted NIR images) is, for example, simply a corollary of this work. The conclusions drawn, thus, do not exhaust the potential of MNVG technology but pave the way for a future rich in new applications and discoveries in various fields of knowledge. Collaboration between different disciplines and technological innovation will continue to fuel the growth and evolution of this promising technology.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article [and/or] in the articles in the reference list.

Declarations

Conflict of interests The authors declare no competing interests with respect to the topic discussed.

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