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Review

Digital methods and techniques for reconstructing and visualizing ancient 3D polychromy – An overview

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ABSTRACT

The digital technologies employed in archaeology since the 1990s have progressively and experimentally been utilized over the last two decades to document and re-present the ancient polychromy of Greek and Roman marble artworks. Given that this remains a developing field of investigation and application, this study offers, for the first time, a systematic review of the endeavours undertaken thus far in implementing information technology for the documentation, analysis, reconstruction, visualization, and presentation of ancient polychromy. This overview is supported by a literature review and existing implementations, organized into methods and techniques employed for 3D colour preservation, analysis, and reconstruction, as well as those used for the visualization and dissemination of findings. The goal is to identify gaps and provide intriguing insights for future research concerning the use of digital technologies as an essential tool in the stages of documenting and disseminating ancient polychromy in architecture and archaeological artefacts. This, in turn, aims to encourage data sharing, contribute to the dissemination of science-based knowledge and resolve substantial barriers associated with the long-term retention of digital data.

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Research aim

The paper introduces a critical investigation of digital technologies and methods used from the early 1990s to the present day for documenting, reconstructing, visualizing, and presenting ancient polychromy. The aim is to provide a systematic overview of the experiences accomplished to date, examine ongoing challenges, and offer recommendations to address them. The study and re-proposition of ancient colours and gilding on Greek and Roman marble surfaces, including architectural elements, sculptures, bas-reliefs, and sarcophagi, remain highly relevant and of significant general interest. However, it is crucial to recognize that complexity and certain factors of uncertainty have imposed substantial limitations on our knowledge and progress in this field despite the availability of advanced technologies. The paper, analysing a vast literature of examples, identifies and discusses these persistent issues and aims to chart a course for science-based approaches and to address the challenges associated with the long-term preservation of digital data.

1. Introduction

In the last fifty years, the increasing use of information technologies has become one of the main features of archaeological research. Since the 1990s, information technology has primarily focused on developing tools and solutions for archiving and managing large amounts of excavation data, creating the first virtual models, and disseminating knowledge. All of this was subsequently transformed into a proper theoretical approach to the challenges posed by archaeological research [1-3]. “Digital Archaeology” in the Anglophone world denotes an approach to modern cognitive archaeology through the application of information technologies [4,5]. Today, digital archaeology – which now tends to experiment more organically and progressively with the interaction between different technological applications – is primarily concerned with the documentation and dissemination of archaeological evidence, particularly through “Virtual Archaeology”, which involves the management and representation of archaeological data using 3D Computer Graphics techniques [6]. The 3D technologies developed for digital acquisition, digital modelling, and additive or subtractive manufacturing – generally referred to as “3D scanning” – allow for the creation of objectively accurate digital models in terms of shape and colour. Technologies for 3D scanning and

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digitization of physical objects have been available since the 1980s. However, it was only in the early 2000s that scanning devices with sufficiently high levels of resolution, accuracy, and precision became more widely accessible and affordable. In addition to visualization applications, 3D scanning can provide a comprehensive and informative method for museum documentation, offering several benefits for conservation practices. As a result, they form the foundation for accurately documenting the current state of archaeological structures and artefacts, which is valuable for conducting digital diagnostics and restoration [7-9], verifying authenticity [10], performing morphological comparisons [11,12], making attributions [13], and also for producing physical reproductions [14-17] as well as for the basis of 3D modelling [18-20]. The current state of research enables the integration of digital reconstructions with archaeological data and the utilization of new communication approaches through specific tools and interactive strategies [21]. The propagation of virtual archaeology is not solely due to the proliferation of three-dimensional modelling techniques in various fields of knowledge but also due to the need to experiment with new systems for better information storage and to establish effective means of communicating this knowledge using visual language. From this perspective, 3D reconstruction applications have become an essential component of virtual archaeology owing to the cognitive interaction possibilities offered by 3D models. More recently, experimentation in the realm of virtual archaeology has led to the creation of virtual museums and interactive applications using virtual, augmented, and mixed-reality technologies [22]. Among these, the segment of "serious games" – referring to the application of interactive technologies to the Cultural Heritage domain – has been expanding, encompassing immersive virtual reality technologies [23-25], bolstered by storytelling and learning-by-doing approaches [26,27]. These technologies allow users to experience history and archaeology both visually and narratively, enabling them to observe and interact with artefacts, architectural structures, and characters from specific historical periods. The historical content conveyed through these media with a scientific approach serves as a means of promoting the dissemination and comprehension of the past [28,29], as well as extending upon the previous overview [30].

The application of digital technologies to the documentation and presentation of ancient polychromy is more recent in comparison to their use in archaeology. Working closely with cultural heritage professionals, digital technologies within this sector have been a research subject since the 1990s, with a notable surge in interest from 2010 onwards. Their utilisation in the study and re-proposition of ancient colours has been conducted experimentally and in isolated contexts. As a result, the domain of investigating and applying digital technologies to analyse and showcase ancient polychromy is still in need of further consolidation. Apart from some recent exceptions we will examine, there is a lack of shared guidelines, or the community still needs to adopt these procedures. Our contribution presents a well-considered compilation of various experiences brought up to date, which, hand in hand with technological advancements, have addressed, on one hand, the necessity for archiving, analysing, and reconstructing ancient polychromy (see Section 2.2), and on the other, the visualization and representation of the original appearances of artefacts and architectural structures (see Section 2.3). The examined projects pertain to the polychromy of Greek and Roman marble architecture and artefacts. They are reviewed chronologically, showcasing the utilization of increasingly sophisticated technologies and yielding more efficient and effective outcomes. Only sporadically are projects from other time periods included, either due to their pioneering nature (as seen in the polychrome reconstructions of the "Xi'an Terracotta Army Warriors" [138]) or due to the development or application of pertinent or cutting-edge methodologies (as seen in the case of Medieval and Gothic polychromy [117-120,141,191,192,211]). For comprehensiveness, the analysis is prefaced by a brief historical overview highlighting the most significant examples of methods employed to revive ancient colours before the rise of digital technologies (see Section 2.1). This overview is substantiated by a review of existing literature and implementations. The critical analysis of the adopted methods and techniques (see Section 3) is complemented by a table (Table 1) wherein we summarize, for each project, the purpose, objectives, resources utilized for physical or digital 3D polychrome reconstructions, and the technologies employed to represent ancient polychromy. The division between "primary actions" and "secondary or consequent actions" is determined by the employed technologies. To facilitate a quick indicative grouping, we used colours that correspond to the side border of the images in the text. To enhance the table's readability, we present charts illustrating the proportions among this data (Fig. 12). Our research aims to identify current gaps, provide intriguing insights, and propose ideas for future research concerning the use of digital technologies as essential support in the phases of documenting and disseminating ancient polychromy in architecture and archaeological artefacts, as well as in achieving FAIR – Findable, Accessible, Interoperable, and Reusable raw and processed data (see Section 3).

2. Materials, methods and results

2.1. Historical review: the revival of ancient colour before the advent of digital technologies

Before the advent of digital technologies, the revival of polychromy relied on drawings and casts. Numerous graphic reconstructions of ancient sculptures and temples rely on the remnants of colour found on the monuments. These vestiges were studied in the 19th century by archaeologists who deviated from the "white" interpretation established by German art historian and archaeologist Johann Joachim Winckelmann [31]. Starting with the polychrome theory and reconstruction of the Jupiter Olympien (Fig. 1a) by Antoine-Chrysostome Quatremère De Quincy [32], a prominent French art historian and classicist of his generation, several significant works related to the rediscovery of polychromy in sculptures stand out. These works and the polyglot dispute concerning ancient polychromy on marble, commonly known as the "querelle", have been extensively studied and are beyond the scope of this work. For more comprehensive information, one should refer to the specialized bibliography [33-40]. Notably, we must mention instances such as the Agrigento, Segesta, and Selinunte temples meticulously examined by the French architect and archaeologist Jacques-Ignace Hittorff [41,42]. Similarly, the Athenian Acropolis garnered attention from English architects James Stuart and Nicholas Revett [43]. These architects were the first Europeans to document the abundant vestiges of original architectural colouration. Their efforts were subsequently complemented by the reproductions featuring the restrained hues of marble buildings by the German historian Franz Theodor Kugler [44] and the German architect Gottfried Semper, a proponent of integral polychromy. He also reported clear traces of colour on Trajan's column in Rome [45]. Another noteworthy example pertains to the sculptures of the Temple of Aphaia on Aegina Island. Discovered in 1811 by Charles Robert Cockerell and Carl Haller [46,47], these sculptures provided further compelling evidence of ancient chromatic practices [48,49]. This evidence was so persuasive that Johann Martin von Wagner considered it imperative to address the painting of sculptures in his work [50]. Furthermore, Leo von Klenze, the architect behind the Munich Glyptothek, which exhibited these sculptures in 1828, went beyond neglecting this aspect. He introduced a stucco re-

Fig. 1. Instances of polychrome reconstructions before the advent of digital technologies: (a) Zeus in Olympia, Phidias' statue in gold and ivory in Olympia's main temple. Frontispiece of the A.C. Quatremère de Quincy book [32]. Image via Wikipedia CC (b) Polychrome plaster cast of the so-called Bluebeard (or Three-Body Man), created by a Danish artist Anne Marie Carl-Nielsen (1863–1945) featured in the "Farben Sehen" exhibition alongside (c) current polychrome miniatures that flank nineteenth-century plaster cast from the Antikensammlung FAU Erlangen-Nürnberg. The images have been sourced from the booklet and website exhibition [67].

lief in the designated "Room of the Aeginetans". This relief featured a polychrome rendition of the frontal facade of the temple of Aphaia.

From the mid-1800s, graphic re-proposition was supplemented by reproductions on plaster casts [51]. A noteworthy example in this context is the comprehensive collection of scaled-down classical architectural elements plaster casts sourced from prominent European museums showcased within the Crystal Palace of Sydenham, London, starting in 1854 [52]. Subsequently, there were endeavours to create scaled reconstructions of architectural structures like the Temple of Zeus in Olympia, undertaken by Georg Treu (1886) and Adolf Furtwängler (1906). These efforts were later revisited by Vinzenz Brinkmann et al. in the early years of the present century [53].

For the 1900s, it is significant to note the cast of a scene from the bas-relief frieze of Trajan's Column, created by Ranuccio Bianchi Bandinelli and displayed in an RAI broadcast in 1972 [54]. Differing from other scholars, Bandinelli believed that the relief was entirely coloured and augmented with bronze applications (such as weapons, sandal finishes, horses, etc.) to enhance visibility, as these elements were less discernible from a distance [55]. The polychrome cast of the XXXII scene, attributed to the Master of Trajan's Enterprises, was produced in 1971 [56,57]. Recently, this reproduction served as a reference for the virtual reconstruction of the column in the "History 3D" project [see Section 2.3.1].

Two instances stand out in the revival of colour in sculpture. The cast of the Peplos Kore (ca. 560 B.C.) was painted in the 1960s at Oxford. The colours (red, blue, and white) were uniformly applied, adapting Émile Gilliéron's watercolour work. The painted cast of the Apollo of Kassel was crafted in the early 1990s. Painter H.D. Tylle used oil paints and wax paint to depict the body and hair in a free manner. Both attempts reflect sensitivity in their respective periods when colour in sculpture was deemed extraneous compared to the beauty of white, still indicative of the purity of form [58].

Another noteworthy, albeit lesser-known, experiment without digital technology occurred between 1987 and 1993 near Trier, Germany, in Igel. The endeavour involved the restoration of a concrete copy made in 1908 and the reconstruction of the painted decoration of the Roman funerary monument known as the Igel Column. This 23-meter-high structure, shaped like a tower crowned with a pyramid, dates back to the mid-third century CE and is crafted from dark reddish sandstone. The relief on its surface portrays scenes of daily life, mythology, and the deceased, once adorned with polychrome hues. A layer of white was first applied to the copy surface and then recoloured based on the few remaining fragments and evidence of contemporary monuments. White figures emerge against a light blue background, while hair, medallions, furnishings, and geometric decorations are recreated in yellow or light brown ochre. The painted column's one-to-one copy was installed within the Rheinisches Landesmuseum (RLM) in Trier starting in 1993. In 2012–2013, 3D technologies documented both the original and its replica [59]. In September 2022, the polychrome copy was removed from the museum's internal courtyard to provide for its physical preservation [60].

Since 2001/03, a new era in polychrome physical reconstructions has been ushered in by the team of Vincenz Brinkmann and Ulrike Koch-Brinkmann, who brought to life the "Bunte Götter" or "Gods in Color" project [61]. This travelling exhibition has since expanded, featuring numerous polychrome reconstructions. In the "Gods in Color - Golden Edition" exhibition, showcasing over 100 painted sculptures at Frankfurt's Liebieghaus Museum [62], visitors can witness the transformation of ancient statues into polychromatic forms and experience the original, vivid hues that were eye-opening in their time. Among these exhibits, there are also several reconstructions of polychrome bronze sculptures [62-66]. These generally constitute polychrome physical replicas that embrace the diversity of materials at a 1:1 scale. They utilize copies created through rapid prototyping or 3D printing from 3D models with extreme geometrical accuracy (see Section 2.2.2.1). We conclude by considering that this activity represents a reference point for numerous temporary exhibitions currently animating museums and utilizing the web as a means of communication to reach a wider audience. Among these, we can mention the “Farben Sehen” exhibition at the Antikensammlung FAU Erlangen-Nürnberg, Germany (March 13–17, 2024) [67]. Here, for example, traditional plaster casts recoloured in the 1800s and 1900s are displayed alongside modern polychrome reproductions of copies from the antiquities collection (Fig. 1b-c). Additionally, “The Role of a Replica - The Parthenon” is an interactive exhibition that explores how historical and artistic replicas are currently used to communicate the latest archaeological discoveries and interpretations. The exhibition will be held from July 14, 2023, to December 31, 2025, in Nashville, Tennessee [68].

2.2. Digital approaches for archiving, analysing, and reconstructing ancient polychromy

Hereafter is a systematic review of experiments involving digital technologies for documenting and re-presenting ancient chromatic traces on Greek and Roman marble architectures and artefacts. Grounded in the analysis of existing literature, this investigation has been categorized into four distinct logical subgroups, encompassing archiving (see Section 2.2.1), 2D and 3D reconstructions (see Sections 2.2.2-2.2.3), and Artificial Intelligence technologies (see Section 2.2.4). Within each subgroup, the experiences are presented chronologically and organized by the topics they address, aiming to provide an exhaustive overview of current progress.

2.2.1. From databases for ancient colour documentation to shared data platforms

The analysis of the existing literature shows that the initial application of digital technologies to ancient polychromy focused on creating tools to catalogue and document colour information accurately. In the early 1990s, Valentina Manzelli [69] developed the “DAIDALOS” database at the Documentation Centre of the Institute for Cultural Heritage of Bologna as part of doctoral research on “Polychromy in Archaic Greek Statuary”. This database addressed various percentage-based inquiries related to the identification of colours in archaic Greek sculpture [69]. The system was implemented using an information retrieval product (SF-SuperFind), which utilized query languages based on text commands. The standardized form was designed to inventory polychrome sculptures, serving as a tool to streamline the storage and research of individual archaeological findings. Additionally, it enabled statistical analysis of the selected colours’ significance, based on their frequency of occurrence. This analysis helped reconstruct the positions and, consequently, the intentions behind the colours displayed in subsequent diagrams [69].

Starting from the 2000s, in addition to this primary cataloguing requirement, the need arose to conduct cross-searches and integrate data of different natures. This was especially true for observing the material structure and colour of the repertoire, extending to investigations encompassing archival and bibliographic sources related to archaeological findings. All of this introduces the possibility of accurately mapping information onto a faithful representation of the archaeological discovery. Between 2009 and 2012, Eliana Siotto [70] undertook an experimental project to modify and adapt the Italian ministerial software S.I.Ca.R. web-based [71] for documenting polychrome artworks (Fig. 2b). This endeavour was part of a doctoral research program focused on “New Technologies for the Study of Polychromy on Roman Sarcophagi: Proposals for Methodological Standardization”. The project was made possible through collaboration between the University of Pisa, the BAP-PSAE Soprintendenza for the provinces of Pisa and Livorno, the Vatican Museums, and the CNR-ISTI. The modified system [72], developed in a Unix/Windows environment using the PHP scripting language (Hypertext Processor) and featuring an open-source license on the MySQL database, can be accessed using either a personal or generic password [73]. However, the polychrome documentation of the so-called “Lateran Sarcophagus no. 150” (Vatican Museums inv. no. 31485), which serves as the cornerstone of this experimental initiative, is not openly accessible due to copyright restrictions.

The “Tracking Colour” website curated by Jan Stubbe Østergaard and collaborators was launched in April 2012 with the purpose of documenting and sharing data about polychromy. It presents colour information from Greek and Roman sculptures analysed at the Ny Carlsberg Glyptotek in Copenhagen through a dedicated database [74] (Fig. 2a), which emerged as a result of the Ny Carlsberg Glyptotek project spanning 2008 to 2013 [75]. This database is freely accessible and available for consultation by both experts and the general public. Additionally, in Paola Andreuccetti’s and Silvia Pedone’s planning process, the “Mediterranean Polychromies in Medieval Art” database aims to follow a similar path. This project aims to establish an online database on colour, its diverse applications, and artistic functions. It will achieve this by comparing data concerning polychrome sculptures from the Middle Ages in both Eastern and Western regions [76].

In Serena Raffiotta’s work in 2014 [77], as part of the “Morgantina color” project led by the Regional Archaeological Museum of Aidone in Enna, the aspiration was expressed to create a database focused on pictorial drawings and the characteristics of pigments. The aim was to comprehend the evolution of techniques, serving experts and being accessible to the wider public. A similar direction is taken by “The Colourant Mapping” project by Ariadne Kostomitsopoulou Marketou and Alexandra Rodler [78]. This interactive web application strives to establish an open-access database containing information about ancient pigments, dyes, and other painting materials (referred to as “colourants”). This resource allows researchers and the general public to highlight patterns of exchange and regional variations. Notably, the project relies on contributions from its users, who can submit new entries through a designated form. Each entry undergoes review by the project team to prevent duplicates and ensure the academic integrity of the database [78,79].

A 3D digital archive [80] represents one of the objectives of the three-year “MANN in colors” project (2018–2021), alongside a more traditional web database with diversified access and data designed for experts or the general public. This project is dedicated to investigating the polychromy of approximately twenty selected artworks from the Farnese Collection, including well-known pieces from the Baths of Caracalla, housed at the National Archaeological Museum of Naples [81,82]. Photorealistic 3D models were generated by the Flyover Zone company for public access and are available on the Sketchfab platform (Fig. 1c) [113]. Notably, certain prominent artifacts from the Farnese Collection, originating from the excavations at the Baths of Caracalla, offer renditions featuring reconstructions of their original colours [80]. Subsequently, these polychrome 3D models will find a new home in the Baths of Caracalla, as part of the “Rome Reborn® VR” project [83] (see Section 2.3.1 for more details).

Flyover Zone, under the guidance of Bernard Frischer, collaborates with esteemed museums worldwide to assemble an expansive digital repository of photorealistic 3D models of Greek and Roman artworks. A substantial portion of these models incorporates polychrome digital reconstructions, targeted for the broader public audience. The “Virtual Museum: Explore Our Collections” initiative currently boasts nearly 1000 3D models crafted by Flyover Zone. These models can be directly accessed on Sketchfab or through a streamlined interface on the website and mobile app, which repli-

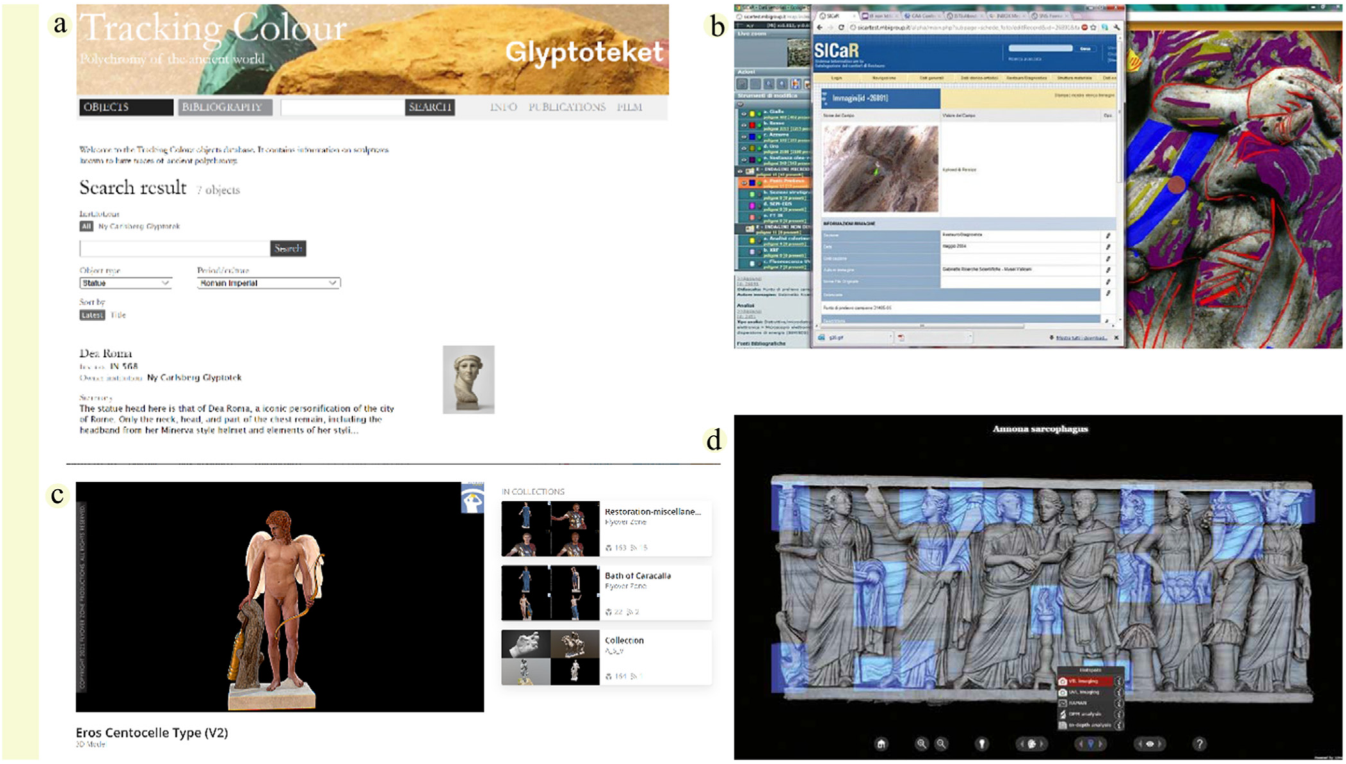

Fig. 2. Instances of databases devised to document and present ancient polychromy: (a) Showcases the Tracking Colour database at Glyptoteket in Copenhagen. b) Highlights the S.I.Ca.R. Italian Ministerial web-based system by MIBAC and CNR-ISTI. (c) Presents a collection of 3D models accessible on Sketchfab, provided by Flyover Zone. (d) Depicts a 3D database web-based system developed by CNR-ISTI. The provided snapshots are captured from their respective online platforms [73,74,85,128].

cates the floor plan of Karl Friedrich Schinkel's Altes Museum in Berlin [84]. Several polychrome reconstructions have been applied to digital replicas obtained from copies, such as the Eros of Centocelle (Fig. 2c) [85]. The fact that these 3D polychrome models are available for purchase underscores the growing interest that ancient polychromy has generated in recent years.

2.2.2. 3D scanning

The increased use of scanning systems, initially involving lasers and later also structured light, to acquire and process three-dimensional geometric models with a high degree of accuracy in both shape and colour, has been underway since the early 2000s, gaining significant traction from 2010 onwards. In the beginning, 3D digital models were primarily employed for creating physical polychrome reproductions (see Section 2.2.2.1). After a few years, these models started forming the foundation for experiments in digitally reconstructing ancient polychromy, eventually evolving into a critical component for comprehending the original colours and their subsequent visual representation (see Section 2.2.2.2). 3D models, generated through scanning and/or photogrammetric technologies (sometimes utilizing drones), serve as the cornerstone for virtual reconstructions of historical buildings and cities. These reconstructions are enriched by incorporating their polychrome decorative elements, achieved through the use of 3D modelling software. The visualization of these virtual reconstructions is often enhanced through the utilization of Virtual Reality and Augmented Reality technologies and tools, enabling users to interact with and immerse themselves in the historical and archaeological content presented by teams of experts (see Section 2.2.4).

2.2.2.1. Physical polychrome models. The initiative involving the creation of life-size 1:1 polychrome replicas of Greek and Roman originals, first showcased in the "Bunte Götter. Die Farbigkeit antiker Skulptur" exhibition held in Munich in 2003, can be regarded as a trailblazer in the application of high-definition 3D digital models [86]. This exhibition emerged through collaboration between the Glyptotek of Munich, the Ny Carlsberg Glyptotek of Copenhagen [87], and the Vatican Museums [88]. For the first time in our century, it presented to the general public the polychrome reconstructions of sculptures predominantly housed in the Glyptotek in Munich, as well as the Caligula head from the Ny Carlsberg Glyptotek in Copenhagen [89-91], and the Augustus of Prima Porta from the Vatican Museums, which was realised with the traditional plaster-cast [92-94]. The exhibition, which travels to different locations, has evolved over various editions to incorporate the outcomes of the "Liebieghaus Polychromy Research Project" [95]. The "Gods in Color – Golden Edition" exhibition, concluded in September 2021, showcased more than 100 painted sculptures at the Liebieghaus Museum in Frankfurt [61]. These copies were predominantly reproduced through artificial marble, a combination of marble dust bound in synthetic resins, or marble through rapid prototyping techniques utilizing 3D geometric models (acquired via laser scanning or structured light systems). Additionally, stucco marble on polymethyl methacrylate was used (Fig. 3). In the latter case, the physical replica is generated through 3D printing based on the corresponding 3D model [96,62]. Regarding the accurate reconstruction of colours on the physical objects, the studio relies on meticulous analytical investigations. Aligned with scientific findings, their polychromy employs natural pictorial materials that closely match the colours used in antiquity [96,62]. Different colour simulations are carried out digitally [48] or directly on plaster reproductions [91]. For reconstructions of ancient bronze sculptures, a recasting process in bronze is followed. To achieve this, the original sculptures are scanned and then produced in sections using 3D printing. These sections, coated with paraffin, subsequently serve as models for the bronze casting process. In the context of

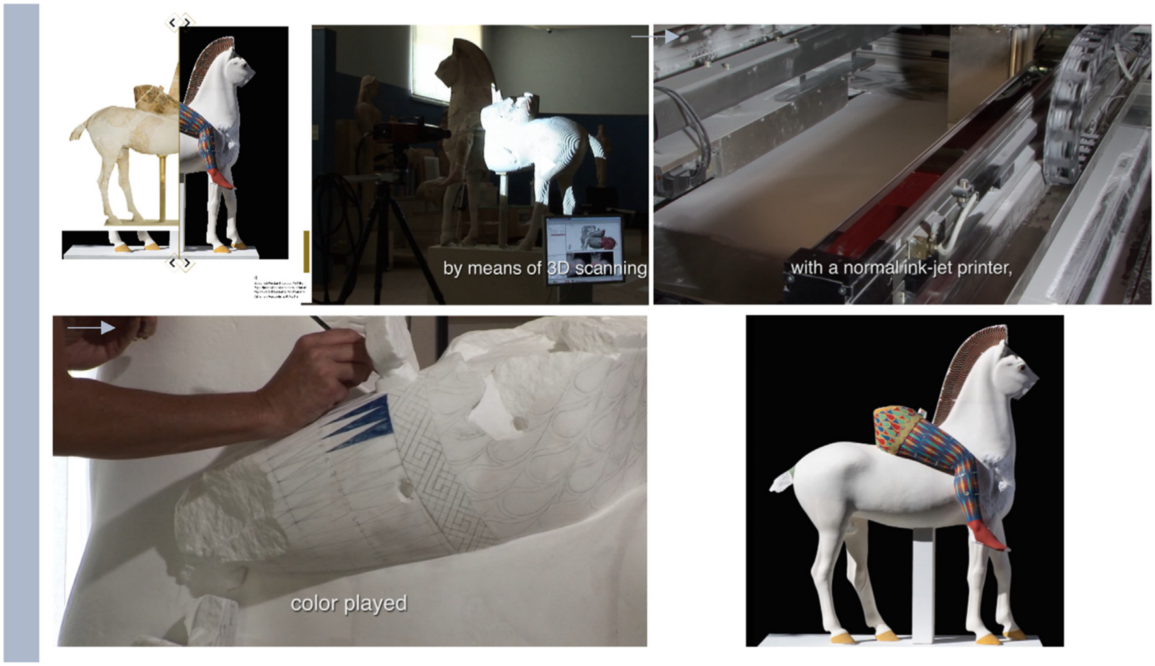

Fig. 3. The process for creating physical polychrome replicas of Greek and Roman sculptures at a 1:1 scale begins with 3D scanning of digital models through, followed by digital fabrication and manual painting. The images have been sourced from the Liebieghaus Polychromy Research Project website [61].

bronze recasting, elements such as liver of sulphur are utilized for artificial patination, alongside bitumen lacquer (a mixture of asphalt, linseed oil, and turpentine oil), pigments, precious stones, and metals [cited from [62]].

In addition to the reconstructions of the "Gods in Color" travelling exhibition project, reproductions of case studies selected from individual university projects or polychrome physical reconstructions permanently exhibited in museums are becoming increasingly common. In both cases, the copies were created using 3D technologies. As an example, we can consider the "Archaic Colors" exhibition program, which began in 2012 and is still ongoing. This program focuses on identifying and reconstructing the colours preserved on the archaic sculptures of Greece displayed at the Acropolis Museum in Athens [97]. For a detailed list, refer to Østergaard 2019 [98], which presents a museographic analysis of communicating sculptural polychromy to the public through permanent gallery installations. Regarding the current instance of polychrome marble copies (produced by Greek artists in scientific studies) of the Parthenon friezes, currently under construction on behalf of the Institute of Digital Archaeology (London) with the support of TorArt, refer to Lidz 2022 [99].

In recent years, there have been instances of creating polychrome physical prints using high-resolution 3D models with gypsum powder 3D printing technology. Examples include the physical reproductions of the Warriors of Mont'e Prama at a 1:10 scale [100], and the replication of a warrior's small polychrome terracotta head at a 1:1 scale, prominently displayed for didactic purposes at the Archaeological Museum in Albano Laziale, Rome [101]. However, the use of polychrome 3D printing still presents several limitations in terms of printing techniques as well as the physical and mechanical properties of coloured gypsum powder. Consequently, despite the contributions from Computer Graphics and the advancement of increasingly sophisticated machinery, the practice of 3D printing polychrome replicas remains limited and relatively costly.

2.2.2.2. Digital polychrome models. 3D technologies are now serving as the foundation for digital reconstructions that accurately capture the apparent colours of cultural heritage, a trend that originated from the activities at the University of Southern California [102]. These activities laid the groundwork for realistic lighting in Virtual Archaeology. "The Parthenon" computer animation [103] provides a comprehensive 3D model of the Parthenon, including its ornamental elements, such as friezes, metopes, and pedimental sculptures, dispersed across various museums worldwide [104]. This animation authentically reproduces the current colour of the building by applying a mathematical function to each point on the surface of the 3D model, thus simulating surface reflectance [105]. The objective is to develop algorithms capable of emulating essential reflectance effects that define the human perception of material, hinging on both lighting direction and observer position [106]. The most effective techniques involve a combination of 3D scanning and photography under varied lighting conditions to capture models encompassing the object's form and reflectance characteristics [107]. Subsequently, a project at the British Museum virtually re-proposed the missing parts and original polychromy of the frieze, metopes, and pedimental sculptures from the ancient temple using 3D Computer Graphics techniques. This virtual restoration was achieved by reassembling fragments obtained through laser scanning and reconstructing missing components and polychromy using 3D modelling software (Fig. 4a). The funding for this project was provided by L.A. Fleischman [108]. In this case, the aim is to offer the public an alternative means to gain a deeper understanding of the significance of the decorative elements in antiquity and how they would have appeared prior to their disassembly.

The experimentation continued between 2006 and 2007 with the virtual re-proposal of the polychromy (colour and gilding) of five Hellenistic sculptures from Delos, undertaken by CNR-ISTI of Pisa as a part of the "ArcheoMed European" project [109]. The 3D digital models were created through laser scanning triangulation acquisitions (Minolta Vivid VI-910), while the colouring process utilized 3D modelling software (3ds Max and subsequently Cinema 4D by Maxon). The colours were determined by referencing the original pigments found in an excavation in Delos. The virtual recolouring of the sculptures was conducted in two distinct meth-

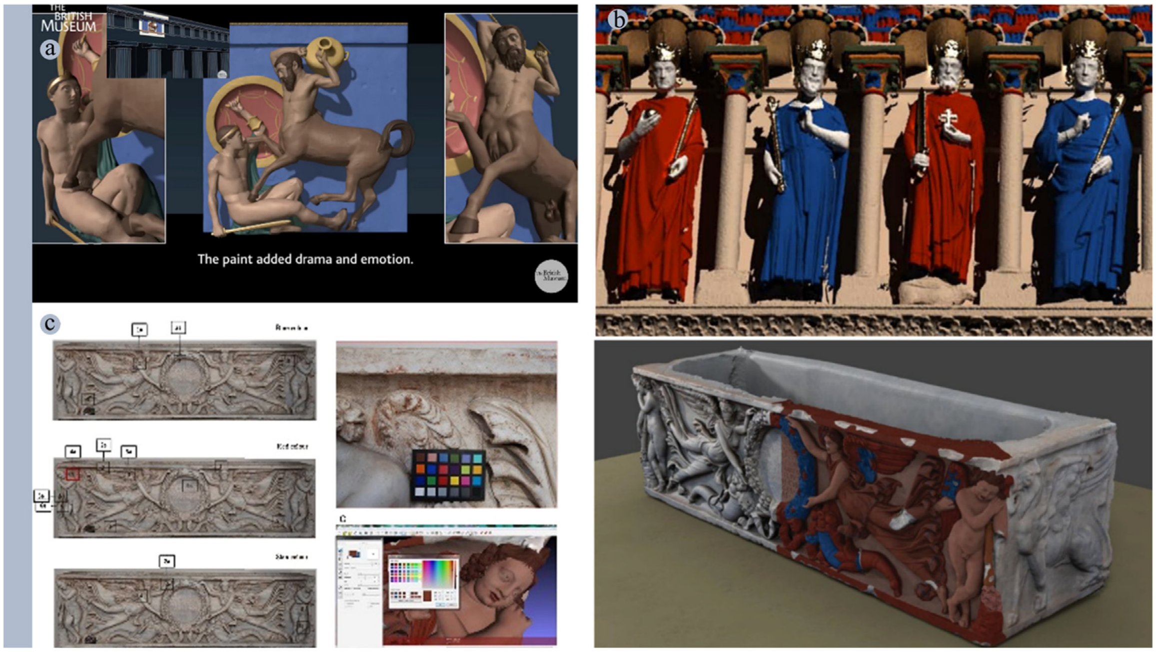

Fig. 4. Illustrative instances of 3D digital models employed for the documentation, examination, and visualization of ancient polychromy. (a) The Parthenon polychrome restauration project, British Museum, London. Snapshots are derived from a YouTube video [108]. (b) The polychromy of Notre-Dame de Paris Cathedral: simulation achieved through Virtuelium employing the photon-mapping algorithm. Image sourced from [120]. (c) Polychromy in Roman sarcophagi: 3D reconstruction workflow validating via open-source software. Images referenced from [127,133].

ods, based on the materials discovered on the sculptures through scientific analysis [110]. A rendering "material", which represents the interaction between light and the surface through a mathematical model, was applied to simulate the gilding effect on the Apollo. Simultaneously, a "texture", an image mapped onto the three-dimensional surface, was generated to replicate the painting of Artemis, Aphrodite, and Artemisia. The details of the garments on these three sculptures, identified with UV fluorescence, were meticulously painted manually using a dedicated interface (paint-to-texture) and the reference colours. This approach aimed to present the sculptures' final appearance as per the project's objective rather than an exact representation of the various layers of preparation and painting. Ultimately, the polychromy was refined within Cinema 4D, and Artemis's sculptural group was situated within its original architectural context, which was modelled using the same software. During the reconstruction of the building, due to the multiple uncertainties, several documented choices were made, and configurable lighting elements were positioned (colour, intensity, lighting mode, etc.), significantly influencing the final rendering. Thus, by simulating sunlight within this vestibule at different times of the day, the authors were able to observe that the sculptural group was in the shadow cast of the side walls during the morning and afternoon while it shone at the zenith of Delian [109].

Between 2009 and 2011, the "Digital Sculpture" project [111], spearheaded by Bernard Frischer from the University of Virginia, aimed to create digital polychrome 3D models of selected sculptures while also developing a WebGL browser. This browser enabled real-time manipulation and viewing of the 3D models. Beyond basic visualization, the browser incorporated a painting tool that empowered end users to swiftly replicate their reconstructive hypotheses [112]. An inspection of the project's website reveals the what one might call an "early version" of Sketchfab, designed for low-resolution geometric model visualization [113]. In terms of original colouration, the "Tool" section of the website [111] allowed free access to a simplified MeshLab paint tool, developed by CNR-ISTI of Pisa, which enabled vertex-based painting akin to the paint tool available in MeshLab [114]. A video showcasing the polychrome reproduction of the Augustus of Prima Porta of the Vatican Museums and comprehensive interdisciplinary and technical studies of the Richmond Caligula polychrome reconstructions can be found [115]. The project's overarching objective is to provide informative insights focussed on scientific outputs. It aims to re-propose the ultimate appearance of Roman sculptures (e.g. the toga for Caligula exists in three variations). Consequently, no colour estimation techniques have been adopted for colour rendering through 3D modelling software.

An isolated experiment employing 3D technology as the primary tool for documenting, reconstructing, and visualizing analytical information pertaining to polychromy was conducted by Chelsea Alene Graham as part of a master's thesis at Lund University in collaboration with the Glyptothek Copenhagen in 2012 [116]. The apparent colour 3D model of the Portrait of a Roman Boy (NGC IN 821) was created using MeshLab [114]. It was employed to map and present analyses with photographic techniques (such as VIL, UVL, etc.) and precisely incorporate analytical information pertaining to the scientifically analysed polychromy. Projecting this information onto a 3D model equips scholars with a tool more closely aligned with reality than two-dimensional photography. Nonetheless, the specialized tool used, designed for processing and visualizing 3D geometric data [114], is unsuitable for the general public. The polychrome digital reconstruction was created in Blender, drawing from general advice provided by experts in ancient polychromy and taking inspiration from the analysis of other sculptures [116].

A study rendering the visual appearance of polychrome and gilded medieval sculpture was presented by Dumazet, Callet, and their collaborators [117,118] at Ecole Centrale Paris in 2008. The employed methodology is denoted as Optical Constant for Rendering Evaluation (OCRE). This approach leveraged the open-source multispectral physically-based ray-tracer software named Virtuelium, developed at Ecole Centrale Paris, to accurately depict the visual qualities of the material. Furthermore, it enabled the execution of multi-scaled simulations of light interactions (Fig. 4b).

The most recent update for Virtuelium was issued in 2013 [119]. Notably, this software was also harnessed for simulating global illumination in spectral rendering, employing the photon mapping algorithm. Moreover, it facilitated the presentation of a novel interpretation of the polychrome effects evident in the Galerie des Rois at Notre Dame de Paris, encompassing even the light-guide effect stemming from the gilding [120].

Beale and Earl 2011 [121] affiliated with the University of Southampton, introduced an innovative methodology for the physical acquisition and visualization of the polychromy preserved by a marble female head discovered in Herculaneum in 2006 [122]. The fundamental concept involves employing the translucent material modelling techniques, available within prominent 3D rendering software, to replicate the existing head's coloration by simulating the interplay between the marble and distinct layers of paint. Beyond achieving a physically accurate visualization, the proposed methodology aspires to align with criteria encompassing flexibility, efficiency, and sustainability, making it adaptable to varying archaeological contexts. This approach comprises two primary stages: (1) capturing the geometry via high-resolution laser scanning systems, ensuring a profound degree of precision in the ultimate visualization; (2) acquiring the apparent coloration through calibrated photographic images to ensure accurate identification and measurement of polychrome evidence. The modelling of materials in 3D rendering process (executed using software such as 3ds Max) unfolded in two phases. The initial phase encompassed the identification of the red pigment present in the hair, achieved through visual examination and a comparative analysis drawing from preceding investigations of Roman sculptures. The subsequent phase entailed estimating and measuring the marble's light absorption and reflection characteristics, along with colour rendering on a physical replica, accomplished through Reflectance Transformation Imaging [123,124]. The photographic dataset derived from this process was then employed to apply colour to pertinent areas on the geometry's surface, delineated through multi-layer distribution maps. Particularly notable, the stratification of paint layers atop the marble's surface was attained by manually specification of light penetration attributes for each individual colour layer [121].

Mulliez et al. 2013 [125] present a 3D colour virtual reconstruction of the "Massalian Treasury in Delphi". The project's workflow commences with the acquisition of the architectural existent portions utilizing laser and photogrammetric techniques. Conversely, fragments or elements that are not extant are reconstructed and assembled through 3D modelling. The process of applying colour is grounded in a comprehensive study of pigments that craftsmen may have employed during the conclusion of the Archaic period. In their endeavour to achieve the chromatic nuances and the gilded effects of the marble in the digital reconstruction of the Treasury, the researchers devised an array of unmixed and mixed colours. This palette enabled them to explore the utilization of pigments that could not be combined and to formulate an understanding of the range of colours attainable by artists of the era. Subsequently, these determined colours and gold were applied to a sculptural fragment fabricated via rapid prototyping technologies. This fragment was then utilized for the virtual polychrome reconstruction through 3D modelling software, replicating the envisaged visual rendition.

An additional advancement was achieved through Siotto's 2013 experiments [70] conducted at the CNR-ISTI in Pisa as part of a comprehensive investigation into the polychromy preserved by Roman sarcophagi crafted in Rome between the 2nd and 4th centuries A.D. [126]. Siotto et al. 2015 [127,128] effectively demonstrate the novel utilization of 3D Computer Graphics techniques as a connecting bridge between archaeological data and scientific analysis outcomes, a breakthrough achievement. This approach not only reaffirms the indispensable requirement for a multidisciplinary framework in the examination and digital reconstruction of the original polychromy but also showcases the valuable contribution of 3D Computer Graphics techniques in the documentation, study, visualization, and dissemination of findings [129]. In the subsequent endeavour, detailed by Siotto et al. 2018 [130], the authors systematically attempted to forge a direct workflow to address the complexities inherent in polychrome reconstructions. This method, combining information technologies with the traditional investigative process – grounded in archaeological comparison and meticulous interpretation of precise cross-analytical data [131,132], culminates in the establishment of a joint working platform, facilitating enhanced comprehension of the examined polychrome artefacts while concurrently enables the widespread dissemination of results.
High-resolution 3D models of the case studies were acquired through laser scanner technology [127] and imaging techniques [128] to assess the merits and drawbacks of these distinct methodologies. The software tools employed for the processing of 3D data (MeshLab), colouring (MeshLab paint), and the creation of layered visualizations (Blender) are all open-source applications [133]. Agisoft Photoscan was utilized to generate spatial 3D data by means of photogrammetric processing of digital images [128]. The RGB coordinates of the selected colour traces were ascertained using calibrated high-resolution images captured via an optical microscope and DSLR camera. Multiple measurements of each colour were taken from various sources to ensure the most accurate representation of reality [[127], pp. 312–313 Table 1]. To achieve a more intricate visual representation of both the current state and the reconstructed ancient colours (Fig. 4c), a combination of software tools, including MeshLab and Blender, was employed. Particular emphasis was placed on rendering distinct and overlapping layers of paint [133]. The web-based system designed for the integration and visualization of ancient polychromy (Fig. 2d) constitutes a dedicated adaptation of the Heritage Online Presenter (3DHOP) software [128,130]. This platform serves as a framework tailored for creating advanced web-based visual presentations, offering a means to interact with high-resolution 3D content [134].

Presently, Siotto and collaborators at CNR-ISTI, Pisa, are working towards formulating a comprehensive work pipeline to achieve a more faithful digital reconstruction of the original colour and gilding. This endeavour is founded upon highly defined geometric models and colour data from scientific analyses, prioritising using open-source 3D modelling software. A rigorous testing phase will precede the forthcoming proposal, scrutinising various modelling and animation software options to spotlight their strengths and inherent limitations. As underscored in the recent work by McCarthy et al. 2020 [135], establishing a defined workflow within digital polychrome reconstructions is imperative to standardise the scientific processing procedures.

2.2.3. Documentation and polychrome reconstructions using 2D painting

Alongside 3D reproductions, which demand advanced graphic skills, numerous scholars in the humanities have begun integrating traditional drawings with two-dimensional (2D) graphic representations through the application of digital painting and image retouching software. Digital painting, a relatively novel yet well-established art form, generally involves the synergy of a computer, a tablet, and software options. Prominent choices include the widely-recognized Adobe Photoshop, often coupled with Adobe Lightroom, which facilitates RAW format file import, modification, and subsequent export in JPEG format. Alternatively, there are open-source software like Krita [136] or GIMP – GNU Image Manipulation Program [137].

Horn 2006 [138] elucidated the process of reconstructing original colour on certain Terracotta in the Army (Xi'an, China) through

Fig. 5. A sample illustration of 2D painting employed artistically to transform authentic images of various individuals into representations that reconstruct the polychromatic aspect of Alexander the Great. The images are derived from a YouTube video [144].

the utilization of 2D painting software. In this context, the colour value is indicated by the averaged blending value derived from several analogous colour fields [138]. Concurrently, through a similar approach, he generated on rendering a warrior in three dimensions using 3D modelling software (3ds Max and Mental Ray) after data scanner acquisition. [138]. Additional instances of polychrome re-propositions through images can be attributed to works carried out over the past decade. Examples include the efforts of Blume 2014 [139], encompassing the polychrome reconstruction of the Small Herculaneum (Athens, National Archaeological Museum, inv. 1827) and the border decoration of a deity statue named Hera (Berlin, Antikensammlung, AvP VII 23). Similarly, Skovmøller et al. [140] proposed two variations of the statue of Gaius Fundilius Doctus (Ny Carlsberg Glyptotek, Inv. 707). Pereira-Pardo et al. [141] managed to reproduce the original appearance of Medieval alabaster sculptures. More recently, Aggelakopoulous and Bakolas [142] marginally employed 2D techniques to depict their study on the polychromy of the Parthenon's metopes and triglyphs. In each of these instances, the assessment of colour remnants is conducted on calibrated digital photographs (utilizing X-Rite ColorChecker Passport) through the "pipette" function of image processing software (such as Adobe Photoshop). The average RGB value is typically generated by "blending" several comparable colour fields. In another way Verri, Opper, Lazzarini [143], showcase a distinct approach. Their 2D chromatic reconstruction of the Treu Head (British Museum sculpture 1597: GR. 1884,0617.1) was elaborated stretching and deforming images of sculptures and portraits from the same period, which preserved pictorial layers akin to those observed on the Treu Head. These manipulations were executed using Adobe Photoshop again. The diverse sequences of pictorial execution, ranging from the background depiction of the eyes to the sophisticated polychromy of the features of the face and skin, are methodically structured as layers. When employed in animation, these layers facilitate the stepwise visualization of the ultimate appearance the artwork could have attained [143].

Numerous artists and designers widely employ this technique in software like Photoshop to contemporize ancient portraits and statues (Fig. 5). A plethora of videos accessible on platforms such as YouTube exhibit the artistic recreation of the countenances of eminent emperors and historical figures. Notable examples include the visage of Alexander the Great [144], Julius Caesar [145], Augustus [146], and even the evolution of appearance from youth to age in the case of Marcus Aurelius [147]. These polychrome reconstructions assume an artistic essence, often accompanied by the intent of serving as Photoshop tutorials, or for educational objectives, and even for-profit intentions [148].

2.2.4. Artificial intelligence for automatic polychrome reconstructions

Artificial intelligence (AI) methodologies, such as deep learning (DL) – a subset of machine learning (ML) that constructs learning models on multiple levels – have been employed in several projects to identify and recreate the authentic appearances of ancient Roman emperors. These projects have recently utilized existing "pre-trained" Deep Convolutional Neural Networks (DCNNs) and employed transfer learning techniques, using photographs of imperial portraits to adapt them for imperial portrait recognition [149]. However, an essential challenge lies in colour attribution (i.e., generating automatic colouring), a matter of significance [150,151], and there is currently no scientific literature that examines its application to ancient polychrome reconstructions.

The pursuit of automatically recognizing the busts of Roman emperors and applying automatic colouring within the "Romans in color – 3D history" project by Danila Loginov and Sergey Bardyshev likely aligns with this direction. Commencing in 2019, the project aims to produce polychrome portraits of significant figures from antiquity based on modern scientific research and ancient sources (Fig. 6a). Notably, qualified post-production work in software like Photoshop plays a substantial role [152].

A digital artistic interpretation of Roman emperors, not grounded in polychrome studies, was produced in 2020 (Fig. 6b).

Fig. 6. An illustration of AI, Photoshop, and historical references utilized for recreating the polychrome appearance of Roman Emperors. (a) Vibia Sabina and Emperor Hadrian from the Antonine's in colors video, part of the Romans in color – 3D History project [152]. (b) Project involving artistic rendering of Roman Emperors by Voshart [153].

The digital artist Daniel Voshart employed an ML tool called Artbreeder, in conjunction with Photoshop and historical references, to create a series of photorealistic portraits of fifty-four Roman emperors ranging from Augustus to Carinus [153]. Although Voshart's Roman emperors do not constitute deepfakes, they share a comparable technological framework – divergent applications of machine learning. Specifically, Artbreeder harnesses Nvidia's StyleGAN, an open-source generative adversarial network (GAN) developed by computer scientists in 2018 [154]. GANs empower algorithms to progress beyond data classification into the realm of image generation. This transpires through the interaction of two GANs striving to deceive each other by deeming an image as "authentic". In the context of Artbreeder, the algorithms scrutinized 800 bust images (many originated in Photoshop by the artist, drawing inspiration from coin portraits and historical sources). This scrutiny aimed to model more lifelike facial contours, features, hair, skin, and vivid colours. Nonetheless, the outcome occasionally incorporates anomalies and tends to standardize features into an average countenance, which counters the objective of preserving an engaging expression. Consequently, Voshart's workflow encompassed iterative Artbreeder downloads, result enhancement in Photoshop, recurrent Artbreeder reiterations using the modified image, and meticulous effects refinement in Photoshop [155].

While browsing the web, one may encounter similar artistic creations, specifically those replicating lifelike portraits of renowned individuals using tools like Artbreeder and Photoshop. These creations are predominantly showcased in the blogs of artists and enthusiasts, including the works of Alessandro Tomasi [156], Becca Saladin [157], and numerous others, whom we collectively cite here for completeness and consider a distinct group (Project No. 64 in Table 1).

2.3. Digital technologies for interacting, visualizing and presenting ancient colour

In contemporary archaeology and cultural heritage, achieving accurate visualization and effective presentation of ancient architecture and artefacts' colours has become a necessity. This section scrutinizes the progressive trajectory of digital technologies in rendering lifelike ancient colours, catering to both expert and general audiences. The ensuing discourse underscores the continuum of advancements, beginning with rudimentary 3D reconstructions characterized by simplified models showcased through videos and culminating in intricate, high-definition polychrome models (see Section 2.3.1), facilitating interactive and immersive experiences via the seamless integration of Virtual and Augmented Reality (VR/AR) technologies (see Section 2.3.2). Moreover, the discourse extends to encompass innovative paradigms, such as Spatial Augmented Reality (SAP), which finds its abode within the broader spectrum of Mixed Reality (MR) applications (see Section 2.3.3).

2.3.1. 3D reconstructions for visualization and interaction with ancient polychromy: web-based platforms versus stand-alone solutions (the "serious game")

Certain experiences have arisen in response to the imperative of employing digital technologies to create virtual models of historical edifices, complete with their polychrome embellishments, using 3D modelling software. The overarching objective is to disseminate knowledge based on rigorous scientific criteria to the general public, achieved through mediums such as videos, real-time navigation, and even video games. In some instances, the revived colours are deduced from available information and historical-artistic interpretations; in others, they derive from scientific evidence gleaned through the perusal of reports and scholarly papers. In both scenarios, the course of technological evolution has wielded significant influence over the quality of reconstructions and the methodologies governing their application. We now find ourselves immersed in increasingly detailed models and videos, a far cry from the rudimentary 3D models of fifteen years ago that merely hinted at the potential architectural forms. An instance of this trajectory is embodied by the "History 3D" project, which took root in 2011 under the stewardship of Danila Loginov and his collaborative team. Nestled within this initiative are the "Roma 3D" and "Romans in colours" sub-projects [158]. The central aspiration

Fig. 7. Examples of 3D digital reconstructions used in educational games and video games that pay attention to the use of ancient polychromy. The first example (a) shows screenshots of the "Peplos Kore" statue being used as an interactive 3D canvas in an online digital game available on the Acropolis Museum website [166]. The second example (b) displays images from the "Assassin's Creed: Odyssey" video game, taken from [169].

revolves around reconstructing the monuments of the Eternal City for the general populace, meticulously adhering to scientific publications on archaeological and polychrome data. This attention to detail is evident in undertakings like the reconstruction of Trajan's Column [159] or the Augustus of Prima Porta [160]. The project is hosted on a web-based platform that is freely accessible to users [158].

Stepping back in time, one of the earliest instances of virtual reconstructions involves the modelling and attribution of colours and materials to temples situated in the Temples Valley of Agrigento and Selinunte during the first decade of the current century. The Park Authority of the Valley of the Temples in Agrigento, in collaboration with the Department of History of Architecture at the University of Florence, undertook a virtual reconstruction effort, which included video depictions showcasing the temples of ancient *Akragas* with their "original" polychromatic aspect. A life-sized scaffold, positioned on-site, served as a canvas for visualizing the temple's likely appearance [161]. A subsequent 3D polychrome reconstruction video of the Temples Valley was introduced in 2015, primarily aimed at dissemination purposes [162]. Around same period, in 2002, the Soprintendenza Archaeologica della Municipalità di Roma introduced a multimedia interpretation of the Forum of Augustus. This initiative followed diagnostic investigations involving painted Lunense marble slabs and proposed an interpretation involving the restoration of the original polychromatic scheme [163]. Both projects relied on stand-alone solutions driven by technological constraints at the time. The internet infrastructure was limited, and advanced tools for creating and visualizing a batched multiresolution mesh had not yet been developed [164].

Over the past decade, the museum environment has witnessed the emergence of educational games that incorporate considerations of ancient polychromy. Notably, the "Archaic Colors" initiative, introduced in 2012 at the Acropolis Museum in Athens, is a representative example. This endeavour seamlessly integrates a dedicated segment on the polychromy of archaic sculpture within the permanent display of archaic sculptures from the Acropolis. The exhibit incorporates pigments, 1:1 physical reconstructions, and accompanying explanatory texts. One prominent reconstruction within this initiative is the "Peplos Kore", which also functions as an interactive 3D canvas in an online digital game hosted on the museum's website (Fig. 7a). Visitors were allowed to utilize brushes and colours of their preference to paint the Peplos Kore statue. Furthermore, they had the option to print and preserve their creations in multiple iterations and variations [165]. The project was hosted on a web-based platform. It is worth noting that the digital game was developed using the Adobe Flash multimedia software platform, which has since become obsolete and no longer usable. Consequently, the reference web page associated with the game has been removed from the museum site [166].

Continuing in a similar vein, ongoing research led by Delfina Sol Pandiani as part of her Ph.D. program in Computer Science and Engineering at the University of Bologna aims to develop an interactive art museum play installation that incorporates colour and features multiple ancient sculptures or replicas. The "ColorColab" application prototype seeks to provide users with the ability to choose from various polychrome visualizations of these sculptures using either an online tool. Four types of palettes are envisaged, and users will also have the capability to dynamically create their own palettes, customizing colours to match their own skin tone, attire, and surroundings. The 3D models employed in this project are generated from image data acquisition, and users can modify different textures, such as hair, nails, clothing, skin, and eyes, through a click-based interface within ColorColab. Notably, ColorColab leverages existing technologies to serve an educational purpose within museum settings, aiming to stimulate curiosity, encourage inquiry, and foster critical thinking, as clarified by the author [167]. The project is hosted on a web-based platform that will be freely accessible to users.

In a related context, "Assassin's Creed: Odyssey" endeavoured to faithfully re-create the visual ambience of ancient Greece during its golden epoch (Fig. 7b). Ubisoft's development team engaged archaeologists and historians to meticulously reconstruct the ancient world, encompassing polychrome statues, temples, and tombs, paying very careful attention to the varied materials (marble, wood, ivory, bronze, etc.) used in their construction or to replicate objects portraying daily life and weaponry [168]. Ubisoft strived for fidelity whenever feasible and pragmatic, especially in areas with well-documented site layouts, such as Delphi and the Acropolis. While trying to convey the polychromy of Ancient Greece, the team behind Assassin's Creed had to exercise artistic license. The polychromatic painting of certain structures could, at times, appear arbitrary, featuring seemingly random colour choices. For instance, the renowned pediment of the Parthenon was depicted with brown-painted marble [169].

In a broader sense, the inclusion of vividly painted elements in Assassin's Creed: Odyssey is often seen by classical scholars as a commendable initiative in constructing a credible environment for players, as evidenced by the ongoing Twitter discourse under the #ACademicOdyssey hashtag. The game draws explicit attention to the application of polychromy, informing players that «Ancient Greece was more colourful than the white marble we see today. Temples and sculptures were painted with organic, mineral, and metallic pigments». The game engine then introduces these colours, infusing urban spaces with a brilliance that encourages and rewards exploration [170]. This approach aligns with the explanation in [171], clarifying that specific sculptures remain white to meet player expectations, even though ongoing efforts aim to convey the accurate historical understanding that the Greco-Roman world was actually coloured. The project is hosted on a web-based platform accessible to users by pay.

In conclusion, the initial models for the virtual reconstruction of Greek or Roman buildings and cities, emphasizing ancient polychromy, were initially based on stand-alone solutions. However, as technology advanced, their accessibility has significantly expanded, now extending to a broader audience through web-based platforms.

2.3.2. Virtual and augmented reality for dynamic polychrome models

Several educational projects have harnessed the potential of Virtual and Augmented Reality to offer a richly interactive and immersive experience within the polychromatic landscapes of the ancient world.

The "Rome Reborn® VR" project, under development since 1997 [172], encompasses a digital reconstruction of ancient Rome within the Aurelian walls as it appeared in 320 A.D. (Fig. 8a). The present model iteration is optimized for real-time use in virtual reality, enabling viewing on laptops, PCs, smartphones, tablets, and VR goggles such as HTC Vive and Oculus [173]. The project originated from collaborative efforts led by the Institute for Advanced Technology in the Humanities at the University of Virginia, in partnership with diverse international scientific institutions, including the UCLA Cultural Virtual Reality Laboratory, the University of Caen, and the Politecnico di Milano. Accessible to the general public via Google Earth since 2008 [174], the model has gained broader accessibility. More recently, companies like Flyover Zone, HTC Vive, and VictoryXR have joined forces, heralding a new approach to VR education within schools. Starting from the close of April 2021, schools have the option to procure VR goggles (Vive Focus Plus) preloaded with thirty titles, encompassing three Flyover Zone Rome Reborn virtual tours [175].

The projects known as "The Baths through the eyes of Diocletian" (Fig. 8b) and "Caracalla IV dimension" were respectively created by the Museo Nazionale Romano in collaboration with CNR-ISTC [176], and by a consortium consisting of the Soprintendenza Speciale di Roma per l'Archeologia, le Belle Arti e il Paesaggio, Coopculture, and CNR-ISTC [177]. These initiatives offer visitors the opportunity to embark on a journey through time, utilizing cost-effective Cardboard Virtual Reality technology. Through immersive reality applications featuring 360-degree 3D reconstructions, they facilitate an immediate comprehension of the architecture of the two ancient thermal complexes. This is achieved through a seamless alignment of the physical monument and its virtual counterpart, supplemented by concise audio descriptions. The projects represent a sophisticated endeavour involving meticulous historical research and elaborate 3D reconstruction, encompassing an authentic portrayal of ancient polychromatic elements. This presentation showcases how the Romans likely perceived floors, columns, mosaics, and sculptures. Notably, the Museo Nazionale Romano has also adopted specially tailored visors designed for younger audiences [175].

Analysing a large number of recent video reconstructions of ancient monuments (e.g., Sibari, Locri, Populonia), a notable exemplar with a "smart" approach is the video showcasing ancient Syracuse [178]. This virtual reconstruction stands at the convergence of scholarly findings derived from archaeological investigations concerning the Temple of Apollo, the expansive complex in Piazza Duomo, and the Greek Theatre of Syracuse. This synthesis unfolds within the "PON Energia Smart City" project (2007–2013). Employing 3D image-based reconstruction technologies, this approach harmoniously reintegrates absent architectural and sculptural components. These elements are virtually reinstated to their original positions, thereby facilitating a dynamic interpretation that amalgamates both tangible and virtual dimensions. Additionally, the authors' contributions highlight the incorporation of Augmented Reality techniques, enabling the exploration of these monuments from unconventional vantage points. The recreation of colours appears to have been informed by comparisons with analogous contemporary structures or edifices, as detailed in scientific publications [179].

Concurrently, a virtual reconstruction project for Temple C in Selinunte was presented as part of the "Land-Lab" project, a collaboration between the University of Lecce and CNR-IBAM [180]. The visualization was facilitated through an interactive totem equipped with a periscope mechanism, enabling viewers to explore a 3D model with a natural stereoscopic effect by utilizing bodily movements and an ergonomic navigation console (Fig. 8c). The educational approach incorporated the integration of numerous audio/video in-depth cards, activated simply by approaching the designated hotspots within the 3D model [181].

More recently, Ferdiani et al. 2020 [30] presented and evaluated a comprehensive workflow designed for the creation of historically accurate 3D assets aimed at interactive and immersive virtual reality products. The workflow is substantiated by a case study centred on the Forum of Augustus, alongside diverse output applications, which underscore distinctive aspects and challenges that arise from a multi- and interdisciplinary approach. The replication of patterns and hues in specific components, such as frescoes, stuccos, marbles, and more, drew from historical-archaeological documentation and heritage [182,183].

In conclusion, museums have increasingly embraced the creation of polychrome 3D models of Greek and Roman sculptures founded on scientific assumptions. These models find application through videos that showcase the comprehensive study and elaborate reconstruction processes. A noteworthy illustration in this context is the 3D digital polychrome reconstruction of the "Athena Parthenos statue" [184] at the Museum of Fine Arts, Boston (MFA), developed by Black Math Company in 2021. Notably for the general public edutainment is also the development of an AR face filter for @mfaboston's Instagram account, enabling users to virtually wear the iconic Athena Parthenos helmet (Fig. 11a) using their mobile devices [185,186].

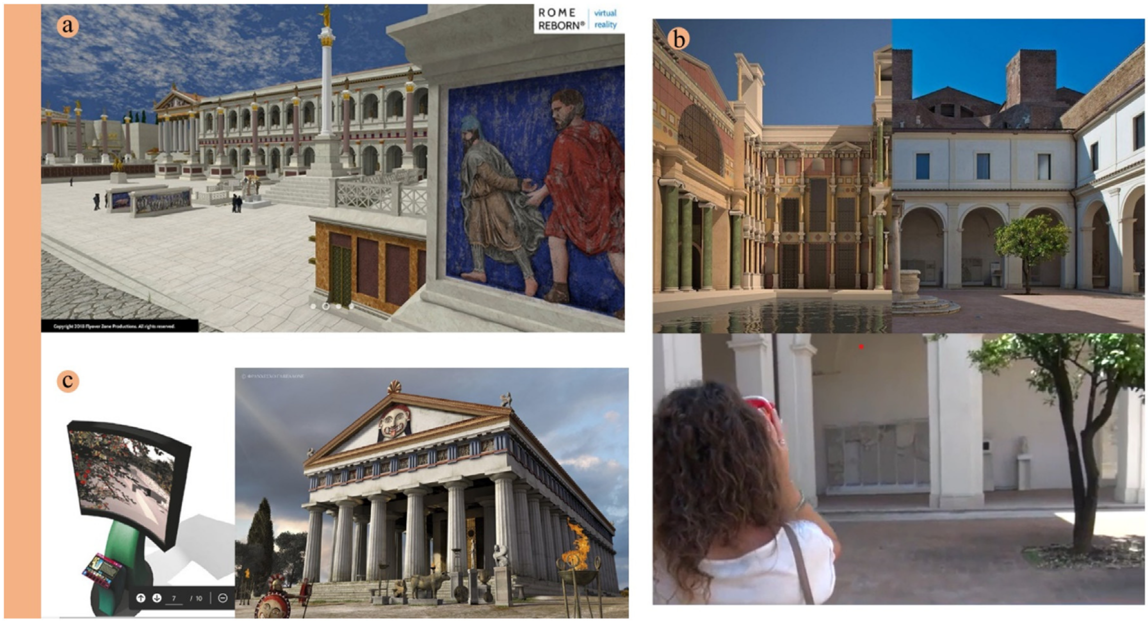

Fig. 8. The illustration showcases various 3D polychrome reconstructions of ancient architectures, along with diverse technologies employed for their interactive or immersive dissemination. (a) Offers a snapshot of the Rome Reborn® VR project – focusing on the Forum [171]. (b) Showcases The Baths through the Eyes of Diocletian project, jointly undertaken by MNR and CNR-ISTC, with images attributed to [175]. (c) Presents a 3D polychrome reconstruction of the Temple C of Selinunte, Italy, utilizing snapshots sourced from the Land-Lab project website [181].

2.3.3. Augmented reality and mixed reality for real-time virtual visualization of colour

Since the end of the last century, a specialised branch of Computer Graphics has been dedicated to developing algorithms and techniques for 3D editing and painting with haptic interfaces and Spatial Augmented Reality (SAR), more generally attributable to the Mixed Reality category. That consists of enriching human sensory perception by incorporating additional information beyond what the observer naturally perceives, mediated by a video projection system and a computer. The application of this technology [187,188] to ancient polychromy is very recent, with instances highlighted in the literature [189,190]. Concurrently, the utilisation of SAR as a basic Projection Mapping (PM) technique is relatively recent [191-197], just as the use of Augmented Reality (AR) support available through mobile devices for museum or exhibition visits has emerged [211].

2.3.3.1. Haptic interfaces. Lange et al. [189] demonstrate how users can generate digital Projection Mapping (PM) content through physical interaction with a proxy object. The proxy object, a scaled-down version of the target object (such as a 3D print of the statue of Augustus Prima Porta), is physically painted by users using actual brushes and paint. This painting process is automatically captured by a camera and translated into a texture, subsequently projected onto the target object (Fig. 9a). The authors emphasize both the advantages and limitations of this digital workflow, as it involves non-permanent painting where the actual/real colour is not applied to the proxy object. Consequently, the physical proxy object can be perceived as a complex-shaped graphics tablet. The authors summarize the outcomes of their user study, underscoring how proxy painting offers an alternative to existing 3D painting software. While the prototype currently falls short of detailed drawings, it effectively caters to domain-specific tasks like material painting. Particularly, users with limited expertise in digital painting benefit from the accessible entry point provided by proxy painting.

Palma et al. [190] introduce a system designed to enhance engagement within a Virtual Reality (VR) experience using low-cost, sensor-equipped replicas of authentic artefacts generated through economical 3D fabrication techniques, which then lead to an Augmented Reality (AR) experience. By combining hardware and software components, the proposed system empowers users to interact with a physical replica (a 3D-printed artefact serving as a tangible interface) within the virtual environment. This interaction allows users to observe the original artefact's appearance (including colour and form). The system leverages a consumer device for real-time hand tracking and a custom electronic controller for capacitive touch sensing. This combination enables the creation of augmented experiences where users can manipulate the virtual appearance of the tangible replica object using a set of personalization actions accessible through a 3D-printed palette of colours (Fig. 9b). Beyond polychromy, the system allows one to insert and see in real-time elements and materials like necklaces, earrings, crowns, precious stones, and set eyes that were part of the original artefact [190].

2.3.3.2. Projection mapping. The technique of video or projection mapping (PM) encompasses a variety of methods, classified into basic and advanced categories. These methods enable the achievement of correspondence between real objects (such as facades, bas-reliefs, and sculptures) and virtual models based on factors like object complexity and Level of Detail (LOD). The fundamental procedure entails the virtual reconstruction (within a 3D or 2D environment) of the object's surfaces onto which the video projection will be applied.

Peral et al. [191] employed PM techniques to virtually restore the appearance of the Virgin statue at Saint Mary's Cathedral in Spain. They projected a designed image onto the original sculpture, which possessed a complex 3D shape, thereby reproducing the polychrome painting from the past. Dynamic projectors were utilized to display the image of the pre-painted 3D model, acquired through scanning techniques, onto the physical item. This projection occurred in real-time, encompassing moving images with dynamic lighting effects and reflections. The authors elucidated the procedural intricacies and challenges encountered in positioning the projector within the portico. These challenges encompassed as-

Fig. 9. Instances of haptic interfaces to recreate 3D digital polychromy without direct contact with archaeological artefact. (a) Test activity images adapted from [189]. (b) Test activity images adapted from [190].

pects like the quality of projecting diverse colours and shapes onto the portico, power requirements, light reflections impacting other light sources, pixel size, etc.

Furthermore, Koroso Arriaga and Muñoz Lozano in 2009 [192] achieved a non-invasive, realistic visualization of the chromatic evolution of the Victoria-Gasteiz Cathedral's portico across different time periods. The primary goal was to define the limitations and attributes of a chromatic reintegration system employing light projection. This project commenced in 2003, with the system being fully installed by 2009. Special emphasis was placed on enabling visitors to perceive colour as pigment rather than projected light. Chromatographic data for all analysed samples were derived from laboratory results, including the acquisition of corresponding colour codes in the CMYK colour model. The reconstruction delineated the portico's evolution throughout its existence, transcending the exclusive representation of a singular historical moment.

Between 2006 and 2010, Borghini and Carlani [193] developed a multimedia museum application for touchscreen devices within Richard Meier's Ara Pacis Augustae Museum, a project commissioned by the Soprintendenza per i Beni Culturali della Municipalità di Roma [194]. This application presents a virtual reconstruction of the original colour of the Augustan monument, accessible in real-time on a 3D model (Fig. 10a). The presentation of this ancient colour re-proposition to the public occurred in late 2008, utilizing beams of light filtered through printed glass (gobos) to project the colour directly onto the monument. This event marked the first instance in Italy (and abroad) of virtually colouring a classical archaeological monument using PM [195].

The selection of projected colours was guided by comparisons with Roman paintings, late-ancient mosaics, Greek architecture and sculptures from the latter half of the 5th and 6th centuries B.C., which served as inspiration for Augustan art. This choice stems from the lack of definitive evidence to ascertain the precise original colours, even though chemical-physical analyses confirm the initial presence of paint [194]. In commemoration of the bicentenary of Augustus' death in 2014, the "The Colours of the Ara Pacis" initiative integrated both hardware and software tools, facilitating an exploratory and educational journey through the Ara Pacis via AR and VR. Special AR viewers (Samsung GearVR) and device cameras were employed to make the monument's polychromy visible [196].

Subsequent to this experience, several other applications in the realm of SAR have emerged for the 3D or 2D video projection of hypothetical original polychrome reconstructions. One such example is an interactive installation based on an off-the-shelf LeapMotion finger-tracking device from 2013 at the Allard Pierson Museum in Amsterdam, where visitors interacted with an Egyptian-era bas-relief to comprehend its original colouring [197,198]. Another instance involves the "Augmented Reality In the Museum" (ARIM) system applied to block NXLVI of the north frieze of the Parthenon, reintroducing its original colours [199]. Similarly, the "Color the Temple" project (2013–2016) at the Metropolitan Museum of Art (MAA) employed PM to reveal the Egyptian Temple of Dendur's original polychromy [200,201]. Another case is the "Mapping Sculptures in Carthago", a temporary exhibition in 2016 at the Carthage National Museum by Design Lab, which utilized video projection to display colour on sculptures (Fig. 10b) [202]. Another instance presumably from the same period or some years before is the reconstruction of the Mithra relief and projection of colour at the Carnuntum Museum near Vienna [204]. Additionally, the "Roman Britain in Colour" project, a collaboration between the Great North Museum and Hadrian's Wall Community Archaeology Project (WallCAP) along with the Novak studio, employed colour projection to bring seven altars recovered from Hadrian's Wall to life. Focussing on scientific outcomes, the animation also offers some artistic interpretations of the altars and the gods associated with them (Fig. 10c) [205]. Furthermore, in the permanent exhibition at

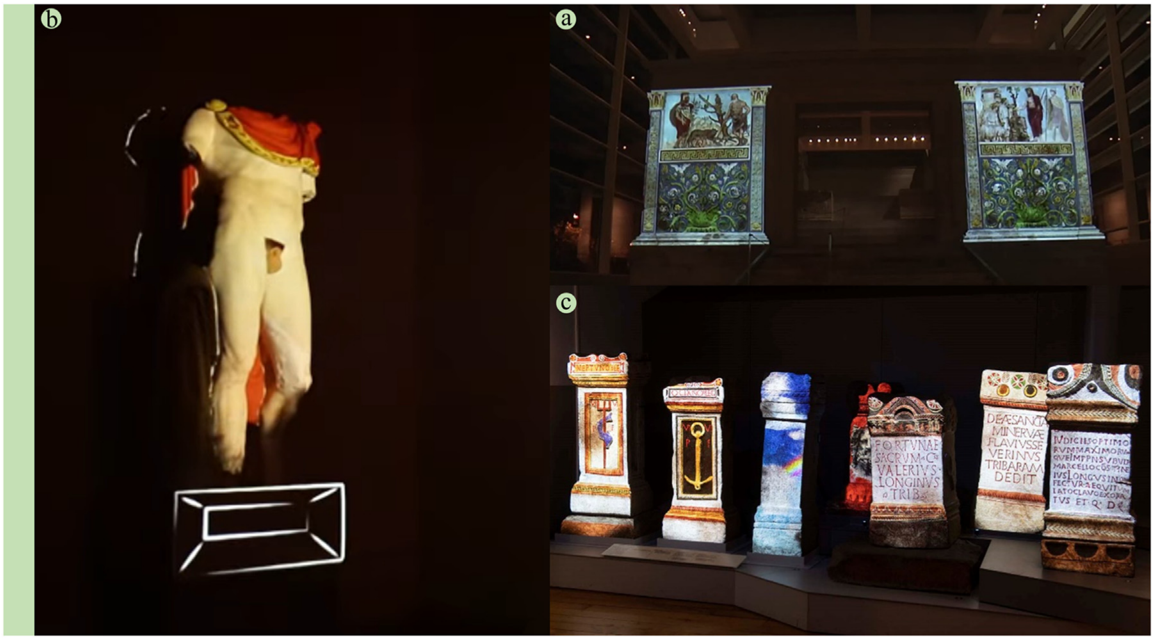

Fig. 10. Instances of PM technology to repropose ancient polychromy for widespread audiences. (a) The Ara Pacis project (2006–2010), Ara Pacis Museum, Rome; snapshot extracted from the project video [195]. (b) Mapping Sculptures in Carthago project (2016) Carthage National Museum, Byrsa; snapshot sourced from the project video [203]. (c) Roman Britain in Colour project (2022), Hadrian's Wall Museum, Newcastle; snapshot acquired from the project video [205].

the "Pergamon Museum. Das Panorama" in Berlin, ancient polychromy is reproduced on the monuments depicted in the 360-degree "Panorama" by Yadegar Asisi, and the PM technique is applied to one of the original sculptures found in Pergamum, based on studies of polychromy in Hellenistic sculptures [206]. In conclusion, all these application projects (and many others beyond the scope of this discussion, including those used to replicate mural paintings in churches and cathedrals) are founded on scientific analyses of polychrome traces. They share the common objective of fostering awareness and educating the general public.

Fig. 11. Instances of polychromy reconstruction AR accessible via mobile devices. (a) Wearable Athena Parthenos Helmet on the @mfaboston Instagram account. Part of the Athena Parthenos project at the MFA, Boston. Snapshot captured from the project website [185]. (b) Utilization of the DIGIPAST project through the Moptil App on a rentable device. Snapshot obtained from the project website [214]. (c) Chroma AR App experience at The Metropolitan Museum of Art (MET), New York City. Snapshot sourced from the project website [218].

2.3.3.3. Mobile devices. The integration of Mixed (Virtual and Augmented) Reality for exhibiting artworks or museum content constitutes a firmly established concept in the realm of Information and Communications Technology (ICT) and Human-Computer Interaction (HCI) research [207-210]. Recent developments have yielded applications aimed at reproducing ancient polychromy. In a recent case study, Khosravi et al. 2022 [211] presented an instance based on a 3D model scan of the Exeter Cathedral's west front. Through digital painting, the model appears with the colours that adorned the original structure centuries ago, serving as a case study for the "VistaAR" project. To optimize the viewing experience, the authors adopted a game-oriented approach, utilizing a low-poly model combined with high-quality textures and normal maps to ensure the resulting images maintained detail and engagement within the "VistaAR" App. The texturing and painting process involved tools like Maya, Substance Painter, Zbrush, Photoshop, and Unity – a premier platform for real-time content creation [212]. The reconstruction of polychromy was guided by prior research involving remnant colour samples sourced from the building's stonework [213].

The "DIGIPAST" project embodies a 3D virtual tour encompassing Greece's most significant archaeological sites (Acropolis, Delos, Delphi, Knossos, Asklepieion of Kos, Lindos, Olympia, Cartagena), developed by Moptil – Mobile Optical Illusions [214]. This app facilitates a 360-degree panoramic view, enabling users to experience a fully 3D reconstructed Acropolis as it existed in antiquity, complete with colours, statues, and the presence of ancient Greeks. This immersive experience leverages Augmented and Virtual Reality to deliver on-site visualizations. Audio narration accompanies the visual components (Fig. 11b). DIGIPAST is available both as a service through Moptil device rentals (iPad or VR goggles) and as an app download from platforms like the App Store or Play Store for personal devices [214]. Polychromy and 3D modelling reconstructions are aligned with archaeological and architectural scholarly resources, although artistic interpretation is evident in cases where certainty is lacking.

Illustrating the potential for app personal smartphones, the "Chroma AR" experience, analogous to the AR colouring book app, enables users to seamlessly transition between the real world, augmented reality, virtual reality, and networked virtual reality [215-217]. The Chroma AR experience enables smartphone users to virtually recreate a coloured rendition of an ancient Greek sphinx sculpture within their own environment. This facilitates a comparison between the vivid reconstruction and its present-day appearance (Fig. 11c). The app comprises both interpretive and playful elements, encompassing multidisciplinary efforts. Chroma AR was conceived for the "Chroma: Ancient Sculpture in Color" exhibition, hosted at The Metropolitan Museum of New York from July 5, 2022, to March 26, 2023 [218].

3. Discussion

This work provides an encompassing overview of digital technologies and methodologies aimed at documenting, reconstructing, visualizing, and presenting ancient polychromy to both experts and the general public. This review spans from the early 1990s to the present day and is exemplified through Table 1 and Fig. 12. Table 1 systematically catalogues the projects, arranged in chronological order, and grouped by thematic categories (e.g., database, 2D painting, physical copies), employing distinctive colours in the first column for swift visual categorization. Within the table, cells are denoted by solid or empty black squares, indicating whether the column's theme qualifies as a "primary action" (■) or a "secondary or consequent action" (□) within each project. This classification is based on the technologies and sources analysis utilized and the projects' intended objectives. Fig. 12, which our discussion references, exclusively considers resources categorized as "primary action". Thus, we analyse proportions concerning the application of various technologies in re-proposing ancient colour, the utilization of resources to reconstruct original polychrome hypotheses, the application of 3D data for both analysis and reconstruction of ancient polychromy, as well as its presentation to the public. Finally, the discussion addresses the aims and destinations of these endeavours.

Our analysis reveals an equilibrium between projects catering for experts and those tailored for the general public, with a discernible recent trend favouring the latter. The latter type is predominantly geared towards presenting polychrome data, and they are accessible to experts as well. On the whole, we can deduce that these endeavours constitute isolated experiments executed by highly qualified multidisciplinary teams. These experiments have incorporated a variety of technologies and have evolved over time. Beginning with the archival and scrutiny of data related to ancient polychromy, they have evolved into primarily scientific-based polychrome reconstructions. This evolution is grounded in outcomes from focused analyses, insights from autopsy inspections, and references from archival records, culminating in a trajectory towards more interactive and captivating modes of dissemination. The integration of digital technologies for archiving, 2D and 3D polychrome reconstruction, and visualization has been a gradual process, albeit with a measured lag compared to the advances in information technology. Notably, we discern a trend where individual experiments converge with larger projects to formulate shared guidelines and methodologies. These endeavours all-roundly address the theme of ancient polychromy, encompassing the creation of standardized language, shared alphanumeric and 3D data platforms, and the production of reconstructions faithful to the originals. This transversal approach extends to the exploration of workflows for shape and colour acquisition, digital processing, apt visualization, and the fabrication of physical reproductions through rapid prototyping and polychrome 3D printing.

In accordance with the format of Sections 2.2 and 2.3, we have structured the discussion into two parts: one focusing on the study and reconstruction problems (see Section 3.1), and another addressing the re-proposition and dissemination of ancient polychromy (see Section 3.2). The projects or experiments mentioned in this discussion are identified by the reference numbers assigned in the first column of Table 1. As previously stated, the colours in this column serve to distinguish and group the projects based on the primary digital technology used.

3.1. Digital approaches for archiving, analysing, and reconstructing ancient polychromy

In the context of ancient polychromy, as well as in archaeology and the broader field of cultural heritage, the foremost necessity, in tandem with technological advancements, was the establishment of searchable databases. The primary objectives revolved around documenting and studying occurrences from the mid-nineties of the previous century (Projects No. 1, 4 in Table 1). These databases then evolved into shared platforms containing "georeferenced" data and maps (Projects No. 2, 3, 5, 6 in Table 1), eventually expanding to encompass platforms for 3D models tailored for both the general public (Projects No. 8, 9 in Table 1) and experts (Project No. 7 in Table 1). A recurring theme emerges across scientific projects from this essential requirement: the gradual inclusion of cultural heritage professionals within genuinely multidisciplinary teams, fostering interdisciplinary interactions. The technology for integrating diverse datasets arising from scientific analyses, 3D models, intricate mappings, and the seamless exchange of even large-scale or high-resolution data over networks is now readily available. The benefits are manifold: efficient documentation,

Table 1
A summary of digital technologies and methods utilized for reconstructing and visualizing ancient polychromy targeted at experts or the general public, from the early nineties to the present day.

No	Project/ Item	Ref.	Destination		2D source		3D source		Technologies						Objective			Link
			Expert	General public	Historic	Scientific	Artistic	3D scanning	Modelling	AI	VR/AR Mix Reality	Video Games	Web	Digital fabrication	Coloured 3D printing	Archival	Study	Dissemination	
1	DAIDALOS	[69]	■			□										■	■		
2	Tracking Colour	[75]	■	□		■							■			■	■	■	
3	Mediterranean Polychr. in the Medieval Art	[76]	■	□		■							■			■	■	□	
4	Morgantina color	[77]	■			■										■	■		
5	Colourant Mapping	[79]	■	□		■							■			■		■	
6	Polychromy in SICaR w/b system	[70, 72]	■			■							■			■	■	□	
7	Polychromy in 3D web platform (3DHOP)	[129]	■	■		■		■					■			■	■	■	
8	MANN in colours	[82]	□	■	■	■	□	■	■				■			□	□	■	
9	Virtual Museum: explore our collections	[84]	□	■	■	■	□	■	■				■			□		■	
10	Terracotta Army in Xi'an	[138]	■	■		■		■	■								■	■	
11	The Small Herculaneum	[139]	■	□		■											■		
12	The statue of Gaius Fundilius Doctus	[140]	■	□		■											■		
13	The appearance of Medieval alabaster sculptures	[141]	■	□		■											■	□	
14	Parthenon's metopes and triglyphs	[142]	■	□		■											■		
15	The Treu Head: animated 2D pol. reconstruction	[143]	■	■	■	■							□				■	■	
16	Web 2D reconstruction of ancient portraits	[144-147]		■			■						■					■	
17	Gods in Color exhibition	[62]	■	■		■		■					□	■			■	■	
18	Archaic Colors	[97]	■	■		■		■					□	■			■	■	
19	Parthenon friezes	[99]		■		■		■						■			■	■	
20	Warriors of Mont'e Prama	[100]	■	■		■		■							■		■	■	
21	Warrior's little head of Albano Laziale	[101]	■	■		■		■							■		■	■	
22	The Parthenon	[102, 107]	■	■		■		■					□				■	■	
23	The Parthenon metopes reconstruction	[108]	■	■	■	■		■	■				□				■	■	
24	Hellenistic sculptures from Delos – ArcheoMed E. Project	[109]	■	■		■		■	■								■	■	
25	Digital Sculpture Project	[115]	■	■		■		■	■				■			□	■	■	
26	3D model of Roman boy portrait	[116]	■			■			■								■		
27	The Galerie des Rois in Notre Dame de Paris: polychrome effects	[117, 118]	■	□		■		■									■	□	
28	The head from Herculaneum: a methodology for a visualization	[121]	■	□		■		■	■					□			■	□	
29	The Massalian Treasury in Delphi	[125]	■	■		■		■	■					□			■	■	
30	Polychr. in Roman sarcophagi: 3D reconstruct. workflow	[127]	■	□		■		■					■				■	■	

(*continued on next page*)

Table 1 (*continued*)

31	Polychr. in Roman sarcophagi: 3D reconstruction and visualisation	[128, 130]	■	□		■		■					■			■	■	■	
32	Polychr. in Roman sarcophagi: open source sw	[133]	■	□		■		■	■								■	□	
33	The Castledermot high crosses, Ireland	[135]	■	□	■		□	■	■								■	■	
34	Polych. in Roman sarcophagi: 3D painting workflow		■			■		■	■				□	□			■	□	
35	Rome Reborn® VR	[172-175]		■	■		□		■				■					■	
36	History 3D Roma 3D	[158-160]		■	■		□		■				■					■	
37	The Baths through the eyes of Diocletian	[176]	□	■	■		□	■	■		■							■	
38	Caracalla IV dimension	[177]	□	■	■		□	■	■		■							■	
39	The Ancient Syracuse video	[179]		■	■		□	■	■		■		■					■	
40	The Temples of Agrigento video	[161]		■	■		□		■									■	
41	The Temple C of Selinunte	[180, 181]		■	■			■	■		■							■	
42	The Forum of Augustus	[30]	■	■	■	■		■	■								■	■	
43	Athena Parthenos MFA Boston	[186]	□	■		■		■	■		□						□	■	
44	Assassin's Creed: Odyssey video game	[168, 169]		■	■		□		■			■	■					■	
45	Archaic Colors: Peplos Kore educational game	[165]		■			□					■	■					■	
46	ColorColab educational game	[167]		■		□	■		□		■							■	
47	Proxy Painting	[189]	■	□			■	■			■			■				■	
48	AV using touch-sensitive 3D-printed objects	[190]	■	□			■	■			■			■				■	
49	The virtual restauration of Virgin in S. Mary's Cathedral, Spain	[191]	■	■		■		■	□		■							■	
50	Chromatic appearance of the Vitoria-Gasteiz Cathedral portico at different times	[192]	■	■		■		■	□		■							■	
51	The colours of the Ara Pacis	[193]	■	■	□	■		■	□		■							■	
52	Egyptian bas-relief Projection Mapping	[197]	■	■	□	■		■	□		■							■	
53	AR in the Museum: block NXLVI Parthenon North frieze	[199]	■	■	□	■		■	□		■			■				■	
54	Color the Temple of Dendur – MET	[200]	□	■				■	□		■							■	
55	Mapping Sculptures in Carthago	[202]	□	■	□	■		■	□		■							■	
56	Mithra relief PM in Carnuntum Museum	[204]		■	□	■		□	■		■							■	
57	Roman Britain in Colour	[205]	□	■	□	■		■	□		■							■	
58	PM on Pergamum sculpture	[206]		■	□	■		□			■							■	
59	Exeter Cathedral West front – VistaAR App	[211]	□	■	■	■		■	■		■							■	
60	DIGIPAST	[214]		■	■		□		■		■							■	
61	Chroma AR App	[218]		■		■		■	□		■							■	
62	Romans in color 3D History	[152]		■	■		□			■			■					■	
63	Roman emperor	[153]		■			■			■			□					■	
64	Web AI reconstructions of ancient portraits	[156, 157]		■	□		■			■			■					■	

Legend: ■ primary action
□ secondary or consequent action
The colours used in the first column help group projects based on the primary digital technology used:
database **2D reconstruction** **digital fabrication** **3D scanning** **3D modelling** **games**
haptic interface **video mapping** **augmented reality App** **artificial intelligence**

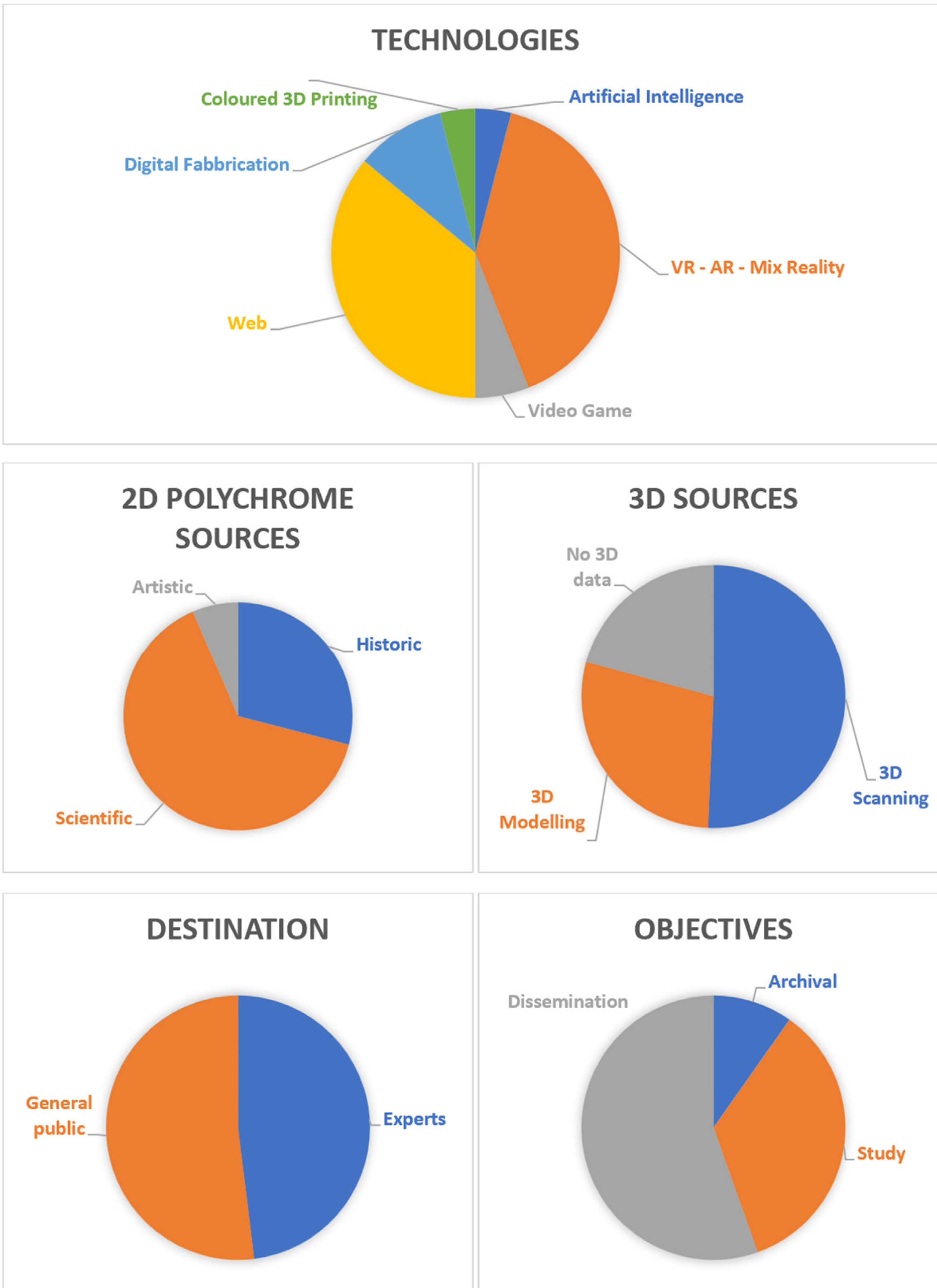

Fig. 12. The graphs depict (a) the distribution of techniques employed for the re-proposal of ancient polychromy, (b) the correlation between the sources utilized for the reconstruction of the original colour, (c) the utilization of 3D data as a foundation for both the study/reconstruction and the visualization/presentation of ancient polychromy, (d) the intended destination, and (e) the objectives of the projects.

streamlined data exchange, and the ability to concurrently collaborate across various global locations. However, challenges persist. Despite the proposal of standardized methodologies and tools for documenting and visualizing ancient polychromy, a universally accepted format or tool/device is yet to materialize, and concerns about data privacy remain unresolved.

The initial digital polychrome reconstructions utilized 2D Computer Graphics, commonly referred to as 2D painting (Projects No. 10, 11, 12, 13, 14 in Table 1). An outstanding advantage of digital painting compared to traditional drawing lies in its capacity to work across multiple layers, control colour opacity, and manage intensity and brightness. Moreover, it permits revisiting any stage of the analytical or creative process. Reproducing an artwork (i.e., the potential for infinite copies) and adjusting its dimensions, even after completion, for printing on various scales obviates the need to start anew. Additionally, the digital colour remains constant. Once the monitor is calibrated, colours retain consistency regardless of the time of day or ambient lighting. In contrast, traditional (manual) painting requires meticulous consideration of colour as a critical element for achieving success (Projects No. 17, 18 in Table 1). 2D technology affords the opportunity to convey to the general public an impression of an artwork's possible original appearance, even in animated renditions (Projects No. 15, 16 in Table 1). However, this colouring is applied to an image of the artwork, which lacks dynamism and geometry. Unlike a photorealistic geometric 3D model, it cannot equally facilitate in-depth studies of polychromy (Projects No. 26, 30, 31, 7 in Table 1). Moreover, the observations made by (Projects No. 32, 34 in Table 1) are pertinent to the colour palette utilized in 2D and 3D painting software, which currently does not encompass ancient pigments and colours.

3D technologies designed for digital acquisition, digital modelling, and additive or subtractive production – commonly referred to as "3D scanning" – are proving invaluable within the specific context of this study, facilitating the visualization of the original apparent colour of archaeological artefacts. The utilization of 3D technologies enables the creation of precise digital models of polychrome artefacts in terms of both shape and colour. These 3D geometric models, harnessed through specialized digital tools, effectively aid in the documentation and examination of ancient polychromy (Projects No. 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34 in Table 1) and contribute to its subsequent reconstruction and visualization (Projects No. 24, 25, 26, 27, 28, 29, 2, 31, 32, 33, 34, 42, 43, 47, 48 in Table 1). Furthermore, 3D technologies offer the potential to bridge the gap between archaeological knowledge and scientific analysis results, thereby assisting in the assessment of the original colour (Projects No. 30, 31, 7 in Table 1). Simultaneously, they form the foundational basis for projects aimed at the visualization and presentation of ancient polychromy (Projects No. 35, 36, 37, 38, 39, 40, 41, 42, 43, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61 in Table 1).

In the contemporary landscape, 3D scanning and photogrammetry stand as established techniques that offer a practical and relatively cost-effective means to attain highly accurate 3D digital representations. It should be noted that utilizing 3D technology for the documentation and study of ancient colour necessitates specific skills and strategies for the application of paint. Presently, the challenge of working with heavy models (such as high-resolution models) essential for accurately re-proposing ancient polychromy through UV mapping in modelling software is being gradually resolved (Project No. 34 in Table 1). Conversely, the issue of incorporating a palette of ancient colours and/or reference pigments into 3D painting software, often referred to as "materials" in 3D applications, remains unresolved. Lastly, when undertaking a 3D polychrome reconstruction, it is imperative to comprehensively elucidate the methodology employed and the decisions taken for digital re-presentation. This is vital both to grasp the scientific nature of the data and to ensure its reproducibility under consistent conditions.

The availability of a high-resolution 3D digital model of an archaeological artefact facilitates the creation of physical replicas at various scales and from a variety of materials, thanks to current 3D printing technologies. Initially, Rapid Prototyping (RP) was employed for ancient polychromy; this subtractive manufacturing technique swiftly produces physical models from a three-dimensional mathematical representation of the object, which is subsequently manually painted (Projects No. 17, 18, 19 in Table 1). In recent years, 3D printing techniques have become more affordable while also enhancing print quality. 3D printing often employs powdered materials such as gypsum and, more recently, marble stucco on polymethyl methacrylate. The results yield objects with a sandy appearance and diffuse, opaque colour on one side and a smooth, glossy, and reflective surface on the other. These physical models are later hand-painted, as observed in numerous museum collections (Projects No. 17, 18 in Table 1). Among the advantages, we note that the manufacturing process is now well-established, accompanied by clearly defined guidelines for the manual painting procedure. Unlike digital recolouring, manual colouring enables the use of pigments and binders similar to those found in ancient artefacts (Projects No. 17, 18 in Table 1). However, challenges remain regarding the application of these pigments to the physical replicas. Moreover, the process is time-consuming, lacks the ability to adjust the outcome during application, and remains costly.

Certain experiments involving the physical printing of polychrome replicas have also been conducted using digital high-resolution 3D models and gypsum powder-based 3D printing technology (Projects No. 20, 21 in Table 1). However, reproducing colour texture on 3D prints still relies on 2D printing strategies, resulting in noticeable detail blurring and colour smudging [219]. To address these challenges, several algorithms have been tested for resolution [220-226]. These issues are less pronounced with the application of Polyjet technology, an advanced 3D printing method that involves depositing small particles of photopolymers in liquid form onto a tray. These polymers are directly polymerized within the machine using a UV lamp, resulting in a physical model boasting distinct aesthetic qualities and more. Nonetheless, precise colour control remains elusive and inconsistent, unlike in 2D printing. While commercially available full-colour 3D printing enables meticulous control over material deposition in volume, achieving an exact replication of a desired surface appearance is hindered by the pronounced subsurface scattering of 3D printing materials, leading to nontrivial colour variations [227]. In conclusion, despite the contributions of Computer Graphics and the evolution of increasingly sophisticated machines, the utilization of polychrome 3D printing is not yet widespread for re-presenting ancient polychromy. Its usage remains largely confined to museum projects equipped with a substantial economic budget earmarked for this purpose.

Recent advances in artificial intelligence (AI) methodologies, including machine learning (ML) and its subset deep learning (DL), have been applied to generate digital polychrome reconstructions of ancient sculptures automatically. The initial instance of this approach involved the automatic identification and colouring of Roman emperors' busts based on ancient textual descriptions (Projects No. 62, 63 in Table 1) or artistic inspiration (Project No. 63 in Table 1). However, following initial enthusiasm, many scholars and researchers adopted a more cautious stance, acknowledging the potential utility of these methodologies but emphasizing their effectiveness when employed within a multidisciplinary scientific framework.

These AI networks develop learning models across various tiers; they can learn from data input provided directly by humans (as in ML) or through statistical calculation algorithms (as in DL). Consequently, the quality of the initial image datasets holds paramount significance. Unfortunately, in the realm of ancient polychromy, such datasets are non-existent. Moreover, arbitrary utilization of 2D photo editing or painting software can inadvertently produce historical inaccuracies, as exemplified by the Vosharts' artistic reconstructions of Roman emperors, which were misused for propagating racial bias [228-230].

As a sidenote can be interested to discuss the troubling phenomenon of idealizing the sculptures' whiteness as a form of supremacy that has been brought to light in recent years by several historians. This cause has been embraced by artists and cultural institutions, leading to the creation of intriguing artistic installations. One notable installation is the work of sculptor Lily Cox-Richard, who in 2019 presented a series responding to the history and materiality of Blanton's William J. Battle collection of plaster casts – a set of 19th-century replicas of ancient Greek and Roman sculptures. Cox-Richard's sculptural installation prompts reflection on the legacy of these objects, raising questions about their role in perpetuating ideals of physical "perfection" and "whiteness" [231-233]. The Battle Casts Museum themselves became part of an installation by the artist inside "Polychromy" project [234,235]. Similarly, the artistic and conceptual installation "Hydra" by Jeff Koons in 2022 explores related themes [236]. Intriguing project is Fabio Viale's "Classic marble sculptures recreated with a set of contemporary tattoos", displayed in 2021 across the Piazza del Duomo in Pietrasanta, Italy. Viale's ancient marble sculptures, each hand-painted with unique tattoos using a special ink, challenge traditional perceptions of classical art [237]. Francesco Vezzoli's exhibition at MoMA between 2014 and 2015 also explores these themes. Vezzoli's Roman imperial busts restore decorated surfaces to the contemporary imagination, which have faded over almost two thousand years [238].

Given the potential impact of these studies on a broader audience beyond the scientific and humanistic communities, it is imperative to reiterate certain key practices while conducting scientific research, reconstruction, and the re-proposal of ancient polychromy (colour and gilding). This is particularly important considering that the preserved colour traces and the basis for entire reconstructions often derive from small fragments, which may also exhibit traces of modern varnishes applied for conservation purposes. Whether these fragmentary remains of polychromy allow for an accurate recreation of the ancient aesthetic is a crucial aspect that merits discussion and in-depth analysis in a separate work. Therefore, it is essential to clearly delineate the methodology employed, and the specifications of the data used and acquired to achieve three fundamental objectives: 1. Ensure experiment reproducibility, 2. Convey a scientifically robust message, and 3. Prevent manipulation of the obtained results.

3.2. Digital technologies for interacting, visualizing and presenting ancient colour

The overview provided in Table 1 and Fig. 12 demonstrates that the initial virtual models of historic buildings were developed to convey the original polychrome appearance to the general public through video films (Projects No. 40, 41 in Table 1), commencing in the mid-2000s. As technological advancements continue, 3D models evolve into more detailed and realistic representations, benefiting from the continuous progress of immersive 3D rendering software. This advancement enables real-time interaction with all elements within the virtual environment through consoles (Projects No. 35, 36, 37, 38, 39, 42, 44, 51, 60 in Table 1).

In this manner, virtual reality (Virtual-, Augmented-, Mixed-Reality) converters into an exceedingly effective communication medium for conveying knowledge about ancient colour (Projects No. 37, 38, 42, 44, 51, 58 in Table 1). The transmission process is preceded by the documentation and study of ancient polychromy, supported by 3D technologies. This proficiency is also essential for Projection Mapping (PM), a display technique that employs a video projector to project a digital image onto a physical surface. Divergent from Augmented Reality (AR), which blends computer-generated visual content with the real scene on a display, PM, also known as Augmented Spatial Reality (ASR), directly projects digital information onto the physical surface.

The utilization of PM technology has amplified visitor engagement and interest, especially within museum settings (Projects No. 51, 52, 53, 54, 55, 56, 57, 58 in Table 1). Generally, within the context of ancient polychromy, a specially designed image is projected over the original bas-relief or sculpture, even those with complex 3D shapes, to re-create the historical polychrome painting (Projects No. 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59 in Table 1). Noteworthy advantages of PM include its non-invasiveness, absence of physical contact with cultural artefacts, and ability to accommodate multiple viewers simultaneously. As a result, it fosters a greater array of hypotheses about the original colour of ancient monuments or sculptures, allowing both experts and the general public to view and appreciate the content in parallel (Projects No. 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59 in Table 1). The visualization of ancient polychromy can be achieved without additional equipment, or it can serve as the foundation for virtual reality experiences using specialized 3D visors or haptic devices (Projects No. 37, 38, 51, 60, 47, 48 in Table 1). Nonetheless, certain technical disadvantages persist, primarily related to lens quality and cost, as well as considerations concerning space, projector placement, and ambient lighting.

The overview presented in Table 1 and Fig. 10 reveals that despite the evolution of algorithms and techniques for 3D editing and painting using haptic interfaces and/or augmented reality since the close of the previous century, the application of this technology [187,188] to ancient polychromy remains a recent development (Projects No. 47, 48 in Table 1). The potential impact of this technology is substantial, as it significantly enhances human sensory perception through the utilization of video projection systems and computing devices. Additionally, it fosters heightened engagement and empathy during the experiential process. Currently, its implementation in the realm of polychromy is tied to two laboratory experimentation cases (Projects No. 47, 48 in Table 1), both of which demonstrated effectiveness in both the study-reproduction phase and the visualization and presentation of ancient colour to the public. Nevertheless, current limitations revolve around technology consolidation, such as ensuring the robustness of spatial tracking systems, as well as facilitating its utilization in environments where individuals without expertise in computer graphics can also operate it. Furthermore, factors like the cost of glasses, control systems, and other accessories still pose challenges.

As for the accessibility of AR on mobile or fixed devices, there remain limited experiences in the context of polychromy-related services, despite the well-established development platforms for creating multiplatform 2D and 3D games and interactive experiences (Projects No. 59, 60, 61, 43 in Table 1). These constrained experiences could potentially be attributed to prioritization decisions often influenced by museum budgets (Projects No. 43, 61 in Table 1) or the organizations tasked with promoting cultural tourism (Projects No. 59, 60 in Table 1).

In addition to the ultimate outcome of all these 3D repropositions intended for informative purposes, particular attention must be directed toward the "philological" and "data provenance" aspects concerning the relationship between virtual reconstructions and the original data. It is crucial to ensure that users are consistently apprised of the "level of reliability" inherent in the entire research process leading to the creation of a multimedia product. This transparency is pivotal in preventing the dissemination of inaccurate or misrepresented information. Moreover, it is of paramount importance that data (including any digital object), metadata, paradata (pertaining to the digital object and its digital history), and infrastructures adhere to the "FAIR Guiding Principles" as delineated in the scientific data publication [239,240]. Hence, whether dealing with 2D and 3D polychrome reconstructions, 2D images, 3D models, videos, or information relating to digital data (including scientific analysis outcomes) and infrastructure, it is imperative that they all adhere to the principles of being Findable, Accessible, Interoperable, and Reusable (FAIR) for computational systems [241]. Given the current stage of technological and cultural advancement, the integration of data, metadata, and infrastructure within the projects scrutinized in this analytical review, as well as those of prospective projects centred on ancient polychromy, is anticipated to align and conform to the FAIR Guiding Principles. These principles accommodate the increasing necessity for a more comprehensive comprehension of ancient polychromy. Thus, if the overarching goal is to achieve the long-term reutilization of data and metadata (*r*eusability), the initial stride involves facilitating their effortless discovery (*f*indability). Subsequently, accessibility, potentially involving authentication and authorization mechanisms that trace their utilization (*a*ccessibility), becomes pivotal. At this stage, data should be structured to enable integration with other datasets and interaction with applications or workflows for analysis, storage, and processing. Pertinent to ancient polychromy, it is imperative to ensure metadata remains accessible even if the underlying data is no longer available. Both metadata and data should be thoroughly described, facilitating their replication and incorporation into various contexts (*i*nteroperability). Achieving this objective would foster an enhanced sharing of knowledge concerning ancient polychromy, markedly streamlining the process compared to the existing digital landscape, where the sharing of data, metadata, and infrastructures remains a persistent challenge.

4. Conclusions

This comprehensive examination of digital technologies and methodologies employed for documenting, reconstructing, visualising, and presenting ancient polychromy to both experts and the general public has provided us with a thorough understanding spanning from the initial experiments of the early 1990s to the present day. The survey has revealed a favourable trend towards the utilisation of digital technologies, accompanied by an increasing emphasis on multidisciplinarity and transdisciplinarity. The progression has transitioned from isolated experimental endeavours towards the establishment of systematic workflows in documenting, analysing, reconstructing, visualising, and presenting ancient polychromy. An equilibrium has emerged between projects catering to experts and those tailored to the general public. The latter are designed primarily for the presentation of polychrome data and are, naturally, accessible to experts as well. Generally, the interest has mirrored the widespread adoption of these technologies within intricate applications. Prominently, the utilisation of 3D technologies is notable not only in the study and reconstruction phases but also in the visualisation and presentation of ancient polychromy. However, despite their promising potential, technologies related to AR and MR (especially concerning applications on mobile devices or within educational and video game contexts) have exhibited relatively limited impact on the aforementioned topics we have deliberated upon. The investigation has also underscored significant reservations regarding the application of AI to the realm of ancient polychromy.

Persisting issues related to colour reproducibility in 3D painting and printing are gradually being addressed, alongside the imperative for the availability of data (or any digital artefact), metadata, and paradata (which encompass information regarding the digital object and its historical digital context) within infrastructures that adhere to the "FAIR Guiding Principles". Such adherence would simultaneously alleviate the considerable challenges associated with their long-term preservation. An attentive approach towards the "philological" and "data provenance" predicaments concerning the relationship between virtual reconstructions and the original data has been assimilated. Similarly, a focus on determining the "level of reliability" of the entire research process has emerged, thereby guiding the development of a 3D digital product ultimately preventing the dissemination of inaccurate or misrepresentative information. In sum, these multifaceted considerations have been thoroughly examined, exposing gaps within technologies and methodologies and illuminating potential avenues for future research endeavours directed towards the application of digital technologies within the context of ancient polychromy.

Declaration of generative AI usage

During the preparation of this work the author(s) used Grammarly: Free Writing AI Assistance in order to grammatically correct some sentences in English. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Author contributions

E.S. conceived the idea and wrote the manuscript, and P.C. supported and supervised the writing of the manuscript.

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