Colour Fragility

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Abstract. This chapter explores the fragility of colour across five scenarios, focusing on the loss of polychromy in ancient sculptures and architecture, colour variations in paintings, textiles, historical photographs, and digital art. It also emphasizes the need for standardized methodologies to reconstruct, simulate, and restore original colours. For each scenario, the state of the art on colour studies is presented, together with the challenges about colour reconstruction and enviCase studies are discussed, highlighting colour features and characteristics. Modern analytical and diagnostic techniques are finally also discussed.

Keywords: Colour Studies · Colour analysis · Colour reconstruction

To better preserve coloured collection, this chapter focuses on the analysis of colour fragility in five different scenarios, that are considered a priority by projects such as PERCEIVE. These scenarios are:

- Scenario 1: lost polychromy in ancient statues and architecture
- Scenario 2: colour change in paintings and works on paper
- Scenario 3: colour change in textiles (dresses and tapestry collections)
- Scenario 4: colour change in historical photographs/film collections
- Scenario 5: colour rendering and visualization in born digital art.

S. Pescarin et al. (Eds.): *Chromatic Visions*, LNCS 15750, pp. 184–222, 2026.
https://doi.org/10.1007/978-3-032-07792-9_6

Colour studies, research questions and objectives are different in these contexts and, therefore, the authors have defined a "scenario-based" methodology to approach the problem of colour preservation and reconstructions, from data acquisition and analysis, to the evaluation of results, from the definition of needed tools and services, to the design of XR and hybrid experiences.

1 Lost Polychromy in Ancient Statues and Architecture

In recent years, new evidence has emerged about the polychromy of sculptures in classical antiquity. This is largely due to new findings and datasets resulting from analytical studies coming from sculptures and architectural elements held in museums around the world. Thanks to the international scientific community, a standardised methodology for data acquisition has been established, thanks to the coordination of the International Round Table on Polychromy in Ancient Sculpture and Architecture, also known as "Polychromy Round Table"[1] To preserve traces of polychromy and convey a statue's original appearance, it has become increasingly important and interesting to visualise the richness of ancient statuary in terms of colour "pantone" and its original appearance. Polychromy reconstructions can contribute to offering a more correct idea of the original aspect, enabling users to perceive its complexity (i.e. with shades and not homogenous colours applied to certain areas) and semantics. Nevertheless, reconstructing the original colours is a challenging endeavour due to the difficulty in identifying the full extent and original appearance of the painted parts, along with their distribution over the surface, the tools and the painting techniques used. It is particularly difficult, moreover, to reconstruct how primary colours are brought out and enriched by highlights and shadows, given the present preservation state of sculptures. Although we have a good understanding of the pigments used in antiquity, we do not have much information about ancient painting techniques, such as used binders or how the paint was applied. Furthermore, the appearance of the artworks might have been significantly altered over the centuries. Therefore, we should highlight here how this lack of information does not allow a reliable reconstruction of the original colour appearance. For this reason, it is important to follow a scientific workflow and provide a minimum degree of reliability and authenticity, connecting results to analytical data and sources, not only for the scientific community, but also for the general public.

Unfortunately, there is a lack of a universally adopted methodological protocol for polychromy reconstruction, and this has led to inconsistencies in the visualisations (both digital and physical copies) proposed by various research groups. These discrepancies can be attributed not only to varying levels of familiarity and thus fluency of interpretation of historical sources and studies, thereby reducing the comparability and consistency of colour reconstructions, but they are also due to the uncertainty of the research results carried out on the artworks themselves. For instance, not all surveys yield unequivocal results that allow a full understanding; unfortunately, in most cases, the information is not sufficient to clearly understand aspects such as the extent of colour, the designs of decorations, etc.

[1] https://www.polychromyroundtable.com/.

After decades of the neoclassical white "pure form", the replicas and reconstructions of polychrome artworks, often provoke a shocking reaction. For this reason, it is essential that the reconstructions are accompanied by additional explanations and descriptions of the reconstruction process, to make them accessible to the general public, who is often unaware that statues were once coloured. From this perspective, the digital format can be a valuable tool in overcoming public scepticism, once we move from the concept of "definite reconstruction" to that of a "potential appearance", based on source analysis and scientific evidence. The possibilities offered by the use of digital media allow us to provide a wide range of hypotheses and to show the whole process and the studies behind it. State of the Art examples of the reconstruction of polychromy on classical statues are still few represented, due to the long and costly process. To ensure the accuracy of the results, much time should be devoted to the research of coeval sources and historical records and to comparing iconographic models among themselves: for instance, the literary source can serve as a starting point to verify the presence of models both in the realm of painting, such as frescoes, and in their translation into stone.; for the same reason it is of great interest to have the possibility to compare diagnostic investigation results on similar typologies of artifacts. The scientific methodology has been firmly established and results are regularly disseminated through conferences and international journals, although it has never been codified and standardized, while the supporting data often remains inaccessible [1–8]. This wealth of content has immense potential and is of utmost importance to researchers, which underlines the urgent need for greater accessibility. For this reason, a starting point should be the drafting of an "investigation manual", establishing a protocol that will eventually be accepted by the entire scientific community, pointing out general guidelines for research, even addressing the issue of the instrumentation used, as well as the method of communicating and making data accessible in an open repository where containing and accurately displaying all data obtained can be "FAIRly" available for comparative studies and reuse. Since the late 20th century, considerable resources have been devoted to producing reconstructions of ancient sculptural polychromy [9]. Today, polychromy reconstructions are mainly made by painting physical copies of the sculptures [10–12]. However, certain experimentations also occur on digital formats, 2D images or 3D models where polychromy is suggested by colourizing well-defined delineated areas in homogeneous, flat RGB tones [13–16]. More sophisticated reconstructions involve the study of contextual or related, i.e. comparative, artworks (such as other sculptures or mummy portraits) to manipulate (e.g. stretch or deform) their digital images and extract colour textures to simulate layers of paint in the element being reconstructed or features on the sculpture being studied [17]. However, the main problem is still the lack of an established, agreed methodological protocol. Heritage scientists and scholars have relied on the reconstruction of physical copies to disseminate the results of the research on polychromy, although digital reconstruction is becoming increasingly widespread. More sophisticated methods of digital colour reconstruction of archaeological buildings and sites have been developed with the support of software that helps to manage the reliability of the reconstruction [18, 19] but the methodologies used have not been tested on ancient statuary. The current restoration of polychrome statues is particularly deficient in terms of nuance and shading: the colour appears flat, with a total absence of the vibrant tones that we know existed and prevailed

in the past. Sculpture was supposed to imitate reality, and it's worth looking at frescoes or analysing the production of Attic ceramics, for example, to understand how detailed the rendering of textiles was and the dedication and care with which artists animated images. Sculpture has certainly not escaped this artistic intention to reproduce reality, but what makes it difficult, if not impossible, to understand lies in its very material nature: what remains today is the substrate and not the finish and we can only work on this layer, which by its very nature does not allow for a better understanding. The efforts of the scientific community are today not only aimed at understanding the possible pictorial characteristics of Greek and Roman sculptures, but also at providing and facilitating physical restoration and virtual reconstruction efforts, to better preserve collections and to raise public awareness, fostering a sense of care.

1.1 Objectives

Our main and ultimate objective is to reconstruct the colour and original appearance of the polychrome statues, improving the quality of rendering, the capacity of available methods and the speeding up of the traditional workflow. The digital reconstruction of the original polychromy is, in fact, a time-consuming process that requires specialised skill (i.e. iconographic comparative analysis takes time). The development of a semi-automatic Artificial Intelligence (AI) protocol to support this research or to suggest possible reconstructive hypotheses can offer a solution to obtain a more reliable colour reconstruction or reconstructions (it would be possible for example to provide more than one potential reconstruction). The aim is to obtain a methodological protocol welcomed by the scientific community and, at the same time, accepted and appreciated by the general audience. If we consider this AI support, there are still not sufficient studies and applications. Although only a few attempts have been made and, when published, widely accepted, there is a clear need to advance the field by developing tools and services that empower researchers to explore and construct multiple reconstruction options, supporting the development of interpretations, fostering dialogue and refining results. Through such an iterative process, researchers can progressively approach a more authentic representation of the object's original colourful appearance.

1.2 Challenges

Although archaeometry techniques enable today to detect minute traces of pigment, even when they are no longer visible to the naked eye, many questions about the appearance of the original polychromy remain unanswered. Some pigments are better preserved than others, and certain pigments change chemically over time. Even when a pigment is scientifically identified, questions often remain as to whether it was applied in its pure state or mixed with other pigments, and whether it played a major or minor role in the overall polychrome scheme [20]. Given these uncertainties, it must be accepted that it is virtually impossible to reconstruct the appearance of the original polychromy. One of the main obstacles to colour reconstruction is the imprecision of the reconstruction itself, since few traces are visible and few comparisons are available, so that the dissemination and presentation of the results is reduced to the strictly scientific data obtained during

the measurement campaign. The meticulous analytical protocol can provide a comprehensive physio-chemical characterization of the colour preserved on the surface of the sculpture. Even the tiniest traces of colour are sufficient for experts to determine the nature and composition of the original materials, identifying the pigment or mixture of pigments, albeit with greater complexity, and possibly determining the type of binding medium. However, while this information, although accurate, relates to the colour preserved in a few small, barely visible areas of the surface, the synthesis of a comprehensive understanding of polychromy and the reconstruction of the original appearance of the object at the time of its creation remains a challenge. The preparation of "mock-ups" (pieces of original material treated and painted according to ancient recipes) could overcome the difficulties of reproducing reliable textures and helps to render the appearance of the surfaces, simulating the original aspect and avoiding the "plastic effect" produced by full-tone painting. Another challenge would be to develop tools to digitally visualize the degree of (un)certainty of the polychromy in the different parts of the reconstruction (e.g. objective data such as the location of the visible traces and the description of lost *polychromy* in ancient publications or archival documents and hypothetical data, such as which part of the reconstruction is based only on hypothesis and comparisons with other similar polychrome sculptures).

1.3 Case Studies

To better develop a methodology and supporting tools, we have therefore selected a number of case studies that we are going to describe in the following paragraphs:

- Various versions of Roman statues representing the so-called "Venus Anadyomene";
- The sculptures and frescoes belonging to the Isis complex in Pompeii

The Venus Anadyomene Statues

We have selected a group of marble statues representing the iconography of "**Venus Anadyomene**" (from the Greek, "Venus Rising from the Sea"), the Goddess of love, depicted in the act of rising from the sea and resting her hands on wet hair. The theme of this goddess is a perfect case study, because it enables us to work on a very well represented type and on pretty well preserved and known polychromy remains, such as in the case of the "Lovatelli", "Bikini", and "Marina" Venuses.

We have chosen to study a selected group of "Anadyomene-type" statues with traces of original polychromy, all conserved at the MANN museum in Naples, using a non-invasive analytical protocol, whose results will help to reconstruct the complete pictorial framework. Moreover, this type of statues is also spread in literature, frescoes and mosaics. In particular, the literary sources provide a precise description not only of the genesis of the myth but also of the appearance that is easily recognizable in its artistic rendition. According to the legend recounted by Hesiod, whose Theogony serves as a cornerstone in understanding Greek mythology, detailing the origins and family lineage of the Olympian gods, Titans, and various other divine beings, the goddess of beauty and love in emerged from Uranus's severed genitals, cast into the primordial sea by Cronus. The iconic image of Venus Anadyomene rising from the sea gained renown in antiquity largely due to a revered painting by Apelles, captivating the imagination of

ancient writers, who frequently referenced it in Latin literature, from Ovid to Pliny the Elder, Servius, and Apuleius. Apuleius, particularly, offers several exquisite passages on the subject, replete with vivid descriptions and rich chromatic imagery: beyond their refinement and visual allure, Apuleius's depictions stand out for their attention to physical detail. For instance, the goddess's flowing locks are described as "undulating locks of hair overflowing in waves," an image steeped in the aquatic symbolism of dishevelled feminine hair: this is one of the reasons why, emerging from the waters, Anadyomene is always depicted with her hands surrounding two large tufts of hair and squeezing them. Not only Hesiod and Apuleius but also Plato, Strabo, Pliny the Elder, Ovid, and Apuleius, the image of Venus Anadyomene continues to resonate in modern literature. Contemporary writers embrace and expand upon this magnificent creation of GreekRoman culture, further enriching its enduring allure, the same does painters as Titian who in 1520, painted an oil with the same subject, now housed in the National Gallery of Scotland in Edinburgh. The longevity of the myth and, simultaneously, the repetitiveness of the pictorial canon, albeit with minimal variations (such as the presence or absence of jewellery adorning the body), have been the reasons why this specific iconographic theme was selected. This allows comparison and representations, and/or, when feasible, also to speculate on a general pictorial composition: the comparison between different media will certainly help to understand if the use of colour was intended to imitate the reality, if there was any link between different works of art, but also for other purposes such as understanding the way shadows and volumes were rendered on different surfaces (neck decoration in Fig. 1).

On the selected statues, Fig. 2, it is still visible residual polychromy. Moreover, there are several versions of statues with the same iconography around the world with similar characteristics to be compared with, and various examples of frescoes depicting Venus which could serve as an iconographic visual reference as well. Beside a naked Venus, other depictions were documented as fully or partially clothed, very similarly to the statuary examples. In archaeological museums displaying collections of statuary beside frescoes, ceramics, mosaics portraying scenes where statues are shown and depicted with either full or partial colouring, the iconographic comparison is made possible. As shown in the images provided below, the representation of sculptures with painted details not only involves fresco technique but also ceramic production and mosaics, in this specific case, opus sectile. These case studies also adopt important iconographic models onto different media, of which we have evidence in stone artifacts (Fig. 4). Figure 3-left depicts a unique coloured sculpture of Artemis on a base (INV 9301), while Fig. 3-right portrays one of the most famous myths of the classical world, the Callipygian Venus on an Attic krater wearing a dark orange mantle, her body's skin coloured in white, and her hair painted to resemble blonde. Finally, the already mentioned Fig. 4 is another extraordinary example of Venus, in this case fastening her sandal, depicted on a precious *opus sectile*, with decorative details, such as the jewellery, realised with a different stone material, the body, the hairstyle, and the anatomical details highlighted to recreate the folds of the abdomen and arms.

The Isis Complex

The Venus type is also diffused in the Temple of Isis in Pompeii (the myth of Venus is strictly related to the myth of Isis in Campania [22]). For this reason, we have extended

Fig. 1. The life-sized depiction (fresco) of the Anadyomene from the House of the Principe di Napoli, Pompeii VI.15.8. It is located on the walls of the exedra, which forms the central area of the triclinium (Wikipedia).

Fig. 2. The selected statues: a) Venus Anadyomene INV 111383, Pompeii, House of Oppius Gratus and Quartilla; b) INV 6292 Venus Anadyomene from Pompeii; c) INV 126248 Venus Anadyomene, from Pompeii; d) INV 6298 Venus Anadyomene from the Iseum of Pompeii; e) INV 152798 Bikini Venus, from the House of the Bikini Venus (I 11, 6–7), Pompeii; f) INV 109608 Lovatelli Venus, from the House of Diomedes, Pompeii (I, 2. 17).

our study to the Iseum [23–25], including not only the sculptures but also the frescoes. This Temple is dedicated to the Egyptian goddess Isis. The walls were all painted in the first and second Pompeian styles, and we may suppose that the statues were also originally painted. Although the site is still visible in Pompeii, even if only partially, the entire decoration, including frescoes, statues and objects linked to the cult, are permanently exhibited at MANN Museum. These remains, excavated in 1764, survived the eruption. They included paintings and fragments of statues, which were scattered across different parts of the temple and later reassembled in the museum. Very few fragments of the frescoes are visible *in situ* today, but the documentation of both the findings and archival sources enables a virtual reconstruction of the entire complex. Additionally, a maquette

reconstructing the Iseum complex at the museum serves as a reference for reconstructing this archaeological site.

Fig. 3. (left) *Fresco with Artemis, INV 9301from Pompei, VI Insula Occidentalis 10* -(right) Bell crater with red figures from Sant'Agata dei Goti INV. 82570. The vase dates back to the second half of the IV century BC; in the banquet scene is depicted a dancing figure who raises her mantle, robes, faithfully replicating the compositional scheme of the much more famous Marble Venus the pattern of the much more famous marble copy.

Fig. 4. INV 109678, Venus tying her sandal in *opus sectile*, from Pompeii (I, 2, 10), 41–68 AD

Among the selected statues, we have focused on two particularly meaningful examples: the statue of Isis (Fig. 5b), showcasing significant polychromy and gilding, and another example of Venus Anadyomene (Fig. 5a):

– a) INV 6298 Venus Anadyomene.

– b) INV 976 Isis with sistrum with traces of polychromy
– c) INV 6290 INV Isis head from acrolith inside the temple
– d) INV 6312 INV Dionysus with panther

Fig. 5. Statues belonging to the Iseum Complex selected. From left to right: a) INV 6298 Venus Anadyomene; b) INV 976 Isis with sistrum; c) INV 6290 Isis head from acrolith inside the temple; d) INV 6312 Dionysus with panther

According to the plan of the temple and the locations of the findings during the excavation, both the Venus and the Isis were originally placed under the portico (respectively INV 6298 on the corner between the south and the west walls, and INV 976 on the corner between the west and the north walls), whereas the acrolith should have been positioned inside the *naos* and the Dionysus in a niche on the west side of the temple. The reason for choosing these sculptures lies in their polychrome and gilded features, notably visible in certain areas (such as on the statue of Isis) to the naked eye. While the Anadyomene contributes to better understanding the seriality of the iconography, the Egyptian – *Egyptianizing* goddess assumes a significant role in comprehending not just its pictorial but also its iconographic background, being particularly rare, if not unique (Fig. 5b).

Among the frescoes, we have selected those belonging to the portico, partially affected by colour changes problems, partially needing their re-location and reconstruction of missing elements:

– Floor plan sketch of the ancient architecture. The layout includes labeled areas such as the Porticos to the south, Temple in the center and Ekklesiasterion to the east (Fig. 6)
– Frescoes of the eastern wall of the portico (Fig. 7)
– Frescoes of the southern wall of the portico (Fig. 8)
– Frescoes of the western wall of the portico (Fig. 9)
– Frescoes of the northern wall of the portico (Fig. 10)

We decided to specifically select these frescoes, since they represent several interesting clues: they ran all around the porticus, following a repeated composition, interrupted only in correspondence of niches or passages. The decorations depict architectural motives: the *zoccolo* is made of oblong panels in yellow, enlivened by sea monsters and sphinxes, while the main ones are painted in red and decorated with architectural elements, divided by additional panels with fine garland ornamentation and vignettes. Finally, the upper part has a white background with thin *aediculae* separated from the main panels, by a scroll on a black background (Fig. 98).

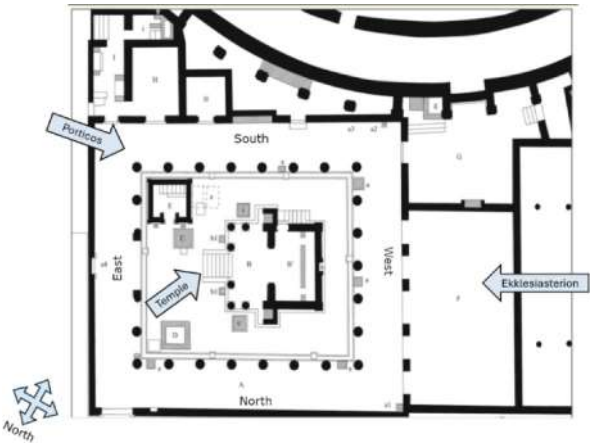

Fig. 6. Floor plan sketch of the ancient architecture. The layout includes labeled areas such as the Porticos to the south, Temple in the center and Ekklesiasterion to the east

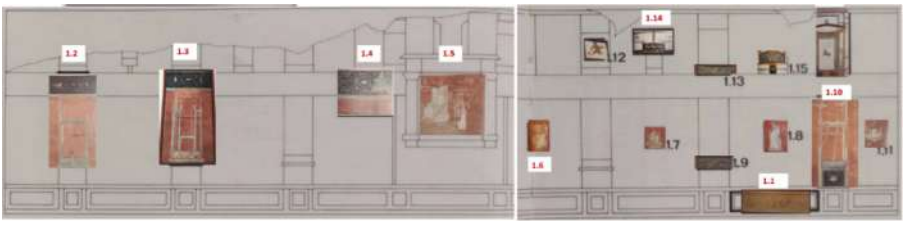

Fig. 7. Re-location of the frescoes in the original walls of the Porticoes (East Wall)

The goal of the project is to reconstruct in 3D the entire complex and to place the statues in their original settings, complemented by colour reconstructions directly linked to diagnostic data. In addition, the frescoes under the portico will be re-located, following De Caro's studies [26] and colour reconstruction will be obtained by the integration with AI and IBR techniques with available historical studies (Fig. 11), while missing parts will be added. In this way, it will be possible to overlap the 3D model of the site, as it is today, with its 3D reconstruction.

Fig. 8. Re-location of the frescoes in the original walls of the Porticoes (South Wall)

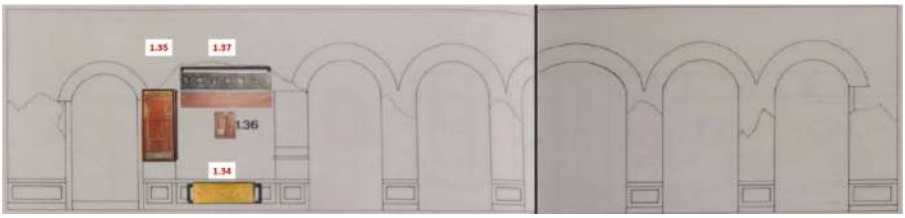

Fig. 9. Re-location of the frescoes in the original walls of the Porticoes (West Wall)

Fig. 10. Re-location of the frescoes in the original walls of the Porticoes (North Wall)

2 Colour Change in Paintings and Works on Paper

Many museums in the world host important collections of paintings that display phenomena of colour change, as is the case of *The Scream* (1910?) from MUNCH museum in Oslo [27], graphic art from the same collection or canvas paintings as those made during the Warne Munde period [28]. We have therefore selected this example to work on the problem of virtual colour reconstruction, and prediction of its potential change over time, based on the use of Colour science and Artificial Intelligence algorithms. Predictive systems together with specific guidelines for the preventive conservation of colours are not fully available and are needed not only for museum professionals, but also for the public in their experience of perception of the art-object as authentic and as a fragile item to be preserved. Scientific literature abounds in studies regarding the use of historically accurate reconstructions for better understanding the original techniques of modern and contemporary artists and the degradation mechanisms involved in the colour change of art materials (e.g., red lakes, cadmium yellow, chrome yellows…) in combination with oil media. Articles published by several authors [29–31], showed

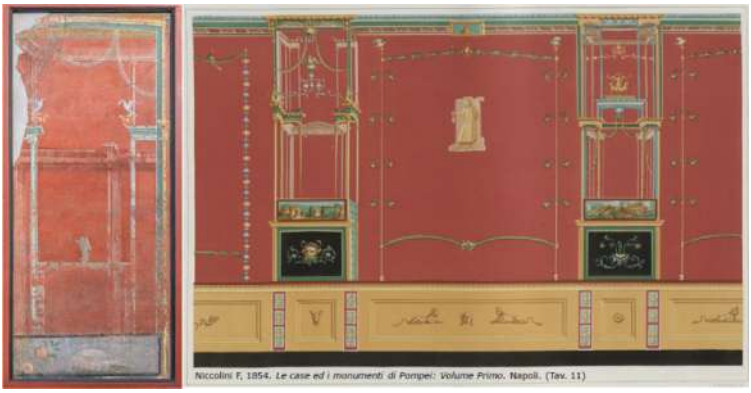

Fig. 11. a) An orthorectified photo of the fresco 1.35 conserved at MANN museum; b) example of manual re-colourisation and reconstruction of a wall with missing parts by Niccolini (19th cent.) Niccolini, F., & Niccolini, F 1854. "Le case ed i monumenti di Pompei disegnati e descritti", 1 (Tav. 11)

the behaviour of 19th century paints when exposed to light or darkness. Specific conditions of lighting, framing or retouching materials can lead to specific phenomena of discolouration phenomena (i.e. fading, yellowing, darkening) in oil paints. Optical characteristics of the paint materials have been measured using colourimetry and Kubelka Munch theory, the latest helping in digitally reconstruct/visualize original colours of discoloured paints. Other authors [32–35] published studies on eosin-based red lakes (e.g. geranium lake) that proved to be highly sensitive to light, leading to rapid fading of many modern paintings where they have been identified and digital reconstructions have been proposed based on the results from several analytical techniques (MA-XRF, micro-Raman, SEM-EDS, colourimetry and micro-fadeometry etc.). Other [36, 37] also published an extensive study on the fading of cadmium yellow paints, observed in many modern and contemporary artworks (e.g. *The Scream,* 1910?), showing the contribution of the manufacturing process and of environmental parameters such as high RH and light in the process of colour change. Spectral pigment mapping using multi and hyperspectral tools has been also reported by several authors [38, 39, 40, 41 pt.1-2-3] on case studies of modern and contemporary artists as source of information for designing a methodology for digital reconstruction of the colour change (fading, darkening, yellowing). Ciortan [42] recently proposed a multi-model approach to model fading effects in the spectral, temporal and spatial dimensions using micro-fading test (MFT) data and hyperspectral imaging on areas of a painting where photodegradation phenomena have been identified. A colourimetric reference of T*he Scream* (1910?) has also been proposed using photographic documentation available in the digital archive of MUNCH and colourimetric data, to approximate the original appearance of the famous icon [43].

2.1 Objectives

The main objective is to design a 3-steps concept and approach for: (I) creation of a sense of embodiment and perception of authenticity; (ii) building a sense of wonder; (iii)

developing a sense of care aiming to strengthen the preservation efforts of these fragile collections. This concept design can be further used and explored for applications by curators/art historians, exhibition designers, other creative industries representatives and a general public.

2.2 Challenges

The main challenge regards the availability of the art objects, especially if they are in a restrictive exhibition set-up (as the case of *The Scream*) or in fragile conservation condition (as mural paintings from MANN) or in a location less accessible. Nevertheless, in some cases there is already available an important amount of scientific data (from previous analytical campaigns) that can be used to start colour processing and reconstructions. In addition, there are challenges regarding the references to be used for colour reconstructions, as in most cases the original documentation (coloured photographs) of the art objects at the moment of their creation is missing. In the case of *The Scream* (1910?) there are few black and white images from past publications in 1930 ca. (Fig. 12), but it is difficult to compare them with coloured photographs taken much later (in 1970s and 1980s). Another challenge is the fact that the taste for experimentation of modern artists, as Edvard Munch or Vincent van Gogh, and contemporary as Jackson Pollock, created the premises for further change in colour due to instability or incompatibility of paint materials [30, 44, 45]. Munch painted The Scream at a time when the paint-making industry was undergoing a rapid transition. Prior to the 1880s, paints were mixed in artists' studios with hand-ground materials, but toward the end of the 19th century, progress in the chemical industry brought tubes of premade paint to store shelves. Highly saturated factory-made pigments lent artists' creations vibrancy, but these paints were rarely, if ever, tested for longevity [27, 46]. Thus, in present times we often observe degradation patterns generated by the composition of the paint formulations and interactions with environments, and change in colour are among these patterns, posing also the question on how the future development of the change can be prevented or mitigated. In the art of Munch, the colours become protagonist of his innovative studio experimentation, applied in thin and/or thick brushstroke, squeezed directly from the tube, blended with crayon lines and contours, pure, mixed or overlapped, sometimes even applied with fingers or other tools than brushes. This taste for experimentation led to severe consequences regarding the stability of paint layers and integrity of the representation [47]. Nowadays many of his works present porous, powdery, de-cohesed paint layers, colour change phenomena (fading and darkening), abrasions and cracks, paint layers losses and lacunae. All these degradation forms lead to a loss of the readability of the image depicted but also to many questions related to long-term survival of these artworks. In a few cases, such as The Scream, the integrity of the object has also been affected by theft (2004) and other vandalic acts [27]. Regarding the concepts of authenticity and accurate reproduction of original colours, one main question is if the scientists would be able to reproduce using mock-ups the original appearance of the altered colours and if these model samples can faithfully model the composition of original paints and their degradation/colour change over time. Also, regarding the predictive models to be used, the question is what exactly we can predict, for how long and to which extent these models can be compared to the real processes of fading taking place (as in some cases

the process of change reached a certain threshold and slowed down, when for others it might be ongoing). Another question to be discussed is the authenticity concept regarding reconstructions hypotheses and what are the main criteria or variables to be taken into account when proposing and displaying them to the public.

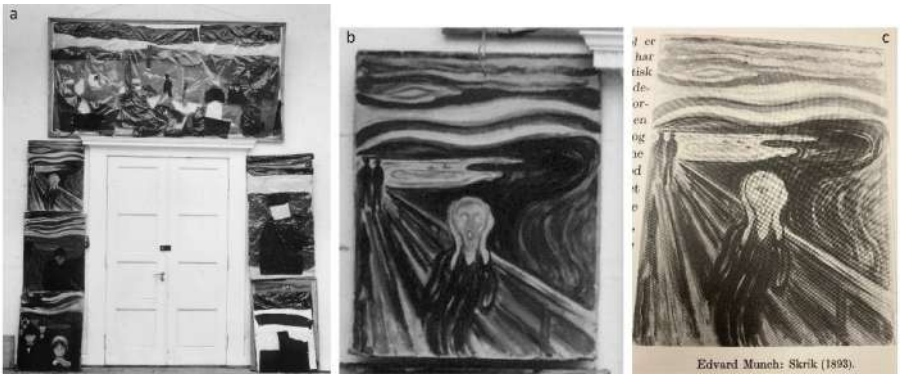

Fig. 12. Black and white images of the Scream around 1930s: a) the studio of Munch at Ekely, where Scream is displayed on a wall together with Anxiety and Despair (photo-archive væring.no/MUNCH, 1938); b) the close-up on Scream (from picture a); c) image published in Østby Leif, Naturalisme til nyromantikk, Oslo 1934, ill. s. 133.

3 Case Studies

We have considered specific case studies:

1. ***The Scream*** (1910?) by Edvard Munch and ***the hand-coloured print*** (1895), with fading phenomenon in areas of yellow and red paint
2. ***Road in Provence (1880–1890)***, a watercolour on paper by Paul Cezanne from the collections of the Art Institute of Chicago with some evidence of colour change and
3. ***Fresco paintings*** from Roman time with changes in colour from yellow to red, housed by MANN in Naples.

The Scream (1910?) by Edvard Munch and the Hand-coloured Print with Fading Phenomenon (1895)

Munch blended various materials such as oil, pastel and tempera to produce "colours that were screaming" as much as possible, to express his own perception of nature's scream when blended with human despair and anxiety (Fig. 13). Unfortunately, over time these experiments challenged the preservation of Munch's artwork. The original yellow brush strokes in the sky in the painting have faded to muted white, or off-white. This also applies to the neck portion of the central screaming. The cadmium sulfide yellow colour is fragile and prone to light induced discolouration as well as some red dye used in the area of the bridge. The thick strips of the sea are also flaking off. A big halo produced by a liquid agent (acting during the theft from 2004 to 2006) generated a deturpated mark in

the left corner of the Scream painting, the cardboard also being heavily damaged in this area. To prevent the painting from decaying even more, the Munch Museum has kept the painting in storage, with controlled environmental conditions (low light exposure levels, a constant temperature of ca.18 degrees C, and ca. 50% relative humidity). Before 2021 when the Scream started to be exhibited in the new location in Bjørvika, the main version was barely accessible. Nowadays, in the new location of the museum, a special set-up has been created in the Infinite semi-permanent exhibition, where the Scream room offers the possibility to see 3 of the versions of the motif (the painting on cardboard, the pastel on cardboard and a lithograph). The type of display chosen was selected also thanks to the outcomes of earlier studies [36], thus scheduling a rotation that assures that each of the 3 artworks exhibited are on display not more than 1h at a time. The hand-coloured print is never on display, being also the most light-sensitive version [48].

Fig. 13. Two versions of the same motif, The Scream, in different techniques and on different supports: left – main version dated 1910?, on cardboard and right – hand-coloured print on paper dated 1895, MUNCH, Oslo (credits MUNCH)

Road in Provence (1880–1890)

Cezanne's *Road in Provence* was chosen as a case study as it shows possible phenomena related to colour change. An historic B&W photograph of the watercolour – the earliest known image captured around 1934 – will serve as a reference point to determine which areas of the watercolour, and to what extent, may have undergone colour change from 1934 to date. Comparisons between the historic photograph and its current condition will be undertaken with the aid of hyperspectral imaging, X-ray fluorescence spectroscopy and the results of new B&W photography. Research on the spectral sensitivity of historic and contemporary B&W film, lighting conditions and other capture parameters will also inform the reconstruction of the visual appearance of the watercolour, as it appeared in 1934. This watercolour on paper by Paul Cezanne belongs to the collections of the Art Institute of Chicago and presents evidence of colour change (Fig. 14).

Fresco Paintings from the Villa of Papyri (Herculaneum) with Colour Shift.

Some of the Pompei frescoes identified at MANN have been already described. To better define a methodology suited in case of colour change, we have also included new more appropriate examples: a series of frescoes from the Villa of Papyri of Herculaneum.

Fig. 14. Road in Provence by Paul Cezanne, watercolour and graphite on tan wove paper (1880–1890), Mr. And Mrs. Martin A. Ryerson Collection, Art Institute of Chicago (Reference number 1933.1221).

They present in fact evident widespread colour toning phenomena caused by the eruption of Vesuvius in 79 AD (Fig. 15).

In a fresco with landscapes from the Villa of Papyri in Herculaneum it is visible the change from yellow to red, widespread over the entire surface; originally it was a yellow monochrome panel but later, due to the heat released by the eruption of Vesuvius [49–51] (around 400 °C), it changed the chemical-physical structure of the pigments on the walls, turning the yellow into red, from goethite to hematite. In a fresco with a duck and deer (Fig. 15 left) the veering occurred in the lower part of the panel, while in the fresco with Cupid (Fig. 15 right), involved the entire surface, leaving intact the upper right part of the painting, between Cupid's wings, where the original red colouring is clearly evident. The same phenomenon of toning is also documented by the pictorial evidence still in situ: an example is in the northernmost room of the first lower level (*basis villae*) of the Villa which has been recently excavated in 2007–8: this room, at the moment of discovery, was totally filled with pyroclastic material, causing part of the stuccoes on the vault to become detached contact, at the time of the eruption and arrival of the pyroclastic flow, between the enormous heat and the paint significantly altered the appearance of the yellow, which turned red. Of particular interest is the impression that the cloud left on the walls, thanks to which the path of access is clearly distinguishable.

This colour toning is exemplified by other known cases in literature from Herculaneum, as those in the House of the Deer in the north wall of corridor A [52]. The frescoes featuring the background decoration painted with yellow ochre (goethite) have experienced oxidation, leading to a change into red ochre (hematite). The chosen panels

will be examined with non-invasive archaeometric investigations to obtain a comprehensive diagnostic overview that can later be compared with other documented examples of toning, not only from Herculaneum but also from Pompeii, although the phenomenon is less documented here [53].

Fig. 15. (Left) Fresco with Duck and Deers, plaster and pigment, atrium, MANN-INV 8759 (Photo CNR ISPC) – (Right) Fresco with Cupid, plaster and pigment. MANN-INV 9319 (Photo CNR ISPC)

4 Colour Change in Textiles

Humankind has been pursuing materials for colouring, painting and dyeing since prehistoric times. There is an astoundingly large number of both inorganic and organic colourant sources to be found in nature worldwide where their identification is currently an intriguing subject because colour is significant to all cultures. Throughout history, organic dyes have been derived from plants and animals and used for colouring purposes; in this context historical textiles reflect the unique artistry and craftsmanship of weavers, artists and craftspeople through time [54, 55]. However, not all colours have resisted the test of time, since fading and degradation occur naturally, and ultimately this has changed our perception and appreciation of the objects as they were originally intended. The colour reconstruction of textiles has therefore generated considerable scientific interest in recent years. Colour, its perception and change in textiles resonate deeply with the public, and the potential for the accessibility of this type of collection is great, including items which remain in archives. Many issues make it difficult for scientists to characterise the origin to dyes in textiles, namely, the large number of

chemical classes they belong to and the wide range of potential dye sources; the small amount of sample that can be available for analysis and the low amount of coloured compounds (chromophore-containing molecules) they contain. Furthermore, the complex breakdown processes of chromophore-containing molecules, which are also linked to matrix degradation processes, are highly influenced by the objects' exposure to light, temperature, relative humidity and atmospheric pollutants [56, 57].

4.1 State of the Art

In recent decades, academia and industry have pursued investigations into online digitisation of textiles that have ultimately supported and supplemented the multidisciplinary field regarding art historical interpretations and visual examinations. The identification of natural dyestuffs in ancient objects is a difficult process because of their complex chemical composition and the possibility of having both chromophores and degradation products concurrently [58, 59]. Due to this, new analytical methods and techniques for the identification and characterization of organic dyes in microsamples have been developed and refined during the past few decades. Furthermore, owing to increasing demand of minimally invasive/non-invasive techniques, more recent developments of novel techniques have resulted in the availability of many alternative/complementary methods and protocols to reveal features leading to the identification of fibre substrates and weaves, original dyestuffs, products and markers of degradation and further contaminants. A combination of multispectral imaging, chromatographic and spectroscopic techniques constitute the modern analytical toolbox [60–64]. These techniques are completely non-destructive and provide the possibility to give a rapid overview of used materials (dyestuffs, but potentially also traces of past conservation treatments) in a larger area. Vibrational spectroscopy, i.e. Raman and infrared spectroscopy are easily accessible methods for dyestuff analyses – most dyestuffs are sensitive in the infrared and visible range of wavelengths, however, in the case of dyed textiles the signals caused by the fabric is dominant and overshadow all bands originated by dyes. Dye characterization in textiles by Surface Enhanced Raman Spectroscopy (SERS) alternatively exploits metallic nanoparticles to enhance Raman signals, enabling the identification of trace dyes with high sensitivity and minimal sampling

The most accurate analyses are however still performed by HPLC techniques due to ther widely available databases. Coupled with an infrared spectrometer or a mass spectrometer, components of the dyestuffs can securely be identified. Results can be improved by adding a second mass spectrometer: after separation of the components by LC, a first mass spectrometer would separate all ions; the second allows to select one ion and fragment it. Secondary ion mass spectrometry techniques which allow surface analyses on microscopic samples become more and more used in dyestuff analyses, however, these analyses require specific instruments which are not accessible for everyone, and specific expertise. To investigate metallic components such as metal threads or mordants, XRF based techniques can be used. The approaches range from the use of a simple handheld XRF instrument to the use of synchrotron-based techniques which provide very high sensitivity and spatial resolution in the micro and nanometre scale. According to the choice of protocol, samples may or may not be consumed during analysis depending on the destructiveness of the analytical procedures employed. It is

frequently more efficient these days to combine the two strategies, using non-invasive techniques to inform object sampling. In any case, whatever the analytical methodology, the analytical data obtained for unknown samples are typically assessed against reference in order to identify the dyeing sources. Therefore, studying reference materials that may have undergone artificial aging is also extremely important. The appearance and mechanical characteristics of textile artifacts are significantly impacted by the fading of coloured fibres as well as the degradation of the textile substrate. For this reason, understanding photo-oxidation chemical routes and fading mechanisms is essential to inform effective preventive conservation measures. To study fibre degradation, one parameter is the degree of crystallinity. This can be determined by polarised infrared spectroscopy and X-ray diffraction. The crystallinity studies may be complemented by chemical analyses, for example of amino acid sequences, and NMR studies revealing changes in the molecular structure of the fibre [65]. The knowledge afforded by the combination of analytical techniques provide a better understanding of the objects' complex genesis, their materials, techniques and recipes, which is a prerequisite for a more accurate reconstructions of the objects' original appearance.

4.2 Objectives

Identify the composition of selected objects and reconstruct their original appearance, creating opportunities for the general public to experience the digitally recreated appearance of the objects. Behind the scenes, conservators and scientists need to be able to visualise how an object was originally intended to appear; this knowledge, combined with research into the interaction of dyed textiles with the environment, will guide conservation and restoration efforts and provide information on how a textile may continue to age.

4.3 Challenges

The reconstruction of the original colour of textile objects is a relatively new field of investigation; although there are studies that can be used to predict degradation, these are of limited scope; the reliability of results could be reinforced by investigating better preserved areas in a textile (such as less exposed or hidden areas of dresses). The study of complex ageing processes and the characterisation of dyeing mixtures is only possible thanks to the increasing availability of highly specific and sensitive analytical procedures, which can be applied to the research on organic dyes in cultural heritage artefacts. However it could be difficult to infer the precise chemical degradation pathway of the materials in unknown environmental settings and therefore reconstruct the appearance of the object reliably. Historical recipes vary widely, and can easily be altered and adapted by individual artists and craftpeople, so it is extremely challenging to pin-point precise materials and quantities for any construction so that accelerated ageing procedures can be carried out with a degree of certainty to evaluate fading rates and determine the lightfastness of components.

4.4 Case Studies

Four case studies have been identified and are presented below. The objects were chosen depending on their availability and accessibility (the V&A recently underwent the biggest storage move since the second world war and many of the objects were inaccessible), but more importantly depending on the type and extent of fading and degradation exhibited. The contemporary kimono is a very good example of how even recent objects can be ephemeral in their appearance, while the Victorian dress shows how the balance of the various colours can be altered dramatically depending on susceptibility of different dyes to fading. This in turn affects the perception and appreciation of them by the general public. The two 16th century objects with tarnished metal embroidery were chosen to provide the general public with an idea of the dazzling appearance that this type of objects was intended to have, to provide a sense of surprise and awe generated by the appreciation of the difference, and engender a sense of care for the changed objects.

Kimono FE.422-1992

Reconstruction of original composition and appearance of a faded silk kimono, using a mixture of micro-destructive and non-destructive techniques (Fig. 16). Many of the green areas have faded since acquisition. Samples from faded and unfaded areas were analysed using spectroscopic methods to understand the degradation pathway, and the results were compared with the artist's original dye recipe. Photogrammetry will also be undertaken to capture the object in its 3D state, to facilitate the creation of digital replicas.

Fig. 16. Kimono (FE.422–1992); left: kimono seemingly unfaded; centre: unfolded to display original green with faded areas, right-higher detail of colour changes in areas of the kimono at V&A

Victorian Dress T.7-1926

Reconstruction of original composition and appearance of a faded cotton dress, using a mixture of micro-destructive and non-destructive techniques (Fig. 17). The bright blue background has faded in all the exposed areas. Threads were removed from significant areas and analysed using chromatographic and spectroscopic methods to identify the dye mixtures used. Colourimetry was used, and photogrammetry will also be undertaken to capture the object in its 3D state and facilitate the creation of digital replicas.

Early 17th Century Purse and Pincushion T.52-1954

Fig. 17. Dress (T.7–1926); at top left the dress; top right: under a fold showing unfaded blue areas; bottom: detail of faded and unfaded areas on the cotton fabric. V&A©

Reconstruction of original composition and appearance of a faded embroidery and tarnished metal threads on a Elizabethan purse and pincushion, using a mixture of micro-destructive and non-destructive techniques. The objects were analysed with mapping XRF to identify the different types of metal threads used and reconstruct the original appearance of the embroidery. Digital microscopy was also employed to evaluate the morphology of the embroidery and provide a record of the current state of the decorated surface. Non-destructive, in situ dye analysis was also undertaken to narrow down the identity of the natural dyes used and identify the original colour of the objects (Fig. 18).

Fig. 18. Details of T.52–1954; left purse, and right – pin cushion ©V&A

16th Century Burse T.40-1986.

Reconstruction of original composition and appearance of tarnished metal thread on an Elizabethan velvet burse used for the Great Seal of England, using a mixture of microdestructive and non-destructive techniques. The burse was analysed with mapping XRF to identify the different types of metal threads used and reconstruct the original appearance of the metal embroidery and identify later repairs and interventions the XRF results. Digital microscopy was also employed to evaluate the morphology of the embroidery and the state of the underlying textile and provide a record of the current

state of the object's surface. Non-destructive, in situ dye analysis was also undertaken to narrow down the identity of the natural dyes used for the textile fabric used underneath the embroidery (blue and red colours can be currently discerned upon close inspection) (Fig. 19).

Fig. 19. Image of an Elizabethan burse (T.40–1986) burse at V&A©

5 Colour Change in Photo/Film Collections

Two early photographic and cinematography processes were chosen for investigation: the **autochrome** and **lenticular Kodacolor**.

5.1 Autochrome

The autochrome is considered the first commercially successful colour photography process. Patented in 1903 and released in 1907, the process was developed by the French Lumière brothers. The process comprises a glass plate, on top of which sits a colour filter made of microscopic starch granules dyed red, green, and blue and a panchromatic silver gelatin emulsion (Fig. 20). In the early twentieth century, the colour process was lauded for its faithful and natural production of colour [70].

Today, autochromes are held in a range of museum collections internationally. Among notable collections is the Victoria and Albert Museum, London, which holds over two thousand plates by noted practitioners. While rare and valuable, autochromes pose a number of conservation considerations for the contemporary museum as they are extremely light sensitive [67], and consequently, colours are prone to fading. In addition, autochromes can be damaged by a range of external factors, including humidity and moisture [68]. Some examples of degradation are reported in Fig. 21.

Fig. 21.Degradation phenomena affecting autochromes plates. Top row: Unknown, Broadstairs Beach, c.1910, autochrome, RPS.699–2020; F A Paneth, 'Vierwaldstättersee', c.1927–8, autochrome, RPS.722–2020. Lower row: Hugh C. Knowles, Still life with flowers, c.1910, autochrome, RPS.529–2020; John Cimon Warburg, 'Melisande in the Wood', 1909, autochrome, RPS.1201–2020; Bernad Alfieri Senior, Portrait of artist's wife and son, c.1910, autochrome, RPS.697–2020. All© Victoria and Albert Museum. The Royal Photographic Society Collection at the V&A, acquired with the generous assistance of the National Lottery Heritage Fund and Art Fund.

Fig. 20. Left: F. A. Paneth, *Sils: Eva and Heinz at Muotathal in the Engadine,* 1927, Victoria and Albert Museum, RPS.853–2020 © Victoria and Albert Museum, London. Right: layered structure of the autochrome [66].

Fig. 21. Degradation phenomena affecting autochromes plates. Top row: Unknown, Broadstairs Beach, c.1910, autochrome, RPS.699–2020; F A Paneth, 'Vierwaldstättersee', c.1927–8, autochrome, RPS.722–2020. Lower row: Hugh C. Knowles, Still life with flowers, c.1910, autochrome, RPS.529–2020; John Cimon Warburg, 'Melisande in the Wood', 1909, autochrome, RPS.1201–2020; Bernad Alfieri Senior, Portrait of artist's wife and son, c.1910, autochrome, RPS.697–2020. All © Victoria and Albert Museum. The Royal Photographic Society Collection at the V&A, acquired with the generous assistance of the National Lottery Heritage Fund and Art Fund.

5.2 Colour Fading

Dye fading is a typical type of degradation affecting autochrome plates [68]. It has been determined that the colour mosaic is light-fast while the photographic emulsion is

comparably more stable. As a result, prolonged exposure to intense illumination causes a loss of colour vibrancy in autochrome plates, sometimes shown as complete fading, or a browning of the dyes, known as tanning'. While the dye particles alter, the silver particles remain preserved. An approach to the digital restoration of faded autochromes is presented. The restoration approach adopts spectral imaging techniques aiming to separate the information corresponding to the two overlapping elements of the plates as depicted in Fig. 22. The dyes constituting the colour mosaic are transparent in the near infrared (NIR), while the absorbance of the silver-based photographic image extends in this electromagnetic region. Therefore, capturing an image of the autochrome plate in the infrared allows for the preservation of the photographic image without the colour mosaic absorption [BHJ∗].

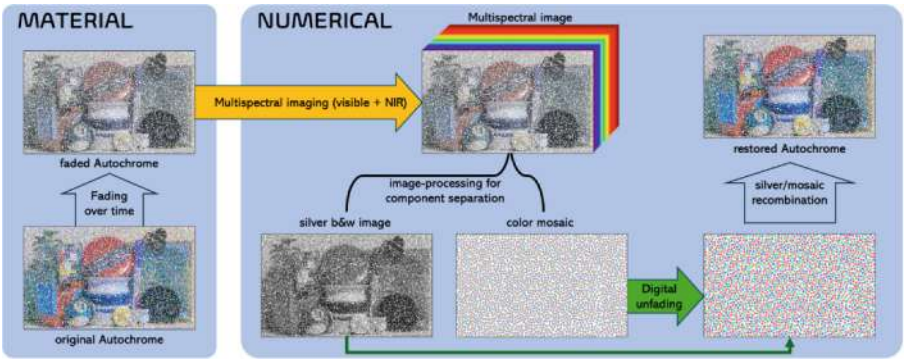

Fig. 22. Illustration depicting the proposed approach for the digital restoration of faded Autochromes

A hyperspectral scan of the plate is conceived to capture the full transmittance information of the colour image in the visible range [69]. An image-processing technique will be developed that combines the information of the NIR image and the hyperspectral cube thus obtaining the transmittance information of the sole colour mosaic. The absorbance of the faded colour mosaic can then be numerically increased to reinstate its supposed original colour. By recombining the restored mosaic and the photographic image a digital representation of the unfaded autochrome can be displayed. PERCEIVE envisions prototypes that introduce a novel approach to exhibiting historical artworks affected by the passage of time. These prototypes provide viewers with a deeper understanding of the restoration process, particularly when it remains faithful to the original. The aim is to emphasise that restoration is an act of care, intended to preserve the artist's original intentions without misrepresentation. This is particularly important because recent projects in early colour photography often involve digital alterations to the plates, such as smoothing or saturating images and colours, which can result in a departure from the faithful representation of the original objects. The use of transparency and transparent materials was favoured by several artists in the early 20th century, such as László Moholy-Nagy (1895–1946), Marcel Duchamp (1887–1968), and John Cage (1932–1992), Fig. 23, who used transparency to create counterpoints between diverse layers of content. As a layering scenario is inherent in the autochromes, it seemed natural to pick up on the use of

layered transparency in the history of art and apply that knowledge to the presentation of autochromes, which would allow the visitor to differentiate between the present and the restored state of an autochrome (Fig. 24).

This presentation also highlights the role of technology in the creation of artworks and how they are affected by the passing of time, allowing viewers to see the condition they were in at the time of their creation. In case of colour fading this concept would translate in creating a layer replicating the silver black-and-white image, a layer replicating the faded mosaic, and a third one replicating the restored mosaic. To convey this, a physical exhibition prototype will arrange the layers in a stack, allowing visitors to observe their see-through combination from a specific viewing point. Substituting the faded mosaic with the restored mosaic creates an experience that vividly demonstrates the layer structure of an autochrome. This tangible representation showcases the fragility of the dyes and highlights the extensive effort involved in restoring the image to its original appearance. The use of a physical presentation model can be seamlessly integrated with digital interactions. This hybrid approach enhances the transfer of knowledge and prevents virtual fatigue, aligning with the latest innovations in dissemination. If the replicas of the autochrome elements on transparent layers are magnified compared to the actual dimensions of the plate, the experience will be more effective in conveying the message This magnification will make the potato starch granules visible to the naked eye (see above). The prototype will be also used to present the digital restoration process that generated new image content to impaint parts where the emulsion was lost. The viewing setting is depicted in the following image (Fig. 25).

Fig. 23. An image of John Cage's artwork "Not wanting to say something about Marcel Duchamp".

Kodacolor

Some of the first home movies shot in colour used a 16mm lenticular film produced by Kodak from 1928 to the late 1930s. This very special film stock called Kodacolor is embossed with an array of hundreds of vertical cylindrical lenses that allowed recording colour scenes on a black-and-white panchromatic silver emulsion (Fig. 26). A considerable amount of surviving lenticular films is today hidden. As a matter of fact, lenticular film appears like a 'normal' black-and-white film at first quick look, so many lenticular

Fig. 24. Image created with Adobe Firefly using the prompt "Museum visitor in a dim environment looks through a transparency that contains a sharp mosaic of red, green and blue circular colour elements randomly arranged. Let's look at the visitor from the other side of the transparency."

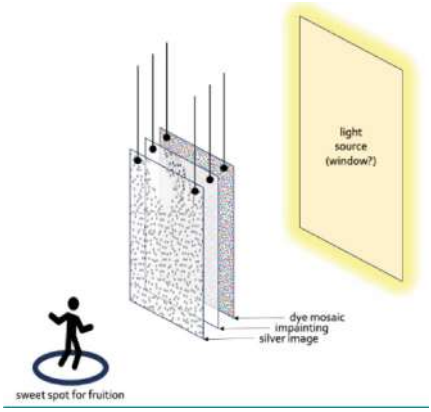

Fig. 25. Viewing setting for autochrome physical exhibition prototype

films have most likely been misclassified by collectors who will need further training to identify them correctly. It is therefore important to revive awareness of the lenticular colour processes thus making these precious historical colour movies available again to the public and securing them for posterity.

The original way to display lenticular Kodacolor consisted of special projection equipment with a tripartite red-green-blue filter that allowed the magnified colour picture to appear on the screen. Today this type of display is outdated. We are currently addressing this issue of technological obsolescence for Kodacolor. There are multiple possible methods to extract the colour information from the film images. Scanning the silver emulsion in high-resolution and letting software extract the encoded colour information represents a modern, efficient method to obtain digital colour images from these historical motion pictures (Fig. 27).

In this context, a new approach based on artificial intelligence has been demonstrated to be more efficient for the localization of the lenticular screen than other previous methods [70]. The results of the state-of-the-art solutions for the colour reconstruction of lenticular film are good. However, some improvements are still necessary. PERCEIVE aims to remove the residual artefacts by improving the quality and dimension of the labelled database, including lenticule warping/curvatures in the data augmentation, treating data as video sequences instead of individual frames, designing a "feedback loop" for data labelling using IQ metrics.

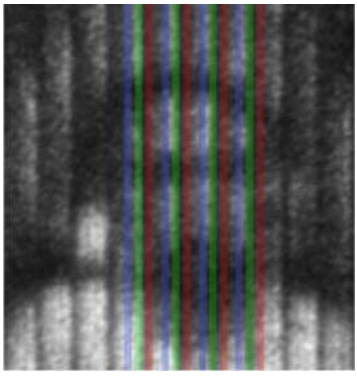

Fig. 26. Spatial colour encoding on black-and-white photographic emulsion in lenticular film

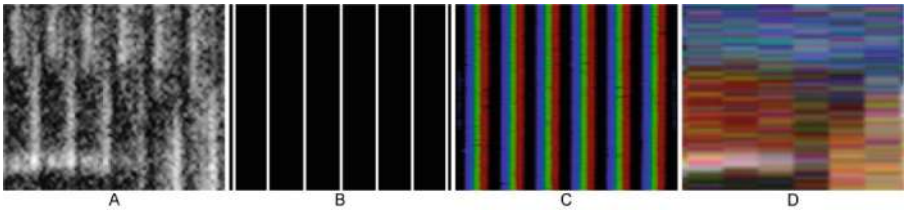

Fig. 27. Digital colour reconstruction process for a tiny fraction of a lenticular image – A: The input black-and-white image

6 Born Digital Art

Born Digital Art represents a transformative shift in contemporary artistic creation. Artists now employ advanced software and coding tools to conceive and realize works entirely within the digital realm. This emerging art form encompasses a wide range of media, including digital painting, three-dimensional computer-generated imagery, virtual and augmented reality experiences, and interactive installations. Defying traditional boundaries, Born Digital Art offers a dynamic and participatory canvas—one that is amplified by its global accessibility. A notable subset of this field, Augmented Reality (AR) art, seamlessly integrates digital content with the physical world, providing audiences with immersive and interactive experiences through AR-enabled devices.

However, the preservation of born-digital artworks poses a significant challenge due to the rapid pace of technological change. Ensuring their long-term accessibility and authenticity requires innovative conservation strategies and adaptive methodologies. Within this context, the PERCEIVE project, part of the European Horizon initiative, is devoted to advancing our perceptual understanding of colour in cultural heritage through the use of emerging technologies. Its primary aim is to develop new approaches for perceiving, preserving, curating, exhibiting, and understanding both historical coloured collections and contemporary digital artworks.

Nonetheless, the preservation of born-digital art remains a formidable challenge, given the rapid pace of technological evolution in the digital sphere. Addressing this issue requires innovative strategies to ensure the longevity and accessibility of these ever-evolving digital masterpieces. The PERCEIVE project, under the European Horizon initiative, is dedicated to advancing our perceptual understanding of colour in cultural heritage through the use of emerging technologies. Its primary goal is to pioneer new approaches for perceiving, safeguarding, curating, exhibiting, and interpreting both historical coloured collections and contemporary digital artworks, thereby fostering renewed public engagement.

By presenting case studies that exemplify artworks conceived within the digital realm and intrinsically linked to the technologies of their creation, PERCEIVE expands its scope to encompass current forms of cultural expression. This perspective invites a deeper reflection on the evolution and continuity of modern art, highlighting the new and dynamic roles that artists and conservators must assume to preserve born-digital works, sustain a living cultural narrative, and safeguard historical continuity.

Shaw 54th Memorial: At Home

The AR Work "Shaw 54th Memorial: At Home" is an innovative Augmented Reality (AR) experience that brings this iconic public artwork into people's homes, enabling remote accessibility through the Hoverlay app. The experience features a three-dimensional reproduction of the memorial accompanied by four holographic narratives that enhance public engagement in a novel and educational way. This work presents a groundbreaking approach to AR art by challenging the conventions of traditional exhibition spaces and expanding its reach to a broader audience. Through its interactive and immersive storytelling, Shaw 54th Memorial: At Home redefines the use of AR as an educational tool, transforming historical narratives into participatory experiences. In times when physical museum visits may be limited, it enriches the home-based encounter with art, emphasizing its capacity to transcend physical boundaries and adapt to our changing world. (Fig. 28).

MetroNeXt+

MetroNeXt+ is a groundbreaking Augmented Reality (AR) journey that virtually connects the bustling heart of New York City with the charming streets of Zurich (Fig. 29). The project transcends physical boundaries, inviting participants to explore Zurich's architecture, arts, sciences, and lifestyle—all from the iconic Grand Central Terminal. Employing cutting-edge 2D and 3D graphics alongside innovative photogrammetry technology, this immersive experience merges floating Platonic and Archimedean solids with 3D models of Zurich's old town, creating a symbolic and experiential bridge

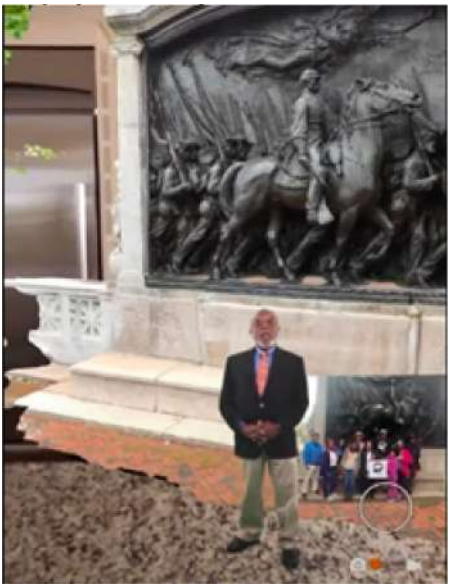

Fig. 28. Shaw & 54th Regiment Memorial: An Augmented Reality Experience – Delve into a digital replica of the iconic Boston Common monument, featuring four accompanying holographic stories. Presented by Hoverlay in collaboration with the National Park Service and the Friends of the Public Garden.

between the two cities. A collaboration between Digital Art Weeks, Virtuale Switzerland, and ETH Zurich, MetroNeXt+ fuses art, technology, and culture to foster a new kind of transatlantic dialogue. It pioneers the concept of virtual transatlantic travel, allowing visitors to move seamlessly from Grand Central Terminal to Zurich's streets within a shared hybrid space that unites the physical and digital realms. By offering an immersive insight into Zurich's culture, the project promotes cross-cultural exchange and dialogue. Its innovative inclusion of a physical subway entrance introduces a "phygital" dimension—blending tangible architecture with virtual experience—to create an exhibition design that transcends the purely digital sphere. Through this approach, MetroNeXt+ redefines how technology, art, and cultural exploration intersect, using photogrammetry to enhance its digital artistry while anchoring the experience in a physical context.

Bring The Greenway Home.

The work "Bring The Greenway Home" is a groundbreaking Augmented Reality (AR) project that transforms your living room or outdoor space into a dynamic AR gallery. Using the Hoverlay app, you can explore historic images of Boston's Greenway corridor while learning about the city's transformation and park's creation (Fig. 30). Contemporary artworks can be experienced at home, and you can share your discoveries through inapp photos and videos. Through a collaboration between the Greenway Conservancy, Boston Cyberarts, and Hoverlay, this initiative reimagines the possibilities of public art and technology. It bridges history, art, and digital innovation, inviting you to explore a century of growth and change along the Rose Kennedy Greenway. The innovation in the "Bring The Greenway Home" project lies in its ability to seamlessly merge art,

Fig. 29. MetroNeXt +: An AR journey from NYC to Zurich, blending 2D/3D graphics and photogrammetry. Presented by Digital Art Weeks, Virtuale Switzerland, and ETH Zurich, it redefines cultural exchange.

history, and technology into the everyday spaces of the public. This project breaks free from the confines of traditional gallery settings by utilizing Augmented Reality (AR) to transport the iconic Greenway corridor directly into people's homes or backyards. It offers a unique educational experience through interactive holographic stories that delve into historical imagery and contemporary art. Beyond expanding accessibility and engagement, this initiative redefines the use of AR as an educational tool and demonstrates the potential for public art to adapt to the ever-changing world. The project's pioneering spirit is in using technology to bring art, history, and community into our personal spaces.

Fig. 30. "Bring The Greenway Home": An AR experience bringing Boston's historic Greenway corridor into your living space. Presented by the Greenway Conservancy, Boston Cyberarts, and Hoverlay, it merges art, history, and technology for an immersive educational journey.

6.1 Objectives

Many colour calibration tools and methods are designed for either analogue (print) or digital (screen) applications. Achieving a perfect match between analogue and digital

colours remains challenging due to the inherent differences between these two media. By developing exhibition scenarios that juxtapose analogue and digital colour, it becomes possible to raise awareness of the challenges involved in achieving accurate colour calibration between real and virtual assets that share common colour palettes. This approach also supports the implementation of a colour-managed workflow—one that maintains visual consistency between the perceived colours of physical objects and their digital representations on AR-enabled devices.

To further enhance the AR experience and enable material and texture adjustments on 3D models, one of the project's objectives is to integrate support for the open-source glTF KHR_materials_variants specification. This integration allows 3D models to store multiple colour renderings and lighting conditions, enabling creators to explore how time, context, and restoration processes affect the visual appearance of cultural artefacts.Once this specification is incorporated into the Hoverlay AR Framework, artists will be able to employ dynamic texture adaptation, ensuring visual coherence in real-world settings where light intensity and quality change over time. This technology benefits not only artists but also museums, offering new possibilities for curatorial practice and the presentation of AR artworks in indoor environments.

Because many AR artworks are site-specific and typically displayed outdoors, there is strong interest in "bringing the outside inside." To achieve this, the project proposes the creation of a Reality Reflectance Bubble—a digital environment that replicates the external site where an artwork is intended to be viewed. This feature would allow artists to test or present AR artworks within a lifelike simulation while enabling museums to exhibit site-specific works within their own spaces. The Reality Reflectance Bubble concept would also rely on the glTF KHR_materials_variants specification, ensuring that the virtual textures dynamically respond to the lighting conditions of the outside world, thereby making indoor exhibitions of site-specific AR artworks possible.

6.2 Challenges

The preservation of digital art has long posed a recurring challenge across artistic disciplines. In the case of electronic and digital media, a central question arises: can a viable long-term conservation strategy truly exist? The answer is complex—while some works can be preserved, others inevitably cannot. This dilemma stems from the dependence of electronic art on the continued availability of the technologies used for its creation and display, or on the artist's provision of sufficient documentation to enable faithful re-creation with contemporary tools once the original equipment becomes obsolete. Whereas an artwork carved in stone can endure for millennia and a painting for centuries, digital and electronic works have a far shorter lifespan due to their reliance on fragile, fast-evolving technologies that often become irreparable or unsupported. This reality raises a profound question about the meaning and feasibility of preserving digital art. Yet, the alternative—allowing such works to disappear—is equally untenable. Maintaining a historical record of each generation's digital cultural expression is essential to prevent enduring gaps in the collective memory, ensuring that future audiences can access and understand the creative heritage of the digital age.

6.3 Case Studies

The following case studies exemplify the impact of colour and transparency in Augmented Reality (AR) artworks, each illustrating how digital aesthetics, technological innovation, and conceptual meaning intersect within the contemporary art context. Together, they highlight the transformative power of AR in shaping perception and in redefining the relationship between the physical and virtual worlds.

"Dante's Inferno" by Mark Skwarek.

Crystal Coffin reinterprets the historical display of Mao Zedong's crystal coffin on Tiananmen Square, transforming it into a virtual meditation on power, history, and ideology. Within the virtual "China Pavilion," designed to reflect state-sanctioned architectural forms, the artists invite viewers to question how political symbolism persists in the digital era. The AR installation employs high-transparency glass textures that simulate realism—viewers can perceive Mao's body through a convincingly translucent surface, while light and reflection reveal the illusory nature of authority itself. By merging simulated realism and historical critique, *Crystal Coffin* exemplifies how transparency functions both as a visual and ideological device.

Fig. 31. Dante's Inferno; Artist: Mark Skwarek; Date of Creation: 2013; Transparency Use: Environmental Masking; Intended Setting: Any public square

The AR Artwork "Crystal Coffin".

Crystal Coffin reinterprets the historical display of Mao Zedong's crystal coffin on Tiananmen Square, transforming it into a virtual meditation on power, history, and ideology. Within the virtual "China Pavilion," designed to reflect state-sanctioned architectural forms, the artists invite viewers to question how political symbolism persists in the digital era. The AR installation employs high-transparency glass textures that simulate realism—viewers can perceive Mao's body through a convincingly translucent surface, while light and reflection reveal the illusory nature of authority itself. By merging simulated realism and historical critique, *Crystal Coffin* exemplifies how transparency functions both as a visual and ideological device (Fig. 32).

Simulated Realism; Intended Setting: Any public square

Fig. 32. Crystal Coffin; Artist: Lily & Honglei; Date of Creation: 2014; Transparency Use:

"Ecce Homo".

Ecce Homo is an AR artwork that merges self-portraiture, colour theory, and cosmology. The piece presents a floating self-portrait of the artist divided into eight cubes arranged as a three-dimensional cross, with intersecting red and blue lines symbolizing the connection between humanity and the cosmos. Through the use of transparency dimensionalization, overlapping colours and textures generate depth and motion, extending the artwork into a fourth-dimensional experience. The work challenges the boundaries between digital representation and metaphysical exploration, prompting viewers to contemplate human identity within the digital continuum. (Fig. 33).

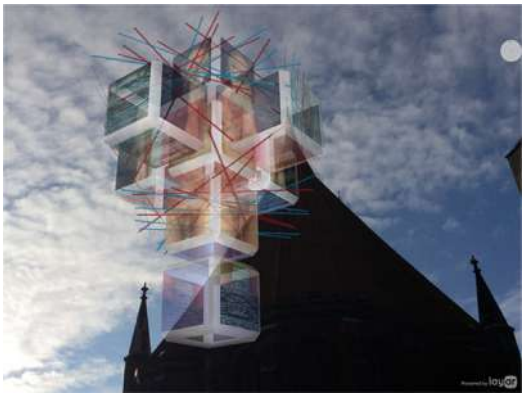

Fig. 33. Ecce Homo; Artist: Arthur Clay & Ingo Lie; Date of Creation: 2017; Transparency Use: Dimensionalization; Intended Setting: Am Markte, Hannover, Germany

The AR Artwork "Ascension of Cod".

Ascension of Cod reflects on the ecological and historical significance of the Massachusetts Bay cod, once central to the region's economy and culture. In this AR experience, a virtual school of codfish ascends through the air like a column of light, symbolizing both reverence and loss. The artwork employs transparency fading to blend digital fish seamlessly with the real environment, allowing natural light to affect their coloration and movement. This dynamic interaction between virtual and ambient light deepens the conceptual duality of the piece—celebration and mourning—while emphasizing the fragility of ecological balance.(Fig. 34).

Fig. 34. Ascensions of Cod; Artist: Will Pappenheimer; Date of Creation: 2014; Transparency Use; Transparency Fading; Intended Setting: Any public square

The AR artwork "The Coming of a New Dimension".

The Coming of a New Dimension draws inspiration from Kurt Vonnegut's fictional *Tralfamadorians*, beings capable of perceiving reality in four dimensions. In collaboration with Virtuale Switzerland, the artist translates this concept into an AR "time capsule" that transitions between day and night, immersing viewers in a temporal journey. Using *transparency layering*, the capsule's textures shift through three stages: 90% transparency during daylight, 50% during transition, and 0% at night. This technique visualizes the passage of time and space travel from Earth to deep space, transforming the experience into a poetic meditation on perception, existence, and the limits of human understanding. (Fig.35)

Conclusion

Collectively, these case studies demonstrate the potential of AR art to merge material and immaterial realities. Through transparency, reflection, and light adaptation, each work redefines how digital art engages perception and meaning. The integration of these principles within the PERCEIVE project highlights how technological innovation can serve both artistic expression and cultural preservation, reinforcing the dialogue between contemporary creation and the enduring challenge of authenticity in the digital age.

Fig. 35. The Coming of a New Dimension; Artist: Arthur Clay; Date of Creation: 2014; Transparency Use: Texture Gradience; Intended Setting: Hannover trade fair site

Acknowledgments. This study was funded by the PERCEIVE project, which received funding from the European Union's Horizon research and innovation programme under grant agreement No. 101061157.

Authors' Contribution. Cristiana Barandoni, Roberta Iannaccone, Donata Magrini, Sophia Sotiropoulou contributed to Section 1; Irina Crina Anca Sandu, Cristiana Barandoni, Letizia Monico contributed to Section 2; Lucia Burgio, Brenda Doherty, Hartmut Kutzke contributed to Section 3; Giorgia Trumpy; Catlin Langford, Lucia Burgio, Arthur Clay contributed to Section 4; Arthur Clay, Chiara Gemma Fedon and Dario Lanfranconi contributed to Section 5.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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