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Perceptive Enhanced Realities of Coloured Collections through AI and Virtual Experiences

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Abstract

PERCEIVE (Perceptive Enhanced Realities of Coloured Collections through AI and Virtual Experiences) is an European project dedicated to the study, analysis, interpretation, reconstruction, conservation and communication of colours in artworks and historical objects, within five different scenarios, including: lost polychromy of ancient sculptures, fading colours of paintings and works on paper, fading of textiles, historical photo and film collections, and of colours of digital born art. This paper describes the overall methodology and presents the main results beyond the state-of-the-art.

CCS Concepts

• Human-centered computing → User interface toolkits; Empirical studies in HCI; • Computer systems organization → Neural networks; • Computing methodologies → 3D imaging;

1. Introduction

The PERCEIVE project (Perceptive Enhanced Realities of Colored Collections through AI and Virtual Experiences), funded under the Horizon Europe programme (Grant Agreement No. 101061157: `www.perceive-horizon.eu`), addresses a long-standing challenge in Cultural Heritage (CH) conservation and communication: the fragility, loss, and misrepresentation of colour in artefacts. Many historical works—ranging from polychrome sculptures and frescoes to textiles and early photography—have suffered irreversible colour degradation due to time, environmental factors, and material instability. This degradation not only affects their aesthetic and symbolic value but also leads to the misunderstandings of their original meaning and historical context.

Colour plays a central role in our perception, interpretation, and emotional engagement with CH. However, the impact of colour changes is often seen as secondary, despite many colourants' susceptibility to fading or alteration. Furthermore, current digital reconstructions often fail to authentically represent historical chromatic appearance, due to the lack of integration between conservation science data, iconographic references, and rendering technologies. As a result, culturally significant narratives may be distorted—such as the persistent myth of "white antiquity" rooted in the loss of polychromy on classical sculptures [ABN*25].

PERCEIVE tackles this critical issue by proposing an innovative, interdisciplinary and ethically grounded approach to the digital reconstruction, simulation, and communication of colour in cultural artefacts. It focuses on improving both the scientific understanding of material appearance changes over time and the capacity to accurately and engagingly represent these phenomena in digital formats (e.g., virtual, augmented, and mixed reality experiences).

PERCEIVE's objectives include:

- *Scientific Modelling and Prediction of Colour Changes*: Developing advanced models for understanding how colours fade or transform, integrating material analysis, environmental factors, and mock-up studies to inform predictive simulations.
- *AI- and IBR-Powered Reconstruction and Rendering*: Employing neural rendering, image-based techniques, and hybrid data-driven and physics-based models to simulate original colour appearance and predict future deterioration.
- *Data Integration and Knowledge Representation*: Creating a robust Knowledge Repository that aggregates and manages scientific, visual, historical, and iconographic data on colour, ensuring transparency and reusability.
- *User-Centred Digital Experiences*: Designing interactive and inclusive experiences for experts, educators, and the general public, using XR technologies to develop authenticity, and to foster

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sense of care, curiosity and engagement towards colour-related heritage phenomena.
- *Methodological and Ethical Guidelines*: Defining replicable and ethically aware protocols for the visualization and communication of digital colour reconstructions in physical exhibitions and digital contexts.

PERCEIVE applies its methodology to five representative scenarios:

S1: Lost polychromy in ancient statues and architecture
S2: Colour change in paintings and works on paper
S3: Colour fading in textiles (e.g., garments)
S4: Colour degradation in historical photographic and filmic collections
S5: Exhibition of born-digital art in XR settings.

These scenarios are used not only to guide technical development but also to tailor the platform's tools and services to the specific needs of museum professionals, researchers, educators, and creative industries.

The project is expected to complete and deliver, before January 2026, a suite of tools, services, and digital products, currently under development, including:

- PERCEIVE Platform: A modular, service-based infrastructure combining neural rendering, data processing, simulation tools, and user interfaces.
- PERCEIVE Tools, Services and API: Accessible instruments for integrating colour reconstructions into curatorial workflows or creative applications.
- PERCEIVE Knowledge Repository: A curated, FAIR-compliant digital resource hosting data, models, and metadata for reuse in research and conservation.
- PERCEIVE Experience Prototypes: Multimodal XR experiences that communicate colour-related research to diverse audiences.
- Methodological Guidelines: visual and technical guidelines for colour study, simulation, representation and restoration in cultural heritage contexts.

Through these integrated outputs, PERCEIVE contributes to redefining how coloured artefacts are studied, interpreted, and exhibited in physical and digital environments, in more sustainable, accessible, and accurate practices, while also fostering inclusive narratives that reflect chromatic and cultural diversity.

The *PERCEIVE* project is supported by a multidisciplinary consortium of 12 partners, including leading research institutions, universities, museums, and SMEs. This collaborative framework enables a comprehensive and integrated approach to the analysis, reconstruction, and communication of colour in cultural heritage.

The **Consiglio Nazionale delle Ricerche (CNR)**, coordinates the project through its Institute of Heritage Science (ISPC) and Institute of Chemical Sciences and Technologies (SCITEC). These institutes contribute advanced expertise in non-invasive diagnostics, 3D modelling, and interactive media. The **Foundation for Research and Technology – Hellas (FORTH)**, participates in PERCEIVE with the Institute of Electronic Structure and Laser (FORTH-IESL) / group of Photonics in Heritage Science and the Institute of Computer Science (FORTH-ICS)/ Computational Vision and Robotics Laboratory (CVRL). FORTH contributes to the development of the service-based, user-centric PERCEIVE infrastructure, as well as a number of tools and services that optimise the integration and accessibility of data, resources, instruments, simulations and reconstructions for reuse.. The **Fraunhofer Institute for Computer Graphics Research (IGD)** in Germany provides cutting-edge solutions in visual computing, focusing on AI-enhanced rendering, computer graphics, and immersive simulation technologies tailored for cultural heritage applications. The **Norwegian University of Science and Technology (NTNU)** participates through its Colourlab at the Department of Computer Science, offering key expertise in material appearance modelling and colour change prediction. Cultural institutions in the consortium include the **National Archaeological Museum of Naples (MANN)**, the **MUNCH Museum** in Oslo, the **Victoria and Albert Museum** in London, and the **Art Institute of Chicago**. These museums provide access to unique collections and conservation challenges, supporting the real-world validation of PERCEIVE's tools and methodologies. Innovation and design expertise is contributed by creative industry partners such as **ANAMNESIA**, with extensive experience in exhibition design and multimedia production, and **IMKI**, specializing in virtual and simulated reality applications. The **Lucerne University of Applied Sciences and Arts (HSLU)** contributes through its Immersive Realities Research Lab, focusing on the design and evaluation of user-centered XR and hybrid experiences in cultural contexts. Together with CNR, ANMNESIA and IMKI, HSLU is also involved in the implementation of interactive prototypes. Together, this consortium forms a network of scientific, technological, and cultural expertise, enabling PERCEIVE to pioneer new approaches to preserving and reimagining the colours of our shared heritage.

2. Technologies for Colour Reconstruction and Simulation

PERCEIVE has worked extensively in the development and improvement of technologies to improve Heritage Science and Computer Graphics, based on traditional Image-Based Rendering (IBM) techniques, supported, where possible, by Artificial Intelligence (AI).

2.1. State of the Art: Virtual Reconstruction of Colour in Cultural Heritage

The analysis, understanding and digital reconstruction of colour in CH has advanced significantly in recent years, yet it still poses complex scientific and technological challenges. Traditional IBR techniques have long been used to capture and replicate surface textures and geometries but often fall short in reconstructing altered or lost chromatic information—particularly when the original colour is no longer visible to the naked eye. The traces of surviving pigments on ancient statuary are so minimal that they do not allow for a solid reconstruction of the original colour's extent, nor do they enable the determination of its composition. The scarcity of traces of original polychromy must also be carefully evaluated from the perspective of their state of preservation; it is well know that surface deterioration, defects or deposits can significantly alter our perception of the object. Moreover, most current digital reconstructions do not account for the full range of material properties, including gloss, translucency, or interaction with light (e.g. absorption and scattering coefficients), and the change of these properties over time, which are critical for accurate appearance modelling.

In the field of colour analysis, many scientific methods, including multispectral and hyperspectral imaging (MSI and HSI), X-ray fluorescence (XRF), fiber-optic reflectance spectroscopy (FORS) and micro-fadeometry (MFT), have been increasingly used to investigate the compositions and light sensitivity of pigments and colourants. However, these data often remain under utilised or overlooked in the generation of digital reconstructions, due to a lack of integration between conservation science and computer graphics. Efforts such as the Tracking Colour project, the APPEAR project by the Getty Conservation Institute, and the MANN in Colours [Bar19b] [Bar19a] initiative have emphasized the importance of integrating scientific evidence with historical iconography, textual/archival sources, and mock-up design and experimentation to inform colour reconstruction.

Beyond scientific research on paint materials and their chemical composition, it is essential to have the support of primary sources, namely iconographic references, written documentation, and ancient literature, to establish a comprehensive framework. Iconography itself is a precursor to defining the areas to be investigated using multimodal analytical approach. Therefore, a successful approach to digital colour restoration must be interdisciplinary, evidence-based, and transparent about the assumptions underlying colour visualizations.

2.2. PERCEIVE Platform: Tools, Services and Knowledge Infrastructure

To address these limitations, PERCEIVE has developed a modular technological infrastructure that combines advanced AI techniques, data-driven modeling, user-centered tools, and a comprehensive knowledge repository. This integrated system is articulated through several core components:

AI-Powered Rendering Pipeline: PERCEIVE leverages a hybrid AI architecture combining Generative Adversarial Networks (GANs), neural radiance fields (NeRF), and differential rendering for photorealistic reconstruction of coloured artworks. These methods can operate with partial data and are trained to infer plausible chromatic states using both real and synthetic data [SKK*24].

Material Appearance Modeling: For "S1", Lost Polychromy, a pipeline was implemented to obtain a material appearance palette. Based on analytical data obtained from selected sculptures, the presence and composition of pigments were accurately located and identified. These findings informed the design of a series of mock-ups, which were developed using fabrication methods derived from both literary sources and ancient recipes. In constructing these mock-ups, several parameters were carefully considered, including the type of marble, the specific pigments and their mixtures, the binders, the ground layers, and the number of application layers. Once fabricated, the mock-ups were analyzed using a multi-angle spectrophotometer to measure their spectral reflectance and capture texture images. These measurements were subsequently used to model the spatially varying bidirectional reflectance distribution function (SVBRDF) using Pantora software, enabling a detailed reconstruction of the surface appearance characteristics. The SVBRDF is then used to create custom shaders which can be applied to 3D models, creating proposed, feasible appearances of polychrome sculptures (Fig. 1).

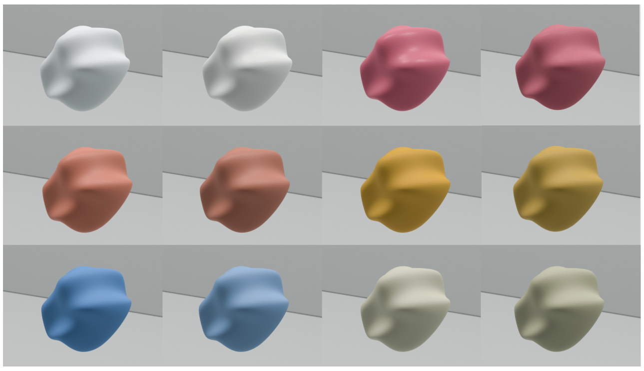

Figure 1: *Example of shaders obtained from mock-ups*

Tools and Services: The PERCEIVE Platform (see Fig. 2) includes various services and tools that communicate through a shared microservice architecture and are orchestrated via the PERCEIVE API, which ensures consistent access, authentication, and data exchange:

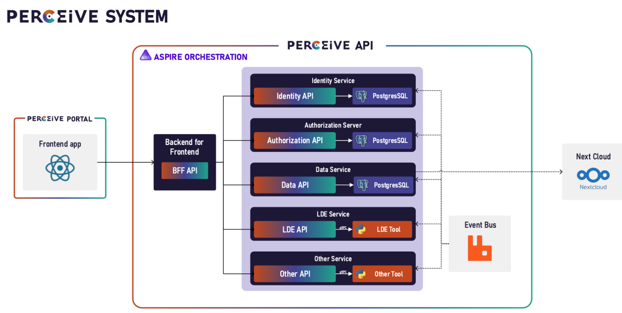

Figure 2: *Diagram of the PERCEIVE Platform, showing the overall structure of the system and its interaction with the front-end, the tools as well as the NextCloud repository.*

- *Colour Reconstruction, Regeneration, Prediction Service*. In PERCEIVE, we approached the problem of colour restoration both from a physically based perspective and a data-driven manner. Mockups that imitate the materiality of the artworks in our scenarios were created, and measured, so that we have the coordinates of the reference colours of the original materials. Then, in the pursuit of unfading, we replaced the colours of the current state with the reference original colours. Prior to the colour replacement, a segmentation step was performed, in order to locate each distinct material on the surface of the artwork. The segmentation was fulfilled either with spectral unmixing techniques, arithmetic operations in the image domain, or atlas-based segmentation in the 3D domain, depending on the available data. in some cases, the application of data-driven models, without the

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need of mockup creations, was sufficient. For instance, the degreening tool is based on an AI-model that learned to separate between the characteristics of an autochrome with greening artifacts from an autochrome without greening artifacts, from examples of images from each class.

- *Light Damage Estimator*. The Light Damage Estimator is a tool that enables researchers and museum professionals to estimate, predict, simulate and visualise possible long-term changes in the appearance of an object due to the effect of prolonged exposure to light of the photosensitive components of the object. It offers a simple risk assessment method for preventing colour changes in paintings or other coloured objects exposed to light under different lighting scenarios. It takes into account the spectral emission profile of a selected light source and available data on the colour change behaviour of the photosensitive materials/pigments mapped in areas of interest on a given object [SMR*25]. The tool can be employed to customise lighting, with the specificities of individual works of art being taken into consideration, by selecting a type of light source and defining safe limits of light exposure. The objective is to achieve a balance between minimum risk and optimal rendering of the object on display. The tool may also be employed for the purpose of experimenting with different lighting scenarios and assessing visually predicted long-term light-induced changes in the appearance of an artwork.
- *Web3D/WebXR multi-layer tool (MuLaX)* targeting S1, S2 and S3. This tool enables both experts and the public to interactively explore and analyze cultural heritage artefacts. It offers interactive inspection of 3D models enriched with analytical data from archaeometric surveys, revealing detailed insights into the surviving traces of ancient polychromy on marble surfaces. Built on the open-source ATON framework [FFD*21], MuLaX supports the interactive exploration of scientific analyses through an annotation system for point-based data (e.g., microscopy, XRF, and FORS), as well as multi-layer discovery of imaging techniques such as VIL and UVL. Such a Web3D tool is cross-device (from mobile up to XR devices) ensuring broad accessibility and compliance with modern web standards. MuLaX also explores dynamic image-based masking tools, enabling efficient annotation and semantic colour mapping. A first assessment was conducted using as a case study the statue of Venus in a Bikini (inv. no. 152798) from the National Archaeological Museum of Naples (from now on MANN), along with its associated diagnostic dataset.
- *Text-2-autochrome*. This tool (Fig. 3) leverages generative AI, specifically Low-Rank Adaptation (LoRA), to create synthetic autochrome images from textual descriptions. This method preserves the historical colour fidelity and aesthetic qualities of original autochromes, enabling users to generate personalized images while retaining their essence. User feedback suggests that the AI-generated autochromes evoke similar emotions and historical context as the originals, although there are areas for further refinement in authenticity. By providing a fine-tuned model and an interactive demo, the tool empowers the community to generate images that evoke this nostalgic style, revitalizing the charm of autochromes. Additionally, the tool can create synthetic data that simulates common autochrome defects, such as greening, oranging, and emulsion cracking. This functionality supports the development of machine learning techniques aimed at repairing these defects, ultimately enhancing the quality of the generated images.

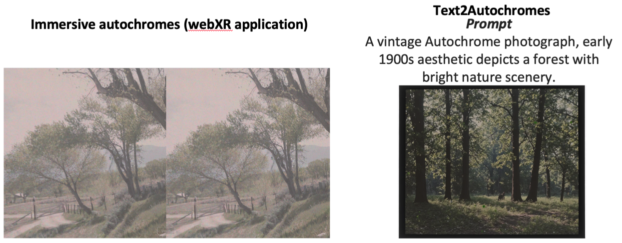

Figure 3: *Autochrome generation from textual description and also visualization of mono autochromes in VR*

- *Immersive Autochromes app*. The app (Fig. 3) leverages deep learning and VR to transform historical autochromes into immersive 3D experiences, enhancing their preservation and accessibility [SHC*25].
- *Degreening Tool*. The tool (see Fig. 4) automatically eliminates greening colour defects in digitized autochrome photographs. It employs synthetic data generation and a specialized loss function to efficiently restore images. While it effectively reduces noticeable defects, it may have difficulty accurately reproducing original colours, occasionally leading to bluish tones. To address this, degreened areas affected by green spotting defects can be colour corrected using inpainting with a fine-tuned diffusion-based model on a dataset of autochromes.

Figure 4: *Greening spotting removal using De-greening tool*

- *SIMTex*. The tool (see Fig. 5) facilitates the visualization of simulations of fugitive colours in historical textiles by allowing experts and lay audiences to explore various evidence sources such as spectral data, mockups, and reference images. It supports three modes of visualization: mockup appearance, spectral unmixing, and reference image data, enhancing understanding of colour changes over time. The segmentation atlas ensures that colour change simulations are applied accurately across the object's surface. Additionally, the application leverages advanced rendering techniques, providing a realistic and interactive experience for assessing restoration possibilities.

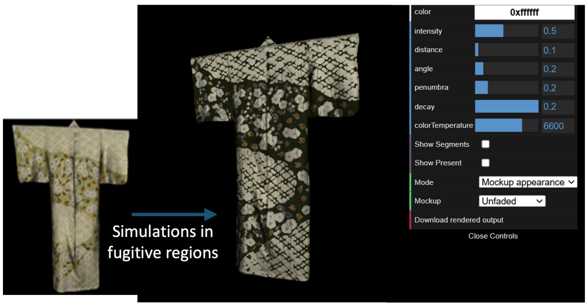

Figure 5: *Simulation of appearance and fading in fugitive areas using mockups, hyperspectral data or reference image. Photogrammetry images of the kimono © Victoria and Albert Museum/Kira Zumkley*

- *Semantic shading using AI methodology*: A hybrid pipeline combining computer graphics and AI [SKR*24] was employed to semantically stylize and shade various areas of S1 objects (see Fig. 6).

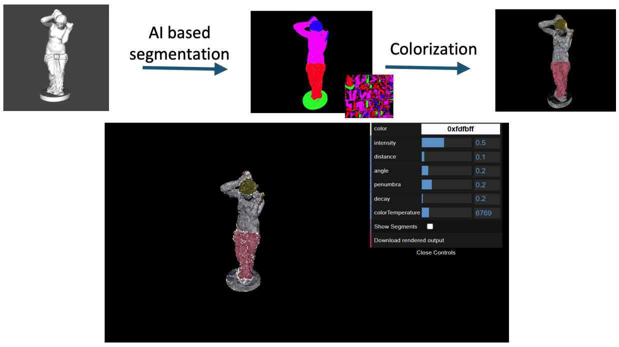

Figure 6: *Colourization of statues from mock-ups or reference images*

- *Hoverlay AR Artwork Migration and Playback Tool*. This tool provides a structured pipeline for migrating legacy AR experiences - originally authored on the LAYAR platform (`https://layar.eu/`) - into Unity and exporting them another platform (Hoverlay). The system parses LAYAR's MySQL-based data (POIs, object transforms, animations) into structured JSON, reconstructing an AR scene in Unity using a local coordinate anchor system. Animated, spatially organized experiences are rebuilt using Unity's Timeline and exported via the Hoverlay Digital Sequence Plugin. This integration enables accurate playback of time-based and geospatial AR artworks on mobile devices and AR glasses, ensuring long-term accessibility and portability of previously platform-bound content.

Colour Knowledge Repository. The Colour Knowledge Repository is designed to host all resources and datasets that contribute to the multidisciplinary knowledge of coloured heritage collections, reflecting the specific needs of the communities around PERCEIVE (for sharing, accessing and re-using data and metadata).

Figure 7: *Arthur Clay, Ingo Lie, "Ecce Homo", Am Markte, Hannover, Germany. Case study of PERCEIVE S5.*

Researchers and professionals are enabled to describe their data accurately and comprehensively with tailored metadata fields specific to colour themes, thus improving the discoverability and visibility of the resources. The system integrates different datasets, resources and content (historical, analytical, conservation, collection design and management) into a single repository so that they are available and accessible for immediate use and further processing by all stakeholders and target groups, such as researchers and scholars in different heritage disciplines, cultural heritage professionals and institutions, as well as students, educators and communication professionals. It is an open and scalable web-based platform (`https://perceive-data.iesl.forth.gr`) developed using InvenioRDM, an open-source research data management platform developed by CERN, which complies with Data Management Plans (DMP) and FAIR data principles in a controlled, scalable and interoperable environment. It also allows for customised license choices, access conditions and embargo policies according to project requirements. The Repository will grow during and beyond the PERCEIVE project to provide high quality, interdisciplinary content and services for enhanced research, innovation and collaboration across domains, opening opportunities for co-creation and community engagement. This technological architecture was designed not only for research and conservation, but also for public engagement and education. Museum professionals, scientists, educators, and creative practitioners can access tailored functionalities, ranging from light exposure simulations to interactive visualization in XR.

2.3. Beyond the State of the Art

PERCEIVE advances the state of the art in several ways:

- **Multimodal Data Integration**. The platform integrates heterogeneous data sources—analytical, historical, visual—into a coherent workflow. Unlike previous projects that focused on specific object types or modalities, PERCEIVE generalizes its ap-

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proach across the five scenarios, adapting tools and models accordingly

- **Hybrid AI and Appearance Modelling**. The combination of data-driven AI with physically based rendering models enables reconstructions that are both perceptually plausible and scientifically grounded. Neural networks trained on mock-up data can infer likely original states and simulate future degradation—pushing the boundaries of predictive conservation.
- **Transparency and Ethical Design**. PERCEIVE incorporates *paradata* and visual uncertainty layers to communicate the assumptions and confidence levels in its reconstructions. This approach is in line with best practices in digital heritage and avoids misleading representations that may distort historical understanding.
- **User-Centric Platform Design**. All tools are developed with stakeholder co-design, ensuring usability across diverse audiences—from expert conservators to general visitors. Functional modules are interoperable but also usable stand-alone, providing flexibility and scalability.
- **Interoperability and Sustainability**. Built on open standards and modular architecture, the platform is future-proofed for integration with museum infrastructures and third-party applications. APIs and cloud services facilitate extensibility and long-term maintenance.

3. Designing for Care, Participation and Authenticity: The PERCEIVE Co-Design Approach

3.1. State of the Art: Designing Interactive Experiences for Meaningful Engagement

In the field of Human-Computer Interaction (HCI), the focus has progressively shifted from usability and efficiency to engagement, meaning-making, and emotional resonance. Particularly within the domain of Cultural Heritage (CH), the challenge is not only to create usable systems, but to foster authentic and memorable experiences that evoke empathy, care, and participation. Studies have shown that users seek not merely information, but connection—both with the past and with the communities around them. Designing systems that cultivate such values necessitates an expanded design approach: one that is inclusive, reflective, and participatory.

PERCEIVE responds to this challenge by grounding its design methodology in a hybrid and experiential paradigm, recognizing that CH experiences often unfold across physical and digital domains. Hybrid experiences—those that merge in situ and remote access, embodied and virtual interaction—are essential to expanding access, engagement, and cultural relevance. Moreover, in the context of fragile chromatic collections, hybrid systems offer an ideal platform for mediating both scientific data and affective narratives.

Three conceptual pillars guide this methodology:

- **Care**: care is not only about preservation, but about fostering empathetic relationships between individuals and heritage. Designing for care involves creating emotionally resonant experiences that enhance users' sense of attachment and responsibility towards the Cultural Heritage [VBC*25].
- **Authenticity**: Authenticity is treated not as an objective property, but as a subjective, multidimensional experience. It is defined through the interplay of the Self (personal engagement), the Others (social dimension), and the World (environmental context). Digital systems must support introspection, social connectedness, and contextual fidelity to evoke an authentic encounter [PCS24].
- **Participation** is crucial to building civic engagement and cultural ownership. Through co-design, open exhibitions, and curiosity-driven interaction, users become active agents in the narrative construction of heritage [CBB*25].

This conceptual framework around authenticity, sense of care and participation has been further elaborated to create a pool of knowledge resources, toolkits and design tools tailored to the understanding and informed perception of coloured artworks and collections.

PERCEIVE has placed particular emphasis on digital (AI-enabled or not) colour reconstructions, as a means of understanding the original intent of the creator and the context in which the artwork was created. Rather than recreating the original appearance of the object, which is unlikely to be successfully achieved, digital reconstructions in PERCEIVE provide a methodological framework, an open-ended path towards the original. A digital colour reconstruction is an attempt to aesthetically restore the integrity of an object that time and circumstances have passed on to us in a fragmentary state, with the primary objective, and more than aesthetic restoration, of understanding the original appearance of the object.

In PERCEIVE, colour reconstructions incorporate all the knowledge available to date. Using advanced algorithms and data-driven simulations, they provide the platform to best combine knowledge, multiple insightful assumptions, interpretation of analytical data acquired on the object and on subsisting residual colours, as well as integration of contextual data to generate solutions that can be immediately evaluated by experts and stakeholders at different levels. The solutions of the colour restoration approaches are therefore iterative, and not closed-form, as they should allow for continuous improvement and refinement of the data-driven and learning-based algorithms, based on updated data collection experiments and feedback from quality assessments from the stakeholders. They also provide the means to communicate our current understanding of the originals, which is not definitive but anticipates subsequent improved versions that will incorporate new knowledge and use new tools. It is a medium to experience a non-touch but direct interaction with the original - the physical object - and also between the public and experts, broadening the user's perception and ultimately increasing authenticity, a sense of care and participation.

3.2. The PERCEIVE Co-Design Toolkit and Experience Prototypes

3.2.1. Co-Design Toolkit: Ideation Card Game and Experiment Planner

To transform this theoretical foundation into a practical strategy that can guide future design, PERCEIVE developed a *Co-Design Tool* as part of its design toolkit. The tool exists in two complementary formats: a card-based board game and a webapp, each facilitating collaborative ideation for the design of XR and hybrid CH experiences. The physical version includes a deck of cards divided into different categories and is meant to guide, step by step, groups of non-expert designers, together with designers, through the main stages: definition of the Context, of Institutional Goals, Audience Goals, Ideation, Storyboarding and Disruption [PMT*25]. It sets the ground for the prototyping of XR and hybrid experiences. The digital version replicates this workflow, allowing for remote, asynchronous collaboration and direct integration with the PERCEIVE platform and its Knowledge Repository. This toolkit has been used extensively in ideation workshops with museums (e.g., MANN, MUNCH, V&A Museums), creative SMEs (e.g., Anamnesia, IMKI), and research institutions. It helps multidisciplinary teams to define needs and requirements, setting constraints and expectations of users and institutions; to explore sense of care and sensory dimensions of colour and authenticity; to simplify the creation of design briefs and collaborative storyboards grounded in scientific and user centered data.

3.2.2. Co-Design Toolkit: Experiment Planner

Included in the Co-Design ToolKit, we have developed a prototype of an "Experiment Planner", a web-based tool aimed at supporting the configuration and management of user-testing sessions in 3D and virtual environments. It allows designers, researchers, and psychologists to configure tasks, monitor users' movements in real time, and collect behavioural data during VR or desktop sessions, including task settings, results, and timing. Its goal is to make cognitive experimentation in virtual museums more accessible without requiring coding skills and to facilitate a collaborative approach to exhibition design through iterative testing [MBF*24].

3.2.3. PERCEIVE Prototypes

In this context, a prototype is an early, interactive model of the envisioned digital or hybrid museum experience [WL22]. It serves as a dynamic tool for testing concepts, gathering user feedback, and refining both technological and experiential aspects before final implementation. Far from static mock-ups, these prototypes integrate real datasets and tools developed during the project, are applied to specific case studies to create functional demonstrators. Designed according to user-centered and concept-driven design principles, they support iterative development and foster collaborative innovation. Importantly, the prototypes are conceived to remain as adaptable and reusable templates beyond the project's duration, offering creative industries and museum professionals a practical foundation to build upon.

Three main prototypes were derived from this process, each integrating tools and services technologies and adhering to user-centered and concept-based design principles developed throughout the project.

Authenticity Prototype. Developed by CNR and MANN museum, this prototype offers collaborative and hybrid XR experiences centered on ancient statues' polychromy. It integrates gamified multiuser and guided interaction, storytelling, and contextual cues to enhance the sense of authenticity and engagement. The prototype is explicitly structured around the three core dimensions of the authenticity framework, Self, Others and the World [PCS24]. The design focused on the recontextualization of the polychrome statue in its original reconstructed and coloured context and is articulated into two phases, first involving the participants in the temple's reconstruction as architects, painters and artisans, and then immersing them in the life and rituals of the temple through a series of collaborative sensory tasks. Merging role play, collaboration, environmental changes delivered through wall projection and light and sounds interactions in the room, the authenticity prototype promotes meaning-making and a deeper understanding of the topic (see Fig. 8).

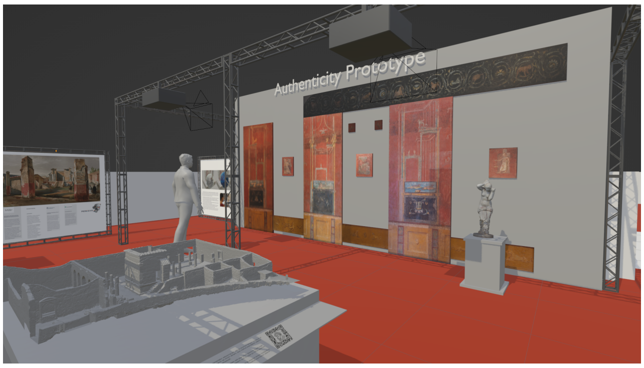

Figure 8: *Authenticity Prototype on Lost Polychromy, 3D visualisation in Blender*

Caring Prototypes. Two different versions have been developed by CNR, MANN and MUNCH museums. They include mixed reality installations, multisensory tangible interactive interfaces, serious games, that elicit empathetic responses and foster affective relationships with coloured collections [Woo23].

The first version of the prototype is focused on S1 and it is developed by CNR and MANN, based on the care theory framework [VBC*25] and on research on how to trigger visitors' curiosity towards ancient polychromy [CBB*25]. The prototype has been applied to the case study of the Temple of Isis in Pompeii (VII,7,28), whose decorative elements (frescoes and sculptures) are no longer in situ but are housed at the MANN museum in Naples. To obtain the necessary dataset for the application, archaeometric investigations were conducted on the Venus Anadyomene statue (INV. 62998), found in the Temple during the excavations, which not only shows evident traces of original colours. The experience is structured around stages that first aim at triggering a sense of loss and urgency to act and then involve visitors in the scientific process of discovering and reconstructing lost colours. At the end, possible colour reconstructions are revealed to the audience, who can finally understand the complexity of these investigative methods (see Fig. 9).

Similarly, PERCEIVE second caring prototype, *Tiny Conservators*, stands out as an innovative example of how playful interaction can cultivate empathy and a sense of care towards vulnerable artworks. Developed by MUNCH, this cooperative 2D platformer game introduces children and general audiences to the material fragility of Edvard Munch's *The Scream* (1910?) by transforming the threats of time, light, temperature and humidity into animated

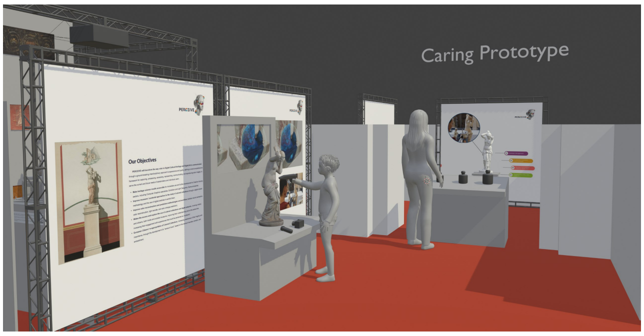

Figure 9: *Caring Prototype on Lost Polychromy, 3D visualisation in Blender*

antagonists. Players embody miniature guardians of art who must work together to defend colour in the magical microscopic world of the painting. Grounded in conservation science, Tiny Conservators offers an emotionally resonant, accessible, and data-informed experience. By blending scientific insight with joyful interaction and collaborative storytelling, the game embodies the project's core values of care, participation, and informed engagement, serving as both an educational resource and an affective interface between audiences and colour-based heritage phenomena (see Fig. 10).

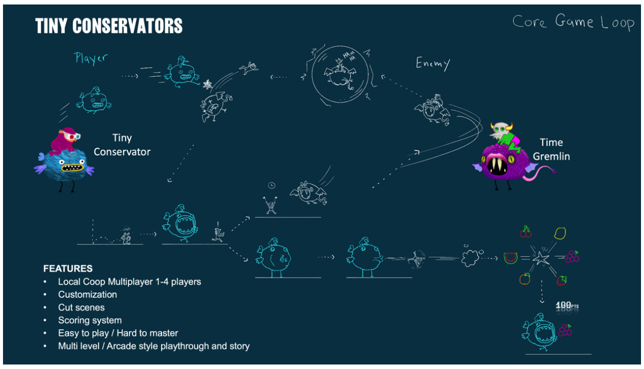

Figure 10: *Illustration of Tiny Conservators characters and core game loop, showing how players protect artwork from damage through cooperative play and colour restoration.*

Participation Prototype. The *Open Space Museum* (OSM) is a modular, portable exhibition concept developed within the PERCEIVE project to foster public engagement through interactive and accessible cultural experiences. Designed as an alternative to traditional museum formats, the OSM operates beyond conventional hours and venues, providing a tranquil yet dynamic environment for artistic interaction and reflection. Central to its design are robust *Case Study Elements* - architectural frameworks that integrate physical artworks with *Engagement Applications*, mobile-accessible digital tools that enrich visitor interaction. These applications offer educational insights, promote participatory exploration, and extend the museum's impact beyond physical boundaries [Sim10]. By partnering with established institutions, the OSM functions as a collaborative cultural extension, offering a pandemic-resilient, inclusive, and immersive platform for showcasing diverse artistic narratives.

While designing the prototypes, we have also tested general concepts by developing early demonstrators, that have included: "Scream Time Machine" and "Soundscape's Colours" prototypes, which allow users to explore chromatic change over time and perceive colours through touch and sound, deepening perceptual understanding:

- **Scream Time Machine**: a multisensory, immersive experience centered on Edvard Munch's *The Scream* (1910?), designed to explore the effects of colour change over time (see Fig. 11). It consists of a video tutorial introducing the painting's conservation history and scientific investigations, high-resolution 2D scans and tactile 3D prints of affected areas, and an interactive board game that engages participants in understanding fading and material deterioration. The experience emphasizes both visual and tactile interaction, making it accessible to visually impaired users and fostering deeper engagement through play and hands-on exploration [CTSB23] [CAŁ*22].

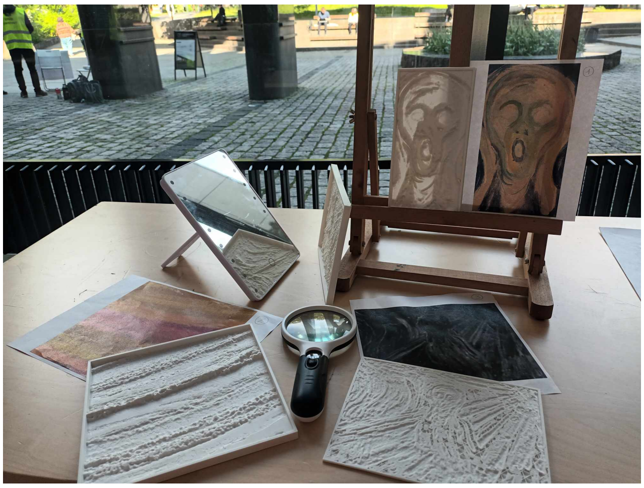

Figure 11: *The 3D prints of two details from The Scream 2D scan, showing colour change areas in a tactile representation – Scream Time Machine prototype (see also [PER25])*

- **Scream Scraper**: a multisensory demonstrator developed by HSLU and FORTH that explores colour perception beyond the visual experience by translating chromatic variations in Edvard Munch's *The Scream* (1910?) into sound and light (see Fig. 12). Based on the comparison between two photographic captures of the painting—taken decades apart—the system generates a 3D topographical map that highlights areas of colour change over time. A near-distance sensor reads this surface, dynamically converting height differences into corresponding audio frequencies and coloured light outputs. This real-time interaction allows viewers to perceive colour differences through multiple senses, creating a rich, immersive sound and visual "landscape." Technically, the system uses FM synthesis and LED modulation to generate a synesthetic response that varies with the user's gestures. The result is a layered exploration of how colour transforms with age, offering a deeper understanding of conservation processes and the emotional resonance of fading artworks. This innovative approach combines visual, spatial, and auditory modalities to convey the impermanence of art and the evolving nature of cultural memory.

Figure 12: *ScreamScaper. The image illustrates how the device is used by a museum visitor.*

- **Autochrome Demonstrator**: it presents a tangible and innovative approach to photo restoration by deconstructing and reimagining the complex layering process behind early colour photography. It separates the two key components of an autochrome plate—the coloured starch mosaic and the black-and-white panchromatic emulsion—into distinct physical layers that visitors can observe individually or as a combined image. When viewed through a front-facing occulator, the layers visually merge into a complete photograph, while side views expose their internal structure. To illustrate restoration techniques, the demonstrator integrates AI-generated elements to reconstruct missing or damaged areas of the emulsion layer, clearly distinguishing between original and restored sections. It also features interchangeable colour mosaic plates, produced using spectral image-processing methods, allowing visitors to compare and experience both original and digitally restored chromatic states. This layered and interactive system offers an insightful exploration of historical photographic processes while showcasing how modern AI tools can contribute to non-invasive cultural heritage preservation (see Fig. 13).

3.3. Beyond the State of the Art

PERCEIVE's design methodology goes beyond the state of the art in several significant ways:

- *Actionable Frameworks*. While concepts like care, authenticity, and participation are often discussed in theory, PERCEIVE transforms them into operational design tools and measurable dimensions for user experience evaluation.
- *Hybrid Design Strategy*. Rather than treating physical and digital museum experiences as separate tracks, PERCEIVE interweaves them through cross-platform prototypes, portable exhibition modules, and multi-sensory interfaces. This convergence anticipates the future of cultural mediation.

Figure 13: *Image of the Autochrome Demonstrator (*`openspacemuseum.blogspot.com`*).*

- *Participatory Infrastructure*. The CoDesign Tool empowers museums, creatives, and communities to co-create XR experiences. This fosters sustainable innovation and democratizes the design process, aligning with broader EU agendas on inclusivity and digital transformation.
- *Reusability and Scalability*. All outputs, from the toolkit to the prototypes, are conceived as reusable templates. Institutions can adapt them to new collections, new audiences, and new technologies, extending the project's legacy beyond its formal duration.

4. Conclusion

The PERCEIVE project addresses one of the most nuanced and often overlooked challenges in CH: the reconstruction, simulation and communication of colour. Far from being a merely aesthetic attribute, colour is a vital medium of historical, symbolic, and emotional meaning. However, due to its inherent fragility, colour is frequently altered, lost, or misrepresented—leading to compromised understanding of cultural artefacts and experiences.

Through its interdisciplinary approach and technological innovation, PERCEIVE offers a paradigm shift. It integrates scientific analysis, AI-powered rendering, human-centred design, and ethical reflection to propose a comprehensive framework for the study, simulation, and communication of colour in CH. The developed platform provides not only advanced tools for researchers and museums, but also accessible and engaging experiences for broader audiences.

Key contributions include a scientifically grounded reconstruction pipeline that integrates multispectral data, historical sources, and mock-ups into hybrid AI/IBR models; a modular platform architecture with interoperable services, APIs, and a FAIR-compliant Colour Knowledge Repository; a participatory design methodology based on care, authenticity, and participation, translated into practical tools like the PERCEIVE CoDesign toolkit; four prototyped user experiences across real suited for hybrid museum contexts, addressing diverse use cases and scenarios; a replicable model for institutions aiming to adopt inclusive, emotionally meaningful, and transparent practices in XR.

By combining technical and methodological aspects, PER-

CEIVE advances the limitations of previous digital heritage initiatives. It avoids pitfalls of speculative reconstruction by embedding every design choice within a more robust framework of scientific evidence, user insight, and citizen responsibility. At the same time, it opens new narrative possibilities—allowing visitors not only to see the colours of the past, but to understand, feel, and care for them.

Ultimately, PERCEIVE demonstrates that reconstructing lost colour is not only a technical act—it is a cultural one. It is about restoring complexity, where simplification once prevailed. The project's legacy aims at extending beyond its tools and prototypes, offering a new approach for how we perceive, interpret, and engage with colour in Cultural Heritage.

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