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Tactile 3D-printed media interaction with the color surface features of paintings. The case of the Scream (1910?) painting

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Due to their fragility and uniqueness, valuable works of art are largely unavailable for direct interaction with the public. They are usually displayed in conditions that restrict access, which inevitably limits the visitor experience, particularly for audiences with reduced mobility and visual impairments. Furthermore, related information is not easily conveyed because of the limited time visitors have to browse the museum, and because it is usually presented in jargon that assumes scientific knowledge, or is presented out of context. In this paper, we aim to address all these aspects simultaneously, using the painting *The Scream* (1910?) from the MUNCH Museum in Oslo as a case study. A combination of high-resolution imaging and computer vision algorithms was used to identify and separate the color surface features for two areas of the painting. The information was then presented to visitors by 3D printing the two areas and placing the color surface features at different heights, creating a relief structure that could be touched and inspected up close. The novel and highly accessible experience was evaluated at the InArt24 conference and at the KHM Museum in Oslo, Norway. During the evaluations, participants reported that interacting with the physical 3D replicas stimulated their interest and motivation, and increased their satisfaction when learning about the painting's color characteristics. These initial findings suggest that presenting information about art objects through multisensory experiences can greatly enhance accessibility and engagement for diverse audiences.

KEYWORDS

3D replica, user experience, Edvard Munch, evaluation, accessibility, knowledge transfer

1 Introduction

Designing a museum application or curating an exhibition space today requires a comprehensive modern museological approach that balances two often conflicting priorities: the preservation of the artworks, and accessibility to the widest possible audience (Hooper-Greenhill, 1999; Simon, 2010). This new approach counters a long tradition of restricting access and placing the protection of objects at the forefront. Furthermore, cultural venues have historically been primarily sight-oriented, reflecting a long-standing cultural bias that elevated vision as the supreme sense for knowledge and intellectual engagement, rooted in Platonic philosophy. Touch, on the other hand, has been relegated to an inferior status, as associated with materiality, impropriety, and even *taboo*. However, this visual-centric paradigm has systematically excluded individuals with visual impairments, for whom touch is a primary means of interaction and understanding, (Sandell, 2007; Eardley et al., 2022). Such exclusion directly challenges the principles of universal access to culture, as articulated in Article 27 of the UNU (1948), which affirms the right of all people to participate in cultural life—*"Everyone has the right freely to participate in the cultural life of the community, to enjoy the arts and to share in scientific advancement and its benefits."* One way to ensure inclusivity is for exhibition and product design to go beyond the traditional visual framework and integrate multi-sensory experiences. Embracing touch and other senses not only addresses accessibility issues but also enriches cultural engagement for all audiences. This shift requires rethinking the entrenched cultural models to foster a more holistic and universal appreciation of heritage, recognizing that meaningful interaction with art and culture should engage as many human senses as possible.

What is more, adding other sensory interaction modalities that simultaneously engage different human senses not only assists users with visual impairments, but creates a multi-sensory experience, which is an effective method of maintaining user interest, prolonging interaction time with the work and enriching the experience by providing knowledge and stimuli that awaken the imagination, offering an original creative experience. As recently suggested in a review by Fioranelli and Garo (2023), prolonged engagement with art may reduce the cognitive decline that is rapidly reaching epidemic proportions in most parts of the first world today (Dyer, 2023).

Furthermore, improving the public's engagement and interaction time with an artwork using multi-sensory experiences, can provide an opportunity to present additional information about it in a more enjoyable way. By presenting additional information about an artwork in a playful and engaging way, it can be more easily absorbed rather than coming across as a lecture.

In summary, providing a memorable and sensually enriching experience (multi-sensory experience) is beneficial for social inclusion purposes and educational purposes whilst making the visit more memorable and enjoyable. It also increases the chances of creating a lasting interest in art in general, prolonging the public's interaction time, which, as mentioned above, can also have important mental health benefits.

1.1 Reasons for current access restrictions

While significant efforts are made to enhance museum accessibility in terms of infrastructure—such as installing ramps, providing Braille labels, and offering multilingual signage—direct interaction with valuable artworks remains highly restricted. Most of the highly valued paintings are displayed under conditions that prioritize their protection: positioned at a distance, illuminated with dim lighting, and protected by glass panels and/or physical barriers. The motivations underlying direct access restrictions are usually inevitable as the preservation of the artwork is paramount to the museum itself, in more detail, access restrictions exist due to:

- Fragility of materials. Many artworks are created using delicate or age-sensitive materials such as oil paints, tempera, paper, or canvas. These materials deteriorate over time as a result of exposure to environmental factors such as light, humidity, temperature fluctuations, and pollutants. Hence, direct interaction, including touching or prolonged close proximity, can introduce oils, dirt, or moisture that accelerate degradation.
- Security concerns. Many artworks are not only fragile but also highly sought-after since they are unique, making them targets for theft, vandalism, or accidental harm. Glass panels, barriers, and controlled access are essential for protecting them in public settings.
- Impact of public interaction. High visitor traffic in cultural institutions means that even minimal individual impacts—such as vibrations, carbon dioxide from breathing, or inadvertent contact—can accumulate over time, posing a threat to the artwork's stability.

However, such proximity limitations as mentioned above have a strong impact on the visitor experience and do not allow for full understanding and a holistic experience of the artwork. The types of visitors that are affected are not only the legally blind, but also the following categories of visitors:

- *Visitors with full-functioning normal vision*. The reduced lighting and distance between the user and the artwork, even for visitors with normal vision, limits the perception of the painting to the image. The visual composition as rendered by the artist is perceived through the contrasts of light and color, but also through shapes, shadows, "reconsiderations," and time signs. It is extremely difficult to give the visitor a sense of the materiality of the artwork, the brushstrokes, the texture and the relief, in addition to the general visual perception of the image.
- *Visitors with reduced functioning vision*. When visitors have reduced visual faculties due to their temporary or permanent conditions, the visual appeal of the artwork is barely perceptible and its reading is compromised in terms of the recognition of figures and shapes, the perception of colors, and architectural composition.
- *Visitors with reduced mobility or visual impairments*. Moreover, visitors with reduced mobility often face significant challenges in accessing and viewing artworks in museums. Physical barriers such as stairs, narrow aisles and inaccessible exhibit layouts can restrict their movement and prevent them from reaching certain exhibits. Even when accessible routes are provided, viewing angles and distances may not be optimized for individuals using wheelchairs or mobility aids, hindering their ability to fully appreciate the details of the artworks. In addition, crowded spaces and poorly designed exhibition areas can exacerbate these difficulties, making it harder for these visitors to enjoy an inclusive and immersive cultural experience.

1.2 The "design for all" guidelines

The previously mentioned effects of necessary restrictions on public access, necessary to preserve the artworks as much as possible, contradict modern "design for all" practices and legislation regarding accessibility, and there needs to be a way to reconcile the two.

The modern concept of accessibility focuses on the creation of environments, products, and services that accommodate the diverse functional abilities of the widest possible range of individuals, regardless of their physical, sensory, or cognitive conditions. This perspective recognizes that functionality exists on a spectrum as highlighted by the World Health Organization (WHO) on the International Classification of Functioning, Disability, and Health (ICF) (WHO, 2001), addressing not only permanent disabilities but also temporary and situational impairments and the progressive decline of mobility and sensory skills of older adults. Such an approach ensures that disabled people are not singled out and that equal participation across cultural, social, and technological domains can be achieved for all.

European accessibility standards also provide a robust framework that drives museums to employ creative ideas to allow the widest possible audience to enjoy art. The European Accessibility Act (EAA) EPC (2019) establishes harmonized requirements across products and services to remove barriers and ensure inclusivity and emphasizes the necessity of removing barriers to accessibility and ensuring that cultural heritage is inclusive and available to all individuals, regardless of disability.

The recently tooted "Design for All" philosophy (Persson et al., 2015) further strengthens this inclusive vision. It advocates for the proactive development of systems and solutions that naturally meet the needs of the widest range of users without requiring adaptations or additional accommodations. This concept has been supported by initiatives such as the EIDD Stockholm Declaration (2004), which emphasizes designing for human diversity, social inclusion, and equality.

Museums are therefore challenged to continually seek ways to reconcile their commitments to the best possible preservation of the artworks in their care and to maximizing public access. To bridge the gap created by the need for restricted access and to engage more of the senses to allow more people to access the artwork in different ways, museums have traditionally used various techniques such as, audio tours (Lee, 2017), high-resolution reproductions, virtual reality (VR) (Bachiller et al., 2023), augmented reality (AR) (Martí-Testón et al., 2021), and interactive digital displays as well as printed 3D copies (Ballarin et al., 2018; Balletti and Ballarin, 2019). These tools allow the public to engage with works of art in a multi-sensory way without endangering the originals.

Our contribution in this work is to complement a multi-sensual visual and activity-based artwork exhibition which includes, (1) a video presentation, (2) a high resolution color 2D scan of the painting presented on a large digital screen and (3) an interactive game, with two tactile 3D printed objects from two areas of the Scream (1910?) painting. By adding a physical dimension to the exhibition directly associated to the colors of the painting, we created a more engaging and stimulating multi-sensory experience whilst and at the same time improved the accessibility of the Scream (1910?) to a wider audience. The method shown can be replicated for similar types of paintings which contain large-area singular color features.

To create the 3D printed artifacts we needed to understand the painter's creative process and determine the order in which the colors were applied, for which we used a recently acquired high-resolution digital scan of the painting combined with image processing. The additional 3D printed artifacts created, show which colors were painted first, next or last by increasing the height they are placed on, which helps visitors perceive the paint layering in a tangible manner.

2 Previous work

As a technology, 3D printing has already been successfully incorporated as part of multi-sensory experiences (Luo et al., 2024; Harada et al., 2018), in diverse fields within the arts and humanities world, namely art history (N.M. Tissen, 2023), museum studies (Ballarin et al., 2018; Wilson et al., 2017), digital humanities (Crompton et al., 2020; Sayers et al., 2015) and education (Menano et al., 2019; Zhang, 2024; Ömer Özeren et al., 2023). It revolutionizes the way people understand and interact with the arts and humanities by opening up an additional channel of information (Luo et al., 2024) through the sense of touch.

2.1 The importance of the "touch" dimension

In the context of this work's proposed multisensory application, it is important to give visitors the freedom to touch the artwork through faithful copies, either next to the original work of art or during a virtual visit. This allows them to better understand the painting process (layering) and perceive the differences in materials compared to viewing them only in high resolution on a 2D screen/display, where materiality, layering, and texture are not discernible. This additional information is perceived and understood through a combination of vision, touch, and hearing: the user sees the artwork and observes the details of the design and color, he/she touches and feels it, decoding the creation process of the composition brushstroke by brushstroke, layer by layer. At the same time, he/she can listen to a narrative explaining what he/she sees while experiencing a tangible sensation of it. The viewer becomes an active receiver and communicator of the artwork's creation. He/she is involved aesthetically and mentally, and he/she is engaged.

Tactile sessions have long been offered to visually impaired visitors, (Taylor et al., 2016; Neumüller et al., 2014; Grosvenor and Macnab, 2013; Anagnostakis et al., 2016; Reinhardt et al., 2024; Vaz et al., 2018). Studies of tactile interactions with replicas in these contexts have found that touch often serves to enhance visual engagement with the object, turning the hand into a kind of "visual prosthesis". Such exhibitions in art museums, using replicas of artworks, have provided opportunities to study the perspectives of tactile engagement in museum exhibitions.

The sense of touch provides, indeed, a unique aesthetic dimension, offering sensory experiences distinct from other modalities. Just as the eyes perceive color and ears capture sound, touch uniquely registers weight, temperature, and texture—sensations exclusive to tactile interaction (Arnheim, 2020). These tactile qualities can produce perceptual harmonies and rhythms akin to those evoked by colors and sounds. The tactile experience goes beyond mere physical sensation; it serves as raw material for intellectual and emotional engagement.

The tactile process is analytical, beginning with an initial exploration to recognize and categorize an object. This preliminary "snapshot" forms a schematic impression stored in memory (Hatwell et al., 2003). Subsequent tactile exploration refines this schema, as the hands meticulously gather and integrate additional details, much like assembling a puzzle. Each step of the hands adds complexity and clarity to the mental representation (Lacey and Campbell, 2006).

Tactile exploration, however, challenges contemporary cultural norms that promote speed and efficiency. Unlike vision, which often perceives instantly, touch requires time to construct a detailed mental image piece by piece. The synthesis achieved through tactile exploration is the culmination of an extended analytical process, offering a depth and richness that transcends the superficial brevity of quick observation (Hatwell et al., 2003).

2.2 Benefits of tangible experiences

Recent sociocultural studies of visitor interactions in museums and art galleries investigate the ways visitors' bodies, gestures, orientations, conversations, and interactions enter visual practices and interpretive processes. Of particular interest is the role of touch in museum experiences and learning.

Studies have shown that family interactions with tactile objects can enhance engagement, narrative creation, and embodied learning (Jewitt and Price, 2019; Ömer Özeren et al., 2023; Menano et al., 2019). Touch is recognized as an important aspect of the museums, providing opportunities for meaningful person-object transactions and phenomenological experiences (Wood and Latham, 2011). In multisensory art exhibitions, touch serves as an interpretive resource, allowing visitors to extend visual observations and discern the shape, texture, and creation process of sculptures (Christidou and Pierroux, 2019). In that case, the context of the study was an art museum exhibition, which was curated to allow for tactile interactions with modernist sculptures. In interpreting their experiments in this paper, the authors found, among other things, that touch proved to be particularly useful in reflecting on the artist's creative act and in object-based explorations, allowing participants not only to discover unseen properties of artworks, but also to confirm and contrast properties they could see. This interaction demonstrates the multisensory and integrative aspects of perceptual experience, where language, observation, touch, gesture, and body are combined in the interpretive activity.

Studies have highlighted the importance of incorporating touch-based interactions in museums to enhance visitor engagement and learning experiences. In fact, digital and multimedia technologies make it possible to go beyond mere physical accessibility, thus extending the user experience and merging it with education and the discovery of new cultural knowledge—also through the proactive participation of the visitor. The user's action, combined with the use of various technological tools, becomes a powerful sensory amplifier, challenging the traditional "don't touch" approach in museums. The presence of digital enhances the opportunities for interaction, play and participation.

Creating 3D replicas of artwork objects using 3D printing for the visually impaired has been previously investigated in the Aptos project (Pistofidis et al., 2021). The project analyzed the specifications that the texture of these 3D printed shapes should have to be meaningful for the visitors. Later (Pistofidis et al., 2023) the project also embedded audio narration in the 3D printed artifacts themselves by incorporating low-cost computer architectures and control buttons which the user can activate to add the sense of hearing in the haptic experience as well.

2.3 Incorporating scientific data into storytelling

But what about the scientific content? What is the best way to convey scientific information to users? Effectively communicating scientific content to users, particularly in a museum or cultural heritage context, requires a process of formal "translation" or "transformation" to make complex information accessible, engaging, and comprehensible. This process involves transforming complex scientific data into visually appealing, interactive, and easy-to-understand formats, while maintaining accuracy and authenticity.

Content can be of different types: literature reviews, spectroscopy and imaging analysis results, micro-faedometric graphs and estimates, simulations of color change using different methods and algorithms, etc.

In some cases, information about a work of art is presented to the public in technical language—less accessible to not specialists; or certain concepts are taken for granted; or, attention is focused on a specific aspect of the artwork, ignoring the context in which such an artwork was developed. Sometimes information is not given at all or is replaced by codes, taxonomic indexes and so on. This makes it difficult to process the information and thus makes the experience less enjoyable (Lin and Yao, 2018).

Curators and museum professionals may also assume that scientific information is not of interest to the general public. This is not true. Experience has shown that the public is extremely interested in learning the details of how the artwork was created, as it helps them to make sense of it, (Lin and Yao, 2018), to understand the materiality of the work and the details of the history of the artwork after its creation. The only caveat is that this information must be presented in an engaging, understandable and accessible way.

In communicating content, narrative has a much greater impact than description. In fact, the latter cannot motivate visitors unless they are already familiar with the subject. Description adopts an impersonal style, without conflict and emotional energy, without personal cues, the rhythm is slow and regular. On the contrary, narration, evocation and dramatization "translate" objects into stories, creating an emotional involvement and an expectation in visitors (Genette, 1972). The story involves multiple points of view, developed through alternating rhythms and the creation of a different space-time dimension into which the visitor is thrust. This is one of the best ways to communicate scientific information.

User experience (UX) evaluations conducted with general public clearly show that narrative, designed as a coherent balance of text, acting, music and sounds, colors, visual mood, camera movement and rhythm, can evoke emotions in visitors. Emotion creates motivation, interest, self-identification and thus transforms the experience into a potential opportunity to learn and remember new information (Goleman, 1995; Ryan and Deci, 2001). Ultimately, narrative creates connections, relationships between objects, contexts, people and meanings.

The challenge is to strike a balance between dramatization, simplification and precision. The aim is not to oversimplify or dilute the scientific integrity of the content, but to adapt the presentation to resonate with different audiences, ensuring that the richness of the scientific information is preserved while being accessible and engaging.

In this paper, we explore a tactile method to address both the limited perception of an important artwork (due to the necessary protective measures usually applied to it) and the limited access to scientific information, by using 3D printing technology, to effectively convey scientific data about the color surface features of the Scream (1910?).

The connection in our case is not made through narrative alone, but by allowing visitors to have a physical speciment to hold, making the experience more personal and engaging, while embedding scientific information within the 3D printed object itself.

2.4 Previous work conducted on the Scream (1910?) painting in relation to colored features and pigments

Due to its cultural relevance and material fragility, The Scream (1910?) from the MUNCH museum collection has been the subject of various analytical campaigns through the years regarding its colored features (Cartechini et al., 2019; Cardinali et al., 2022; Sandu et al., 2018; Spring, 2011).

These studies, combining through the years both non-destructive and imaging techniques, revealed an intricate composition and artistic process, that sees the experimental approach of different techniques and interplays of the materials responsible for specific degradation effects that undermine the stability of the artwork. In fact, MUNCH's main version of The Scream (1910?) is executed in mixed media (tempera, casein, oil, glue and resins were identified) on a cardboard made of mechanical pulp and no varnish is present over the painting layers.

HSI imaging performed in the NIR spectral region revealed an underlying sketch in correspondence of the central figure's face and the bridge's handrail (Figure 1).

MOLAB access awarded in 2017 through the access to the facility of the European Research Infrastructure IPERION HS and ERIHS.together with the collaboration with AXIS and ARCHES research groups from Antwerp University in 2024, unveiled the color palette of The Scream (1910?) and also some degradation products.

The MA-XRF and MA-XRD non-invasive analyses (Bijker et al., 2024), integrated with Vis hyperspectral imaging, reflection FTIR and Raman point measurements at several locations on the paint surfaces demonstrated how Munch was open to the introduction of new synthetic pigments such as cadmium sulfides (CdS, in the hexagonal and cubic forms), lead chromates (as $PbCr_{1-x}S_xO_4$) and viridian green (hydrated chromium oxide, $Cr_2O_3 \bullet 2\,H_2O$) applied in the Scream (1910?) as dense paint brushstrokes or pastel drawing strokes on the bare cardboard support. More traditional materials, such as vermillion, ultramarine and cobalt blue, and Zinc white, were also found.

These analyses also allowed to establish correlations between layers of paint and the pigments and additives present in them, as well as their presence in mixtures (Figure 2). The detailed identification and localization of specific pigments is crucial for conservation purposes. In fact, the sensitivity of these materials to decay has been proven to be a consequence of the type of the industrial formulation they were produced with, the environmental conditions and the interactions with the binder (Monico et al., 2018; Gabrieli et al., 2017; Monico et al., 2015a,b).

Unlike the discolouration caused by a varnish degradation (varnish tends to yellow or darken, depending on its composition), which can appear uniform across the surface of a painting, the change in color of the pictorial layers in the case of Scream (1910?) is less uniform. Specific damage was caused by a liquid agent during the period (2004–2006) when the Scream was stolen, affecting the lower right corner of the cardboard and paint layers, while other areas of Cd yellow (face, sky) have faded (and are probably still fading to a lesser extent) due to cumulative exposure to light and high relative humidity.

For this reason, micro-fadeometry testing (MFT), that measures the sensitivity of materials to light exposure, allowing to establish a dose of light that is safe for the studied object (Whitmore et al., 1999), has been applied to evaluate the stability of the different pigments in the painting (Chan et al., 2022). Based on the MFT testing campaign in 2019, the main version of The Scream has been cataloged in a BW2/BW3 category of sensitivity, with Vermillion being the most light-sensitive pigment, leading to a darkening of the red shades (Chan et al., 2022). Some brushstrokes containing cadmium yellow and red lakes instead have been found to be fading in different areas of The Scream (1910?), contributing to the change in appearance of the painting and its perception compared to the original intention of the artist. On this topic of cadmium yellow fading in modern paintings as the Scream, Monico et al. (2020) published an extensive study, showing the contribution of the paint manufacturing process and of environmental parameters such as high relative humidity and light in the process of color change (and color instability).

Other pigments as Vermillion and Chrome yellow, also present in the painting, are known for their tendency to darken under prolonged exposure to high levels of illumination.

From a technical perspective, the Scream technique and choice of materials is generally poor and the colors seem to be applied in a quick, not too elaborated manner. The cardboard is made of mechanical pulp with a tendency to yellowing and there are no ground layers over it. The tempera and oil paint is not entirely covering the surface of the support, in between overlapping shades of color we can see the cardboard (Figure 3). In some

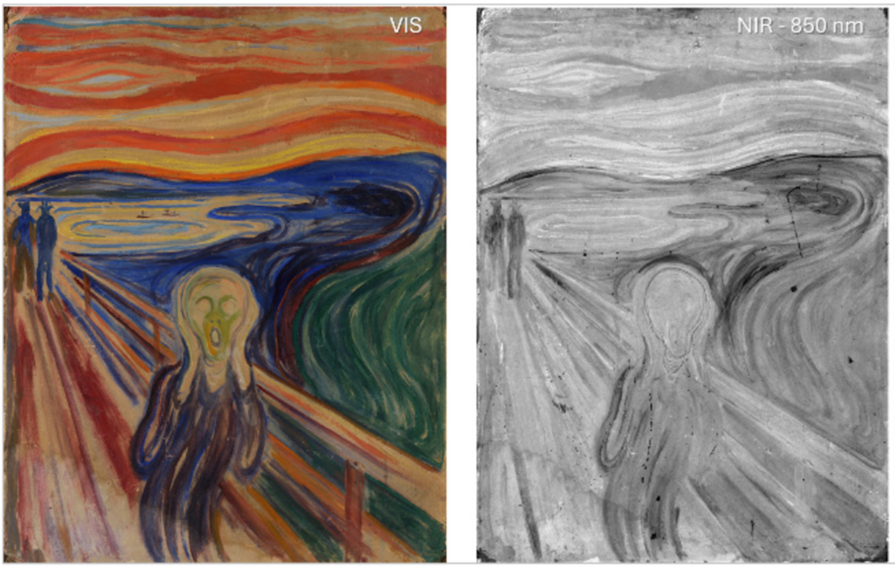

FIGURE 1
Visible **(left)** and NIR 850nm HSI **(right)** images showing the underlying sketch in The Scream (1910?).

FIGURE 2
Details from MA-XRF elemental maps of the screaming face. From left to right: zinc K-lines map, chromium K-lines map, RGB image, cadmium L lines map and mercury L-lines map.

areas as it is shown in this figure, a Chrome yellow crayon has been used in between or over shades of orange or yellow color. Some areas display thick brushstrokes while others are more diluted and transparent, barely covering the cardboard. This mixed technique used by Munch in this version of the Scream shows his experimentalist style of painting and also very little concern with the quality of materials or their compatibility. The above points represent a concise summary of the main findings from the breadth and depth of information gathered from the analytical studies of the painting, and the careful cross-interpretation of the detailed multi-analytical studies. In addition, a recent 3D digital scanning campaign using the Hirox microscope has produced a high-resolution 2D scan of the entire surface, as well as 3D scans of three areas of interest on the painting. These scans provide a close-up 3D view of the paint surface and allow experts to visually confirm the data obtained from the interpretation of analytical data. Furthermore, the Hirox images can help, in a tangible visual way, even those unfamiliar with analytical data to understand this information that experts read in XRF, VIs-NIR imaging data, and so on.

The methodology presented in this paper differs from these previous campaigns in two ways: first it leverages unpublished data collected recently by an extremely high resolution scanning microscope, and secondly, it goes one step further than simply analyzing the data as the previous methods have done, but also proposes the creation of 3D physical reproductions, that easily communicate the results acquired to the visitor directly.

The visitor can therefore perceive, through sight and touch, the distinct colored features of the painting which were identified by the microscope, and which elude to the painting process followed by the painter when creating the painting.

FIGURE 3
Details of the paint layers showing the way Munch applied the paint and areas of exposed cardboard.

3 Materials and methods

The methodology developed to generate 3D prints began by acquiring high-resolution image scans of the painting surface with the HIROX microscope, in two different areas of interest. The aim was to map the different perceived color surface features in high resolution and to enhance their perception through the use of 3D printing.

The main steps followed in the methodology of this work are:

1. Acquisition of a full size 2D scan of colored areas using a high resolution Hirox digital microscope
2. Color clustering /segmentation
3. Greyscale mapping of segmented colors on specific height layers
4. 3D printing of segmented color layers

3.1 2D scan acquisition

In March 2024, a Hirox Digital microscope HRX-01 with a 1,000 × 1,000 × 75 mm XYZ motorized stand was used to fully scan the surface of the Scream (1910?) in 2D (Figure 4). The entire painting was automatically scanned at 30× (4 um per pixel) using the Hirox multifocus software (focus stacking method) and telecentric optics with polarized light. A total of 20,898 multifocus tiles were captured and then stitched using the Big Picture tiling software from JYFEL. The output was a TIF color image for the whole painting. From the resulting stitched 2D scan TIF color image, two areas presenting particular interest were selected to apply the proposed methodology further detailed in the following section (3.2). A zoomable panorama of the full painting is accessible on the HIROX website.

3.2 RGB color segmentation

From the high-resolution 2D color image of the entire painting acquired using the Hirox microscope, two specific details were selected as a case study, (i) the screaming face and (ii) part of the sky, which are shown in Figure 5. The size of the regions of interest was dictated by the maximum print area dimensions (20 × 20 cm) provided by the printer used to produce the 3D prints. With this in mind, the areas we focused on were chosen to be small so as not to lose the high resolution and clarity of information available in the Hirox microscope images. The sky area, with an original size of 11 × 11 cm, was scaled up 2× (doubling in size), while the face area, which measures 18 × 11 cm, was scaled at a 1:1 ratio.

The color clustering of these two selected areas was performed manually in Matlab using the Color Thresholder tool, Figure 6. Layers were created based on a combination of filtered red, green, and blue image channels (see Supplementary Tables S1, S2 in Supplementary material), creating distinct regions that seem to correspond to distinct color surface features of similar color. The high resolution of the RGB image, made it possible to capture the fine details of the features.

3.3 Grayscale mapping

The colors segmented in the details of the "face" and the "sky," were assigned to successive heights or levels, as shown in Tables 1, 2 respectively. The sequence of the colored regions was chosen by the researchers to better reflect the distinct color features/paint layers perceived on the painting's surface. The order of the colors

FIGURE 4
Image showing the experimental setup used by HIROX for the high resolution image scan of the painting.

by height on top of the cardboard (the cardboard support is the lowest or first level) is followed to show the order of the paint layers as applied by the artist.

In Figures 7, 8, we present the "face" and "sky" areas side-by-side, as rgb images and the resulting greyscale images representing the height assigned to each feature, with black representing the lowest height and white representing the maximum height.

3.4 3D printing

There are many types of 3D printing technology, in this work we used Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), the most common and cost-effective type of 3D printing, where a coil of filament is melted and passed through a printer head that moves across a flat surface. When a layer is completed, the surface is lowered and the process is repeated. In this way, an entire 3D object can be created.

The 3D models of the two painting areas were 3D-printed using FDM technology in white-colored plastic. For the 3D printing, an Artillery Sidewinder X2 Desktop FDM printer was used. This option was selected as it was the simplest and most cost-effective option available, which also offered a large enough printable area (20 $\times$ 20 cm) allowing the 3D prints to be created in one piece.

The minimum possible layer height and therefore feautre height selectable for the 3D printer used was 0.2 mm, well within the range that people with visual impairments find acceptable according to Pistofidis et al. (2021), where a haptic tracing feature height of $>$1 mm or more was found to be adequate. We therefore selected to produce a 2 mm feature height for each color feature level, double that recommended by Pistofidis et al. (2021) by using a 0.4 mm layer height (5 3D print layers per feature) to reduce the 3D printing time. The printed layer height was increased compared to the minimum possible of 0.2 mm to keep the production time to a reasonable amount ($\sim$10 h), whilst also keeping feature detail and definition.

The technical parameters used for creating the 3D print are listed in Supplementary material, Supplementary Table S3. A rendering of the 3D models printed for both the face area and the sky area are shown in Figures 9, 10.

4 Results

The 3D printed objects created were presented to the public at the InArt24 conference (Figure 11), which took place in Oslo, Norway from the 3rd to the 7th of June 2024, and at an all-day exhibition at KHM in Oslo on June, 8th 2024. InArt24 was the 6th edition of the International Conference on Innovation in Art

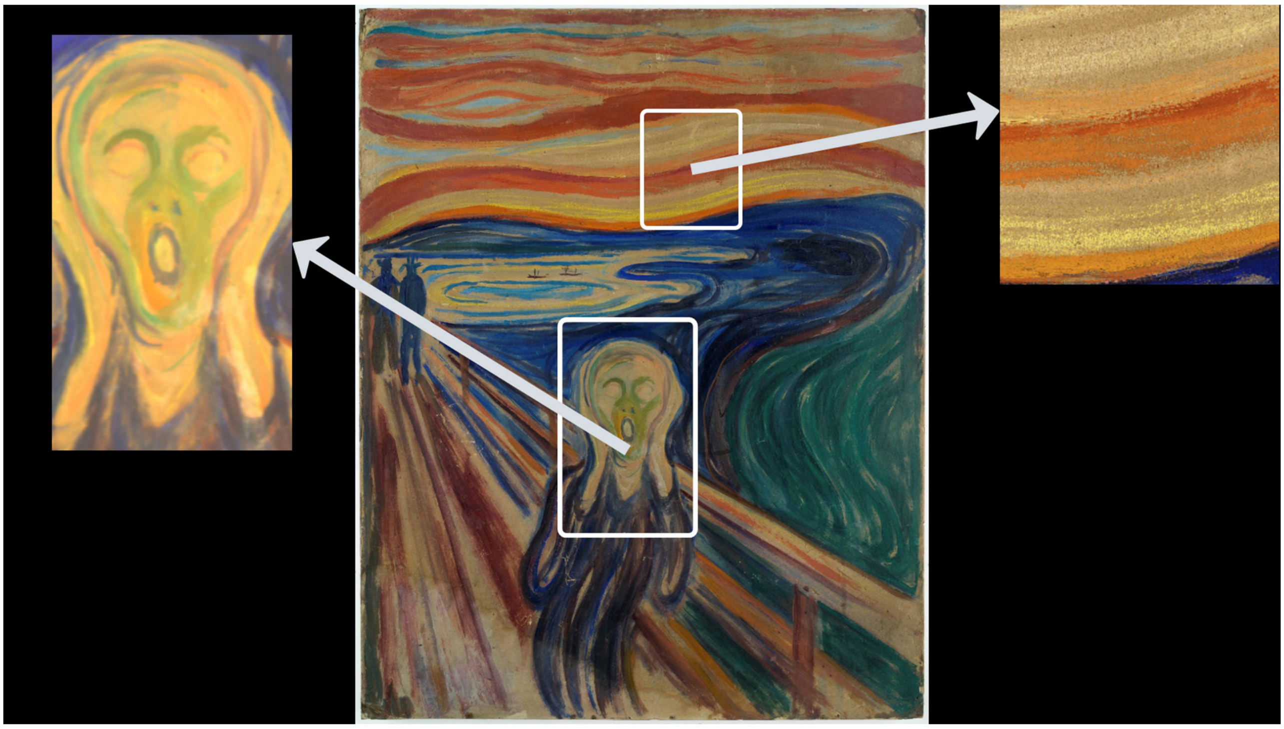

FIGURE 5
The two areas of the painting which were investigated. The one on the right is referenced as "Sky" and the other as "Face" in this work.

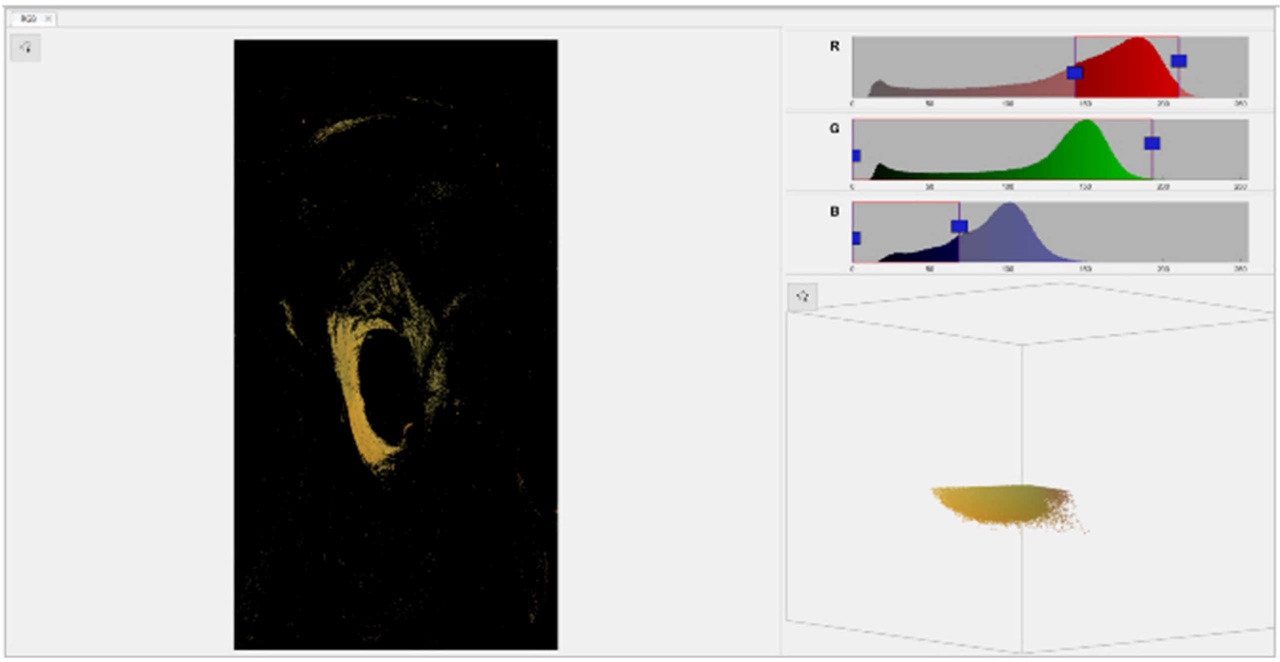

FIGURE 6
Using the Matlab Color Thresholding tool to separate different colors in the detail of the face, based on specific combinations of Red, Green and Blue intensity bands.

Research and Technology. The scope of InArt24 is to build a bridge between the natural sciences and conservation, in line with the interdisciplinary nature of the PERCEIVE project, within which the work presented here was carried out. For this reason, InArt24 was a venue for the submission and publication of research contributions from several partners in the PERCEIVE consortium. In addition to

TABLE 1 Height-coded sequence of colors, (after color clustering and segmentation of the 2D scan) in the detail of the screaming "face."

Level (from lowest to highest in sequence of layers)	Color segment associated to each level
Level 1	Cardboard (ochre-gray)
Level 2	Pale yellow (white)
Level 3	Yellow
Level 4	Green
Level 5	Blue

TABLE 2 Height-coded sequence of colors, (after color clustering and segmentation of the 2D scan) in the detail of the "sky."

Level (from lowest to highest in sequence of layers)	Color segment associated to each level
Level 1	Cardboard (ochre-gray)
Level 2	Yellow
Level 3	Blue
Level 4	Orange
Level 5	Red

the scientific participation, the consortium decided to organize a public exhibition to facilitate the work-in-progress of the project, to evaluate the first multimedia outputs and to conduct a user experience evaluation with the conference audience, which had different levels of expertise in the cultural sector.

4.1 The Scream Time Machine exhibition at the InArt24 conference

The Scream Time Machine exhibit which was setup at the InArt24 conference and which included the work in this publication, was a multi-sensory experience focused on allowing visitors to explore the surface of the painting (The Scream 1910?, MUNCH) and its color changes (mainly for yellow and reds). It is in this context, that the aforementioned 3D-printed areas were presented to the public.

The exhibition was designed to have 3 main parts:

1. A video tutorial. A video dubbed with voice recording and provided with subtitles in English (*video tutorial here: Scenario2-Paintings—PERCEIVE (perceive-horizon.eu)*. The tutorial has ca. 6 min length and shows the historical background of the Scream, the art techniques and evolution of the object's image along time, from around 1930 to the present

FIGURE 7
RGB color clustering and greyscale mapping **(right)** of "Face" area **(left)** of the Scream 1910? painting by Munch (Figure 5).

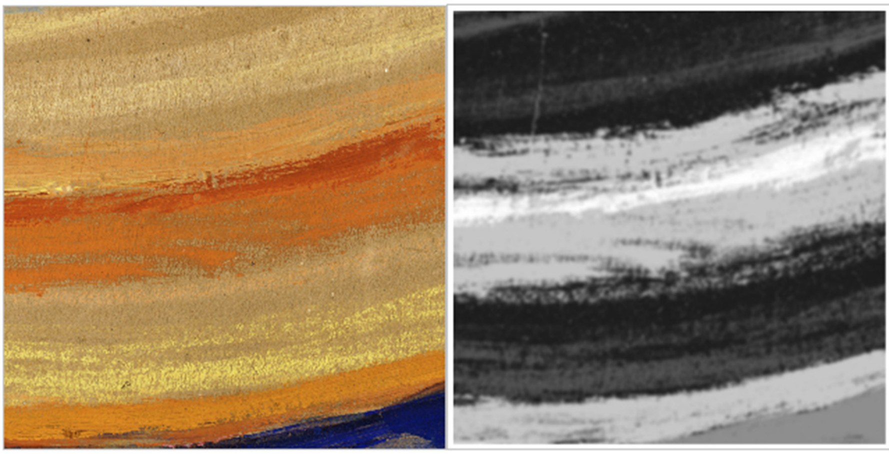

FIGURE 8
RGB Color clustering and greyscale mapping **(right)** of the "Sky" area **(left)** of the Scream 1910? painting by Munch (Figure 5).

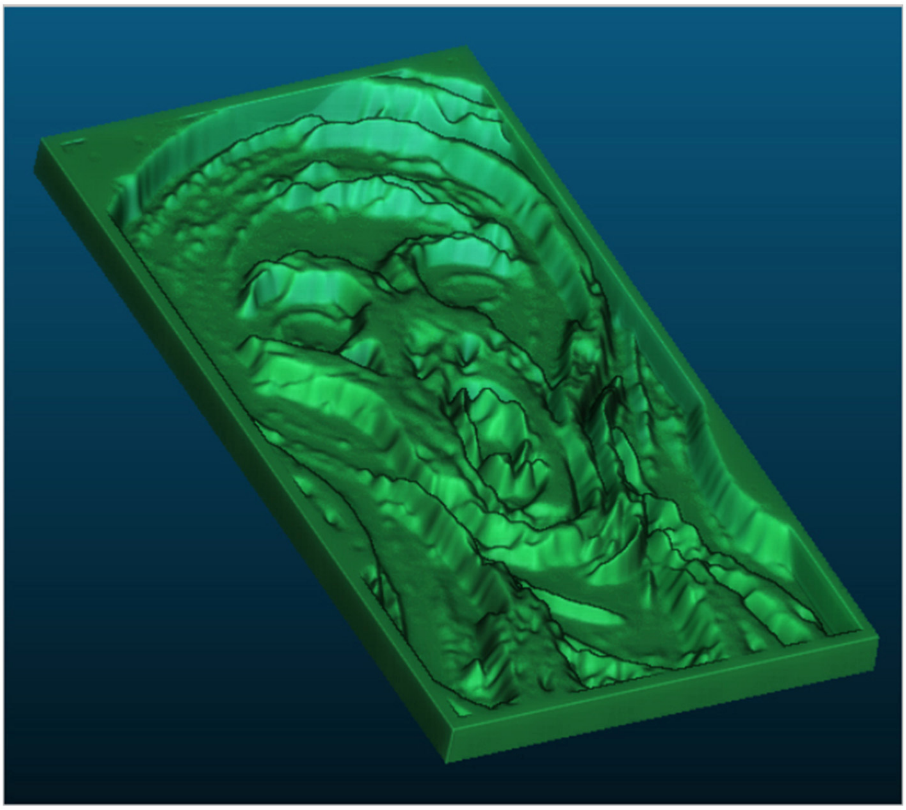

FIGURE 9
3D model of the topography of the 3D printed "Face" area.

(documented by the 2D scan and 3D prints) together with simulations of how color change could evolve in the future. This tutorial also was used to explain the various parts of the exhibition including the production and background behind the creation of the printed 3D objects of the exhibition. It also includes keywords and images that were used as elements of the next component of the exhibition, the Board Game.

2. Board game, which uses images of the Scream for playing around the chronology of color/image change. The game is made of 3 different decks (identified each with a color for the background: *Dark blue* for *Playing cards* of the *Timeline*, *Red* for *Danger* cards), and Green for *Care* cards and also a dashboard made of a cardboard having a color similar to the one Scream is made on. The dark blue cards represent 8 digital

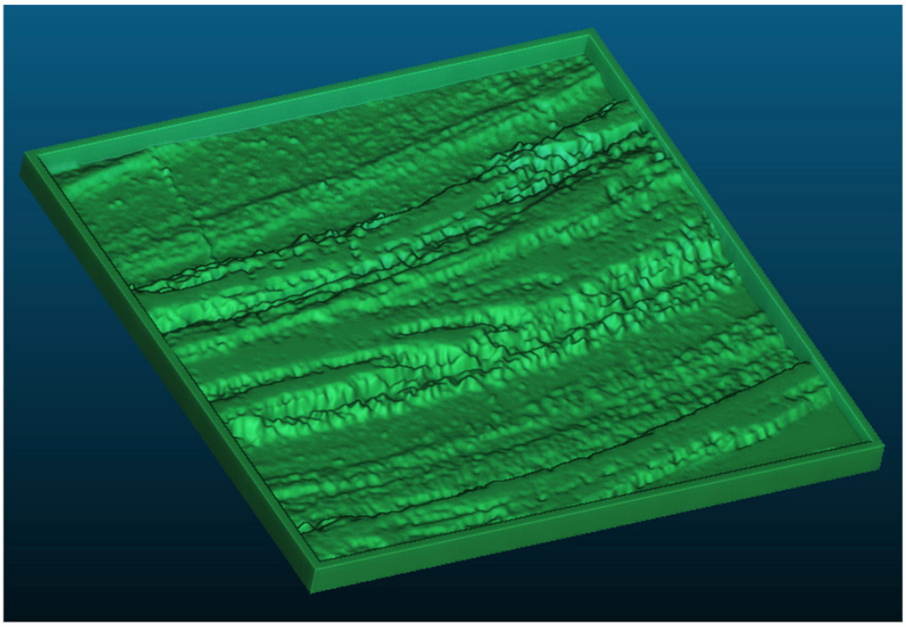

FIGURE 10
3D model of the topography of the 3D printed "Sky" area.

photographs, B&W and colored, of the Scream, taken in several years from 1938 to 2024. The game is designed to be used by min 2 players, one can be a *Danger Master* and all the rest *Time traveler(s)*.

3. Scream reinvented area. In this section of the exhibition the 3D prints designed in this work were available for close examination. Additionally, a set of 2 full-size prints of the painting at 30x magnification were printed in 2.5D provided by Canon in collaboration with Hirox Europe.

4.2 Evaluation goals

The objectives of the evaluation of the user experience (UX) considered:

- The product in its entirety. Instrumental qualities such as ease of use, functionality, and efficiency in achieving the intended purpose; aesthetic qualities such as visual appeal and design coherence; usability tests were conducted according to the Nielsen/Norman guidelines (Norman, 2013).
- The attitude and/or ability of the user and the relative level of understanding of the content. Instrumental / non-instrumental qualities, such as experiential qualities such as immersion; social aspects, including accessibility, inclusivity, and the potential to foster collaborative or shared experiences among users; emotional engagement, including curiosity and satisfaction; cognitive impact, such as how effectively the content communicates key messages or enhances understanding; and the overall sense of empowerment or inspiration derived from the interaction. Investigations relating to Pedagogical affordances were investigated.
- The nature of the interaction with multimedia. Hedonic properties, ease of navigation, clarity of instructions, and adaptability to different user needs; but also accessibility, cognitive learning, and emotional stimulation tests were carried out (Goleman, 1995).

What authors aimed to address was:

Research Question 1 (RQ1): can the specific novel tactile 3D-printed reproductions of artwork surface features depicted in this work enhance accessibility and inclusivity, especially for people with visual impairments?

Research Question 2 (RQ2): does integrating high-resolution imaging and scientific data into tangible, multisensory exhibits improve public engagement and understanding of the artwork's material and conservation aspects?

Research Question 3 (RQ3): how do users respond—emotionally, cognitively, and socially—to a multisensory, interactive experience involving 3D-printed models of a painting's surface?

4.3 Quantitative and qualitative evaluation tools

The PERCEIVE project used the multi-partitioned analysis as its operational methodology (Pagano et al., 2016). It is composed of three evaluation tools—**observation, direct interview and guided-scenario**—used according to a predetermined time-frame and a specific operating method. These tools allow for a more in-depth view of the user profiling and experience. The multi-partitioned analysis involved both quantitative and qualitative research, different both in terms of the operating methods and the tools used.

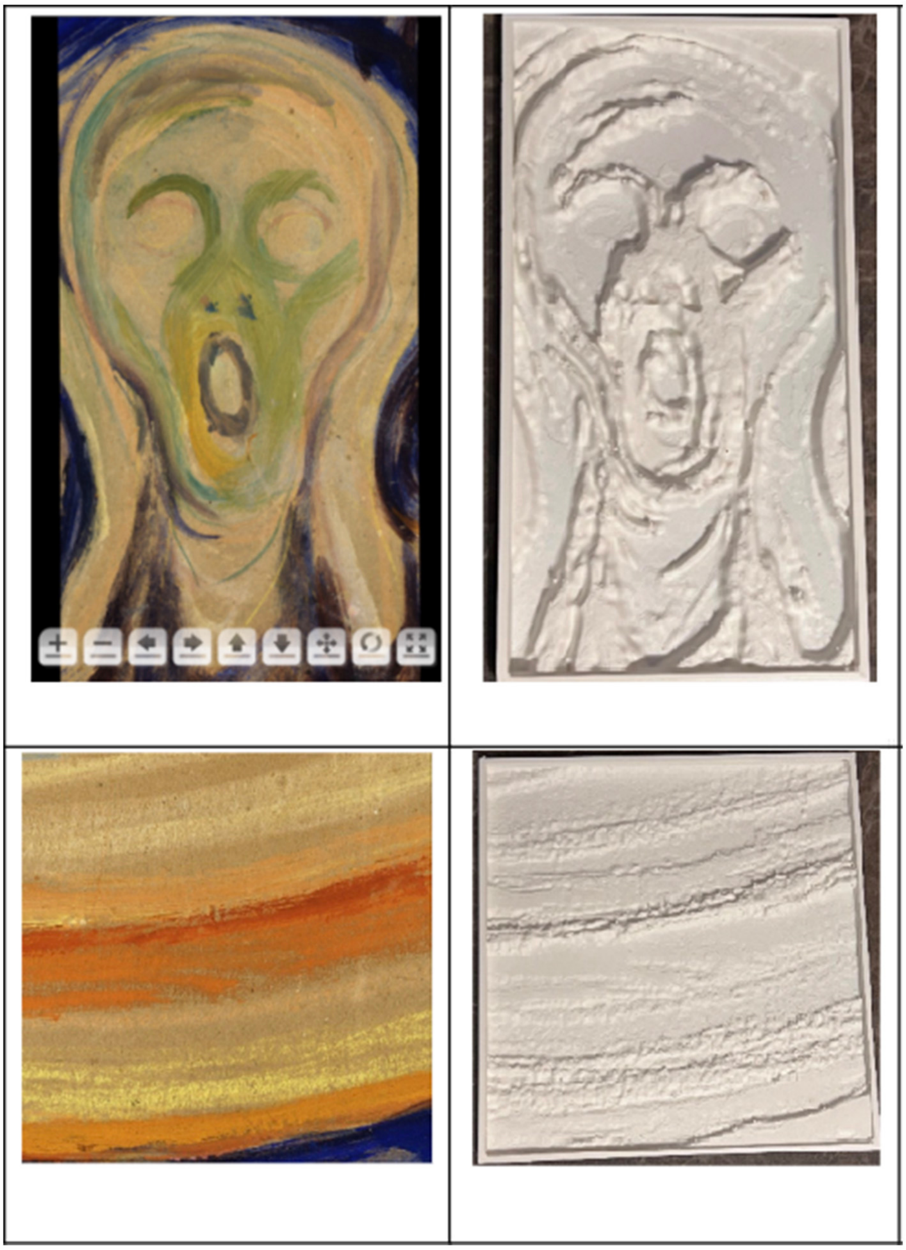

FIGURE 11
The sections of areas of the painting which were studied **(left)** and the corresponding 3D-printed artifacts **(right)**.

The methods used to collect quantitative data are mainly paper-based or online questionnaires, both of which take an average of 5–7 min to complete. In the PERCEIVE project, we used tablet-based questionnaires developed on Google Form. In general, the questions required a rating from 0 to 10 or multiple choice items using a graphic symbol. The data is then converted into numbers, graphs and statistics. In this project, we adopted both rating and multiple choice.

Observations also fall partly into this category: they collect objective-subjective data from the users who are being monitored; their actions, gestures, glances and paths are recorded according to a predetermined form. In this case, too, quantity is essential in order to obtain a credible basis for results. In this case, too, observation was carried out according to a predetermined template.

Qualitative research, on the other hand, is a type of empathic, empirical, exploratory, direct, and physical research. It is used to understand the reasons, motivations, opinions, and trends that lie behind the more numerical data of quantitative research. The most commonly used techniques are F2F (Face to Face), the so-called *focus groups*, in which a very small sample of respondents (carefully selected participants) are interviewed over a very long period of time. Another technique is in-depth questionnaires, or open-ended questionnaires, which allow the user to freely express their thoughts, doubts, or to respond to a specific request or opinion, voluntarily and unconditionally. In the PERCEIVE project, we used both in-depth and open-ended questionnaires, again based on a pre-defined template.

4.4 Logistics

The UX evaluation was submitted in three moments:

- *an initial presentation moment*, for making the user understand the usefulness of this activity (for research and development purposes), its anonymity, the free nature of this test, and the freedom to refuse to be interviewed/observed.
- *a second moment of use of the application by the user*; he/she was followed by the operator who observed his/her behaviors, his/her naturalness, his/her psycho-physical and verbal reactions, any discomforts and times of overall use.
- *a third moment of direct and detailed evaluation*, where the operator spoke directly to the user, retracing some moments of the interaction and explaining some sensations felt.

The evaluation experience lasted no more than 20 min, from the moment of the meeting with the user until the closing of the questionnaire together with the operator. The UX evaluation was carried out via laptops/tablets, through an online service for collecting data in a unique repository (google form). The user was accompanied in filling out the "Post-experience" questionnaire by the operator; the latter, autonomously conducted the previous "During the experience" and "Pre-experience" templates.

The procedure included this combination of tools and timing:

- "Pre-experience" questionnaire (QST), where the demographics and profile of the user were collected before the interaction with the demonstrator
- "During-experience" observation (OBS), hidden to the user, where the evaluation operators silently noticed the reactions of the users according to several predefined criteria
- "Post-experience" questionnaire (QST), where the user was asked a set of questions about the quality of the experience.

4.5 Target

No type of user was selected *a priori*, to respect the randomness and variety of the public that can potentially reach the InArt24 conference, at any time and use the product.

The target audience for PERCEIVE UX evaluation reflected the ideal users envisioned for the multimedia product being developed based on Much painting and 3D print. This ideal profile certainly derived from the domains of cultural heritage, conservation science as well as tourism. The target audience could be hence categorized into the following groups:

- *Experts, professionals, and enthusiasts*. These individuals may visit the cultural site independently, driven by professional, academic, or personal interests. For these audiences, the multimedia experience should be focused and enriched with additional perceptual stimuli and in-depth materials that complement their existing knowledge and provide a deeper understanding of the cultural content.
- *Local and international tourists*. These may be organized groups, families, or individuals visiting the cultural site and engaging with the technology application out of curiosity or enthusiasm rather than expertise. This audience is typically encountered during holidays or short stays in cultural destinations or, if local, at weekends and special opening events.
- *Children and adolescents*. Reached through schools, summer programmes, associations, or families. They are often involved through activities tailored to their interests, abilities, and needs. Educational and social contexts shape their experience to a large extent, requiring cultural and multimedia applications to be participatory and inclusive.
- *Persons with disabilities*. Especially those with visual impairments. The design of technological solutions for cultural heritage must adopt an inclusive approach, ensuring that multimedia applications are accessible to a wide and diverse audience.

The evaluation was carried out on a sample of approximately 30 users per each OBS and QST. This number was considered to be more than sufficient to establish the first behavioral trends, that could be compared with other evaluations in the future. Furthermore, this number far exceeds the qualitative and quantitative standards set by the EU and ISO (which suggest test cases with 15–20 participants).

4.6 Outcomes

4.6.1 Data collection

The InArt24 UX evaluation collected data in an attempt to match target goals. The study involved two groups: 38 observed users and 39 questioned users, for a total of 77 participants.

Based on **OBS** analysis, the majority of participants (56.76%) were female, with males making up 43.24%. The majority of participants were adults (91.89%), with teenagers and retired individuals making up smaller proportions, 5.41% and 2.70%, respectively.

The environment of the activity was predominantly quiet, as reported by 67.57% of participants, although some noted that it was confusing (21.62%) or slightly crowded but still manageable (8.11%). A small proportion (2.70%) reported distracting background noise. In terms of video engagement, 70.27% of participants watched the video, with the same percentage watching through to the end. Additionally, 67.57% seemed interested in the video, although a small group found it less relevant or did not engage with it.

Interaction within the activity was largely collaborative, with most participants working in pairs (70.27%), although smaller groups of three or four also participated. About half (51.35%) of the participants knew their partners, while 40.54% did not. The majority (72.97%) talked to others during the activity, while a smaller group (18.92%) remained silent.

Understanding and comfort levels were high among the participants. Some 78.38% said they understood what they had to do, and 83.78% felt comfortable during the activity. However, a small percentage expressed confusion or noted difficulties.

Emotionally, curiosity was a dominant observation, often associated with feelings of wonder, excitement, and pleasure. Relaxation was another common emotion, suggesting that participants found the activity enjoyable. However, a small group expressed confusion or disorientation.

Engagement with the interactive surface was notable, with 75.68% of participants actively touching it. Finally, the duration of engagement with the activity was significant, with most participants (75.68%) engaging for more than 60 s. A smaller number spent 30–60 s (10.81%) or less than 30 s (8.11%).

QST instead revealed that the knowledge of Munch's *The Scream* varied from user to user. The majority of questioned users (74%) reported only minimal knowledge, often stating that they had "heard of it" without giving further details. A smaller proportion of respondents (13%) demonstrated a moderate understanding, referring to specific aspects such as the painting's iconic status, its theft and recovery, or basic historical context. Interestingly, a minority (10%) demonstrated an in-depth knowledge of the artwork, discussing topics such as the different versions of the painting, conservation challenges, and scientific research into its deterioration. Only 3% of participants admitted to having no knowledge of *The Scream*. These findings suggest that while the painting is widely recognized as a cultural symbol, there is significant potential to broaben public understanding of its artistic, historical, and scientific importance.

In terms of audience profile, **QST** data collected shows that the majority of respondents (68%) visit cultural sites or museums more than five times a year, indicating a strong interest and commitment to cultural heritage. A smaller group (24%) visit 3–5 times a year, while 8% are infrequent visitors, visiting 1–2 times a year. In terms of preferred support during visits, the most commonly chosen options are guided tours with a physical person and self-guided exploration (e.g., using paper-based guides or visiting without any support). Many respondents (around 50%) also expressed interest in interactive or digital tools, such as mobile applications, touch totems, or multimedia installations. In particular, tangible interactives (such as touchable replicas or 3D prints) and playful elements are favored by a subset of users, reflecting a desire for engaging and immersive experiences. For receiving information, the majority prefer reading panels with text and images, in line with their tendency toward self-guided exploration. Secondary preferences include listening to a guide (via audio guides or personal tours) and watching videos. Some participants also appreciate multimedia installations as a dynamic way of learning, while playful and game-like interactions are less universally desired, but remain important for a niche audience.

In summary, the typical user profile of InArt2024 users reflects what we expected as the preferred audience for the "Scream Time Machine" demonstrator.

4.6.2 Key findings of quantitative and qualitative data

OBS data revealed varied levels of participant engagement during the "Scream Time Machine" activity. Initial interactions often began with silence and observation, as participants tried to understand the activity or listened to presentations. While some appeared disengaged or confused early on, engagement levels increased during the hands-on tasks and the game. Participants frequently asked technical and contextual questions, particularly during the tactile and video experiences, showing curiosity and interest in the materials and concepts presented.

Some individuals demonstrated deep engagement, such as actively exploring 3D prints, commenting on scan details, or asking about height differences. The interactive game elicited mixed responses; some found the card chronology challenging but still engaged enthusiastically, often expressing excitement or humor. In particular, background noise, low audio levels in the video, and moments of confusion were cited as barriers to full immersion.

Collaboration varied, with some participants working closely with others and others navigating tasks individually. Participants often showed a general desire to engage with organizers and other users, emphasizing a shared enthusiasm for the experience. In general, tactile and game elements were highlighted, which promotes interaction, curiosity, and enjoyment despite occasional confusion or technical challenges.

QST data confirmed and reinforced the OBS results. The "Scream Time Machine" experience was overwhelmingly enjoyed by the participants, with 92% rating it 4 or 5 out of 5. Many commented on the engaging combination of tactile interaction, visual storytelling, and innovative educational approaches. The 3D printed replicas emerged as the star feature, praised by 68% of the users for their reliability and ability to make the artwork more tangible. As one participant noted, *"The tactile replicas sparked wonder and made the artwork feel accessible."*

Another popular element was the card game, which 52% described as entertaining and interactive. Comments like *"It was fun and engaging, combining learning with creativity"* captured the sentiment of many who enjoyed the hands-on nature of this activity. Meanwhile, 40% noted the introductory video as a highlight, with its ability to set the tone and tell a compelling story. One user shared, *"The story told in the video brought a new perspective to the Scream."*

The sensory and emotional aspects of the experience made a strong impression. The tactile exploration was particularly powerful, with 84% expressing feelings of curiosity, excitement, and wonder. Participants often mentioned the emotional connection facilitated by the colors and light projections, which 72% found relaxing. One participant affirmed *"The tactile exploration allowed me to feel excitement and pleasure, while the colors and projections added depth."*

Curiosity was the most commonly cited sensation, resonating with 80% of the participants, with excitement and complexity close behind. However, some noted that, while the innovative elements added depth, they occasionally felt overwhelming or confusing. As one participant put it, *"The innovative approach is great, but some aspects felt a bit complex."*

The video tutorial also received mostly positive feedback, with 76% agreeing that the language was easy to understand. However, there were some suggestions such as *"improve speaker quality"* or adding subtitles to make the content even more accessible.

In general, the "Scream Time Machine" succeeded in combining technology, storytelling, and tactile interaction to create a memorable and multifaceted experience. As one participant concluded, *"The high-res scan of the Scream and 3D replicas made the experience feel real and reliable."*

Users' reactions to the various images of Munch's "Scream" and the feelings associated with them varied, reflecting a mixture of intellectual engagement with the story of the artwork and emotional responses to its visual impact. They often spoke of feelings of fear, anxiety, and discomfort with the Scream images, describing feelings of "chaos," "anguish," and "terror." They also mentioned nostalgia, sadness, and depression, suggesting a complex emotional connection to the images, especially when considering their historical context.

Some users noted feelings of curiosity and wonder, particularly when viewing images that revealed new perspectives on the painting or its history, such as the first black-and-white photographs or damaged versions. Others felt a sense of awe or admiration for the original piece. A few expressed indifference or confusion, often indicating that their focus was more on understanding the story behind the painting, rather than having an emotional response to the image itself.

There was also an appreciation for the high level of realism and color in the images, with a few people noting that certain images were more vivid or engaging than others. Overall, users' responses suggest that the emotional complexity of the "Scream" is central to their experience, evoking a range of responses from curiosity and wonder to sadness and anxiety.

At the end of the "Scream Time Machine" experience, users reported having gained several key insights. A key takeaway was an understanding of how the colors in Munch's "Scream" have changed over time, with many users reflecting on the importance of studying these shifts as a part of the artwork's historical narrative.

The experience also provided a deeper appreciation of the variety of documentation methods used to present the painting. Users noted that the experience enabled them to explore different versions of "The Scream" and various studies conducted on the painting, offering new perspectives on its history and significance. This full understanding of the changes to the artwork, both in terms of color and form, as well as the diverse documentation and 3D printing methods, enriched their overall appreciation of Munch's masterpiece and its continuing impact.

In definitive, the evaluation results clearly support the core research questions. First, the overwhelmingly positive response to tactile 3D printed models, praised by 68% of users for making the artwork "feel accessible"—demonstrated that such physical reproductions can **significantly improve accessibility and engagement**, particularly for those with visual impairments (Research Question 1). Secondly, the integration of high-resolution imaging and pigment analysis into the exhibit allowed visitors to understand complex conservation issues, such as color degradation over time. This was evidenced by the participants' ability to recall scientific insights and express increased appreciation for the material history of the painting, supporting **effective transfer of public knowledge through multisensory methods** (Research Question 2). Lastly, the combination of emotional responses (curiosity, wonder), extended engagement times and positive feedback on the interactive storytelling elements confirms the exhibit's ability to **foster deep emotional and cognitive involvement** (Research Question 3). These findings validate the effectiveness of the "Scream Time Machine" demonstrator in transforming passive observation into active, meaningful interaction with cultural heritage content.

5 Discussion

This first UX evaluation of the PERCEIVE project at the InArt24 conference, in Oslo, tested the multi-sensory "The Scream Time Machine" exhibit with members of the public. Although the evaluation pertained a global experience with different stages and cognitive phases, the 3D printed artifacts created were central to the exhibition. We identified some key areas for improvement and success factors, such as the power of (a) knowledge transfer about lost polychromy, color changes over time, different colored versions of the artwork, as well as the integration of the conservation process, and (b) the overall experience of the demonstrator and the interactive modes.

In terms of **knowledge transfer** (a), users highlighted the importance of the visual and tactile elements in enhancing their understanding. They appreciated the clear demonstration of color changes over time and the ability to compare different color versions of the artwork. The integration of the conservation process into the narrative was particularly effective, allowing participants to connect the technical aspects of art conservation with the emotional and historical significance of The Scream.

Moreover, the combination of high-resolution scans, 3D printed replicas, and interactive storytelling was praised for making complex concepts accessible and engaging. Participants also appreciated the structured approach to explaining the lost polychromy, which provided a deeper appreciation of the artwork's original aesthetic and historical context. These insights highlight the importance of combining educational content with hands-on, multisensory experiences to foster a deeper and more memorable connection with cultural heritage.

In terms of the **overall experience** (b), the demonstrator had a very positive impact. This response indicates that the content itself is highly engaging and intriguing to users. It suggests that with the right guidance and information, the overall 3D prints experience can effectively engage and educate audiences. Capitalizing on this interest by enhancing the content and presentation could further improve user satisfaction. In particular, user feedback has allowed us to make some suggestions.

- Added Value of Backlighting. The feature of shining a white light behind the 2D prints did not resonate with many users, who did not perceive it as adding significant value to their experience. This may be because the backlighting did not improve the visual quality or understanding of the prints in any meaningful way. Re-evaluating this feature and considering alternative enhancements, such as interactive elements or augmented reality overlays, could provide a more impactful user experience.
- Success of High-Resolution Scan Exploration. The exploration of the high-resolution scan was a success. Users appreciated the opportunity to examine closely detailed images, which

probably led to a deeper understanding and appreciation of "The Scream." This positive feedback suggests that incorporating more high-resolution scans or interactive elements that allow users to explore artworks in detail could improve educational outcomes and user satisfaction.

- Subject of inquiry. The most interesting part of the experience was the innovative way of demonstrating the scientific information in the artwork through 3D printing and gaming. Tactile exploration creates feelings of curiosity, wonder, and complexity, which are ultimately those that increase visitor engagement and interest in learning about scientific data related to an artwork, confirming the initial hypothesis of our work.

This research focused on the creation of haptic 3D printed samples, by height-separating the color surface features of the Scream 1910? painting, in the order they were layered, eluding to the color painting technique and the sequence of color application in two specific areas of the painting (an area of the sky and the screaming face). The separation of the color features was created by performing RGB clustering of a high-resolution 2D image scan of the painting.

We find that for similar paintings with large areas of consistent color, the approach shown here to create the 3D printed artifacts is sufficient but, to expand the method performed in this work to more complicated artworks with more mixed color areas, we believe that RGB thresholding would not be as useful as a hyperspectral unmixing approach to create the pigment layering, since the Scream has large distinct color areas and is easy to segment, but for other types of artworks, this may not be as straightforward.

In terms of expanding the shown method to the whole painting, the only limiting factor we would predict to be a problem would be the computer's memory (RAM), since a small 10×10 cm ^{2} area scanned at 90× magnification requires about 800 MB of storage. Additionally, if one wants to blow up the size of the final 3D printed artifact by 2 times, as was done in this work, if the size of the area becomes larger than the printing bed area available then the 3D print would have to be created in tiled sections and combined afterwards.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: PERCEIVE Color Knowledge Repository, https://perceive-data.iesl.forth.gr/records/s4q5s-qkd22.

Author contributions

PSt: Visualization, Resources, Writing – original draft, Formal analysis, Project administration, Methodology, Data curation, Validation, Investigation, Writing – review & editing, Conceptualization, Software. AP: Writing – review & editing, Writing – original draft. BB: Writing – review & editing, Writing – original draft. PSi: Writing – review & editing. SS: Writing – review & editing, Writing – original draft. EL: Writing – original draft, Writing – review & editing. VS: Writing – review & editing. GT: Writing – review & editing. IS: Writing – review & editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomp.2025.1597880/full#supplementary-material

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