Supplementary Information

Physical restoration of a painting with a digitally-constructed mask

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I. Procurement

To demonstrate the benefits of physically-applied digital restoration, we obtained a painting for physical experiments in this study. As explained in the manuscript, digital methods are especially useful for paintings with intricate details and widespread, complex damages. Here, we describe in greater detail how such factors influenced the choice of the painting.

A lamination approach is sensitive to topographical variations, requiring application of pressure to ensure full contact between the infill mask and the surface of the work; poor adhesion results in optical defects immediately apparent to a viewer. As such, paintings with non-planar surfaces are considerably more difficult to restore with the lamination approach. Many Impressionist, modern, and late Baroque paintings have such non-planarity from generous application of paint without smoothing. Conversely, high Renaissance works, especially on smooth substrates such as wood and copper, often exemplify highly planar painted surfaces as a consequence of glazing (the application of several thin layers of paint to depict smooth gradients and deeper tones). The nature of the paint is also of significance; fragile materials such as tempera and watercolor can be damaged more easily, whereas multi-layer oil points can be more robust to physical effects, especially with varnishing. As such, we sought an oil painting for this study with a smooth surface on a solid substrate to ensure a laminated mask would preserve the optical properties of the painting.

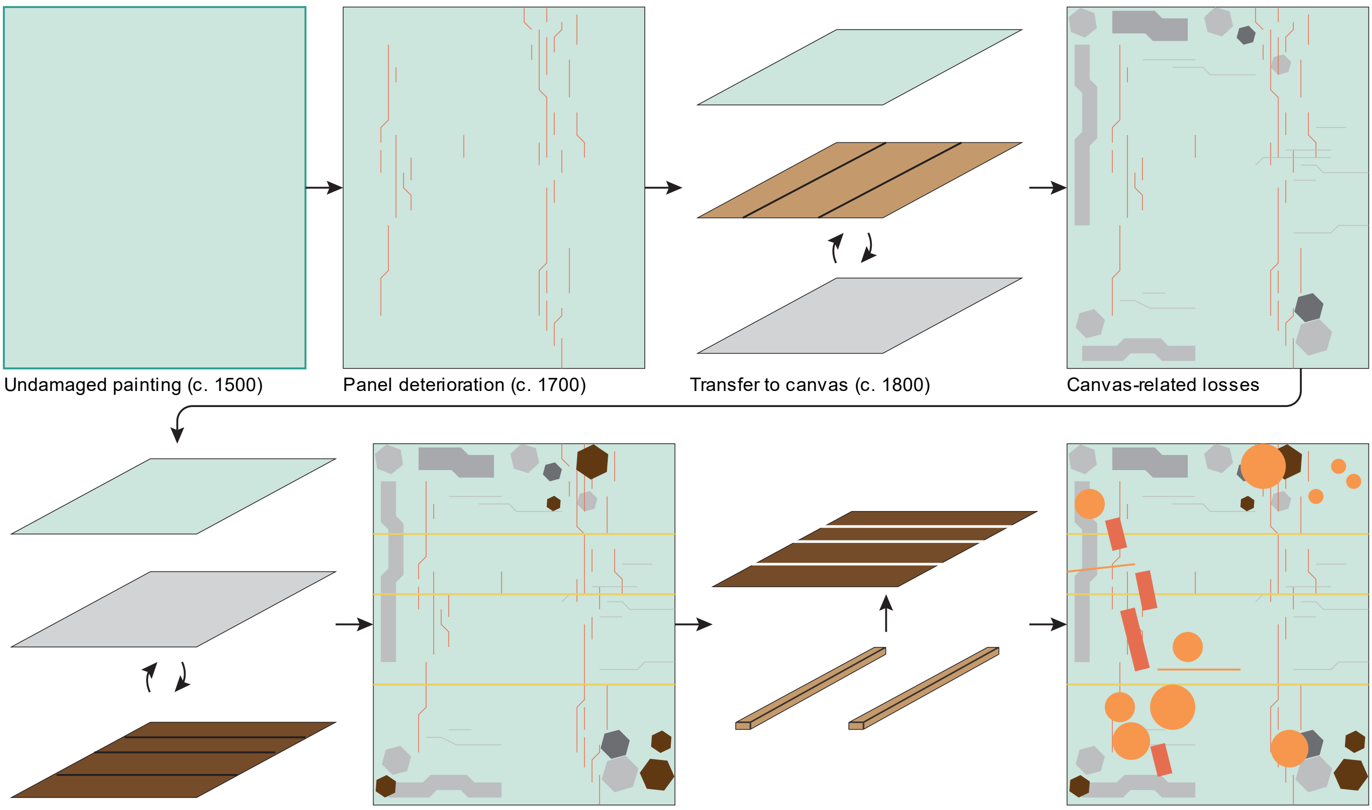
Applying the physical mask takes only a few hours owing to the parallelized infilling of losses, while manual restoration is inherently a sequential approach to restoring individual regions. The benefits of applying an infill mask are apparent when the number of losses is high. Paintings empirically accumulate losses with time; exposure to inadequate environmental conditions, improper conservation treatments, accidents, and degradation of materials have led to greater damage in works painted centuries ago compared to more recent oeuvres[1]. We narrowed our selection to older paintings with high amounts of accumulated damage to exemplify the pertinence of our infill protocol.

Manual restoration of highly intricate visual features requires substantial skill and time. An infill mask is agnostic to the visual complexity of the restored details, taking the same amount of time to apply regardless of the intricacy of a given infill region. Losses in a painting in areas of high visual complexity, such as human faces and fine details, can be infilled with greater expediency by a printed infill mask. While many schools of art espoused detail in paintings, some of the most intricate visual features and precise gradients in early oil works are found in those of the Flemish Renaissance[41-43]. Some artists (e.g., Jan van Eyck) painted with a single hair to create sub-mm features in their ornate works. Such small features are incredibly difficult to manually restore, especially if the area of loss is of complex geometry; a scratch on a gradient requires careful application of individual colors in a highly precise manner as opposed to brush-based smoothing or glazing, as would have been used to originally create the gradient by the artist. Printed infill masks do not suffer from such difficulties. This consideration finally narrowed our search to early Netherlandish oil paintings on panel or copper substrates with extensive amounts of damage to intricate features.

We chose to obtain a painting for this study rather than lend one from an existing collection. Works stored by cultural institutions are generally in stable environmental conditions and are not likely to undergo further damage. Those offered for public sale, especially in auctions of dilapidated estates, can originate from neglected or abandoned storage with no clear avenue for adequate storage and conservation. We obtained the painting in this study at an estate auction (Boulogne Encheres, Contents of a Breton House, 2022, lot 51), where the painting had clearly been neglected; abundant damages, cobwebs, evidence of prior rudimentary restorations, and haphazard storage within an abandoned domicile all pointed to ongoing severe deterioration of the piece. No information on provenance or authorship was known by the auction house. Stylistically, the painting followed many conventions of early Netherlandish painting, with intricate details and immense amounts of damage, being painted with oil on a wood panel and meeting our selection criteria for this study.

II. Damage assessment

To prepare for cleaning and digital restoration, we undertook an analysis of the painting in an attempt to derive the complex restoration history it has undergone and the origins of damage to the piece. Our hypothesized chronology is depicted in Supplementary Fig. 1, with the full damaged painting shown in Supplementary Fig. 2. Several factors lead us to hypothesize that the work was originally painted on a single panel comprising vertically aligned boards; vertically-oriented damage comprising significant cracking is present around the right third of the painting spanning the height of the piece. The vertically-oriented damage on the surface of the painting implies that at some point the panel support began failing, either at a weak point in the wood grain, from a seam in a composite panel, rotting, or deterioration from an insect infestation. It would be highly unusual for a portrait aspect painting to have been originally painted on horizontally-oriented panels, further suggesting that the current support is not original.



Supplementary Fig. 1 | Hypothesized damage chronology. From physical examination of the damaged painting, we believe there were several prior restoration attempts that have led to the complex damages currently present. Vertical craquelure patterns may indicate an original panel support with vertically-oriented panels, the deterioration of which may have led to a transfer to canvas, as was popular in the late 18th century. Damages from the transfer and a change in conservation preference may have led to a transfer to the current, horizontally-oriented panels. Major losses at the panel joining seams may have led to the recent application of a rudimentary cradle, with neglected storage and poor conservation thereafter leaving the painting with widespread damages of highly varying nature.

We postulate that at some point in the 18th century the painting was transferred to canvas in an attempt to mitigate further damage to the work, as was popular restoration practice at the time[35,36]. Imaging of the surface under a raking light shows transferred woven canvas texture on some areas (Supplementary Fig. 2c), a possible remnant of the bygone procedure. Alternatively, the transferred canvas texture may have been from storage with a canvas placed on the surface of the painting, or from a restoration procedure where the paint layer was temporarily fixed to a canvas for transfer to a new support. Regardless, the current panel support of the painting, comprising four horizontally-oriented wood boards adhered together, appearing to be made of oak, was likely configured at the turn of the 20th century as canvas transfers lost popularity and conservation practice turned to maintaining paintings on an originally-intended substrate[1]. Oil-based retouching discovered during cleaning may have taken place during this treatment; broader strokes over the blue robe with good color matching suggest professional work and that extensive damages had already occurred when the painting was on its prior support. Most tellingly, the face of the central figure had been overpainted to a warmer skin tone, concealing the brighter blue-gray coloration of the original paint layer; this may have been done to appease the preferences of an owner, as was widespread practice in the era[1,36,40]. This treatment also likely involved the application of a yellowing varnish that could not be easily dissolved with conventional conservation-grade varnish removers.

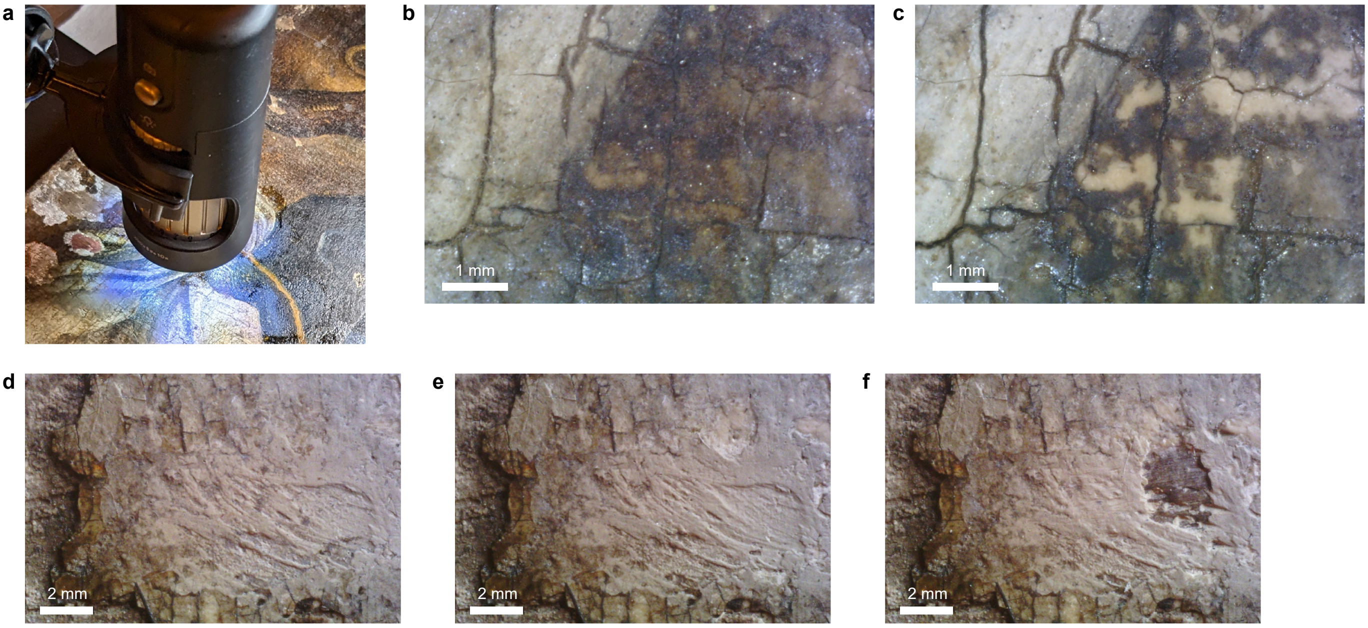
Improper storage likely contributed to the warping of the horizontal panels over time, leading to major losses along the seams of the boards of the panel support. Evidence of insect boring on the rear of the wood support may imply excess humidity, commensurate with the warping and fissure between individual boards comprising the panel. The pale nature of some areas of red pigment (see the red robe on the left side of the painting) coupled with surface protrusions may imply the formation of lead soap aggregates, having further led to scattered losses independent of structural or environmental conditions. Sometime in the 20th century, an unfinished restoration procedure involved watercolor-based infilling of several missing regions, most notably the face of the infant (Supplementary Fig. 2b), as well as broader level infill of point losses present in the dark blue robe. The watercolor infilling was applied directly to areas with missing ground paint layers, without leveling the surface by filling cavities with gesso or other materials, suggesting a more rudimentary conservation treatment. At some point in the past century, epoxy was applied to several losses, perhaps as an attempt to prevent the paint surface from degrading, or by accident as suggested by smearing in some areas.

Supplementary Fig. 2 | Damage prior to cleaning. a, Full photograph of the painting in this work prior to cleaning, showing extensive overpainting in the lower half of the painting, with abundant stains, varnish yellowing, epoxy smears, and accumulated dirt especially at the upper part of the work. Exposed gesso and wood panel are especially noticeable at the lower left. **b,** Closeup of the infant, showing the prior manual restoration with overpainting of losses, poor color matching, and poor feature reconstruction owing in part to the miniscule scale of intricate visual losses. **c,** Closeup of the lower left of the painting, showing remnant traces of a woven canvas texture, possibly indicating a prior canvas support.

Further losses up to the present day stemmed from rough handling of the painting and storage in humid conditions. Evidence of mold and rot on the rear of the panel, abrasion of the edges of the panel, as well as the abandoned location of the painting prior to acquisition for this study imply that the broad paint flaking present in the piece is distinct from the complete losses in other regions (e.g., the beams near the top of the painting), which likely occurred before the painting was transferred to the current panel support. This is further evidenced by a varnish layer present on exposed portions of the wood support, which followed paint and ground layer losses in such regions. The sparse infilling of missing regions indicates either significant losses after the previous attempted restoration, or perhaps more likely an owner giving up on restoration and instead attempting to preserve the work with varnish until a future conservation effort. The vast number of losses, their significant effect on aesthetic cohesion, and the complexity of their effects in areas with fine details all make the painting an excellent case study for applying digital restoration. A manual restoration of all losses would take extraordinary effort, dexterity, and time. Digital tools in this case can vastly expedite the process.

III. Cleaning and stabilization

Cleaning of the painting surface followed conventional evaluation of different solvents for compatibility and debris removal primarily through solvent application or in limited cases mechanical removal[1,12,32,36] (Supplementary Fig. 3). Digital microscope imaging during cleaning provided real-time information on microscale reactions between cleaning solvents, varnish, debris, and the paint layer, preventing potential damages to the surviving paint layer (Supplementary Fig. 3a). We began with cotton tip spot testing several solvents (all from Sigma Aldrich, Saint Louis, USA) in different areas of the painting to determine compatibility. Isopropanol, methanol, white mineral spirit, and acetone were evaluated alone and diluted in de-ionized water at concentrations of 25%, 50%, and 75%. Conservation-grade varnish remover (Winsor & Newton, London, England) and de-ionized water alone were also spot-tested. The differing types of damage on the painting required use of different solvents and combinations thereof in different areas. Full cleaning proceeded with cotton tips or cotton swabs saturated with the most dilute organic solvent concentration able to address the target damage. The upper-most layer of varnish could be removed with 50% isopropanol in water (Supplementary Fig. 3b-c). Areas with watercolor-based infill from previous restorations then required cleaning with pure water, underneath which yellowed varnish could then be removed with pure white spirit. Conservation-grade varnish remover was not found to be effective in any area, likely due to the primitive and non-conservation grade composition of varnishes from previous treatments. Some areas with previous infill contained oil-based pigments, which in some cases we did not remove owing to possible damage to surviving paint. In areas of exposed ground these oil-based infills were able to be removed with pure methanol or white spirit. In areas where epoxy-based structural infilling was present (Supplementary Fig. 3d), no solvent was able to remove excess applied material (Supplementary Fig. 3e) and mechanical scraping with a scalpel or tweezer was used to remove material (Supplementary Fig. 3f). In some areas, the risk of damage to the paint layer when removing epoxy led us to forego their removal. We expect a future conservation with more precise technological capabilities may be able to address them.



Supplementary Fig. 3 | Solvent-based cleaning. a, A digital microscope was used to see the effects of different solvents on the paint layer to ensure adequate cleaning without damage to surviving areas. **b,** An area at the edge of the blue robe prior to cleaning, showing darkened varnish, overpainting, and accumulated grime, with surviving paint fragments faintly discernable. **c,** Following cleaning, the grime and discolored varnish are removed, with the appearance of the white underlayer showing the thin nature of the applied paint and a plausible overcleaning during a prior conservation attempt. **d,** An area near the bottom left of the painting, with a crudely-applied epoxy layer. **e,** Solvents were found to be ineffective at removing the epoxy. **f,** While mechanical abrasion was able to chip away at the epoxy, the risk of shattering adjacent paint was deemed to high to warrant extensive removal.

We followed basic techniques for structural panel conservation[1,35]. The lower panel of the painting was found to be tenuously attached to other panels, with a clear gap having formed between them owing to warping. The cradle and lower panel were detached with mechanical abrasion of the sparse surviving adhesive and selective application of white spirit for cleaning solvent residues (Supplementary Fig. 4). Following drying, the panel was re-adhered to the remaining panels with wood-grade adhesive. No backing cradle was made or attached to the painting following the current conservation practice of allowing panel flexure in response to environmental changes.

Supplementary Fig. 4 | Panel support reconstruction. a, An existing cradle applied within the past century made of low-quality wood stock, suspected to be pine. **b,** The cradle was removed through abrasion of the sparsely-applied and mostly-detached adhesive. **c,** The lower panel of the support was found to be completely detached from the three remaining panels, and was re-adhered with wood adhesive prior to scanning. This step reduced the misalignment that was present from the prior positioning with the rear cradle.

IV. Imaging

High-magnification images for analysis of cleaning solvent performance were obtained with an Amscope Digital Microscope. Images of the painting at different stages in the conservation process for documentation and color balance were obtained with a Sony IMX363 camera and a Sony Alpha 7 camera. High resolution scans of the painting surface for digital treatment and mask construction were obtained by stitching together scans from a KIC Bookeye 4 V2. The raw scan color space (CMYK) is accurate for print reproduction, not digital display. To improve the clarity of visual features for human interpretation, all images in the manuscript are presented in RGB format, with scans of the painting having gammas increased to +2, contrast increased by 100, and blue color balance increased by 25. Images from the Sony Alpha 7 also have color balance adjustments (cyan -20, blue +20) and saturation decreased by 40. These values were set by adjusting the digital color representation of images to resemble that of the Sony IMX363 camera, images from which are unaltered and closely match human perception on a digital display. Rendering of the exploded view componentry was conducted with SolidWorks Visualize.

V. Attribution

We attribute the painting in this study to MPA on the basis of stylistic deviations from a predicate work by Schongauer, similarity of scale to the six known works by MPA, overlap in unique aesthetic techniques, evidence of plausible templating common to works by MPA, and historical considerations. We emphasize that the attribution is of utility here solely for the use of visual information from works similar to the piece at hand. We have not undertaken a detailed investigation of the chemical properties of the piece, analysis of the wood grain pattern for age determination, infrared imaging for underlayer analysis, or pigment identification through energy-dispersive x-ray spectroscopy, as would ordinarily be used for more rigorous attribution[1]. Our only purpose in attribution is to obtain a corpus of visually similar works from which visual features may be borrowed to reconstruct missing areas in the painting. This approach is inherently broadly applicable, as paintings of unknown origin may still be digitally restored with features borrowed from visually-similar works, helping expedite the conservation process.

The painting in this study follows the composition of the *Adoration of the Shepherds* by Schongauer held by the Staatliche Museen zu Berlin (Supplementary Fig. 5), helping us glean what missing areas may have originally contained based on the Schongauer version. However, there are several significant differences pointing to MPA as the author; the painting in this work is roughly twice the scale as the Schongauer, possessing several compositional differences: the addition of two swans on the lake, changes in the orientation of limbs on the infant, variations in facial structuring, addition of a trefoil motif to the blue robe, additions of ray halos, differing types of vegetation, a modified pattern on the cloth beneath the infant, and generally coarser brushwork.

Supplementary Fig. 5 | Visual comparison with prior work by Schongauer. a, The painting used in this study. **b,** The *Adoration of the Shepherds* by Martin Schongauer at the Staatliche Museen zu Berlin. Note the significant scale difference.

Several paintings visually related to the one in this study are shown in Supplementary Fig. 6. The scale of the painting in this study (50.2×59.8 cm), around double that of the Schongauer (28×37.5 cm), is nearly identical to that of four of the six extant works by MPA; The *Nativity* held by the Birmingham Museums Trust (50.1×58.4 cm, Supplementary Fig. 6b), The *Adoration of the Magi* held by the Museo del Prado (54.6×59.5 cm, Supplementary Fig. 6c), *The Presentation in the Temple* held by the National Gallery of Art (47.8×57.9 cm, though with some trimming of left edge, Supplementary Fig. 6d), and *The Flight into Egypt* held by the Burrell Collection (50.8×58.4 cm). The other two works known by MPA are cropped fragments of originals that may plausibly have been of similar size as well; the *Annunciation* held by the Burrell Collection (35.6×58.4 cm) and *Saint Anthony Rebukes Archbishop Simon de Sully in Bourges* held by the Phoebus Foundation (34×43 cm).

Supplementary Fig. 6 | Scaled visual comparison between related works of art. With exception of subpanel **e** all paintings are depicted at the same scale, showing the unique dimensional similarity of the painting in this study with works by MPA. **a,** The painting in this study. **b,** The *Nativity* by MPA held by the Birmingham Museums Trust. **c,** The *Adoration of the Magi* by MPA held by the Museo del Prado. **d,** *The Presentation in the Temple* by MPA held by the National Gallery of Art. **e,** The substantially larger central panel of the *Saint Columba Altarpiece* by Rogier van der Weyden held by the Alte Pinakothek, from which the identity of MPA is conventionally derived. **f,** The *Adoration of the Shepherds* by Martin Schongauer at the Staatliche Museen zu Berlin. **g,** The *Adoration* by Hans Memling held by the Museum für Angewandte Kunst Köln. Scale bars are 5 cm.

The similarity of physical dimension was a significant factor in the original attribution of the six known works by MPA[42,43], and is an important here as well, plausibly implying a common source of the original panel supports for the painting in this study and those by MPA. The physical dimensions of these works (around 50×60 cm) are substantially different from related works by other artists possessing similar stylistic attributes, further supporting a common attribution. The central panel of the *Saint Columba Altarpiece* by Rogier van der Weyden held by the Alte Pinakothek (138×153 cm, Supplementary Fig. 6e), is over double the size. MPA copied this central panel, with the under-drawing showing pentimenti from that of van der Weyden, suggesting contact between the two artists and forming the basis of the contemporary identity of MPA in the literature[42,43]. Formerly, works by MPA were attributed to Hans Memling[41-43], whose finer and smoother painting technique is evident in the *Adoration* held by the Museum für Angewandte Kunst Köln (21.5×29 cm, Supplementary Fig. 6g).

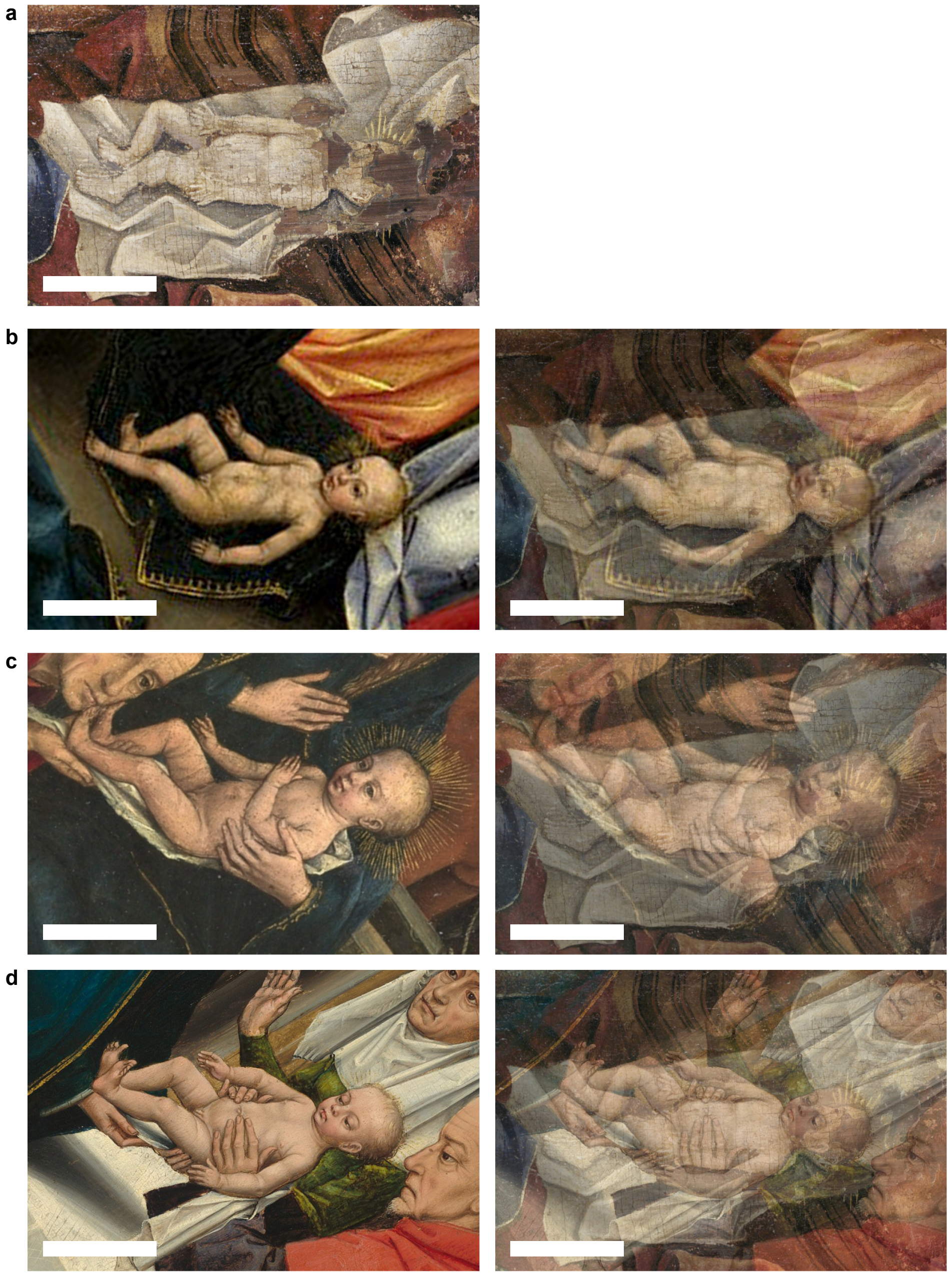
Aside from equivalent physical dimensions, the painting in this study possesses numerous unique stylistic similarities to extant works by MPA suggesting the use of common templates. The trefoil pattern on the edge of the blue robe is present in all but one of the extant works by MPA, having a distinctive design comprising two bands with the patterned trefoil running alongside. This trefoil pattern is also present in the corpus of works by Hans Memling, though at under half the physical scale. The embroidered loops of the white cloth near the top of the blue robe are also present in works by MPA and Memling, with the latter again painting at substantially smaller scale. The nearly identical scale of the infant in the painting in this study and that of other infants by MPA, discussed in detail later in this section, is further evidence of templating.

More broadly, the coarser depiction of figures in paintings by MPA, with flatter appearance of skin and cloth, matches the style and technical execution of the painting used in this study. Blue and red robes are commonly emphasized, with substantial areas of the painting devoted to their depiction, and additional effort made to incorporate folds in excess of those present for other garments. The figure at the upper right of the painting in this study has nuanced skin gradients and fine depiction of facial features, contrasting with the coarser depiction of the figure at the left; these variations in technical execution are noted in other works by MPA, with some historians suggesting the role of guild apprentices contributing to minor elements of the works[41-43]. The thin application of pigment in the painting used in this study (especially on the face of the upper right figure, the background landscape, foreground, and infant) echoes the nuanced translucency seen in all other works by MPA at close examination, evidencing a similar painterly technique.

While the composition of the painting in this work follows that of Schongauer, the composition is stretched to a wider aspect ratio than the Schongauer, possibly to ensure coverage of the full area of the original panel support. MPA did so with several paintings following established compositions[43]. Combined with the modification of compositional features and addition of visual elements, these differences point to the artist of the painting in this work having their own aesthetic sensibilities, choosing to modify compositional elements instead of directly copying all attributes. While copying of paintings and compositions was a common practice at the height of the Flemish Renaissance[42], the distinct visual additions and styling here point to the artist having greater discretion over the composition than a mere copyist. The modifications MPA made to their version of van der Weyden's *Saint Columba Altarpiece* closely follow those done to the painting in this study relative to Schongauer's *Adoration*, including the modification of panel dimension to ~50×~60 cm, incorporation of the trefoil motif on the edge of the robe, landscape simplification, lighter application of pigment, and coarser depiction of facial features, all supporting a common attribution.

Several historical considerations further support a connection of the painting in this study to MPA. The clear compositional following of Schongauer aligns with historical assessment of the connection between painters of the era. Works by MPA were originally attributed to Memling, both being considered pupils of van der Weyden and working in his studio[42,43]. Schongauer, of the same generation as MPA and Memling, following van der Weyden, is known to have been extensively influenced by van der Weyden and Memling as well[41]. Some historical accounts describe Schongauer's work as equivalent in quality and manner to Memling[41]; it would be unsurprising for MPA and Schongauer to have been in contact, sharing compositions following those of van der Weyden and each other.

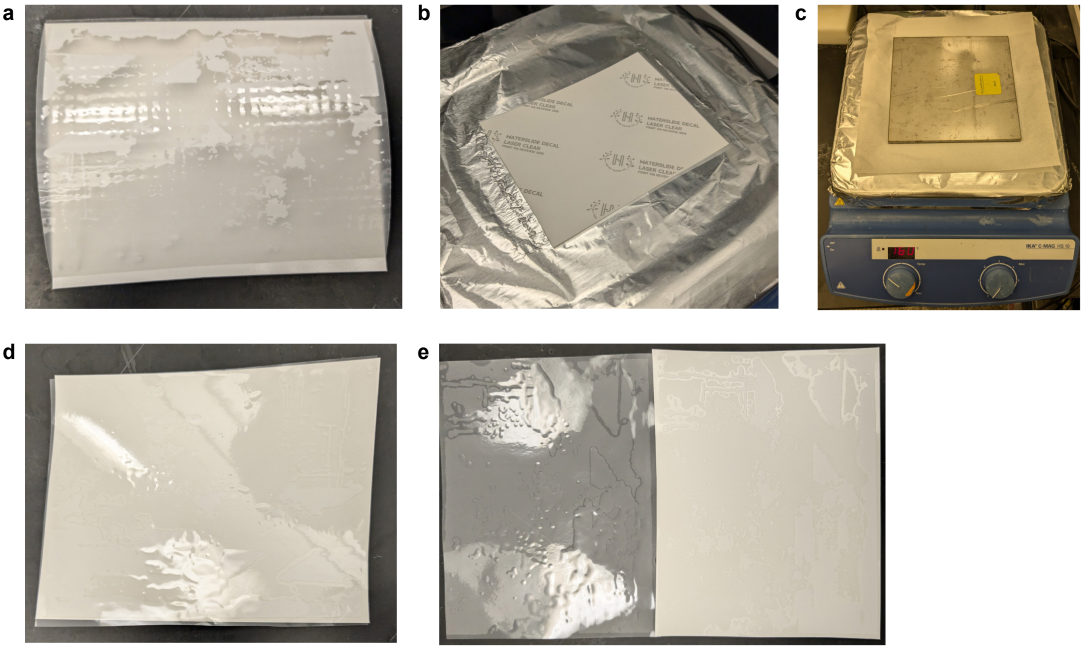
We use the MPA attribution to directly transfer missing areas to the infill pattern for the face of the infant, as detailed in the manuscript. MPA painted several infants of practically identical scale to the one in this work (Supplementary Fig. 7), reinforcing the stylistic attribution and giving us the liberty to choose a specific infant to transfer visual features from.



Supplementary Fig. 7 | Visual overlay of infant torso. All images are of identical scale and rotated to angularly align with each other. The right column of images corresponds to three infants in other works by MPA overlayed at 50% opacity on the damaged infant in the painting in this study. **a,** The damaged infant from the painting in this study. **b,** Infant from the *Nativity* held by the Birmingham Museums Trust. **c,** Infant from the *Adoration of the Magi* held by the Museo del Prado. **d,** Infant from *The Presentation in the Temple* held by the National Gallery of Art. Scale bars are 3 cm.

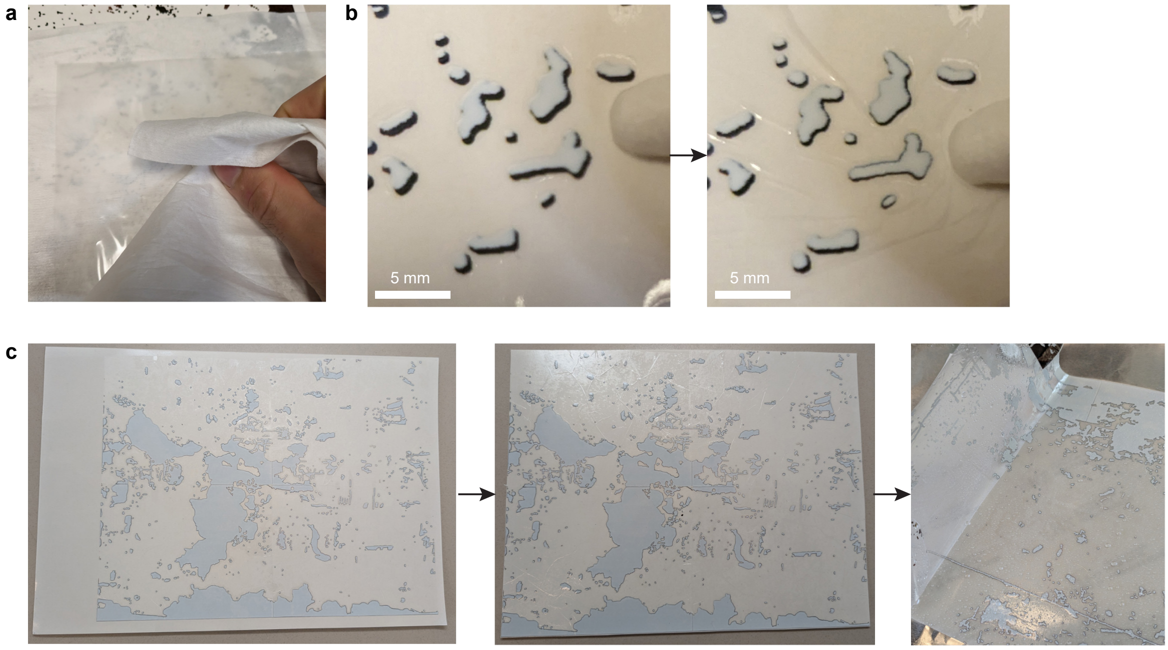
VI. Nuances of physical infill masking

Several stages of the construction and application of the laminate infill mask are depicted in further detail here to aid in protocol replication. The full heat transfer sequence for the white ink laminate construction is shown in Supplementary Fig. 8. The white ink layer is originally inkjet-deposited on a thermoplastic layer, and is applied to transfer paper through pressure on a hotplate. The ink layer must be closer to the hotplate than the transfer paper, as this ensures the subsequent peeling of the thermoplastic backing occurs smoothly with all regions transferred.



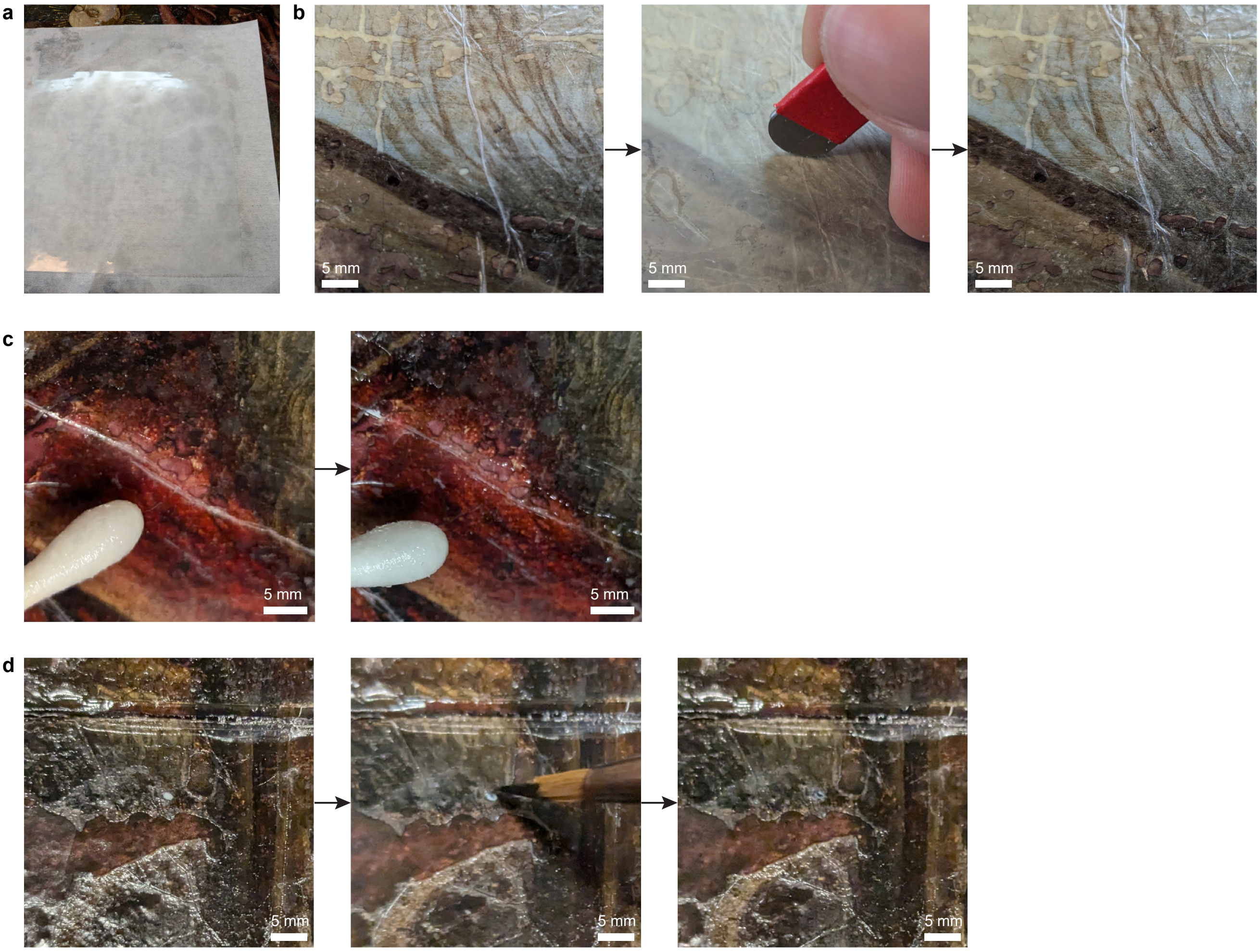
Supplementary Fig. 8 | Heat transfer of the white ink layer. a, The white ink layer sector, originally inkjet deposited on a thermoplastic film, is trimmed and placed over a piece of transfer paper. **b,** The stack is placed film-side down onto a hot plate. **c,** Pressure is applied with a pre-heated steel plate placed over the stack. **d,** After thermal transfer, the stack is left to cool. **e,** The original thermoplastic backing is peeled off, leaving the white ink on the transfer paper.

Significant steps in the alignment of the white ink layer with the color ink layer are shown in Supplementary Fig. 9, including the removal of excess water, local alignment of regions, and final treatments prior to the beginning of the full infill process on the painting. Four white ink sectors are applied per each color ink sector, prior to varnishing, trimming, and sealing of edges with additional application of varnish. The full mask can be peeled after saturation of the substrate with water in the same manner as the white ink layer.



Supplementary Fig. 9 | Mask fabrication techniques. a, Water removal from the applied white ink layer via pressure applied to a plastic film and underlying lint-free cloth. **b,** Local alignment of regions with a cotton tip. **c,** Trimming, varnishing, and peeling of the fully-aligned infill mask.

The application of the color mask to the painting and subsequent surface treatments are shown in greater detail in Supplementary Fig. 10, demonstrating several techniques to ensure optical transparency of the applied mask; water removal, crease flattening, and cosmetic infilling. These steps are necessary to avoid visual defects from creasing arising from the local alignment of infill regions.



Supplementary Fig. 10 | Mask application techniques. a, Excess water removal from mask placement with an applied lint-free cloth. **b,** Crease flattening with applied pressure through an overlayed plastic sheet. **c,** Optical transparency improved for creased areas with application of solvent. **d,** Final cosmetic infilling of sparse failed mask regions (i.e., areas where the white ink layer is completely exposed) with gray watercolor.

VII. Stability and reversibility

We follow the American Institute for Conservation Code of Ethics and Guidelines for Practice in this study. We emphasize two important areas of compliance. First, the digital nature of the infill mask provides a complete record of loss compensation on a work; the printed nature of the mask is readily visually-distinguishable from adjacent painted areas, ensuring visibility of the compensation and providing downstream conservators with ample information to inform cleaning decisions. Second, as an applied laminate film isolated by conservation-grade varnish, the mask can be easily removed from the surface of the painting without damage to the piece.

Conservation treatments should be fully reversible[1] and ideally preserve a painting for at least a century without significant deterioration of the visual state. We have not had a century to evaluate whether our infill mask will survive the variety of environmental conditions the painting may go through. However, to demonstrate the reversibility of the masking approach and evaluate short-term environmental exposure effects on the infill mask layer, we applied a prototype infill mask to the painting and removed it after 2 months of storage in ambient conditions with indirect sunlight illumination, environmental temperature and humidity control, but no physical movement as might be expected during transportation (Extended Data Fig. 8). No significant visual changes were noted after the initial hardening of varnish layers; only the slight accumulation of dust on the surface was found to be affecting the visual state (Extended Data Fig. 9c).

To remove the applied infill mask, starting from the bottom edge, the film is manually peeled through application of a force transverse to the surface of the painting. The interface between the varnish layer applied to the painting and the adjoining varnish layer applied to the surface of the transfer film is deliberately weak, the mask easily coming off in most locations. However, locally, the process may result in a significant applied force to the paint layer. To avoid damage, any areas found not be readily peeling away are gently pried off with an isopropanol-soaked cotton tip, which aids in severing the interface between the mask and the varnish on the paint layer. If necessary, the mask can be completely dissolved in a stubborn area with white spirit (Extended Data Fig. 8b-c). The infill mask can be removed in nearly one piece, with the surface of the painting wiped with a lint-free cloth to finish the removal process. Excess remaining varnish can be removed conventionally as needed.

VIII. Estimating a comparable manual infilling

The restoration conducted in this work involved the application of infill to 5,712 loss regions of varying size and complexity, spanning simple area color infilling to highly intricate facial feature reconstruction. In an effort to contextualize the significance of the infill step requiring only a few hours, here we aim to estimate the approximate duration that a comparable manual infilling would require. As ancillary portions of the conservation process (including the cleaning and stabilization of the work, varnishing, and framing) follow current practices, we narrow our focus to the timing required for infilling.

Commercial vendors, institutional conservation departments, and knowledgeable individuals generally estimate restorations for meter-scale works with high damage taking several months[1,4,9,11-14,16,17,32,35,36], with larger paintings taking as long as several decades to undergo treatment. Such general estimates would imply that our method of physically-applied digital restoration is several times quicker compared to conventional conservation, however we are unaware of any published method to estimate the specific duration of infilling for a painting. Any such method would have to account for variables spanning the extent of feature reconstruction, the scale of features to be restored, and additional complexities stemming from attributes such as surface non-planarity and substrate weakness. Here, it is pertinent that conventional restoration relies on manual application of pigment with a brush, with fundamental differences on a structural level to the application of a printed mask; fine features with complex boundaries cannot be readily infilled by hand, often leading to overpainting. That said, color approximation through manual iteration can result in a better visual integration of infill than with the general algorithmic approach we take. A greater number of manual color iterations will result in a longer duration of the infill process, adding nuance to the dependence of overall restoration time on the quality of the outcome. We conservatively estimate that the duration of a conventional manual infilling with comparable results to our physically-applied digital restoration would take 232.4 hours. We derive this figure from the visual and spatial properties of the infill mask, and several estimates of human speed in conducting manual infilling.

The most generous estimation of manual infilling would entail the direct reproduction of all infill mask regions, comprising 36,942,703 px^2 with 57,314 unique colors. Each color change would require iterative manual color adjustment; an accurate color reproduction with 3 color iterations each taking 15 seconds would lead to a color selection time of 716 hours. Application of color to each pixel at a careful manual painting speed of 1 px^2/s would result in an additional duration of 10,262 hours, for a net infilling duration of 10,978 hours, or approximately 5.3 years of full-time labor (with 52 40-hour work weeks per year). While some notable restorations have taken years to complete, for the painting in this work this is a substantial over-estimation given anecdotal examples of similar treatments.

The most conservative estimation of manual infilling would rely on a cruder reproduction of the mask used in this work. The mask area of 662 cm^2, construed as a topographically simple region (i.e., without fine features), could be covered with an inpainting speed of .2 cm^2/s (as may be expected with a broad brush) in 55 minutes. Simplifying the coloring to 12 primary colors and direct combinations thereof (for a total of 88 colors), the color selection time would be 66 minutes, with the net infill time at just over 2 hours. Unfortunately, manual restorations of such nature would be utterly unacceptable, with vast amounts of overpainting and completely inadequate feature resolution. Some rudimentary or low-resource restorations can show these traits, as was evident in the original damaged state of the painting in this work; a rudimentary treatment led to crude inpainting and broad coverage of surviving paint fragments in lieu of finer detailing.

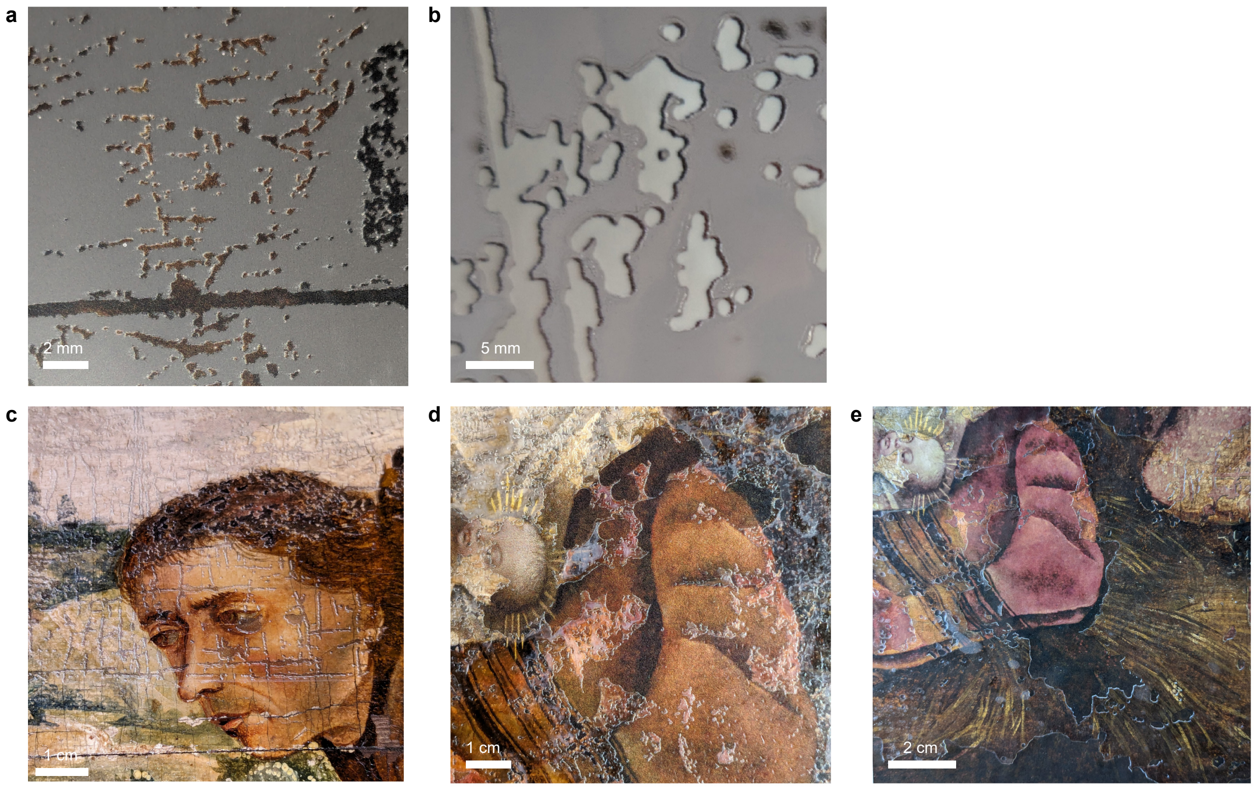
We attempt to derive a more reasonable estimate of comparable manual infilling by considering the number of colors that generally suffice to reproduce the mask, and more precisely estimating the inpainting speed by considering the scale of features to be restored. The distribution of colors relative to the area they correspond to is not uniform in the infill mask (Extended Data Fig. 6b). We can restrict ourselves to the number of hues to be reproduced, along with the number of saturation and value variants thereof. As there are 256 hues digitally possible in an 8-bit mask, we start with this number of base colors in the manual infill palate. Each base color has saturation and value variants, which in practice are obtained by mixing in white or black paint into the fully-saturated pigment[1,2,16]. As seen in Extended Data Fig. 6c, most hues correspond to only a minor portion of the space spanned by value and saturation; on average, each hue has 221 variants of value and saturation (standard deviation of 433), with only a few hues having over a thousand variants, and none approaching the digital maximum of 65,536 variants. In a manual infilling, this granularity of color representation is not practical; we limit the number of variants per hue to a reasonable 100 (10 of value and 10 of saturation), which for the infill mask used in this work integrates to 12,118 hue variants. Making each variant from a base hue requires less time than individual color iteration; each variant can be reasonably made within 30 seconds, for a net color selection time of 101 hours. We consider the scale of manual inpainting to be equivalent to the minimum restorable feature area of the mask used in this work (.42 mm^2), taking 3 seconds to inpaint, a fast pace for fine application of pigment with a brush reasonable for a skilled practitioner. The area of the mask subdivided into such units results in 157,631 restorable regions, for a net infilling duration of 131.4 hours. The net manual infilling time is then estimated at 232.4 hours, roughly 6 weeks of full-time labor. Accounting for other components of a conservation (e.g., cleaning) the expected duration of the full treatment approaches the conventional several-month timeline. We emphasize that this is a conservative estimate; many restorations involve more arduous selection of colors, with far more variants per given hue, and even the most skilled conservators may struggle to inpaint at the high speed we use for calculations. Relative to the 3.5-hour duration of the infill mask application protocol we present in this work, a manual infilling is expected to take 66.4 times longer.

IX. Other physical approaches

Several alternative methods were attempted in this work, spanning variations in the digital infill mask construction, commercial procurement of the mask, fabrication protocol, and application procedures. Here we document several specific variations that help illuminate the importance of the full protocol presented in the manuscript, highlighting difficulties with alternatives that may otherwise be appealing for their efficiency.

Infill mask fabrication in the final protocol presented in the manuscript relies on alignment of a white ink layer on a separate color ink layer in order to ensure color reproduction accuracy, taking several hours of manual labor. We evaluated several alternative methods of mask fabrication (Supplementary Fig. 11) spanning the procurement of commercially-made masks and variations in our fabrication protocol, all in an effort to reduce labor requirements. We found inadequate spatial alignment stemming from the tolerance of commercial printing equipment and the lack of an iterative alignment mechanic for protocol variations.

Several commercially-available printing methods can produce color infill masks with a white backing layer, requiring considerably less labor to do so relative to our manual laminate alignment approach. Two commercial providers of masks relying on powder-based color layer deposition on a thermoplastic sheet with an inkjet-deposited white backing layer were evaluated (Direct-to-Film Transfer, Jiffy, Wilmington, USA and UploadTransfers, Ocala, USA). Both were found to have initially reasonable alignment of the layers when using a higher choke level on the white ink (exemplary mask sector shown in Supplementary Fig. 11a), however the thermal transfer to a plastic membrane for application to the painting revealed large bleed and offset issues (Supplementary Fig. 11c-d). The measured lateral alignment error was 197.7 ± 51.0 µm (n=50). The error originated from the misalignment of the white ink layer and the color ink layer, followed by the pressure-driven expansion of the white ink during thermal transfer.

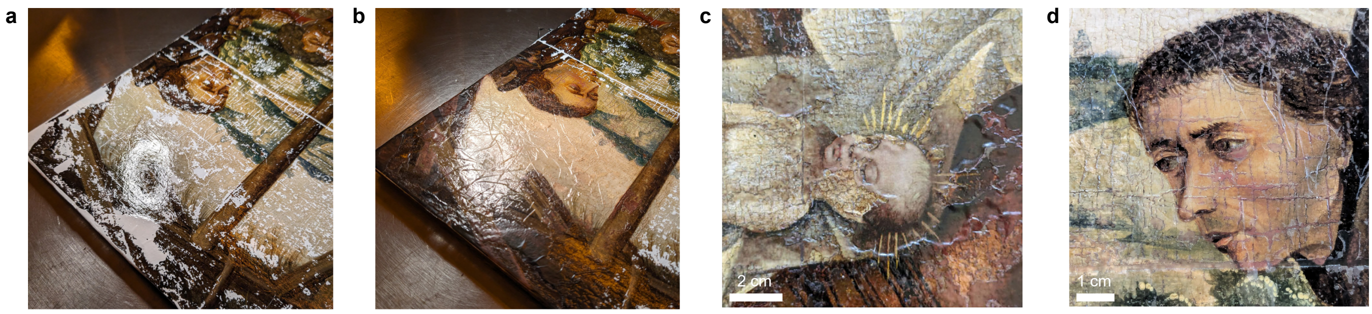


Supplementary Fig. 11 | Alignment tolerance of alternative methods. a, Commercially-fabricated thermal transfer mask comprising laser-deposited powder color inks with underlying inkjet-deposited white ink. **b,** Commercially-fabricated direct transfer mask comprising inkjet-deposited color and white ink layers. **c,** An applied, commercially-fabricated thermal transfer mask made with powder color inks, showing clear edge white ink bleed. **d,** The same mask applied in the lower right of the painting, showing edge defects and optical transparency issues. **e,** An applied mask made without a water-soluble adhesive at the interface of the white and color ink layers, showing consequent misalignment.

Commercial UV-curing of jetted color inks and a jetted white ink layer on a transfer sheet for direct application to a substrate was also evaluated (UV Direct-to-Film, Jiffy, Wilmington, USA). As-printed, the misalignment between the color and white ink layers was found to be immediately severe (Supplementary Fig. 11b), with the lateral alignment error at 295.8 ± 73.7 µm (n=50). A variant of the mask fabrication protocol presented in the manuscript with a flipped white ink layer was evaluated to determine the necessity of the water-soluble adhesive layer. The lack of lubrication between the two layers during initial alignment prevented iterative adjustment of regional position, leading to an unacceptable misalignment of 446.9 ± 105.0 µm (n=50), shown in Supplementary Fig. 11e.

The complexity of our tolerance analysis-informed mask construction pipeline stems from the need for conservative infilling, avoiding overpainting and only restoring regions where human vision perceives an aesthetic necessity of doing so. Without tolerance analysis, the mask can be constructed to restore areas at scales limited by the 300 dpi resolution of the white ink layer (i.e., a pixel size of 84.7 µm). Further, the thicker nature of a bilaminate infill mask complicates local regional alignment, with numerically-higher alignment error (124.1 µm for the full mask vs 37.1 µm for single ink layer alignment). We evaluated a full restoration attempt without a minimum restorable feature criterion and with sequential application of mask layers to the painting, i.e., the white ink laminate applied directly to the painting followed by application of the color ink laminate. Supplementary Fig. 12 shows a full restoration attempt made with such a mask, possessing several thousand additional microscale infill regions compared to the mask used in the final protocol of this study. Supplementary Fig. 13 shows the process of sequential layer application. The difficulty of determining the local positioning of white ink regions leads to downstream errors in alignment, with additional alignment errors stemming from the anisotropic stretching of the applied color layer to compensate for the initial white layer misalignment. The end result has substantial misalignment, especially in regions with complex infill geometries, supporting the need for a complete bilayer color mask for application as done in the final protocol used in this work. Many regions end up suffering from misalignment such that their infilling effect is either insignificant or completely absent, with direct overpainting and visually-detrimental effects owing to the incompatibility of the minimum feature size with the physically-achievable alignment. Optical defects in the transparency of the layers are also of greater presence owing to more frequent creasing and plastic deformation of the transfer membranes to account for greater positioning errors.

Supplementary Fig. 12 | Masking absent tolerance analysis. a, A mask constructed at the minimum feature size possible with the white ink layer printing method, ignoring tolerance analysis, showing restoration of many more fine areas as compared to the final mask used in this work. **b,** The physical result, showing alignment issues at the local level and optical defects stemming from the incompatibility of the set minimum feature size with the results of tolerance analysis.



Supplementary Fig. 13 | Sequential ink layer application. While the white and color ink layers can be applied in series directly to the painting, the difficulty of alignment leads to poorer results. **a,** The white ink layer applied directly to the painting. **b,** The color ink layer applied over the white ink layer. **c,** Misalignment visible in the region of the infant. **d,** Misalignment visible at the upper right of the painting, along with extensive creasing stemming from said misalignment.

We evaluated several variations of binding mechanics between the layers of the infill mask. In the protocol presented in the manuscript, at least five varnish coats are used, along with two transfer membranes and two layers of water-soluble adhesive, each reducing optical transparency and the eventual color saturation of the painting as viewed through the layers. However, simpler physical constructions lead to severe optical defects as shown in Supplementary Fig. 14. An attempt at expediting mask fabrication by not conducting flattening procedures in the alignment of the white ink layer with the color ink layer results in substantial opacity (Supplementary Fig. 14a). Direct thermal transfer of the white ink onto the color ink layer requires only a single transfer membrane and adhesive layer, completely avoiding manual alignment of individual ink regions relative to each other, thus having considerable appeal from a protocol standpoint. We attempted to do so directly, with an interstitial layer of varnish, and at lower transfer temperatures: all attempts resulted in misalignment and severe discoloration with tinted bleed of the white ink layer (Supplementary Fig. 14b). Finally, attempting to speed up the application of the infill mask to the painting by foregoing water removal and crease reduction leads to highly-noticeable air bubble formation beneath the applied mask (Supplementary Fig. 14c). Though the protocol presented in the manuscript suffers from considerable complexity and additional labor time from the two separate manual alignments, the optical deficiencies of simpler approaches necessitate the more involved process.

Supplementary Fig. 14 | Interlayer binding failures. a, A restoration attempt with poor adhesion between the color and white ink layers in the applied mask, with a section removed at the middle left of the painting for contrast. The higher opacity of the layers emphasizes creasing and substantially decreases saturation. **b,** A restoration attempt with thermal transfer of the white ink layer directly onto the color ink layer, showing discoloration and edge effects from incompatibility of pigments and process steps. **c,** A restoration attempt with poor adhesion between the infill mask and the painting surface, showing formed sub-surface air bubbles.