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From 'Vermeer Illuminated' to 'The Girl in the Spotlight': approaches and methodologies for the scientific (re-) examination of Vermeer's *Girl with a Pearl Earring*

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Abstract

Girl with a Pearl Earring by Johannes Vermeer (c. 1665) is the most beloved painting in the collection of the Mauritshuis in The Hague, The Netherlands. The *Girl* was last examined during a 1994 restoration treatment, within the project *Vermeer Illuminated.* Conservators and scientists investigated the material composition and condition of the painting using the analytical and scientific means that were available at the time: technical photography (visible light, ultraviolet fluorescence, and infrared), X-radiography, and stereomicroscopy. To understand the build-up of the paint layers, they investigated paint samples, often mounted as cross-sections. Their results were published in the book *Vermeer Illuminated* (1994), and as a chapter in *Vermeer Studies* (1998). This paper reviews the results published in the 1990s and considers them in light of a recent research project, where new findings were made possible by advances in non-invasive imaging, chemical analysis and data science. The project *The Girl in the Spotlight* is a Mauritshuis initiative, and involves a team of internationally recognised specialists working within the collaborative framework of the Netherlands Institute for Conservation+Art+Science+ (NICAS), with some scientists from other institutions. In 2018, the painting was examined in front of museum visitors at the Mauritshuis. The complementary imaging techniques employed included: technical photography, multispectral infrared reflectography, reflectance and fluorescence imaging spectroscopy (hyperspectral imaging), fibre optic reflectance spectroscopy, multiscale scanning optical coherence tomography, 3D scanning, 3D digital microscopy, macroscopic X-ray fluorescence and macroscopic X-ray powder diffraction. Furthermore, the samples mounted in 1994 were re-examined, and new forms of microscopic, organic and inorganic analysis were carried out to identify the pigments and binding media. Advances in computation and data science allow the results of these techniques to be co-registered and compared, and new results to be generated. These complementary research methods have allowed the *Girl in the Spotlight* team to: visualise and identify materials at and beneath the surface of the painting, scan the surface topography, and examine the surface at an extremely high magnification. Ultimately, they reveal the steps Vermeer took to create the iconic image of the *Girl* using layers of paint and subtle optical effects. They also provide information about how the painting originally looked, and the changes that have occurred over time.

Keywords: Technical examination, Conservation, Restoration, Samples, Seventeenth century, Vermeer

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Fig. 1 Visible light photograph. René Gerritsen Art & Research Photography

Introduction

In 1994, Johannes Vermeer's *Girl with a Pearl Earring* (c. 1665, Fig. 1) was restored at the Mauritshuis in The Hague, The Netherlands, together with *View of Delft* (c. 1660–1661). Museum visitors could observe the treatment in progress through a glass wall, and from above through a skylight. This was one of the first times that a painting restoration treatment intentionally took place in front of the museum public. An article [1] and the book *Vermeer Illuminated* [2] were published by the Mauritshuis conservators directly after the 1994 treatment. They describe the painting's conservation and restoration history, and some aspects of Vermeer's technique. In 1995–1996, both artworks were unveiled in the blockbuster *Johannes Vermeer* exhibitions at the National Gallery of Art, Washington DC and at the Mauritshuis. The exhibition prompted a new assessment and scholarly interest in Vermeer's oeuvre and painting technique, culminating in the multi-author book *Vermeer Studies* (1998) [3]. A chapter by Groen, van der Werf, van den Berg and Boon, entitled 'Scientific Examination of Vermeer's *Girl with a Pearl Earring*' presented the results of scientific analyses related to the restoration treatment [4]. It is the only chapter in *Vermeer Studies* dedicated to the technical examination of a single painting.[1] It addresses the state of knowledge about the *Girl* under the sub-headings: history and condition of the painting, ground and underpaint, paint layers of the figure, paint layer of the background, traces of former restoration procedures, and conclusions. These themes serve as the framework for the current paper, which reviews their findings.

In 2018, a *re*-examination of the *Girl with a Pearl Earring* brought Vermeer's materials and techniques into the spotlight once again. In February–March 2018, an international team of specialists carried out a technical examination of the *Girl* as part of the research project *The Girl in the Spotlight*, within the collaborative framework of the Netherlands Institute for Conservation+Art+Science+ (NICAS), with scientists from other institutions such as University of Antwerp and National Gallery of Art, Washington DC. This examination was also carried out in view of museum visitors, within an enclosure in the Golden Room of the Mauritshuis. The *Girl in the Spotlight* research team recognised that while the conservators and scientists in the 1990s had achieved the best possible result with the technology that was available at the time, over the last decades, scientific technologies for the examination and analysis of artworks have developed tremendously. Non-invasive imaging methods that do not require sampling or touching the painting have been developed to identify and localise materials at and beneath the painting's surface [6, 7].

Techniques for the examination and analysis of the inorganic and organic components of paint samples have also improved in specificity and accuracy. The 2018 *Girl in the Spotlight* research project prompted the re-examination of the paint micro-samples collected in the 1990s. The cross-sections were analysed using state-of-the-art laboratory and synchrotron techniques, and organic analysis was carried out on small fragments that had not been embedded. Results of the *Girl in the Spotlight* investigation are described in articles also published in this special issue [8–14].

Scientific examination in 1994

The 1994 technical examination of Vermeer's *Girl with a Pearl Earring* was carried out alongside the treatment, and was primarily motivated by issues of conservation and restoration (Fig. 2). The scientific examination was coordinated by Karin M. Groen, Conservation Scientist at the Cultural Heritage Agency of the Netherlands, and some additional analysis was carried out at FOM/AMOLF and DSM-Research.[2] Samples embedded as cross-sections were examined using: light microscopy, scanning electron microscopy–energy dispersive X-ray analysis (SEM–EDX) and Fourier transform infrared spectroscopy (FTIR). Some

[1] *Vermeer Studies* includes a chapter that discusses Vermeer's materials and techniques in a broader context [5].

[2] For a complete list of analyses performed, see Appendix 2 in Groen et al. [4]

Fig. 2 Examining *Girl with a Pearl Earring* in 1994. Jørgen Wadum (Paintings Conservator, Mauritshuis) and Karin M. Groen (Conservation Scientist, Cultural Heritage Agency of the Netherlands)

small fragments not embedded in resin were analysed using: polarised light microscopy (PLM), high-performance liquid chromatography (HPLC), direct transform mass spectrometry (DTMS), pyrolysis-tetramethylammonium hydroxide-gas chromatography mass spectrometry (Py-TMAH-GCMS), thin-layer chromatography (TLC), and microchemical tests. These analyses enabled the scientists to identify and characterise the pigments, oil, and old restoration materials within different layers of the painting.

To help answer specific research questions related to the conservation/restoration treatment, and to find out more about the painting's stratigraphy, nine microscopic samples of original material were taken, adjacent to existing damages (Fig. 3, Additional file 1: Appendix S1).[3] The publications from the 1990s [1, 2, 4] describe how flaking paint that had become dislodged in the past provided other opportunities for collecting samples without causing further damage to the painting. As a result of exposure to moisture—almost certainly related to a glue-paste lining that took place in the late nineteenth century—the canvas shrunk, causing the edges of the cracks in the paint to lift (so-called 'cupping'). Tiny fragments became dislodged and some stuck onto the surface in an unrelated part of the painting. These were also removed from the painting and used as sample material: so-called 'B' samples where the precise original location is unknown (Additional file 1: Appendix S1).[4] Based on the stratigraphy, pigment composition, and comparison to other samples, an educated guess could be made as to the general area they originated from.

Fig. 3 Visible light photograph, labelled with sample sites: Samples from a known location, taken in 1994 ('A' samples, red). Samples taken in 1968 by Hermann Kühn (green). Samples taken in 2018 (purple). Not shown: 'B' samples (dislodged fragments where the precise original location is unknown: see Additional file 1: Appendix S1), 'C' samples (fragments primarily containing non-original restoration materials)

Treatment history and condition of the painting

The 1998 publication by Groen et al. [4] took the dark background of the *Girl with a Pearl Earring* as a starting point to investigate Vermeer's materials and techniques. The research focus of the 1994 team was prompted by questions related to the restoration treatment; however,

[3] Typically, obtaining a sample a canvas painting involves: choosing a suitable sample site under the microscope (adjacent to an existing damage), and using a scalpel to dislodge a tiny fragment containing the complete layer structure. The sample can subsequently be mounted in a resin block, polished as cross-section to reveal its stratigraphy, and examined under a binocular microscope in different lighting conditions. Small fragments of loose material (not embedded) can be preserved or used for further analysis. Remarkably, only a subset of the samples from the *Girl with a Pearl Earring* were taken in this typical way: the so-called 'A' samples (Fig. 3 and Additional file 1: Appendix S1).

[4] One 'B' sample was a dislodged piece of paint that had previously become stuck to the *Girl*'s earring and was removed in 1994 [2, 3]. A photograph of the painting in 1904, showing dislodged fragments, is illustrated in Groen et al. [4]. 'C' samples contain mostly non-original material applied during previous restoration treatments. While it is vital to comprehend the conservation history of the painting in order to understand its current condition, the 2018 *Girl in the Spotlight* project concentrated on reanalysing the 'A' and 'B' samples.

in order to assess the painting's condition, it was also vital to understand its conservation history [2, 4].

When the painting was purchased at auction by A.A. des Tombe in 1881, its condition was described as being in "a sorry state of neglect."[5] Before the painting entered the Mauritshuis collection in 1903, it was treated in Antwerp in 1881 by a restorer named Van de Haeghen (first name unknown). He lined the painting using a starch-based adhesive and probably consolidated the front of the painting with animal glue. In 1915, Derix de Wild 'regenerated' the upper layer of varnish without affecting earlier retouchings, then he varnished the painting. De Wild performed another regeneration treatment in 1922. In 1960, Jan Cornelis Traas carried out a full restoration: he relined the support with a wax-resin adhesive, removed most old varnish layers, applied a new varnish, and retouched damages [4]. Despite—and largely because of—these interventions, *Girl with a Pearl Earring* has survived in relatively stable condition.

When the painting was earmarked for restoration in the early 1990s, structural treatment was not necessary; however, an aesthetic treatment was desirable (Fig. 4). The varnish and retouchings applied in the past had discoloured significantly. The pronounced craquelure in the varnish layers and the paint was visually disturbing, and in some areas the cracks contained black residues [4]. There were small losses and displaced fragments scattered throughout the surface of the painting. During the 1994 treatment, the conservators carefully removed or adjusted the old restoration materials (including varnish and retouchings) using mixtures of organic solvents, sometimes employing mechanical removal to thin them during the process. They filled small losses with a mixture of chalk and polyvinyl alcohol, applied an isolation varnish of dammar, then retouched in two stages: the underlayers were painted with watercolour, and dry pigments in polyvinyl acetate were used for the upper layers. The final varnish was dammar, with a hindered amine light stabiliser (Tinuvin 292) added to slow down any yellowing [1].

The *Girl* is currently in a stable state of preservation, and there are no plans to treat the painting in the near future.

Ground and underpaint

A topic of interest to both the 1990s and 2018 research team was the early steps that Vermeer carried out to sketch and lay in the composition.[6] The canvas of the *Girl with a Pearl Earring* was primed with a ground that Groen et al. describe as "yellowish-white…on examination with the naked eye" [4]; however, where it is visible on the remains of tacking margins, or in losses and damages, the ground can also be described as a light grey. Small samples were taken in 1968 by Hermann Kühn [16], as part of his scientific survey of ground layers in paintings by Vermeer (Fig. 3).[7] Samples from the 1990s [4] identified the materials in the ground [2, 8].

Fig. 4 Condition before 1994 treatment. Slide taken in 12/1990

On top of the ground, Vermeer started to lay in the composition using underlayers, which would eventually be (partially) covered by the surface paint. Even prior to the 1994 treatment, researchers were aware of dark paint layers beneath the surface. In 1980, van Asperen de Boer and Wheelock examined the painting under the stereomicroscope, and used infrared reflectography to detect carbon-containing underlayers beneath the shadows of her blue headscarf, yellow jacket and skin [4]. Groen et al. [4] compared cross-sections from different areas of the painting and confirmed that these underlayers vary in thickness and colour. The authors concluded that "the purpose of the dark underpaint must have been to brush in a monochrome image on the smooth light-coloured ground."

[5] From the Mauritshuis archives: Nieuwe Courant 1903. Broos and van Suchtelen provide a history of the painting and its acquisition [15].

[6] New findings about the canvas and ground are discussed in Vandivere et al. [8].

[7] The samples that Kühn took from *Girl with a Pearl Earring* are marked in green on Fig. 3.

Paint layers in the figure

Light microscopy of cross-sections showed that Vermeer built up the paint efficiently, usually with only a single paint layer on top of the underlayer. Groen et al. [4] describe the simple technique as follows: "Vermeer seems to have adjusted both the colour and the thickness of the final paint layer and the brownish-black underlayer in order to obtain the desired effect. In the light areas, on top of the thin, dark underpaint there is a rather opaque top paint layer. In contrast, in dark areas the dark underpaint is thicker and the top layer more transparent" [4]. The layers are straight and distinct from one another, confirming that Vermeer left underlayers to dry before applying surface paint on top.

In the 1990s, the pigments in the upper paint layers were identified by combining stereomicroscopy of the paint surface with analysis of cross-sections. Pigment identification focused on the background, but Groen et al. [4] also illustrated and described cross-sections from the light and shadow areas of the *Girl*'s yellow jacket.

Background paint layers

Past restoration procedures and light exposure from display had dramatically affected the appearance of the dark background surrounding the *Girl*. During the 1994 restoration treatment, the patchiness and lack of saturation in the background prompted the researchers to thoroughly investigate its material composition, layer structure and degradation. Groen et al. [4] concluded that originally, the background would likely have been an "even, smooth, glossy, translucent, hard green paint, made to look darker and given depth by a dark underpaint". The dark underlayer is visible in the cross-sections analysed in 1998; however, using the analytical means available, they misidentified it as containing (only) bone black [4]. On top of the black underlayer in the background is a glaze that contains a blue dyestuff and a yellow lake pigment, bound in linseed oil. The organic components of the glaze were analysed in 1998 using HPLC, which detected indigo (blue) and luteolin (the colourant in the yellow lake, weld).[8] The inorganic substrate of the yellow lake pigment was identified as alum and chalk using SEM–EDX [4].

Groen et al. [4] remarked that even "after the 1994–1995 restoration, the background still appears uneven… washed-out, matte and milky".[9] It was concluded that the patchiness of the background could likely be explained by the (partial) fading of these light sensitive pigments due to exposure to light and moisture [4].

Traces of former restoration procedures

The appearance of the painting at different stages of the restoration treatment was documented using imaging techniques available in 1994: microscopy, examination and photography using different wavelengths and lighting conditions: X-radiography, ultraviolet (UV) fluorescence, visible light, raking light and infrared.

Understanding how past restorations had affected the condition of the *Girl* was crucial to decision-making prior to and during the 1994 restoration treatment [1]. Materials used to line the canvas support, consolidate flaking paint, 'regenerate' the varnish, varnishing and retouching were detected in samples using HPLC, DTMS and Py-TMAH-GCMS. The 1998 detection of copaiba balsam using Py-TMAH-GCMS was especially notable [4]. It seems that the *Girl with a Pearl Earring* was treated with the so-called Pettenkofer method during a treatment by Derix de Wild in 1915 and/or 1922.[10] In order to regenerate the uppermost blanched varnish layer, de Wild probably exposed the surface to alcohol vapour and copaiba balsam. Although copaiba balsam is now known to have negative effects, including softening and swelling of paint films, it only appears to have adversely affected the paint layers of *Girl with a Pearl Earring* in one specific area: namely, in the highlight on her forehead [17, 18]. While the surrounding paint appears stiff with raised edges, the paint in this area has rounded edges, and the cracks contained dark residues.

2018: *The Girl in the Spotlight*

The conclusions of the publications from the 1990s [1, 2, 4] clearly show that the scientific analyses and observations associated with the restoration treatment contributed valuable information about the materials and techniques that Vermeer used to paint *Girl with a Pearl Earring*. The research by Groen et al. [4] was motivated by treatment needs, and their investigation of Vermeer's materials focused primarily on the background. As time went by, new possibilities for scientific research were developed, which inspired the Mauritshuis to initiate the research project *The Girl in the Spotlight.* Specific questions about the material-technical aspects of the painting were:

What steps did Vermeer take to create the painting?

[8] The presence of indigo was confirmed using DTMS, and the binding medium was analysed with Py-TMAH-GCMS [4].

[9] The conservators' ethical decision not to retouch a well-preserved area in the background to match with the surrounding degraded paint is described by Wadum and Costaras [1] and Vandivere et al. [14].

[10] Documentation in the Mauritshuis conservation department (cor. nos. 218, 225 and 1916 no. 83).

What can we find out about layers beneath the surface?
Which materials did Vermeer use and where did they come from?
Which techniques did Vermeer use to create subtle optical effects?
What did the painting look like originally, and how has it changed?
What is the chemical and physical condition of the painting?

The 2018 project was not prompted by specific conservation concerns or a potential treatment, but instead with the broader goal to find out as much as possible about Vermeer's materials and techniques—and the evolution of the painting—using the non-invasive scientific technology that is now available. The opportunity was seized to apply state-of-the-art scientific examination methods to a single painting, and to co-register and compare the data from several of these methods using computational analysis. It was also an opportunity to educate scientists, museum professionals and the broader public about the possibilities for non-invasive examination and analysis in a museum setting. In the Golden Room of the Mauritshuis, museum visitors could observe the examination in progress, learn about the examination methods on screens and tablet computers, and look closely at a 3D print of the *Girl* on an easel. Those who were not able to visit the museum could read a series of blog posts written by the head researcher Abbie Vandivere; 'Girl with a Blog' was updated daily, and is archived on the Mauritshuis website [19].

The fact that both the 1994 *Vermeer Illuminated* treatment and the 2018 *Girl in the Spotlight* examination were visible to the public is significant. *Girl with a Pearl Earring* is the most beloved painting in the Mauritshuis collection, so it was imperative that the painting remained visible as much as possible during the examination. Time had to be allocated efficiently for the different examination methods, while still ensuring that sufficient data could be collected according to the highest scientific standards. The technical examination took place 24 h a day for a two-week period in late February and early March 2018, in the Golden Room of the Mauritshuis.[11] During the day, members of the research team were present to set up and carry out the different imaging and examination techniques. Overnight, scanning methods were employed that could be monitored remotely or operated safely without constant supervision.

The different methods of non-invasive analysis carried out in the 2-week period involved scanning methods, macroscale imaging spectroscopy techniques, and microscopic techniques. The types of non-invasive imaging are listed in Table 1, with references to publications where the experimental methods are described in detail. The complementary examination methods were selected so that they would collectively give as complete a picture as possible about the material composition of each part of the painting's structure. One overarching condition for the 2018 examination was that all of the methods employed in this phase of the project had to be non-invasive: they did not make contact with the painting. The non-invasive imaging data collected were also correlated with (re)analysis of samples and examination of the paint surface to achieve the fullest data interpretation.

Scientific examination methods used in *The Girl in the Spotlight*

High resolution technical photography

Before the technical examination in front of the public began, *Girl with a Pearl Earring* was brought to the conservation department of the Mauritshuis and unframed (Fig. 8a).[12] Accurate measurements were taken of the painting's dimensions so that images could later be precisely stitched and overlaid (Fig. 8k).[13] Digital photography, carried out by René Gerritsen Art & Research Photography, was used to document the current condition of the painting in different light sources and at different wavelengths (Fig. 8b). Visible light photographs were taken with and without a polarisation filter. The polarised image shows a greater contrast between the figure and background, and colour nuances in the background that are not visible to the naked eye (Fig. 5). In UV fluorescence, the natural resin varnish layer fluoresces greenish, and areas retouched in 1994 can be distinguished from the original paint as they appear darker (Fig. 6). The texture of the surface was captured using raking light shone at eight different angles around the perimeter of the painting. Carbon-containing pigments, at an beneath the surface of the painting were visualised and photographed in infrared.

X-radiographs were taken of the painting at several different voltage and current settings. The atomic number and mass of the element(s), and the thickness and density of the paint determine how much radiation reaches the X-ray film; therefore, the X-ray shows primarily the

[11] A temporary enclosure was installed to ensure the safety of the artwork and the museum visitors. Additional safety measures were also undertaken; for instance, the installation of lead screens during the phases of examination where X-radiation was used.

[12] When the painting was unframed, a white horizontal band was revealed along the top edge: this is a fill that was applied during a previous restoration treatment to enlarge the composition, presumably to fit into a frame.

[13] Measurements were carried out by Rob Erdmann, who also assisted in lighting the raking light photos.

Table 1 Non-invasive imaging performed in 2018

Non-invasive imaging	Abbreviation	Reference for experimental method
Computer-assisted thread-level canvas analysis		[8]
Fibre optic reflectance spectroscopy	FORS	[8, 9]
Fluorescence imaging spectroscopy	FIS	[9]
High-resolution 3D colour/gloss scanner	High-Res 3D scan	[10]
High-resolution 3D digital microscopy		[8, 10, 12–14]
Macroscopic X-ray fluorescence	MA-XRF	[9, 11–14]
Macroscopic X-ray powder diffraction	MA-XRPD	[11]
Multi-scale optical coherence tomography	MS-OCT	[10, 14]
Multispectral infrared reflectography	MS-IRR	[8, 9]
Reflectance imaging spectroscopy: visible-to-near-infrared (400–1000 nm) and shortwave infrared (967-1680)	VNIR/SWIR	[8, 9, 12, 13]
Standard-resolution 3D colour/gloss/topography scanner	Std-Res 3D scan	[10]
Stereomicroscopy		[2]
Technical photography		[8], see below
Ultraviolet	UV	see below
X-radiography		[8]

Fig. 5 Polarised light photograph. René Gerritsen Art & Research Photography

Fig. 6 UV-induced fluorescence: excitation 365 nm, with 2e and TG1 filters in front of lens. René Gerritsen Art & Research Photography

distribution of lead white: most prominently in the *Girl*'s earring, collar and eyes.

The high-resolution technical photographs and X-radiographs served as reference material throughout the examination, but also documented the appearance and condition of the painting at this specific moment in time. Historical photographs and slides from the files of the conservation department of the Mauritshuis show small

Fig. 7 MA-XRF within an enclosure in the *Golden Room* of the Mauritshuis, February 2018

changes in appearance over the last century, both as a result of—and helped by—conservation and restoration treatments in the past.[14]

Elemental mapping and pigment identification

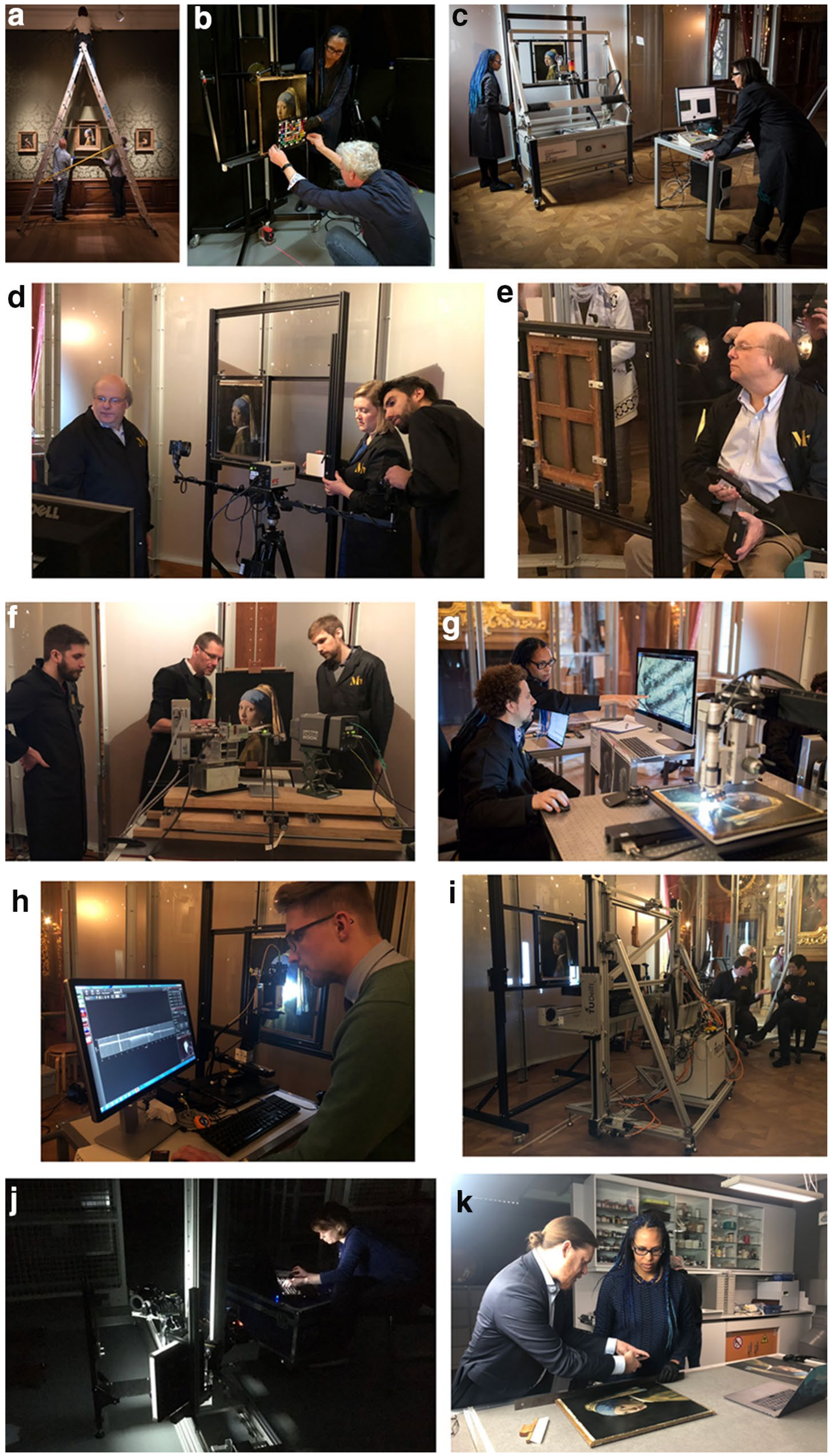
Prior to the 2018 examination, information about the pigment composition of the paints came from the samples that were taken in 1968 and 1994, and the pigment distribution was extrapolated through the careful observations made by the conservators and scientists during the restoration treatment [2, 4, 16]. Chemical imaging spectroscopy techniques developed in the last two decades—including macroscopic X-ray fluorescence imaging (MA-XRF), reflectance imaging spectroscopy (RIS), and macroscopic X-ray powder diffraction (MA-XRPD)—made it possible to study surface and sub-surface layers in a non-invasive manner. These gave the *Girl in the Spotlight* research team unprecedented information about the distribution of pigments and degradation products over the entire painting.

Macroscopic X-ray fluorescence (MA-XRF) scanning was the first examination technique to be carried out in the Golden Room in front of museum visitors (Figs. 7, 8c) [20]. Annelies van Loon from the Mauritshuis/Rijksmuseum operated the Bruker M6 Jetstream large area micro X-ray fluorescence spectrometer. Scanning the painting, in two sections at 400×400 µm^2 step size, took 2 days and nights. The instrument consists of a measuring head with a rhodium-target microfocus X-ray tube and a 60 mm^2 XFlash silicon drift detector (SDD). By slowly moving the measuring head on the *XY*-motorised stage, the painting was scanned pixel by pixel, line by line. By recording the emitted X-ray fluorescence radiation, MA-XRF maps the distribution of chemical elements, at and below the surface of the painting. Each map showed the distribution of an element, which can be related to pigments in different colour areas of the composition. Since the element maps contain contributions from all paint layers, it is not always straightforward to determine whether an element is present in a surface layer or in an underlying layer. Also, matrix effects of layered materials need to be taken into account when interpreting the element maps: particularly lower level emissions that can be blocked by overlying lead white layers.

Visible and near-infrared reflectance imaging spectroscopy (RIS) is complementary to MA-XRF imaging and can provide information at the molecular level. This can help differentiate between pigments that contain the same elements (e.g. iron-containing earth pigments). Electronic transitions related to the colour of materials occur in the visible spectral region; vibrational transitions related to molecular functional groups occur in the infrared spectral region. John Delaney and Kathryn A. Dooley from the National Gallery of Art (NGA) in Washington, DC employed one visible and one infrared spectral imaging camera to collect reflectance image cubes of the painting in different spectral ranges: visible-to-near-infrared (VNIR: 400–1000 nm) and shortwave infrared (SWIR: 967-1680) (Fig. 8d) [21]. From these datasets, pigments were identified and their locations within the painting were mapped. They also performed fluorescence imaging spectroscopy (FIS), using a UV lamp or a filtered slide projector (460–532 nm) to excite the pigments. An additional infrared camera was used to perform infrared reflectography at high spatial resolution (~ 500 px/inch) in three different spectral bands (1100–1400 nm, 1500–1800 nm, and 1900–2500 nm), here defined as multispectral infrared reflectography (MS-IRR) [22]. This allowed for the visualisation of underlying layers such as carbon-containing sketch layers and compositional changes. All of these data sets were spatially aligned to each other and to a high-resolution colour image using an algorithm developed for registering such image sets [23]. The NGA scientists also used fibre optic reflectance spectroscopy (FORS) to collect reflectance spectra (350 to 2500 nm) at many points (2–3 mm in diameter) on the painting, concentrating on the *Girl*'s blue headscarf (Fig. 8e). The larger spectral range of the site-specific reflectance spectra helped to complement the spectral range of the imaging cameras, and were used to assess the pigments found throughout the composition. The reflectance and fluorescence examinations took less than 2 days in total.

Macroscopic X-ray powder diffraction imaging (MA-XRPD), the third chemical imaging technique used to analyse the *Girl*, is capable of identifying and quantifying crystalline phases in pigments and possible degradation products in the painting. A mobile MA-XRPD

[14] Technical images taken before, during and after the 1994 treatment are preserved on slides, which have been digitised.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(See figure on previous page.)

Fig. 8 Photographs taken during the *Girl in the Spotlight* examination in February–March 2018. **a** Deinstalling the painting in the gallery of the Mauritshuis (photo: Martijn Beekman); **b** technical photography, René Gerritsen Art & Research Photography; **c** MA-XRF, Rijksmuseum; **d** MS-IRR, NGA Washington DC; **e** FORS, NGA Washington DC; **f** MA-XRPD, AXES research group, University of Antwerp; **g** 3D digital Microscopy, Hirox; **h** MS-OCT, TU Delft; **i** High-Res 3D scan, TU Delft; **j** Std-Res 3D scan, TU Delft; **k** measuring painting for data science, Rijksmuseum/UvA

scanner for in situ analysis was developed by researchers from the Antwerp X-ray Analysis, Electrochemistry and Speciation (AXES) group of the University of Antwerp (Fig. 8f) [24]. Since this technique is slower than MA-XRF and RIS, it was only possible to image selected areas of the painting in the allocated time. The complete face and neck, including small areas of the adjacent background and blue headscarf, were scanned in reflection-geometry at a step size of 2×2 mm^2. A smaller area was scanned in transmission-geometry at a reduced step size of 0.9×0.9 mm^2. This took 4 days and nights in total. Depending on the geometry different information can be obtained. Reflection mode analyses compounds like pigments and alteration products in the upper layers, while in transmission mode the entire paint stratigraphy, including the ground, is probed by the X-ray beam.

Surface: microscopy, topography and gloss

During the 1994 treatment, the conservators examined the painting carefully under a binocular microscope, and took some microphotographs as slides.[15] During the recent *Girl in the Spotlight* examination, advances in microscopy and scanning technology allowed the researchers to document the painting's topography, gloss and colour at a very high resolution.

The Hirox RH-2000 3D digital microscope combines optical microscopic imaging with 3D topographic information. This allowed every part of the painting to be recorded in great detail, from individual brushstrokes to pigment particles. The Hirox microscope can also make a three-dimensional profile of the surface of the painting to provide information about the surface topography. For the *Girl in the Spotlight* project, Hirox developed a special stand allowing high magnification (with very low vibration), a large high precision motorised *XY* stage (500 × 500 mm with 0.2 µm steps) and special software to acquire images in *XYZ* axes, fully automatically without pixel limits. Emilien Leonhardt and Vincent Sabatier first used a low- to mid-magnification lens (6×–140×) to document some details—the eyes, lips, signature, earring and details of her clothing—with the microscope on a flexible arm stand while the painting was vertical on an easel. Afterwards, the painting was placed flat on the 500×500 mm purpose-built stage with the microscope secured above, and the entire surface was 3D scanned at 35× magnification (Fig. 8g). This produced an image with a spatial sampling of 4.40 µm per pixel—9100 multifocus images, captured in 10 h scanning time. Then 3D close-ups of 10 selected areas were taken at 140×, and additional single images at 700×.

The dark background of the *Girl with a Pearl Earring* was the focus of the chapter in *Vermeer Studies* [4]. Their findings about the stratigraphy of the background, including the glaze on the surface, were based on visual examination and analysis of samples mounted as cross-sections. In 2018, the composition and layer structure of the background was investigated using a combination of non-invasive imaging methods [14], including multiscale optical coherence tomography (MS-OCT). Tom Callewaert from Delft University of Technology used MS-OCT to image and measure (semi-)translucent layers at the surface: the varnish (applied during the 1994 treatment) and Vermeer's original glaze layers (Fig. 8h). He employed a Thorlabs Ganymede-II-HR spectral-domain OCT system. This system uses low coherent near-infrared light (900 nm), which allows it to penetrate into translucent paints and to capture high-resolution depth profiles of the layer structures [25]. *f* for example, the blue headscarf, where Vermeer used ultramarine glazes to create a transition from the light to dark. From this data, each point can be viewed as a 'virtual cross-section,' or stitched together to form an image cube from which a transparency/reflectivity map could be created to visualise the distribution of (semi)translucent layers in larger areas of the composition. Also, a surface topology map, and a glaze layer thickness map of the background glaze could be produced from the MS-OCT data.

The strong crack pattern in the *Girl*, primarily in her forehead, was mentioned in the 1994 publication as possibly being exacerbated by former restoration procedures involving regeneration with alcohol [2]. The network of cracks and the cupping of paint fragments is apparent in the raking light photos taken during the technical photography that preceded the investigation. In 2018, the topography of the surface was measured and visualised using two 3D scanning systems, based on fringe-encoded stereo imaging developed at Delft University of Technology, under the supervision of Joris Dik. The first is a high-resolution scanner (High-Res 3D scan) capable of

[15] A microscope photograph of the cracks in the *Girl's* forehead are illustrated in Groen et al. ([4], p. 176, Fig. 11). Other areas of the painting were photographed as slides, which have been digitised. The precise location where these microphotos were taken on the painting is sometimes unclear.

measuring colour and topography at a spatial resolution of 7 μm, which was operated by Mathijs van Hengstum (Fig. 8i). The complete painting was scanned within six hours, and the result is a high-resolution image with differences in height displayed in gradations of grey. A second 3D scanning instrument (Std-Res 3D scan), developed by Willemijn Elkhuizen at Delft University of Technology, scanned the painting at a lower resolution (25 μm *XY* resolution), and captured additional information about the surface gloss (Fig. 8j). In order to capture the surface with the greatest colour accuracy and avoid unwanted reflections, this 3D scanner operated overnight in complete darkness, before the *Girl* returned to her usual place hanging in the Mauritshuis.

Computational analyses and data science

Each technical examination and analytical technique used in the *Girl in the Spotlight* project provided new information about how Vermeer painted *Girl with a Pearl Earring*; however, the most valuable and innovative findings come when the data from the different methods are combined, co-registered and compared (Fig. 8k).[16] Robert Erdmann from the Rijksmuseum and University of Amsterdam oversaw the data science for the project, using sophisticated multiscale image processing and machine learning algorithms. These algorithms enable every one of the images to be co-registered into a common coordinate system using a multi-level hierarchical system to achieve subpixel accuracy at each stage. A deep neural network learns the precise feature-extracting filters necessary to enable any of the raw technical images to be precisely placed relative to a (possibly lower-resolution) image of another type even when the two image types differ significantly in their content. This then enables the correction of lens distortion and parallax errors caused by the three-dimensionality of the painting and, with such precision, allows to also infer the colour-modifying effect of different cameras, such as the camera attached to the 3D digital microscope. The result of this process is a large stack of precisely registered images from each imaging instrument, which can then be analysed to perform semantic segmentation, feature identification, cluster analysis, anomaly detection, and automatic annotation of the image dataset. These images can be explored interactively using the 'curtain viewer' developed by Robert Erdmann, thereby removing the difficulty of managing a collection of images when each one is tens or hundreds of gigabytes in size. Computer-assisted canvas analysis also provided information about the canvas support and how it was prepared [8].

[16] When the painting was unframed prior to the examination, Robert Erdmann took accurate measurements of the dimensions of the painting to ensure that stitching and registration would be precise.

(Re)analysis of samples

The reanalysis of samples collected during the 1994 treatment showed that, for the most part, the results from the 1990s [1, 2, 4] are accurate; however, by using state-of-the-art analytical techniques developed over the last two decades, more information could be extracted from the samples, with greater specificity and accuracy. The analyses performed on micro-samples in the 1990s and in 2018 are listed in Table 2, with references to publications where the experimental methods are described in detail. In 2018, the 'A' and 'B' samples (Fig. 3 and Additional file 1: Appendix S1) were examined with two different SEM–EDX instruments at low and high vacuum. The low-vacuum SEM–EDX carried out by Annelies van Loon at the Rijksmuseum can examine uncoated samples, thereby leaving the surface of the cross-section available for further analysis using other techniques. High-resolution backscattered-electron images revealed the layer build-up, and pigment particle morphology, by detecting contrast between areas with different chemical composition in the paint. These images also gave information about paint degradation processes. Changes in particle morphology and distribution can be indications of chemical/physical reactivity in the paint. In a later step in the analysis process, the high-vacuum SEM–EDX—carried out by Ralph Haswell at Shell Technology Centre Amsterdam (SCTA)—necessitated coating the sample with carbon, but provided the possibility to map the distribution of the elements within the cross-section at high resolution and with great precision. This combination showed the specific location of elements associated with pigments in different layers, and also allowed detection of trace elements and degradation products.

Some samples underwent further analysis. Inorganic and organic components in the cross-section samples were analysed and identified using: focused ion beam combined with transmission electron microscopy (FIB-STEM), Fourier transform infrared—attenuated total reflectance spectroscopy (FTIR-ATR), lead isotope analysis, and secondary ion mass spectrometry (SIMS). Small dislocated fragments from the painting, removed from the surface in the 1990s but not embedded as cross-sections, were made available for micro-destructive forms of organic analysis of dyestuffs and binding medium: ultra-high performance liquid chromatography with a photo diode array, attached to a fluorescence detector (UHPLC-PDA-FLR), and thermally assisted hydrolysis and methylation, pyrolysis gas chromatography–mass spectrometry (THM-Py-GC/MS).

Although the 'A' and 'B' samples taken in 1994 provided information about several areas of the painting—especially the background and the *Girl*'s jacket—two important areas of the painting were underrepresented. Only one (incomplete) 'B' sample—probably from the *Girl*'s face—was

Table 2 Analyses performed on micro-samples in the 1990s [4], and in 2018

Micro-sample analysis	Abbreviation	Reference for experimental method
Cross-sections		[4, 8, 12–14]
Direct temperature-resolved mass spectrometry	DTMS	[4]
Focused ion beam-scanning transmission electron microscopy	FIB-STEM	[8, 12, 14]
Fourier transform infrared spectroscopy	FTIR	[4]
Fourier transform infrared–attenuated total reflectance spectroscopy	FTIR-ATR	[12, 13]
High performance liquid chromatography	HPLC	[4]
Lead isotope analysis		[12]
Light microscopy	LM	[4, 8, 12–14]
Paint micro-samples		[4, 8, 12–14]
Polarised light microscopy	PLM	[4]
Pyrolysis-tetramethylammonium hydroxide-gas chromatography mass spectrometry	Py-TMAH-GCMS	[4]
Scanning electron microscopy–energy dispersive X-ray analysis	SEM–EDX	[8, 12–14]
Secondary ion mass spectrometry	SIMS	
Synchrotron: microscopic X-ray powder diffraction	μ-XRPD	[11, 12]
Synchrotron: microscopic X-ray absorption near edge structure spectroscopy	μ-XANES	[13]
Thermally assisted hydrolysis and methylation, pyrolysis gas chromatography–mass spectrometry	THM-Py-GC/MS	[14]
Thin-layer chromatography	TLC	[4]
Ultra-high-performance liquid chromatography with a photo diode array, attached to a fluorescence detector	UHPLC-PDA-FLR	[12–14]

available, and there were no clear samples from her headscarf. In order to clarify the findings of the non-invasive techniques, especially questions about the layer structure raised by the MA-XRPD examination, four microscopic samples were taken following the *Girl in the Spotlight* examination (Fig. 3, samples 39–41). This demonstrates that, despite the sophisticated non-invasive imaging methods at the research team's disposal, there are some questions about the stratigraphy that can only be answered fully using the combination of sampling and imaging. Cross-sections of these new samples were analysed using some of the methods mentioned above, as well as synchrotron-based X-ray methods (μ-XANES and μ-XRPD).

Conclusions

The *Vermeer Illuminated* examination and restoration project in the 1990s, and the 2018 *Girl in the Spotlight* project have produced hitherto unknown information about the materials and techniques that Vermeer used to paint *Girl with a Pearl Earring*. The chapter by Groen, van der Werf, van den Berg and Boon in *Vermeer Studies* [4] was ground-breaking at the time, as the first thorough technical analysis of a painting by Vermeer to be published.[17] In the conclusion, the authors summarised the results of the microscopic analyses of paint cross-sections, briefly posit the steps that Vermeer carried out to build up the various paint layers and bring the *Girl* 'to life', and discuss the conservation history of the painting.

The recent *Girl in the Spotlight* examination builds on the analysis of the 1990s by examining Vermeer's *Girl with a Pearl Earring* with the latest non-invasive technology. Vermeer's materials, techniques and working process were discovered through the analysis of microscopic fragments combined with the mapping and scanning of materials, including those that are hidden beneath the surface, but have a profound influence on the eventual composition. The results from the recent examination are explained in seven articles in this special issue, each combining the results of different examination methods to provide information about a stage in Vermeer's working process, or an area of the painting: layers beneath the surface [8], the distribution of pigments [9], topography [10], secondary reaction products [11], the *Girl*'s skin [12], ultramarine [13], and the background [14]. A concluding paper seeks to bring together the findings of the *Girl in the Spotlight* project, and place them in a broader technical and art historical context [26].

[17] Kühn's 1968 publication [16] was an important technical investigation of Vermeer's ground layers and pigments that preceded this. He combined results from several paintings by Vermeer, rather than focusing on a single artwork. Since 1998, there have been a number of important technical studies of Vermeer's paintings, including: Oberthaler E, Boon JJ, Stanek S, Griesser M. The Art of Painting by Johannes Vermeer: History of treatments and observations on the present condition. In: Haag S, Oberthaler E, Pénot S, editors. Vermeer, *Die Malkunst* – Spurensicherung an einem Meisterwerk. Exhibition catalogue from Kunsthistorisches Museums Wien. Vienna; 2010. p. 322–327; Verslype, I. The restoration of Woman in Blue Reading a Letter by Johannes Vermeer. Rijksmuseum Bulletin. 2012;60:2–19.

Experimental methods and abbreviations

A full summary of experimental methods is available from the main author.

Technical photography

The camera body is a Hasselblad 503CX, with a digital camera back: Leaf Credo 80 WS (wide-spectrum) with an 80 MP CCD sensor, sensitive up to 1100 nm. The exposure settings for most images were: ISO 35, exposure time 1/60 s, and aperture f/11. For the UV-fluorescence images, the exposure settings were ISO 50, exposure time 45 s, aperture f/11 (for reference a UV innovations target was used, UVA Version 1.1 low-medium).

The lens is a Carl-Zeiss 120 mm macro-planar lens. A TG1 filter (which blocks UV and IR) was positioned in front of the lens for the normal light and raking light photographs. For UV-fluorescence photography, TG1 and Kodak 2e filters were placed in front of the lens. To photograph the painting in infrared, a 1000 nm filter (Heliopan digital RG 1000) was placed in front of the lens. For polarised light photography, a TG1 and circular polarising filter were placed in front of the lens, and polarising foil was positioned in front of the lamps.

The light sources used were Broncolor strobes with 640 W halogen modelling lights. For normal light, infrared, raking light and polarisation photography, two P70 reflector shells were used.

For UV-fluorescence photographs, two Philips HPA 400-W lights (with Wood's glass/18A filter) with an excited wavelength of 365 nm were used. The exposure settings were: ISO 50, 45 s, aperture f/11.

For raking light photographs, the lighting was: Broncolor strobe, one P70 reflector and a honey grid. The angle of light relative to the painting surface was 10–15°. One photograph was taken at each position while the light was shone at eight angles around painting: 0, 45, 90, 135, 180, 225, 270, 315°.

For each type of photograph (with the exception of raking light and polarised light), the whole painting was photographed both as a single image (output 16-bit, eciRGB v2 ICCv4, 430 MB 7760 × 9300 px) corresponding to an on-painting spatial resolution of 50 µm/pixel, and at a higher resolution of 16 µm/pixel in the form of sixteen images (output 16-bit, eciRGB v2 ICCv4, 4.5 GB 25,850 × 31,000 px) that were stitched and precisely registered to the whole-painting overview image. Calibration was done with X-rite ColorChecker digital SG, with BasICColor 3 profiling.

Capture One software was used to capture images, using a custom camera profile, and creating an LCC-lens profile, output 16-bit eciRGB v2 ICCv4. BasICColor input 3 was used to create a custom camera profile. Photoshop CC was used for end (final) corrections.

Additional file

Additional file 1: Appendix S1. Table of samples from *Girl with a Pearl Earring* that were (re-)examined in 2017–19.

Abbreviations

AXES: Antwerp X-ray Analysis, Electrochemistry and Speciation; CATS: Center for Art Technological Studies and Conservation; DSM-Research: Dutch State Mines; FOM/AMOLF: Fundamental Research on Matter/Institute for Atomic and Molecular Physics; NGA: National Gallery of Art, Washington DC; NICAS: Netherlands Institute for Conservation+Art+Science+; RCE: Cultural Heritage Agency of the Netherlands; STCA: Shell Technology Centre Amsterdam; TU Delft: Delft University of Technology; UvA: University of Amsterdam.

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Authors' contributions
AV wrote the main body of the text and was the Head Researcher for the *Girl in the Spotlight* project. JW, KJvdB and AvL have made significant contributions to the content, reviewed the whole text and made valuable comments and suggestions. The members of the *Girl in the Spotlight* team have reviewed the descriptions of the analyses and their individual and collective contributions. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. The datasets supporting the conclusions of this article are included within the article and its additional files.

Competing interests
The authors declare that they have no competing interests.

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