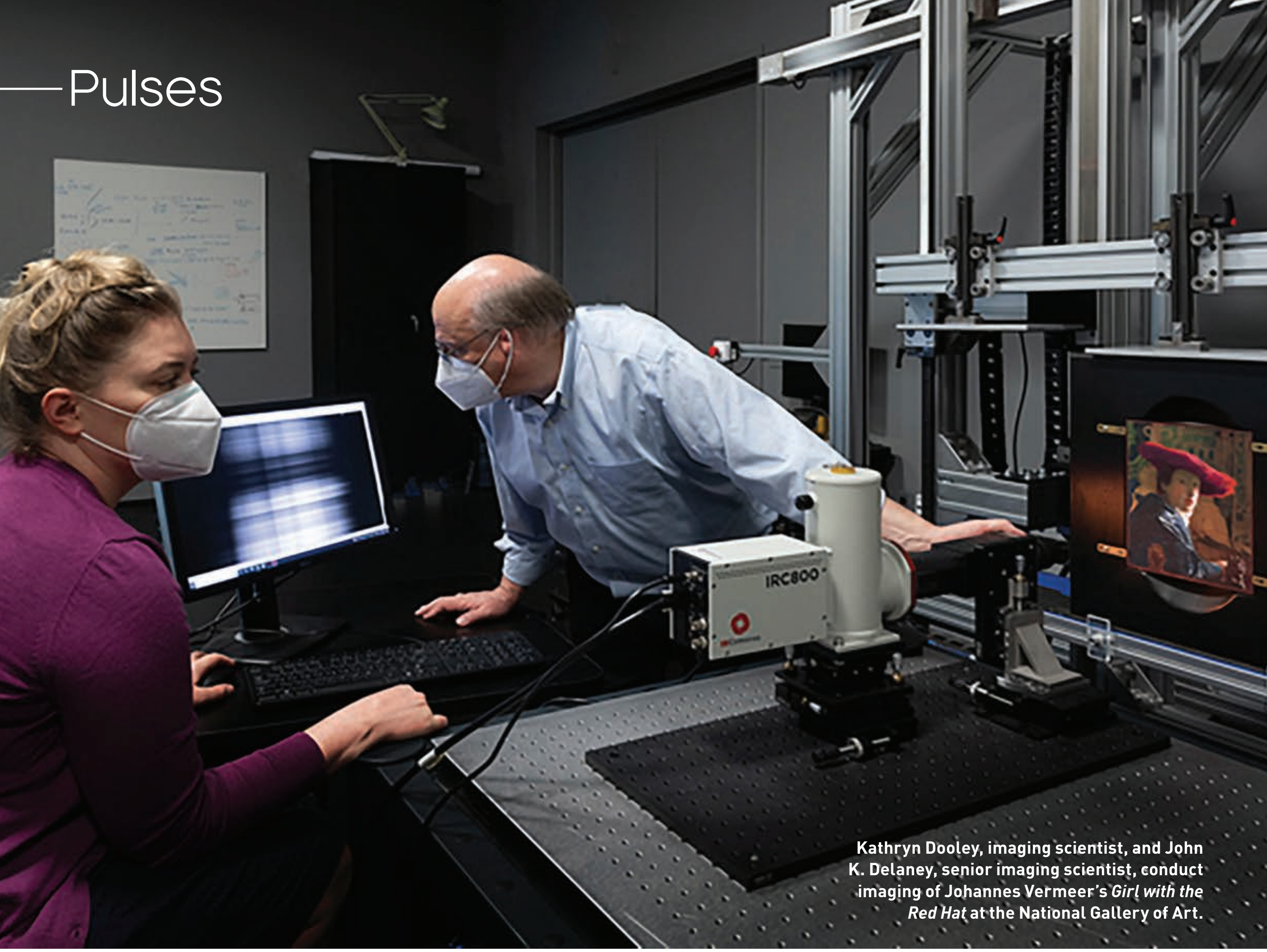


Kathryn Dooley, imaging scientist, and John K. Delaney, senior imaging scientist, conduct imaging of Johannes Vermeer's *Girl with the Red Hat* at the National Gallery of Art.

Courtesy of National Gallery of Art

PROFILE

The Art of Discovery

Imaging scientists at the US National Gallery of Art are building an optical toolkit for investigating masterpieces ancient and modern.

Stewart Wills

Most visitors to the National Gallery of Art in Washington, DC, USA, are struck by the wealth of beauty and emotion conveyed by the painted artworks. But to John Delaney, the museum's senior imaging scientist, and his colleague, imaging scientist Kathryn Dooley, what's beneath the surface of those works holds a lot of intrigue, too.

Delaney and Dooley together run the National Gallery's chemical-imaging lab, where they deploy optical techniques to help answer questions about the museum's masterpieces. In one particularly notable recent example, the lab's imaging beneath the painted surface offered new and surprising insights on the working methods of the 17th century Dutch painter Johannes Vermeer. OPN had the opportunity to visit the lab and talk with Delaney and Dooley about their work.

Dynamic duo

Delaney started full time at the National Gallery in 2007, after an industry career that included work as a lens designer and systems engineer in high-acuity standoff reconnaissance cameras—some of them for the U2 spy plane. Those efforts gave him a strong understanding of wave propagation from the ground through the air to the camera—and of developing performance criteria and specs for systems to capture those waves.

While still in industry, he consulted part time with the National Gallery on projects to improve infrared imaging of paintings from a variety of periods. Such imaging efforts, Delaney notes, actually had started in the art community in the 1960s, when vidicon camera tubes—a low-cost vacuum tube technology—were used to capture the images. Those systems had their problems, including a limited useful spectral range and "shadowing" artifacts. As a consultant, Delaney helped the museum make the transition to solid-state imaging arrays, which substantially ratcheted up the quality of the resulting images.

When a large grant materialized to up the National Gallery's imaging game in support of its conservation efforts, Delaney jumped at the chance to join as a full-time staffer and head the chemical-imaging lab. "It was an opportunity to build cameras and do things more quickly," he says—as well as to tackle some challenging problems.

Dooley joined the museum a few years later, in 2012, as a postdoctoral research associate, after wrapping up a Ph.D. centered on using Raman spectroscopy to study bone biomechanics and development. "I like using light to investigate materials," she says, and studying artwork "is a really cool application for it." After the postdoc finished in 2015, Dooley stayed on as a full-time research scientist. "Kate came as a postdoc," says Delaney, "and after about six months I knew she was hooked."

What lies beneath

Delaney's background in physics and applied optics and Dooley's in chemistry has, the team believes, proved an ideal combination for the task at hand. "What we've tried to do here," Delaney says, "is simply steal from remote sensing and steal from chemical imaging," to solve problems in art history and conservation.

Courtesy of J.K. Delaney and K.A. Dooley

A false-color detail (right) of the Leonardo da Vinci masterwork *Ginevra de' Benci* (c. 1474–78) at three infrared wavelengths (2100 nm, 1850 nm and 1350 nm) reveals carbon-black dots transferred from Leonardo's initial drawing, as well as the underpainted plan for the area eventually covered by the juniper bush in the final version (left).

Delaney's background in physics and applied optics and Dooley's in chemistry has proved an ideal combination.

The chemical-imaging lab itself is nestled between a large, open studio where painting conservators do their painstaking work, and another lab that focuses on high-resolution visible-light imaging of the museum's artworks. That layout provides a rich, interdisciplinary setting where one group's effort can play off of the others, quickly testing hypotheses and generating new ones.

The chemical-imaging component has two main goals, according to Delaney. One is trying to peer beneath the surface paint to image the sequential layers concealed below: preparatory underpaint, preliminary sketches and even the ground material—all of which provide insight into the artist's technique and processes. The other goal is attempting to chemically identify the pigments used by the artists, without the need for invasive sampling of the painting. Delaney and Dooley use two tools for the job: visible and infrared reflectance imaging spectroscopy (RIS) and X-ray fluorescence (XRF) imaging spectroscopy.

RIS is a hyperspectral technique, in which diffusely reflected light—from 400 to 2450 nm, in the lab's setup—is captured for each imaging pixel. The captured spectrum can then be used to identify or infer the presence and chemical composition of the artist's materials, pixel by pixel (see "Hyperspectral Imaging for Safety and Security," OPN, October 2015, p. 26). By extending the hyperspectral imaging into the shortwave infrared (SWIR), information about the underlying paint layers can often be obtained due to the decrease in light scattering and absorption from the pigment particles.

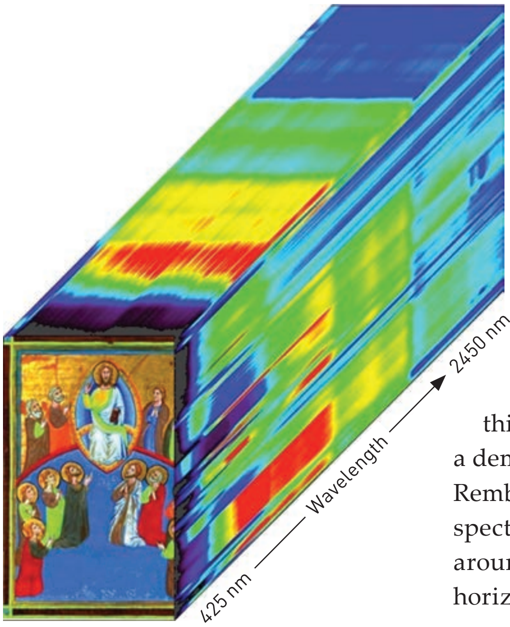
In XRF imaging, also called XRF element mapping, a light source fires X-rays into the painting at a single point; that radiation excites inner-core electrons of specific atoms, which leads to re-emission at a different X-ray energy when the atom relaxes to the ground state. Those characteristic secondary X-rays can be used to identify specific chemical elements, and to create element maps to infer the pigments used by the artist. X-ray emissions at higher energies often can provide information about underlying paint layers.

Home-built for purpose

Needless to say, the components for such imaging aren't found at the local hardware store. The team has lovingly home-built its hyperspectral cameras using off-the-shelf parts from a variety of optics vendors—with an eye toward some of the unique imperatives of its craft.

One of those is the need for very low light levels. "These hyperspectral cameras, they're usually used outside," where illuminance levels are on the order of 30,000 lux, Delaney explains. "In the National Gallery, we're supposed to be at 300 lux—half of the room light." That requires very sensitive focal planes; Delaney selects specific models for the task, including electron-multiplied CCDs in the visible spectral region and low-noise InGaAs focal planes in the near-infrared.

The team mounts its cameras on an optical table around 25 cm away from the painting, which is secured in a computer-controlled motorized easel. (When OPN visited, the team was studying a Rembrandt from the Gallery's collection, *Man with a Sheet of Music* [1633].) The easel has optical linear encoders that can be read to determine its absolute position within tens of micrometers. In a reversal of



In reflectance imaging spectroscopy, full spectral data are captured for each imaging pixel, resulting in a "data cube."
Courtesy of J.K. Delaney

The team has home-built its hyperspectral cameras—with an eye toward the unique imperatives of its craft.

the typical remote-sensing scheme, where a mobile camera flies over a stationary landscape, the camera in the chemical-imaging lab remains stationary, and the "landscape" of the painting is scanned in front of it.

"People think this is the craziest thing in the world to do," says Delaney. But it lets the team easily swap in different cameras with different functionalities or wavelength ranges without painstaking realignment.

In the RIS imaging at the National Gallery, the entrance slit of the imaging spectrometer is oriented vertically, and the easel moves the painting horizontally in front—analogous to the "pushbroom" scanning of traditional hyperspectral remote sensing—to build up the hyperspectral data cube, which for each pixel consists of the x and y position and the full reflected-light spectrum at that point (captured digitally at spectral intervals of around 3 nm). RIS imaging is faster than XRF imaging because of the large number of pixels along the vertical spectrometer slit. This allows things proceed relatively quickly; a demo scan of the face in the Rembrandt painting using a hyperspectral InGaAs camera took only around two minutes to collect 640 horizontal lines. The XRF spectroscopy, which proceeds pixel by pixel in single-point measurements, is much slower; collecting the same demo scan would take around five hours.

Lining things up

What comes out of this process, Dooley says, is a set of hundreds of images—false-color infrared images, XRF element maps—that can be compared with a high-resolution photo of the painted surface when placed in a layered file in the image-editing program Photoshop. While it's a lot of data, Delaney adds, it's well within the reach of "a small-end workstation."

The thornier trick is "registering" the data—precisely lining up the hundreds of images from different instruments and even different labs, pixel for pixel, to enable comparisons. It's a familiar problem from remote sensing, where, for example, researchers might need to align topographic-mapping data from lidar scans with reflected hyperspectral data from the surface (see "Hyperspectral Lidar: A Progress Report," OPN, November 2021, p. 38). But in those cases, the job involves the (relatively) easy alignment of the same surface features in different images. In art explorations, the infrared images are pulling signal from deeper layers that might be quite unlike the painting surface.

In remote sensing, "when you take a picture of a tree in the visible or the infrared, it's still a tree," says Delaney. "Our stuff is different in the sense that when you go into the infrared, things disappear, change, or something else might pop up."

A former Ph.D. student at The George Washington University working with the National Gallery, Damon Conover, solved the problem with an algorithm that does the registration in phase space. "He played around and found the right set of wavelets" to allow the data from the different modalities to be pulled together, says Delaney. As a result, "we can get things registered to about a third of a pixel."

"Doodles" under the surface

With the images aligned, the exploration of the artwork's layers begins—a highly collaborative and interpretive process involving continual interaction with National Gallery's curators and conservators. "You can look at the [stack of] images, and view false-color images" of the infrared signal that hint at patterns beneath the surface, Dooley says. "Or you can drill through the stack of images and see how the light intensity varies with wavelength, look at your reflectance spectrum." And both the RIS and XRF imaging together help to identify specific pigments used to build up the final artwork, as well as in the layers beneath.

Using this workflow, Delaney, Dooley and the National Gallery's curators have investigated works by artists ranging from Leonardo da Vinci and Hieronymous Bosch to modern masters such as Pablo Picasso and Jackson Pollack. When OPN visited the lab, Dooley shared her work on one of the museum's Picassos, *The Tragedy* [1903], a famous oil-on-wood image of a suffering family.

The RIS revealed a rich set of previous designs beneath the surface—"like doodles in a sketchbook," says Dooley. Other, still earlier drawings hint that Picasso originally had something very different in mind for this particular wood panel: a bullfighting scene. Moreover, the chemical imaging revealed that the compositional features of that earlier scene were painted—and the XRF element maps even allowed identification of the paint as mercury-containing vermillion.

National Gallery of Art

Left: A composite image of a color photograph of Johannes Vermeer's *Girl with the Red Hat* [c. 1669] with an infrared reflectance image. Right: *Girl with a Flute* [c. 1669–1675], previously listed as "Attributed to Vermeer" in the National Gallery catalog, is now described as "Studio of Johannes Vermeer."

A deep (optical) dive into Vermeer

Most recently, the chemical-imaging lab has gained attention for its part in illuminating the works of an artist working three centuries before Picasso. The Vermeer project was, Delaney says, "the only good thing about COVID," as the National Gallery's pandemic-related closure allowed the collection's four works associated with Vermeer to come off of the walls for a rare deep interpretive dive. The investigation is featured in the National Gallery's special temporary exhibit "Vermeer's Secrets" (nga.gov/exhibitions/2022/vermeers-secrets.html).

"The pandemic, with the museum being closed, gave us the opportunity to bring them off the walls without receiving letters from the public," demanding to know where these popular paintings are, says Dooley. And the ability to spend meaningful time with the paintings "changed the whole dynamic," according to Delaney. "We thought we'd get a couple of days," he says. "And they said, no, a couple of *weeks*."

The team aimed to answer questions about Vermeer's working methods—questions resulting from decades of micro-sampling, microscopic and XRF examination of the painting by National Gallery researchers Melanie Gifford and Lisha Deming Glinsman, among others. The results from the chemical-imaging lab substantially broadened the picture, providing an image of Vermeer more nuanced than the standard view of a meticulous, lone perfectionist.

For example, as smooth, precise and luminous as the artist's

R. Radpour, T. Kleynhans, M. Facini, M. Westerby and J. Delaney

Left: Color image of *Initial I with David* [1430s?], Master of the Cypresses. Center: Pigment map from a 1D neural network, trained to infer pigments from RIS data. Right: "Truth map" from a separate study.

brushwork looks on the surface, the XRF copper maps show an underpaint layer characterized by spontaneous, rapid brushstrokes, with evidence of features revised and rethought by the artist as the painting developed—a glimpse of Vermeer's creative process at work. Chemical imaging and image processing also added details to a partly completed and abandoned painting of a black-hatted man already known to underlie Vermeer's *Girl with the Red Hat*.

The study revealed much about what's on the surface, too—such as how Vermeer achieved his characteristic luminous effects. In the painting *A Lady Writing*, chemical imaging (expanding on knowledge gleaned from microscopic surface examination) showed that, in just one small portion of the subject's yellow jacket, Vermeer combined no fewer than four different yellow pigments to create the final painting's subtlety of light and shadow.

A "Vermeer studio"?

The real headline news from the project, however, concerned a painting that the National Gallery's curators now conclude is *not* by Vermeer. *Girl with a Flute* had long been listed in the museum catalog as "attributed to Vermeer," based on microscopic evidence of characteristics of the surface paint, composition and technique that don't show Vermeer's typical approach and mastery. Yet some aspects of the painting did seem distinctly to mirror Vermeer's methods.

The recent study added data to help clarify the view—and, to the curators, was enough to tip the scales. *Girl with a Flute*, they now believe, is by an artist familiar with Vermeer's methods, but lacking his sublime talent. This has raised the tantalizing possibility that Vermeer, long thought of as a quintessential "lone genius," may have actively trained pupils or apprentices in a "Vermeer studio."

"Most museums would rather find a Vermeer than being told they have one that isn't," says Alexandra Libby, the National Gallery's associate curator for northern European paintings. "But I think that's kind of missing the excitement about this personally, which is that we're finding a studio. That's something that no one has ever thought was possible."

An optical toolkit for investigating art

As is so often the case in both science and art, not everyone is convinced by the interpretation. An upcoming major exhibition of Vermeer's works at Amsterdam's Rijksmuseum, for example, will include *Girl with a Flute*—as a genuine Vermeer.

To Delaney, the work of the chemical-imaging lab isn't about drawing those conclusions, but about creating a new toolkit and new data sets that let the museum's curators and conservators test such hypotheses. One thing the team would like to do to keep that toolkit moving forward is extend their current studies into the mid-infrared. "We want to get into the region beyond three micrometers and out to 16," says Delaney, "because some chemists tell me there are a lot of vibrational bands out there."

He, Dooley and colleagues at the Rochester Institute of Technology have also recently been exploring the use of artificial-intelligence techniques and machine learning to speed up the identification of pigments from RIS studies. Their work has focused on a set of illuminated manuscripts dating from the 14th and 15th centuries. Using, as a training set, results from works already extensively studied by other means, the team is programming an artificial neural network to automate the process of inferring pigment composition from RIS data in these complex works. The results thus far have been encouraging. The neural net is "in the 80th percentile accurate" in inferring the pigments used in previously unseen samples, according to Delaney.

That's enough, he suggests, to reduce the number of areas requiring study, and perhaps dramatically speed up the interpretive process—using a set of techniques that would have been unimaginable to the monks laboring to apply the paint in the first place seven centuries ago. Science, and art, march on. OPN

Stewart Wills is the senior editor of *Optics & Photonics News*.