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Kandinsky's fragile art: a multidisciplinary investigation of four early reverse glass paintings (1911–1914) by Wassily Kandinsky

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Abstract

This work highlights the rediscovery of the technique of reverse glass painting by the artists of the "Blaue Reiter" collective in the early 20th-century and focusses particularly on the role of Wassily Kandinsky (1866–1944). Kandinsky created more than 70 reverse paintings on glass and showed several of them in exhibitions together with paintings on canvas and cardboard, implying a coequal importance of these techniques. Four of his early (1911–1914) reverse glass paintings (*Auferstehung*, *Allerheiligen II*, *Rudern*, *Apokalyptischer Reiter II*) were selected for investigation and their iconography, painting techniques and painting materials were examined. Two paintings were executed on so-called cathedral glass, revealing a "hammered surface", whereas Kandinsky used a corrugated glass panel for *Rudern*. A multi-analytical, non-invasive approach [X-ray fluorescence (XRF), diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), VIS spectroscopy (VIS), Raman spectroscopy] was taken to identify the pigments and classify the binding media. The results reveal a broad palette of materials. Several pigments like lead white, zinc white, strontium yellow, Prussian blue, viridian, cadmium yellow, ultramarine blue, cinnabar and carbon black were found in most of the four paintings. The use of the rare synthetic organic pigments PR60 and PB52 is discussed. In two works of art, cadmium carbonate is associated with cadmium yellow. The identification of aluminium foil along with tin foils in *Rudern* indicates an early use of this material for reverse glass paintings.

Keywords: Kandinsky, Reverse glass painting, Non-invasive analysis, Pigment identification, DRIFTS, Synthetic organic pigment, Cadmium carbonate, Aluminium foil

Introduction

In the past, the technique of reverse glass paintings was often considered to be part of the stained glass genre; however, in contrast to stained glass, reverse glass paintings are viewed in reflected light and their creation does not involve a firing step. The paint layers are, compared with paintings on canvas, applied in reverse succession, starting with the front most layer and ending with the backing layer. Little art-historical research has been done on this technique and especially its importance for 20th-century art is poorly understood. The mass production of folkloristic reverse glass paintings in the 19th-century created a rather undervalued image of this technique in art history. A very limited number of scientific studies on reverse glass paintings have been published. Several publications deal with 14th to 19th-century reverse glass paintings including sampling of the objects [1–4]. Transportation and sampling of paintings is often restricted due to the fragility of the glass support, hence non-invasive methods have been carried out to collect information on the materials [5, 6]. Recently, non-invasive analyses of 20th-century reverse glass paintings has been published [7–9]. A publication on Chinese reverse glass paintings from the 19th-century discusses a possible influence of these paintings on European 20th-century reverse glass painting from the "Blaue Reiter" collective [10].

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This paper will highlight the rediscovery of the technique of reverse glass painting by the artists of the "Blaue Reiter" collective in the early 20th-century and in particular will shed light on the role of Wassily Kandinsky (1866–1944). Four of his early reverse glass paintings (*Auferstehung*, 1911, *Allerheiligen II* 1911, *Rudern*, c. 1912, *Apokalyptischer Reiter II*, 1914) were selected and their iconography, painting technique and painting materials were examined. The main objectives of this study are: (1) to work out the starting date of modern reverse glass paintings (2) to discuss the importance of this technique for Kandinsky's oeuvre, (3) to examine the painting technique, (4) to highlight the influence of folkloristic 19th-century reverse glass paintings from Bavaria, and (5) to conduct non-invasive, in situ spectroscopic analyses to identify the colourants and classify the binders.

Art historical context

Folkloristic art was an important source of inspiration for Wassily Kandinsky, Gabriele Münter (1877–1962) and their colleagues from the "Blaue Reiter" collective. In September/October 1908, Kandinsky and Münter together with their friends Marianne von Werefkin (1860–1938) and Alexej Jawlensky (1864–1941), spent their first summer stay in Murnau near Munich. The four artists came back next year in the summer of 1909, enjoying the natural surroundings and the quiet life in this small village. Until 1914, Kandinsky and Münter lived not only in Munich, but also spent several months every year in Murnau, where Münter bought a small villa.

Murnau, Seehausen and Uffing am Staffelsee were the main sites of folkloristic reverse glass painting tradition, a technique that started to disappear at the turn of the century. Generally, Münter states that this technique was new to their entire group and that they first came in touch with it in Murnau. Moreover, it was Jawlensky who introduced them to the local master brewer Johann Krötz and to the artist Heinrich Rambold (1872–1955) [11, 12]. The private collection of Krötz included numerous traditional Bavarian reverse glass paintings, which were important sources of inspiration for the artists. Kandinsky, Münter and Jawlensky started to build up their own collection of European and non-European reverse glass paintings, which they used to decorate their flats [13]. Heinrich Rambold was the last artist in the region who created folkloristic reverse glass paintings as souvenirs for tourists. He focussed primarily on 19th-century templates of religious motifs including saints, votive pictures and titular saints in various sizes, but he also created his own designs in an expressive colour style [14]. Münter was the first one of the four to start with this technique by learning from Rambold and copying some of his paintings [11, 12]. She also inspired Kandinsky to try this technique, and they spent evenings creating reverse paintings on glass with their own style and motifs. Traditional 19th-century reverse glass paintings reveal characteristic features like two-dimensional areas of unbroken colour, simplification of the forms, reduction of the colouration and dominance of the line. The combination of the graphic contour and pictorial elements was a contemporary achievement of non-academic pictorial art. The graphic enclosing of coloured areas also played an important role in the works of Paul Gauguin and of the members of the "Nabis" and "Fauves" groups. Jawlensky and Werefkin in particular, studied these French painters and discussed their observations with Kandinsky and Münter in Murnau. The four artists became enthusiastic about the intense and luminous paintings by Georges Braque, André Derain and Henri Matisse [15]. The same luminosity of colours can be found in the traditional Bavarian reverse glass paintings. Hence, for the "Blaue Reiter" artists, the "primitive" originality of the folkloristic reverse glass paintings corresponds to the modern pictorial principles of the avant-garde movements. To achieve a look of simplicity, nativeness and originality, the "Fauves" and "Brücke" artists searched for oriental and exotic artworks; however, the "Blauer Reiter" collective found these desired features in the folkloristic art of the surrounding rural area. There were no academic rules and guidelines for the technique of painting on the reverse side of a glass panel, so it became an important source of inspiration, that supported the striving for clarity of expression and simplification of composition. This led Münter and Kandinsky to consciously adapt their art to the pictorial principles of the folkloristic art.

Wassily Kandinsky—reverse glass painter

Kandinsky must have thought highly about this technique, as he created more than 70 reverse glass paintings in his career and allowed three of them to be shown in the first "Blaue Reiter" exhibition at the Moderne Galerie Thannhauser in Munich in 1911/12 [11]. His fascination and intense focus on the technical and stylistic opportunities of this technique are especially visible during his stays in Murnau and when he was finalizing his search for a fundamental, novel pictorial conception in 1911. Kandinsky also states in a letter to Franz Marc that he hardly knows any work that is more delightful than creating reverse glass paintings—unfortunately, these paintings are so fragile [16]. He continued with this technique during his stays in Moscow (1915–1921) and Paris (1933–1944). Besides Gabriele Münter and Heinrich Campendonk (1889–1957), Kandinsky created the largest number of reverse glass paintings among the artists associated with the "Blaue Reiter" collective, which

further indicates that this genre plays a substantial role in his oeuvre.

His first glass painting dates from 1909, when, in contrast to Münter, he already starts with his own sketches (e.g. *Mit Gelbem Pferd*, 1909 and *Abendmahl*, 1909/10). After these first attempts, Kandinsky started to use typical stylistic elements like closed contours with dark lines. He painted motifs like saints, apocalyptic scenarios or All Saints' Day, which are in close relation to his early works (Fig. 1). Several pictorial topics and motifs were first painted on glass, and later executed on canvas or paper or as woodcut. For example, Kandinsky created two analogies of the reverse glass painting *Allerheiligen I* (1911) as a coloured woodcut and an oil painting on cardboard. Religious topics and motifs are especially present in his artworks from 1911 until 1914, where they express a hidden flow of encrypted symbols [17]. The reproduction of glass paintings with other techniques led to a loss of the aesthetic properties of the glass substrate. The interplay of the material iconography and the painted objects for reverse glass paintings has hardly been described in art historical research. However, Kandinsky used structured glass panels, like cathedral glass or ornamental glass for several works, that reveal an experimental character [18]. Three of them (*Rudern*, *Mit Kneifer*, *Mit Reiter*, all dated 1912) are listed in the catalogue raisonné and are explicitly described as paintings "on corrugated glass" [19]. Wackernagel states that Kandinsky wanted to distance himself from the folkloristic tradition of reverse glass painting by using structured or corrugated glass panels [20].

Kandinsky integrated the corrugation of the panel in *Rudern* (Fig. 2) as an independent stimulus and complicated the exploration of the subjects by integrating metal foils as collage-like objects [8]. The left half of the painting shows a boat that, as indicated by thick black brush strokes, is lifted by a big wave. The dimly visible people hold six oars that extend radially in pairs out of the boat. The entire glass panel is filled with colourful areas that do not depict specific objects. The combined use of structured glass and metal foils hinders a clear identification of the graphic elements, which indicates that the veiling of the motifs was done solely externally with technical media [8]. Hence, Kandinsky's paintings on structured glass panels seem to avoid a straightforward recognizability of the motifs. This can also be observed in his abstract canvas paintings, which he created in parallel from 1911 onwards. The corrugated glass structure of *Rudern* is not only an attractive material property, but also directly implies the representation of water and waves. The combined observation of the reflections from the metal foils and the glass surface can be interpreted as light reflections on the water. In 1910, Kandinsky created a watercolour painting that shows several similarities with *Rudern*: six black lines (the oars) with double arcs above, the continuous red line painted from the right to the left, and

Fig. 1 Photographs of the framed paintings: **a** *Auferstehung*, 1911 (GMS 112), **b** *Allerheiligen II*, 1911 (GMS 122), **c** *Rudern*, c. 1912 (GMS 108), **d** *Apokalyptischer Reiter II*, 1914 (GMS 106); ©Städtische Galerie im Lenbachhaus und Kunstbau München

Fig. 2 Photographs of *Rudern*, c. 1912 (GMS 108), Städtische Galerie im Lenbachhaus und Kunstbau München (**a**–**c**): **a** unframed front side, **b** reverse side in transmitted light, **c** reverse side, along with a photograph of the canvas painting *Improvisation 26 (Rudern)*, 1912 (GMS 66) (**d**). ©Städtische Galerie im Lenbachhaus und Kunstbau München (**a**, **d**); ©Simone Bretz (**b**, **c**)

the red, gently contoured area in the lower right part of the painting. The side-inverted illustration of the oblique oar lines indicates that Kandinsky used this watercolour painting as a draft for *Rudern* and for the canvas painting *Improvisation 26* (*Rudern*) (Fig. 2d). The objects in the watercolour painting can still be read clearly, whereas the other two paintings show an advanced mystification of motifs. Kandinsky created *Rudern* and *Improvisation 26* (*Rudern*) in a close context in 1912. The painting *Improvisation 26* (*Rudern*) yields details of the drawing, the watercolour painting and the reverse glass painting; however, the illustration of the content becomes less clear as the motifs and forms further dissolve and as the colours gain greater importance, in direct contrast to the disappearing forms [8]. The painting appears more differentiated and the border between clear recognizability and mystification of the motifs remains fluent. The statements of Zweite [18] imply that the reverse glass painting *Rudern* was also a preliminary study for *Improvisation 26* (*Rudern*); but unlike his drafts, drawings and sketches, Kandinsky showed reverse glass paintings together with paintings on canvas in his exhibitions (e.g. gallery "Der Sturm") implying a coequal importance of the two techniques.

Description of the paintings

Four reverse glass paintings (*Auferstehung*, *Allerheiligen II*, *Rudern*, *Apokalyptische Reiter II*) by Wassily Kandinsky (Fig. 1), housed in the Städtischen Galerie im Lenbachhaus und Kunstbau in Munich, were examined during the research project "Hinterglasmalerei als Technik der Klassischen Moderne 1905–1955" (2015–2019). They were created between 1911 and 1914 in Murnau and stored in Kandinsky and Münter's villa after Kandinsky had to leave Germany in 1914. Kandinsky and Münter used *Allerheiligen II* and other reverse glass paintings to decorate their dining room as shown in a photograph taken by Münter in 1913 (Fig. 3). Kandinsky's reverse glass paintings remained in Murnau until 1957, when Münter donated them among other artworks to

Fig. 3 The dining room of the Murnau house; the wall is decorated with reverse glass paintings by Kandinsky. Photo: Gabriele Münter (1913), Gabriele Münter- und Johannes Eichner-Stiftung, Munich (Inv.-Nr. 2235)/©VG Bild-Kunst, Bonn 2019

the Städtischen Galerie im Lenbachhaus und Kunstbau in Munich.

One of the four paintings (*Allerheiligen II*, 1911) is signed with the monogram "K". Münter wrote with a pencil "Kandinsky/Gemalt im August 1911/in Murnau"on the backing cardboard of *Auferstehung* (1911) and "Kandinsky (Glasbild) Rudern" on the backing layer of *Rudern* (c. 1912). *Apokalyptischer Reiter II* (Fig. 4) dates from 1914 and was the last reverse glass painting that Kandinsky created in Murnau. Moreover, as already discussed in the introduction to *Rudern*, Kandinsky created several paintings with the same content on different supports, like canvas, paper, cardboard and glass. In 1911, Kandinsky executed *Allerheiligen II* as a watercolour, canvas and as a reverse glass painting (Fig. 5). A glass fragment of the preliminary study for *Apokalyptischer Reiter II* from 1914 has been preserved, showing roughly painted lines on the upper part of the painting. The analogue watercolour painting dates from 6. July 1914 and shows the same central motifs in a mirror image, but the oval cartouche and the four illustrations of animals on the edges are missing.

Painting technique

The major artistic challenge of painting on the reverse side of a glass panel may be the reverse succession of the paint layers. Kandinsky had to apply the frontmost layer (i.e. the most visible layer) first and the background layer last. He started his paintings with black contours and lines, followed by the detailed painting of internal areas and the application of the background.

The four paintings reveal multi-layered paint systems (2–3 layers) showing variably thick paint layers. Kandinsky used a variety of brushes and stippled the paint or swiftly coloured large areas. He painted wet-in-wet or applied the paint as dots side by side or one upon another, indicating an optical mixture of colours. The typical structure of an inhomogeneous application of colour indicates the use of a bristle brush in several areas of *Rudern* (Fig. 2b, c), whereas the white area of the painting seems to be stippled. Compared with *Rudern*, the application of paint layers in *Auferstehung* (Fig. 6) was more

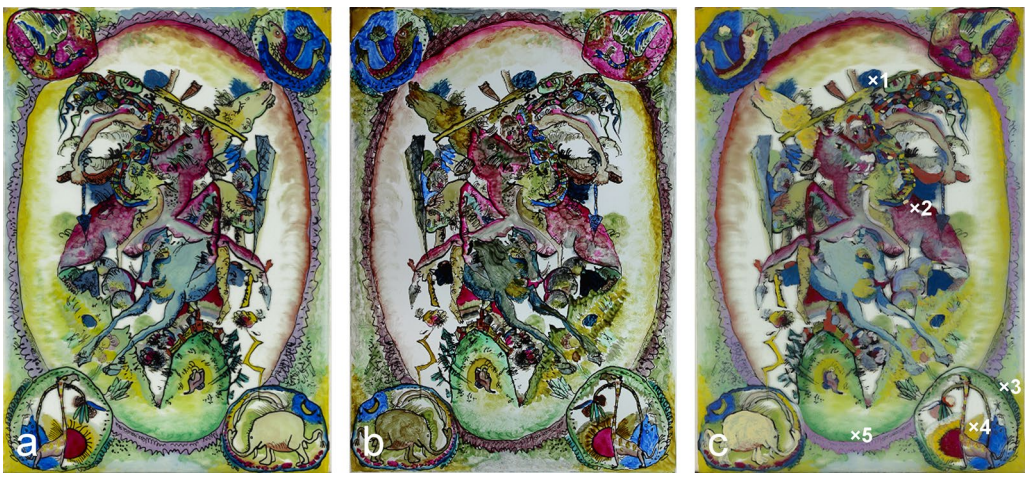

Fig. 4 Photographs of *Apokalyptischer Reiter II*, 1914 (GMS 106), Städtische Galerie im Lenbachhaus und Kunstbau München: **a** unframed front side, **b** reverse side in transmitted light, **c** reverse side. ©Städtische Galerie im Lenbachhaus und Kunstbau Munich (**a**); ©Simone Bretz (**b**, **c**)

Fig. 5 Photographs of *Allerheiligen II*, 1911 (GMS 122), Städtische Galerie im Lenbachhaus und Kunstbau München (**a**–**c**); **a** unframed front side, **b** reverse side in transmitted light, **c** reverse side, along with a photograph of the watercolour painting *Allerheiligen II*, 1911 (GMS 616), Städtische Galerie im Lenbachhaus und Kunstbau München (**d**). ©Städtische Galerie im Lenbachhaus und Kunstbau München (**a**, **d**); ©Simone Bretz (**b**, **c**)

Fig. 6 Photographs of *Auferstehung*, 1911 (GMS 112), Städtische Galerie im Lenbachhaus und Kunstbau München; **a** unframed front side, **b** reverse side in transmitted light, **c** reverse side. ©Städtische Galerie im Lenbachhaus und Kunstbau München (**a**); ©Simone Bretz (**b**, **c**)

intense and homogeneous. One needs to consider that these paintings make their impressions solely from the front side, hence the gloss, brush structure, and pastosity of the reverse side were not of artistic importance.

Kandinsky often used cardboards painted black as supports for his reverse glass paintings as they further intensify the depth of colours [21]. Such black-painted cardboard was used in *Auferstehung*, *Allerheiligen II* and *Rudern*. Black-painted supports (paper or wooden veneer) are also known from traditional Bavarian and Swiss reverse glass paintings from the 18th and 19th-century respectively [22]. 19th-century Bavarian reverse glass paintings may also have been Kandinsky's source of inspiration to decorate the frames of his paintings (Fig. 1). The folkloristic paintings from Oberammergau, in particular, have black frames painted with flower motifs. Kandinsky used a commercial wooden frame for *Auferstehung*, which he decorated with green, blue and violet paints (Fig. 1). He chose industrially gilded frames for the other three paintings, which he partially overpainted with lustre paint (Fig. 1).

Glass technique

For paintings on canvas, the final application of varnish creates a certain depth of colours and protects the uppermost paint layers. The glass panel of reverse glass paintings, however, itself behaves as a varnish, which gives rise to the painting's great luminosity and protects the paint layers from the front. Kandinsky used glass panels of variable sizes in landscape and portrait format. The glass panels of the studied paintings show the following dimensions: $21.9 \times 11.4 \times 0.28$ (*Auferstehung*), $31.1 \times 47.8 \times 0.41$ (*Allerheiligen II*), $21.5 \times 25.7 \times 0.44$ (*Rudern*) and $30.3 \times 21.2 \times 0.25$ cm (*Apokalyptischer Reiter II*). The surface structure of the glass panel plays an important role for the final visual appearance of a reverse painting on glass. Generally, artists prefer flat glass panels, because light reflections of an uneven surface distract the observer's attention from the painted motifs. Kandinsky created most of his reverse glass paintings on flat panels, but ten paintings on structured glass are known from his Murnau period between 1911 and 1913. He used commercial products, that were sold for different applications (e.g. windows). Generally, there were two different types of structured glass panels: ornamental glass (3–4 mm thick) that shows a corrugated surface and the thinner cathedral glass (2–3 mm) that reveals a "hammered" surface structure (Fig. 7a). Both types were produced in the rolling process, which was invented in 1847 [23]. Rolled plate glass was made by thinning molten glass between two rollers and then placing it on the casting table. The surface structure of ornamental glass was first engraved into the table in which the molten glass was then cast. This procedure was expensive, so the process was adapted in 1884; now the structures were engraved in an extra pair of rollers, which pressed into the already thinned glass [23]. The rolling process for cathedral glass included a higher temperature and a faster rolling procedure, and the thinned glass was drawn out on a water-cooled casting table. The quick cooling led to a quick contraction of the glass surface, yielding a "hammered" appearance of the surface. The other, rolled side of the glass panel was not affected by this procedure and stayed rather smooth. Kandinsky did not always choose the same side to paint onto. In *Auferstehung*, the structured surface is the front side (Fig. 7a), whereas for *Allerheiligen II*, the smoother surface is the front side (i.e. he painted on the structured side). In *Rudern*, Kandinsky painted on the corrugated side of the ornamental glass (Fig. 2c).

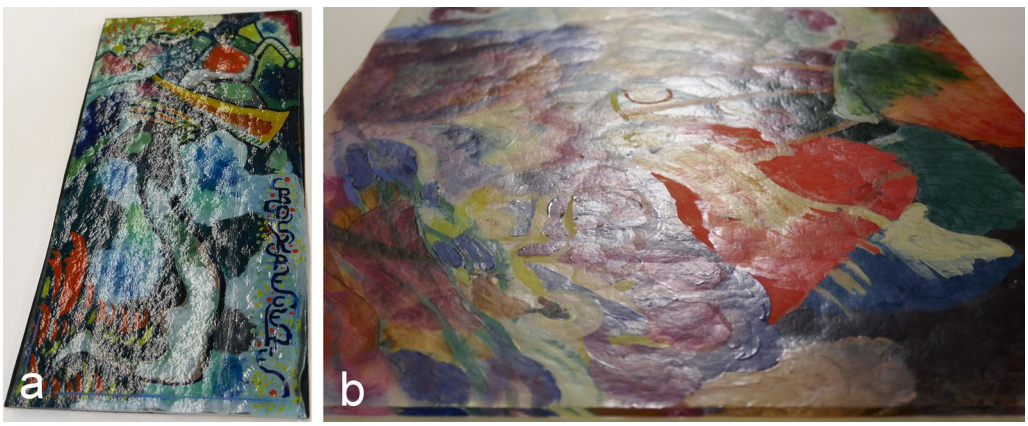

Fig. 7 Photographs of **a** *Auferstehung* (front side) and **b** *Allerheiligen II* (reverse side) in glancing light, showing the structured surface of the cathedral glass. ©Simone Bretz

Methods of the material analyses

X-ray fluorescence (XRF)

The handheld spectrometer Tracer III-SD (Bruker AXS Microanalysis GmbH) was fixed on a tripod perpendicularly to the sample (sample to spectrometer distance ~1 mm, spot size ~10 mm). The instrument consists of an electrothermally cooled Xflash SDD detector (energy resolution = 150 eV for Mn Kα radiation) and an X-ray tube equipped with a rhodium anode. The excitation parameters were set to 40 kV, 15 µA and 20 s (acquisition time).

VIS spectroscopy (VIS)

The spectrophotometer SPM 100 (Gretag-Imaging AG, Regensdorf, Switzerland), measures the reflection of visible light (from 380 to 730 nm) with a spectral resolution of 10 nm. The surface of the sample is illuminated for half a second, using a 2 W bulb (spot size 4 mm). The reflectance spectra are normalized, and the first derivative is plotted for better peak comparison.

Diffuse reflectance infrared fourier transform spectroscopy (DRIFTS)

Diffuse reflectance spectra were recorded, using a 4100 Exoscan FTIR spectrometer (Agilent) fixed on a tripod perpendicularly to the sample (sample to spectrometer distance ~1 mm, spot size ~10 mm). In this configuration, the reflected signal is collected inside an imaginary cone of 45° around the emission beam, which supports the detection of diffuse reflected light. The instrument is equipped with a ZnSe beam splitter, a Michelson interferometer and a thermoelectrically cooled dTGS detector. For every spectrum, 500 scans were recorded in the mid IR range (650–4000 cm^{-1}) with a spectral resolution of 4 cm^{-1}. A gold reference cap was used for background calibration. The spectrum intensity was defined as pseudo-absorbance $A' = \log(1/R)$. The Thermo Scientific™ OMNIC™ Specta software (Version 9.7, Madison, WI, USA.) was used for comparison with internal databases.

Raman spectroscopy

Raman measurements were performed with an i-Raman®Plus spectrometer (B&W Tek Inc.) equipped with a handheld fibre optic probe and a CCD detector. The probe was connected to a microscope head (BAC151B, B&W Tek Inc.) with an Olympus 50× objective and was fixed on a motorized xyz stage of a tripod. After focusing through the microscope, the maximum laser power of the 785 nm diode laser was ~160 mW. The recorded spectra range from 100 to 3300 cm^{-1} (spectral resolution 4 cm^{-1}) with varying acquisition parameters of 1–200 s and 2–10% laser power. The holographic grating was fixed at 1200 lines/mm. The Thermo Scientific™ OMNIC™ Specta software (Version 9.7, Madison, WI, USA.) was used for baseline correction and for comparison with internal databases.

Analytical results

The reverse side of *Auferstehung* (1911) (Fig. 6c) is dominated by yellow, green and bluish colours. These areas partly cover the orange and red areas, that are visible from the front side. Zinc white (ZnO) and smaller amounts of lead white ($2PbCO_3 \cdot Pb(OH)_2$) were present in all coloured areas, whereas the white uppermost layer consists only of zinc white. A small amount of Gypsum ($CaSO_4 \cdot 2H_2O$) was detected and other fillers were absent. Prussian blue ($Fe_4[Fe(CN)_6]_3$) was used solely for the blue and dark blue painted areas. The dominant green hues of the reverse side comprise mainly mixtures of Prussian blue with various yellows. Strontium, Naples and chrome yellow were admixed to achieve greenish yellow to bluish green hues. Strontium yellow ($SrCrO_4$) and chrome yellow ($PbCrO_4$) were also individually used for the yellow and dark yellow areas. Both pigments yield fingerprinting Raman spectra. Strontium yellow shows typical CrO_4 bending modes at 338, 349, 372, 400 and 431 cm^{-1} and intense CrO_4 stretching bands at 865 (ν_s), 892 and 914 cm^{-1} (ν_{as}) (Fig. 8e) [24, 25]. The intense Raman band at 838 cm^{-1} (CrO_4 stretching) along with several weaker ones at 344, 358, 375 and 399 cm^{-1} (CrO_4 bending) (Fig. 8f) properly identify chrome yellow in the greenish yellow area (Fig. 6c, spot 2) [26]. Characteristic bands at 278, 535 (FeC stretching), 2094 and 2154 cm^{-1} (CN stretching) prove the presence of Prussian blue [27, 28]. An additional weak spectral feature at 251 cm^{-1} originates from an underlying layer and can be ascribed to cinnabar (HgS). Intense Sb peaks in the XRF spectrum of the bluish green areas (e.g. Fig. 6c, spot 1) hint at Naples yellow ($Pb_2Sb_2O_7$). Due to extensive fluorescence, it was not possible to record a usable Raman spectrum from these areas. However, Naples yellow yields one major band in the mid IR range, so it could be identified using DRIFTS (Fig. 8a). The prominent inverted and broad band (*reststrahlen* band) shows a minimum at 675 cm^{-1}, whereas the other IR active modes are out of range for this device [29, 30]. The DRIFT spectrum also reveals an intense band at 2098 cm^{-1} originating from Prussian blue (CN asymmetric stretching) [31]. Despite this variety of mixed greens, Kandinsky also used a green pigment. The XRF spectrum of spot 4 (Fig. 6c) is dominated by Cr and Sr signals, suggesting the presence of viridian (hydrated chromium oxide) and strontium yellow. Both pigments were detected in the DRIFT spectrum (Fig. 8b). Viridian yields a typical weak band at 1064 cm^{-1} and two spectral

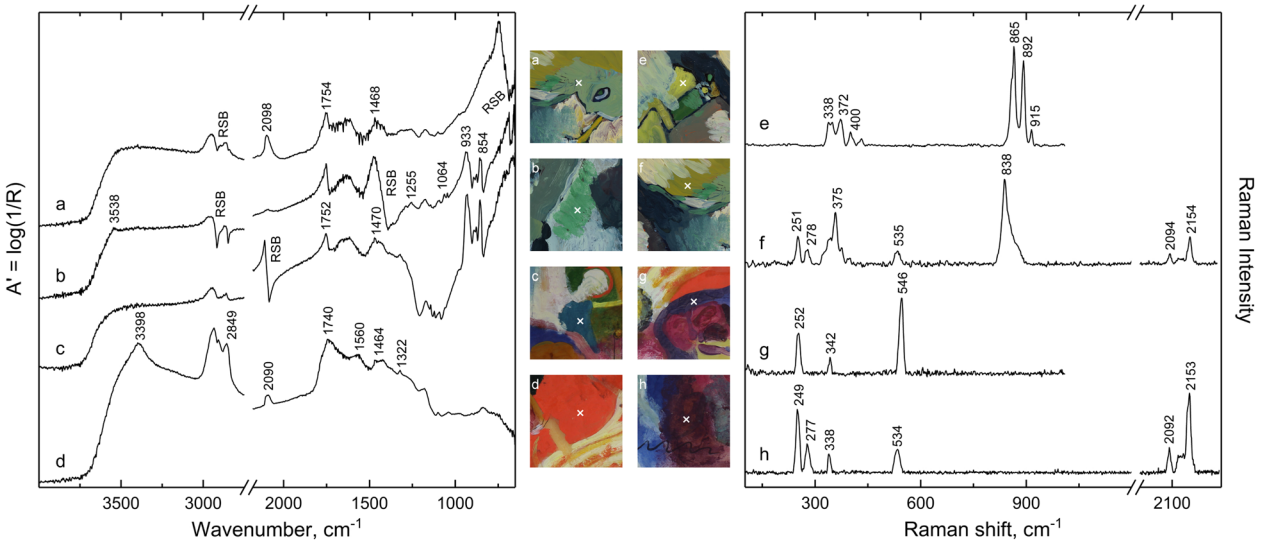

Fig. 8 DRIFTS (a–d) and Raman spectra (e–h) of *Auferstehung* (a, b; e, f) and *Allerheiligen II* (c, d; g, h) along with detailed photos of the measured areas; offset was applied for better comparison. DRIFT spectra originate from the following spots: a) the green area of Fig. 4c (spot 1), b) the green area of Fig. 4c (spot 4); c) the bluish green area of Fig. 5c (spot 3), and d) the orange area of Fig. 5c (spot 1); RSB = *reststrahlen* band. Raman spectra originate from the following spots: e) the yellow area of Fig. 4c (spot 3), f) the greenish yellow area of Fig. 4c (spot 2); g) the violet area of Fig. 5c (spot 2), and h) the pinkish red area of Fig. 5c (spot 5). × = measured spots

features at 1255 and 1287 cm^{-1} originating from chromium borate, a by-product from the production process of the pigment [32]. Strontium yellow shows intense bands at 854, 876 and 933 cm^{-1}. Additionally, several lead white bands also appear in the spectrum: 1046 (CO_3 symmetric stretching), 3538 cm^{-1} (OH stretching) and an inverted band with a minimum at 1392 cm^{-1} (CO_3 antisymmetric stretching) [7]. The presence of cinnabar and brown earth pigments in the red–orange and brown areas was confirmed by XRF respectively. All measured areas yield typical bands for drying oil. An example is given in Fig. 8a, showing bands at 1468 (CH_2 scissoring) and 1754 (C=O stretching) cm^{-1} and inverted spectral features with minima at 2848 and 2915 cm^{-1} (CH_2 stretching) [7, 8, 33].

The palette of *Allerheiligen II* (1911) (Fig. 5a–c) is summarized in Table 1. Zinc white and, in minor amounts, lead white were found in all colours. Gypsum was identified only in the bluish green areas, whereas other fillers (e.g. barium sulfate, chalk) are again absent. The thin contour lines and black areas were painted with carbon black. Prussian blue and ultramarine blue ($Na_7Al_6Si_6O_{24}S_3$) were individually used for the blue areas, and both were mixed with cinnabar to create violet and pinkish red hues (Fig. 5c, spots 2 & 5). The Raman spectrum of the bluish violet area (Fig. 8g) shows an intense ultramarine blue band at 546 cm^{-1} (stretching of the S_3^- radical ion) and two bands at 252 and 342 cm^{-1} originating from HgS stretching vibrations of cinnabar [34–36]. Raman measurements of a pinkish violet area (Fig. 8h) also yielded typical cinnabar bands at 249 and 338 cm^{-1} along with bands of Prussian blue at 338, 534, 2092 and 2153 cm^{-1}. Kandinsky mixed Prussian blue in various ratios with strontium yellow and minor amounts of cadmium yellow to obtain bluish green and green hues (Fig. 5c, spot 3). Both major pigments can be clearly identified by their DRIFT spectra (Fig. 8c), as Prussian blue yields an intense *reststrahlen* band with a minimum at 2084 cm^{-1} (CN asymmetric stretching) and strontium yellow reveals its strong IR bands at 856, 878 and 931 cm^{-1} [31]. The yellow hues were created with a mixture of strontium yellow with minor amounts of cadmium yellow. The brownish to dark yellow areas (Fig. 5c, spot 4) yielded intense Cd, S, Zn and Pb signals in the XRF spectrum, suggesting the presence of zinc white, lead white and cadmium yellow (CdS). The DRIFT spectrum (Fig. 9c) of the same area shows a sharp inverted band with a minimum at 855 cm^{-1} (CO_3 out of plane bending) and a weak combination band at 2472 cm^{-1}, which can be assigned to cadmium carbonate ($CdCO_3$) [37, 38]. A detailed interpretation is given in the section below (cf. "Analytical results" section). Drying oil was classified in most DRIFT spectra as binding media, yielding bands at 1470, 1752 cm^{-1} and two spectral features in the 2840–2930 cm^{-1} range (Fig. 8c) [7]. Only the spectrum of the orange area gives a hint at a different binder (Fig. 8d), showing a broad band at 1560 cm^{-1}, which can be ascribed to the amide II of a proteinaceous compound

Table 1 Comparison of the analytical results of the four paintings

	Auferstehung (Jüngstes Gericht), 1911 (23 spots tested)	Allerheiligen II, 1911 (34 spots tested)	Rudern, c. 1912 (27 spots tested)	Apokalyptischer Reiter II, 1914 (32 spots tested)
White	Zinc white[a], lead white[a,c], gypsum[c]	Zinc white[a], lead white[a,c], gypsum[c]	Zinc white[a], lead white[a], gypsum[c], barium sulfate[a,c]	Zinc white[a], lead white[a], barium sulfate[a,b]
Black	–[e]	Carbon black[b]	Carbon black[b], bone black[a]	Carbon black?
Red	Cinnabar[a,b]	–	PR83[c]	Cinnabar[a,d], PR60[b]
Orange	–	Cinnabar + cadmium yellow[a,d]	–	–
Yellow	Chrome yellow[a,b], strontium yellow[a,b,c], Naples yellow[a,c]	Strontium yellow + cadmium yellow[a,b,c,d], cadmium yellow[a,c]	Strontium yellow[a,b,c,d], cadmium yellow[a,d], yellow SOP[c]	Cadmium yellow[a,d], cadmium yellow + strontium yellow[a,c,d]
Green	Viridian + strontium yellow[a,c], Prussian blue + chrome yellow[a,c], Prussian blue + strontium yellow[c], Prussian blue + Naples yellow[a,b,c]	Prussian blue + strontium yellow + cadmium yellow[a,c]	Viridian + strontium yellow[a,d], Prussian blue + strontium yellow + cadmium yellow[a,b,c], Prussian blue + yellow SOP[c], PB52 + yellow SOP[c]	Viridian + strontium yellow[a,c,d], emerald green + strontium yellow[a,c], viridian + emerald green + strontium yellow[a,c]
Blue	Prussian blue[a,b,c]	Prussian blue[a,bc,d], ultramarine blue[a,b,c,d]	Prussian blue[b,c], ultramarine blue[b,c],PB52[b,c]	Prussian blue[a,b,c,d], ultramarine blue[a,b,d], cobalt blue[a]
Violet	Prussian blue + cinnabar[a,b,c]	Prussian blue + cinnabar[a,b,c], ultramarine blue + cinnabar[a,b,c]	Ultramarine blue + PR83[a,c]	Prussian blue + PR60[a,b,c], cobalt blue + PR60[a,b]
Brown	Brown earths[a]	–	Brown earths[a,c,d]	–
Metal	–	–	Aluminium foil[a], tin foil[a]	–
Binder	Drying oil[c]	Drying oil[c], proteinaceous binder + lipids[c]	Drying oil[c]	Drying oil[c]

SOP synthetic organic pigment

[a] XRF

[b] Raman

[c] DRIFTS

[d] VIS

[e] colour not in the painting

(e.g. egg white, casein), along with intense signals (1740, 2858, 2935 cm^{-1}) of lipids (oil, egg yolk) [7]. The spectral feature at 1464 cm^{-1} may be a combination of the amide III band from the protein and the CH_2 scissoring vibration of the fatty compound. Additionally, a weak band of an oxalate (1322 cm^{-1}) [39] and one of an unknown substance (3398 cm^{-1}) are visible.

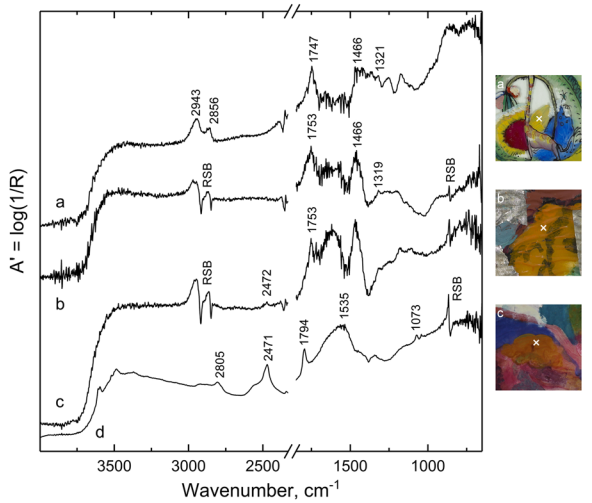

Fig. 9 DRIFT spectra of yellow areas of a) *Apokalyptischer Reiter II* (Fig. 6c, spot 4), b) *Rudern* (Fig. 3c, spot 2) and c) *Allerheiligen II* (Fig. 5c, spot 4) along with a cadmium carbonate powder spectrum (d). RSB = *reststrahlen* band. × = measured spots

The reverse side of *Rudern* (c. 1912) is partly covered with aluminium and tin foils (glossy silvery appearance and whitish matt, respectively) (Fig. 2c) showing different surface structures (Fig. 10b). Zinc white dominates among the white pigments, while lead white appears in small amounts. Gypsum was found only in the brown painted area, associated with iron oxides. The use of barium sulfate ($BaSO_4$) is restricted mainly to some greenish areas that contain synthetic organic pigments (SOP). Kandinsky used pure carbon black for the thick contour lines and bone black ($C + Ca_5(PO_4)_3(OH)$) for the black painted area. Ultramarine blue was identified in the blue areas by its intense Raman band at 546 cm^{-1} (Fig. 11f). The light greenish blue hues (Fig. 2c, spot 1) originate from anthraquinone lake, PB52, which is partly mixed with Prussian blue. PB52 yields a characteristic Raman spectrum (Fig. 11e) with an intense doublet at 1303 and 1358 cm^{-1} and weaker bands at 483, 712 and 1251 cm^{-1} [40]. Kandinsky used four different mixtures for the green and bluish green areas.

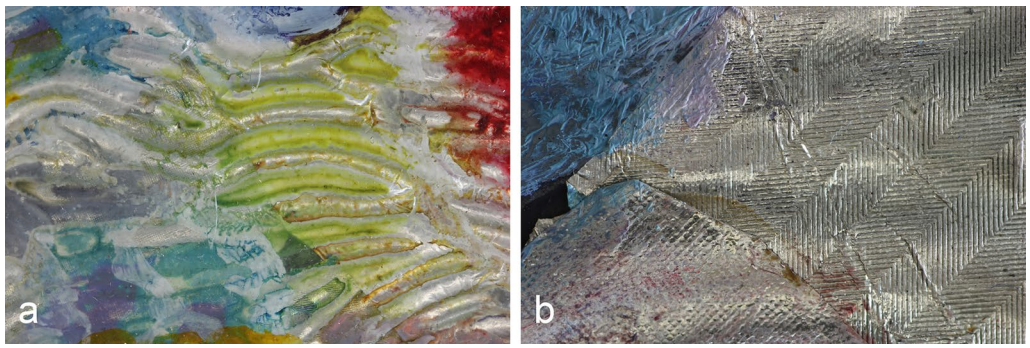

Fig. 10 Detailed photographs of the metal foils of *Rudern*: **a** front side, **b** reverse side. ©Simone Bretz

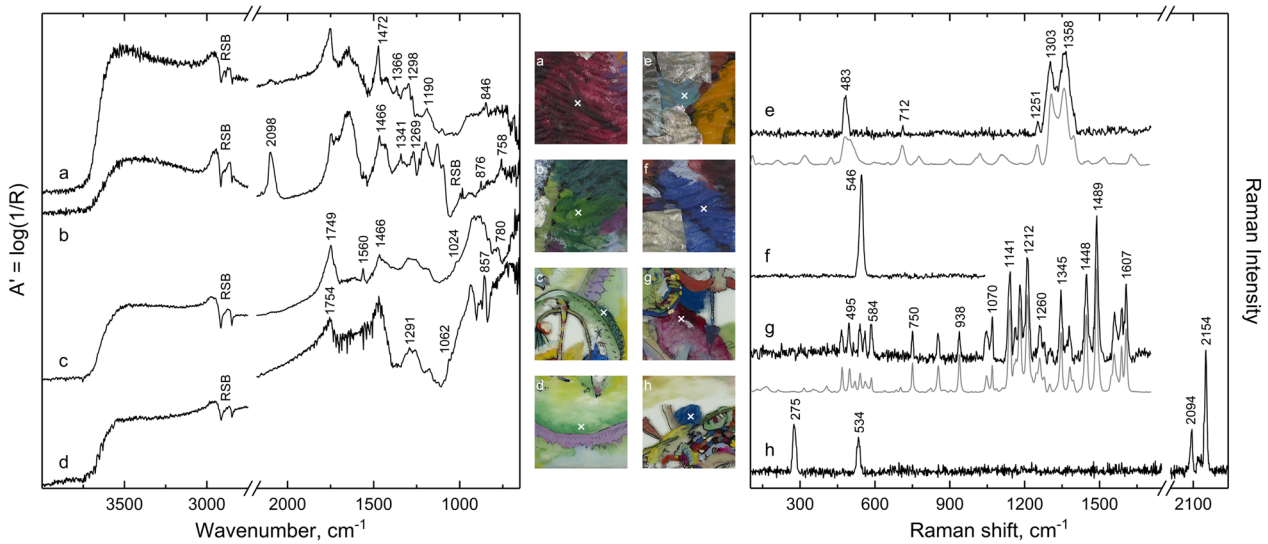

Fig. 11 DRIFTS (a-d) and Raman spectra (e–h) of *Rudern* (a, b; e, f) and *Apokalyptischer Reiter II* (c, d; g, h) along with detailed photos of the measured areas; offset was applied for better comparison. DRIFT spectra originate from the following spots: a) the red area of Fig. 3c (spot 5), b) the green area of Fig. 3c (spot 4), c) the bluish green area of Fig. 6c (spot 3) and d) the green area of Fig. 6c (spot 5); RSB = *reststrahlen* band. Raman spectra originate from the following spots: e) the greenish blue area of Fig. 3c (spot 1), f) the blue area of Fig. 3c (spot 3), g) the pinkish red area of Fig. 6c (spot 2) and h) the blue area of Fig. 6c (spot 1). Reference spectra (grey lines): cf. [40]; × = measured spots

Both viridian and Prussian blue were mixed with strontium yellow to obtain bluish green hues. Mixtures of an unknown yellow SOP with either Prussian blue or PB52 were found in the light green areas (e.g. Fig. 2c, spot 4). The Raman spectra of these areas were covered by extensive fluorescence, whereas the DRIFT spectrum reveals several bands at 758, 876, 996, 1160, 1235, 1269, 1341 and 1466 cm^{-1} that can be ascribed to the yellow SOP (Fig. 11b). Please note that the ~1000–1150 cm^{-1} range is covered by the structured *reststrahlen* band (minimum at 1064 cm^{-1}; SO_4 asymmetric stretching) of barium sulfate [41]. Due to this extensive band overlapping, an exact identification of the SOP was not successful. Additionally, the strong IR absorption band of Prussian blue is visible at 2098 cm^{-1}. Strontium yellow and cadmium yellow were identified in the yellow and dark yellow areas respectively. The DRIFT spectrum of the cadmium yellow, as in *Allerheiligen II*, shows characteristic signals of cadmium carbonate (sharp, inverted band with a minimum at 855 cm^{-1}) (Fig. 9b). An alizarin-based red was found in the red areas, yielding typical bands at 846, 1190, 1276, 1298, 1351, 1366 and 1472 cm^{-1} in the DRIFT spectrum (Fig. 11a) [7, 9]. It needs to be emphasised that a clear discrimination between PR83 (synthetic alizarin) and natural madder lake is not possible with this method, but we would rather assume PR83 in the 1910s than its natural analogue. A mixture of PR83 and ultramarine blue

was identified in the bluish violet area. Drying oil was classified as the binding media; however, a correct classification was sometimes hampered by extensive band overlapping in the DRIFT spectra. An unaffected spectrum is given in Fig. 9b, showing intense bands at 1466 and 1753 cm^{-1} and inverted bands with minima at 2849 and 2916 cm^{-1}, which classify drying oil properly [7, 8, 33].

The painting *Apokalyptischer Reiter II* (1914) reveals several unpainted areas (i.e. the glass substrate is visible) and thin paint layers (Fig. 4a–c). XRF measurement of the glass shows high amounts of calcium, potassium and silicon and weak peaks of manganese, iron, strontium and lead. Zinc white and small amounts of lead white were reported from every spot. Barium sulfate was found only in the red areas, associated with a SOP. Kandinsky used ultramarine blue and Prussian blue (Raman bands at 275, 543, 2094, 2154; Fig. 11h) for the blue areas. The presence of significant Co peaks in the XRF spectra of the greenish blue (body of the horse) and lilac areas (the oval form around the inner scene) (Fig. 4c) suggest the presence of cobalt blue (Co-metal oxides, variable composition). Viridian was found in most green areas, where it is mixed with strontium yellow. Viridian yields typical IR bands at 1062, 1259 and 1291 cm^{-1} (Fig. 11d), of which the latter two indicate chromium borate, a by-product of the production process [32]. Strontium yellow shows characteristic bands at 858, 878 and 935 cm^{-1} in the DRIFT spectrum. XRF measurements of the bluish green areas (Fig. 4, spot 3) yield particularly high values for copper and arsenic, suggesting the presence of a Cu–As green. Emerald green ($3Cu(AsO_2)_2{\cdot}Cu(CH_3COO)_2$) was identified by means of DRIFTS, showing typical bands at 780, 1024 (CH bending), 1466 (COO symmetric stretching) and 1560 (COO antisymmetric stretching) in the spectrum (Fig. 11c) [42]. Moreover, a combination of both greens can be observed in some areas. Kandinsky used cadmium yellow, sometimes mixed with minor amounts of strontium yellow, for the yellow hues. Cadmium carbonate was not present in any DRIFT spectrum of these areas (Fig. 9a). Cinnabar and the red SOP PR60 were found in the red and pinkish red areas (Fig. 4c spot 2) respectively. PR60 yielded a high number of intense Raman bands, which are in good agreement with the reference spectrum (Fig. 11g) [40]. PR60 was mixed with cobalt blue to create the lilac hue of the oval form around the inner scene. Drying oil was classified in all spectra, and a typical spectrum is given in Fig. 9a. Bands at 1466, 1747, 2856 and 2943 cm^{-1} can be ascribed to the oily binder, whereas the small spectral features at 1321 and 1365 cm^{-1} originate from oxalates [39].

Discussion

Pigments

A direct comparison of the pigments used in the paintings is given in Table 1. The results reveal specific differences in the palettes, but the following observations are valid for all the paintings: (1) zinc white is dominant among the white pigments, whereas lead white appears only in minor amounts and fillers were scarcely detected; (2) Prussian blue and ultramarine blue were mainly used for the blue areas and both were mixed with various reds to obtain violet hues, whereas only Prussian blue was mixed with various yellows for green hues; (3) Kandinsky particularly used strontium yellow and cadmium yellow for yellow areas; (4) violet pigments are absent; here these hues are always mixtures of blues and reds; and (5) viridian mixed with strontium yellow is the most common green in the paintings. Kandinsky used up to four different mixtures for green hues in one painting, but only one mixed green is reported from *Allerheiligen II*, where he varied the ratio of Prussian blue and strontium yellow (with minor amounts of cadmium yellow) to obtain green to bluish green hues (Fig. 5a–c).

Kandinsky's choices of materials evolved with his painting style throughout his career, as several technical examinations suggest [e.g. 20, 43–46]. Unpublished reports by the Doerner Institut and several technical studies [44–46] of paintings between 1901 and 1913 allow a comparison of the used pigments with the presented results of our study. Generally, the previously reported results are consistent with our observations: zinc white is the dominant white pigment; Prussian blue and cadmium yellow are the most common blue and yellow pigments, respectively; cinnabar, Naples yellow, strontium yellow, chrome yellow and yellow ochre were also found in some paintings; viridian was mostly used for green areas, and violet pigments are completely absent. Additionally, unpublished results of Kandinsky's Munich palette from 1910/11 reveal the presence of cobalt blue, viridian, cinnabar, cadmium yellow, chrome yellow, bone black, zinc white and a synthetic red lake (unpublished report, Doerner Institut). Certain differences need to be emphasized when comparing them with the results of the four reverse glass paintings. Several proofs of PR3 in paintings from 1910 and of cadmium red in a painting of 1913 indicate an early use of these pigments by Kandinsky [44, 46], but both reds are absent in our study and in the Munich palette. The identification of emerald green in *Apokalyptischer Reiter II* proves that Kandinsky must have used this pigment also in his Munich period and not only in his later paintings [43].

McMilian et al. investigated a cardboard painting (1930) and four canvas paintings (1938–1941) and explored Kandinsky's use of *Ripolin* colours, a French

brand of oleoresinous enamel paint [43]. The results show that mainly emerald green and viridian, sometimes mixed with cadmium yellow, Prussian blue or cerulean blue, were used for the green hues in these paintings. Cadmium yellow appears in four paintings, whereas strontium yellow is completely absent. Prussian blue, ultramarine blue and cobalt-based blues were identified as blue pigments. Moreover, the authors reported cobalt violets (Co-arsenate in one painting, Co-phosphate in three paintings) from the violet areas. Some organic yellow and red pigments were found in two paintings, but a closer identification was not possible with the methods applied. Microscopic investigation of several paint samples confirmed that Kandinsky mixed tube paints with dry pigment powders and other tube paints before applying them [43]. Generally, the palette reveals significant differences from the pigments identified in our study: (1) strontium yellow is absent; (2) cobalt violets were used instead of mixing red and blue paints; and (3) titanium white (production started 1909/10 [47]) is present in three paintings along with zinc white, lead white, barium sulfate and chalk.

The use of synthetic organic pigments in two paintings needs to be further emphasised. PR83 (synthetic alizarin; CI 58000:1) and anthraquinone lake PB52 (CI 63000) were reported in *Rudern*. PR83 is a common SOP and can be considered as part of the standard palette of artists at that time. It has often been reported in various artworks and 20th-century reverse glass paintings [e.g. 7, 9, 48]. PB52 is formed by combining an acidic (Alizarin Saphirol B, CI 63010) and a basic dye (Methylene Blue, CI 52015) [49] and was previously identified in a product palette for artists' colours made by Farbenfabriken vorm. Friedr. Bayer & Co (1924) [50]. No further information on this pigment is available, and to the best of our knowledge only one proof of it in an artwork has been reported so far: Stege et al. found PB52 in the painting *Masken auf der Strasse* (1910) by Ernst L. Kirchner [51]. Its unspectacular greenish blue hue and its limited use in the painting could indicate that this colour was not so important for Kandinsky and that the pigment could be a cheap replacement product for a more expensive inorganic blue. This situation is well known for cinnabar, which was often replaced by PR3 at that time. Moreover, the naphthalene sulfonic acid pigment lake PR60 (CI 16105) was identified in *Apokalyptischer Reiter II*. It was mentioned as a pigment among the *Mussini* resin-oil colours (H. Schmincke & Co. GmbH & Co. KG), where it was used at least until 1922 [48]. It was also found in two *Eilido* colour charts (Pelikan/Wagner) from 1912 and 1926/38, which further indicates its use as artists' colours [52]. PR60 was reported in several paintings by Ernst L. Kirchner between 1913 and 1926 and in a lithographic ink of a printed poster from 1919 [51, 53]. Kandinsky painted large areas of *Apokalyptischer Reiter II* with PR60, revealing a characteristic, intense scarlet red hue (Fig. 4) that is unattainable with inorganic colourants. Hence, in contrast to PB52 (*Rudern*), Kandinsky very probably used PR60 intentionally, and it played a major role in the composition of *Apokalyptischer Reiter II*.

Another important aspect of reverse glass paintings is the use of metal foils (cf. *Rudern*; Fig. 10), as they enhance the gloss and create a glittering effect when the painting is viewed in reflected light. Metal pigments (e.g. fine-grained bronze powder) were also reported in other early paintings by Kandinsky [20]. Moreover, such metal powders and a tin foil were found in some reverse glass paintings by Heinrich Campendonk, who joined the "Blaue Reiter" collective in 1911 [7, 54]. Tin foils were common packaging materials for cigarettes and chocolate bars in the 19th and early 20th centuries [55]. Historical references also recommend tin foils as a backing layer for reverse glass paintings [55, 56]. Kandinsky not only used tin foils, but also, in *Rudern*, glossy and silvery aluminium foils. The first commercial aluminium foil was produced in Switzerland in 1910 and started to replace its more expensive tin counterpart [57]. Its first use in Switzerland and Germany was for wrapping chocolate bars [57].

The presence of cadmium carbonate in two paintings (*Allerheiligen II*, *Rudern*) was proven by DRIFTS (Fig. 9). The measured area of *Rudern* does not seem to show any colour change, whereas the area of *Allerheiligen II* reveals a significant browning (Fig. 5c, spot 4). Cadmium carbonate was reported in early 20th-century paintings by Henri Matisse, James Ensor, Pablo Picasso and Edvard Munch and is often accompanied by other Cd phases like sulfates, oxalates and chlorides [58–64]. Synchrotron-based spectroscopic methods applied on the microscale have allowed researchers to reveal the distribution of various cadmium compounds and confirm that cadmium carbonate can occur as a photo-degradation product of cadmium yellow and as a remnant of the production process [55, 56]. It was not only used as a starting agent for cadmium yellow synthesis [47, 65] but was also added as a lightener to the pigment powder [66]. However, the source of $CdCO_3$ in the study presented here cannot be determined, and further investigations are needed to answer this question. Please note that cadmium carbonate is absent in *Apokalyptischer Reiter II* (Fig. 9a), although Kandinsky used cadmium yellow for the yellow areas. Reasons for this observation cannot be proven with the data available, and the following hypotheses need further investigations to be validated: (1) the paintings are all dated in a narrow timespan of 1911–14, which may be too short to see differences in alteration of the

same substance (i.e. when the preservation conditions have been equal for all paintings); (2) Kandinsky worked with painting materials from different brands and companies throughout his career, hence it is likely that he did not used the same cadmium yellow in 1911 and 1914; (3) it needs also to be considered that one brand may also include the same pigment in different pigment qualities; and (4) other paintings (canvas, watercolour) from the same time should be further investigated to reveal if cadmium carbonate and/or degraded cadmium yellow occur to a larger extent.

Binding media

Barnett [67] described the painting technique of the investigated works of art as tempera (*Auferstehung*), tempera and china ink (*Apokalyptischer Reiter II*) and tempera and oil (*Allerheiligen II*; *Rudern*). It cannot be determined if this classification is based on inspections of the front or of the reverse side. Our visual inspection of the reverse side of the paintings suggests oil-based binders for *Auferstehung*, *Rudern* and *Apokalyptischer Reiter II* rather than tempera, indicated by the slightly pastose, glossy and wet-in-wet application of the paint. China ink can be found in *Allerheiligen II*, *Rudern* and *Apokalyptischer Reiter II* and shows the typical craquelure pattern. *Allerheiligen II* displays differences in the visual appearance of the painted areas ranging from glossy to matt (Fig. 7). This suggests the use of tempera and oil-based paints and confirms the description of Barnett [67].

Kandinsky mentions that he divides his artworks between oil and watercolour paintings, although he states that he also used different materials (tempera, gouache, watercolour, oil) in both categories [68 and references therein]. Personal notes on the binding media systems of his reverse glass paintings are not known, but Roethel [69] mentions that Kandinsky was not yet using glass as a special kind of surface, as the character of brush strokes is in no way different from that used on canvas. Tempera paints can be roughly described as water-thinnable paints (e.g. egg) or as a system with a continuous aqueous phase (e.g. oil in a water emulsion of egg yolk and linseed oil), but the exact definition may vary distinctively for different artists and periods [68]. Around 1900, Kandinsky conducted many experiments with tempera, as several handwritten recipes prove. For all mixtures marked "tempera", he used egg yolk and various water-soluble (e.g. casein, gum arabic) and -insoluble components (e.g. mastic, wax, copal, Canada balsam) [70]. Several of his historical tube paints (tempera and oil paints) are preserved, but many of them cannot be exactly dated [71]. In Germany, the earliest reference to commercially available, tempera-based tube paints dates from the 1870s [68]. Analysis of the binders of nine paints from Kandinsky's Munich palette (1910/11) identified beeswax, drying oil, egg yolk and resins as major and polysaccharides (e.g. gum arabic) as minor components, but all the paints are mixtures with at least two binders [70]. The results suggest that Kandinsky used tube paints, which he modified sometimes by adding other components (mainly beeswax in turpentine) to adjust the texture, drying time and gloss of the paint [70]. The results of the four paintings in our study classify drying oil as the main binder. Only the DRIFT spectrum of the orange area of *Allerheiligen II* gave a hint at the presence of proteins as the water-soluble part of a tempera. The matte appearance (Fig. 7b) further suggests a different binding media system for that specific orange area. Generally, the structure (i.e. brush stroke, pastosity) and gloss of the painted surface do not play an important role for reverse glass paintings. That might be why Kandinsky used mainly oil-based colours for these paintings. Furthermore, oily binders provide the best adhesion properties for the smooth, non-porous glass surface. It is likely that Kandinsky preferred the oily binder to create more durable paintings rather than creating complex paint surfaces with different appearances using tempera mixtures. The four paintings show a good state of preservation, indicating a skilful use of materials.

We want to emphasize that DRIFTS may not be sensitive enough to detect small amounts of other binders, which could be also present in the other paintings. Please note that a mixture of one-part egg yolk and one-part oil (i.e. maximum oil content for egg tempera) would yield a dry paint with ~ 90% lipids and only ~ 10% proteins after evaporation of the water [72]. Furthermore, DRIFTS is restricted to the surface and cannot probe underlying paint layers. Advanced analyses (e.g. GC–MS), including micro-samples, are needed to get more precise information on the binders used in these paintings. Therefore, although it cannot be excluded that some of the studied paints are tempera paints, it seems rather likely that they are indeed oil paints.

Conclusion

The results show clearly the great importance of this technique in Kandinsky's oeuvre, as he not only used it in Murnau between 1909 and 1914, but also continued with it later in Moscow and Paris. Kandinsky presented several of his reverse glass paintings in exhibitions together with paintings on canvas and cardboard (e.g. "Der Blaue Reiter" exhibition, 1911), implying a coequal importance of these techniques [11]. He found inspiration in folkloristic Bavarian reverse glass paintings from the 19th- century and adapted his paintings with their characteristic features like black-painted backboards and painted frames or their stylistic features like two-dimensional areas of unbroken colour, simplification of

the forms, reduction of the colouration and dominance of the line. The use of corrugated glass and cathedral glass, however, could be evidence that Kandinsky wanted to distance himself from the folkloristic tradition of reverse glass painting [20]. The presented analytical results of the four reverse glass paintings reveal a broad palette of materials. Kandinsky painted not only with inorganic pigments, but also with synthetic organic pigments. For the scarlet red pigment PR60 in *Rudern*, a deliberate choice of this specific pigment seems likely, despite that time's ongoing debate on the fastness and stability of coal tar pigments in general. The application of metal foils is a specific feature of reverse glass paintings. The aluminium and tin foils in *Rudern*, which were both used originally as wrapping material, create a glittering effect that can be interpreted as light reflections on the water. Further research on Kandinsky's reverse glass paintings from different periods is needed to compare the palettes and may define certain mixtures as specific for this technique. Moreover, advanced analyses of binding media (e.g. GC–MS), including micro-sampling, would give precise information also on the minor binding media components.

Authors' contributions

SS conducted the measurements and was responsible for most of the writing of the manuscript. SS, HS and OH interpreted the data. DO and GG examined the iconography and the art historical context. SB, LF and IW investigated the painting and glass technique and made the photographs available. GG managed the research project. All authors contributed to the discussion of the results and reviewed the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets used and/or analysed in this study are available from the corresponding author on reasonable request.

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