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Zinc white marker paint in Mondrian's neoplastic paintings

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Abstract

This research provides new insights into the composition of zinc white paints used by Piet Mondrian during his neoplastic period. Nine paintings, dated between 1921 and 1935, were studied, with a focus on three works in the collection of the Fondation Beyeler (Basel, Switzerland)—*Tableau I* (1921–1925), C*omposition with yellow and blue* (1932) and *Composition with double line and blue* (1935)—and on *Lozenge composition with yellow lines* (1933) in Kunstmuseum Den Haag (The Netherlands). Cross sections from other paintings, most of which previously studied by Van Asperen de Boer in the early 1990's, were reexamined as well. The analyses revealed a zinc white paint with aluminum phosphate inclusions (ZW-Al/P). In two of the works, a zinc white paint with aluminum sulphate was also found. The occurrence of aluminum phosphate (or aluminum sulphate) in 1920–1930's paint formulations, and in paintings by Mondrian, has never been reported so far. Likely, the use of this zinc white paint in Mondrian's and other artworks is more widespread than currently known, but it may have been overlooked in similar case studies, since its identification can only be accomplished with detailed scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM–EDX) analysis of cross sections. Mondrian's use of pure 'bright' ZW-Al/P paint is limited to the later paintings (1932–1935) of this study, whereas in the earlier works (1921–1929) it was mostly mixed with lead white, likely conveying a different hue. Both the ZW-Al/P and Zn-Al/S 'marker paints' were also added to yellow, blue or black paint in specific paint layers of the planes and lines, respectively. It was also shown that Mondrian used the same paint on the frames as in the white planes and that the frames were painted while still working on the composition, and not only when he considered the work completed. Indeed, the detection of the zinc white marker paints might help to delineate the chronology of Mondrian's working process in other paintings and may also be important in the interpretation of overpaints in the course of a treatment when removal of certain paint layers is considered.

Keywords Zinc white, Mondrian, Paint, Aluminum phosphate, Aluminum sulphate, Neoplastic

Introduction

The Dutch painter Piet Mondrian (1872–1944) is most famous for his neoplastic paintings. In these abstract compositions 'white' plays a vital role. In the early paintings of these series the 'white' planes are still rather greyish in tone. They become lighter and brighter over the years, but never completely white until the 1930s. In order to give each 'white' rectangle its own hue, Mondrian added very small amounts of blue, red, yellow or black to the white paint and alternated the direction of the parallel brushstrokes in subsequent layers. In that way he tried to establish the perfect balance within the

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composition, together with the coloured fields and black lines. The white planes are optically influenced by the surrounding coloured rectangles and squares, due to complementary contrast [1].

Mondrian used different sorts of white paint over time, in general preferring lead white in his earliest works, then switching to zinc white, which is often preceded by lead white-containing underlayers. The use of titanium dioxide white is generally believed to be limited to his New York period [2, 3].

The aim of this study is to shed light on the composition and use of the zinc white paints that Mondrian used in his neoplastic works.

Piet Mondrian

Piet Mondrian worked in the Netherlands, Paris, London and, finally, in New York. Born in Amersfoort, he studied at the State Academy of Fine Arts in Amsterdam and in a few years he became an established landscape painter. At the end of 1911 he decided to make a new start and moved to Paris. During this first stay (1912–1914) he experimented with the stylistic features of Cubism, introducing a revolutionary idea: the sense of depth and the difference between back- and foreground was abolished. In a few years he evolved from realism, via Cubism, to geometrical abstraction [4, 5]. During the First World War, Mondrian was again in the Netherlands. In these years he continued exploring the possibilities of abstraction with both figurative and non-figurative forms, which resulted in 1917 in the founding of "De Stijl", together with Theo van Doesburg, Bart van der Leck and Gerrit Rietveld, among others. This movement embraced an abstract, pared-down aesthetic, centered in basic visual elements such as geometric forms and primary colors. It was envisioned by its creators as a universal visual language appropriate to the modern era [6].

Upon his return to Paris in 1919, Mondrian concentrated on a wholly non-objective pictorial language, in which he confined himself to arrangements of vertical and horizontal black lines in combination with planes in white and the three primary colors. The artist himself called this style, Neoplasticism and wrote "As a pure representation of the human mind, art will express itself in an aesthetically purified, that is to say, abstract form. The new plastic idea cannot therefore, take the form of a natural or concrete representation—this new plastic idea will ignore the particulars of appearance, that is to say, natural form and colour. On the contrary it should find its expression in the abstraction of form and colour, that is to say, in the straight line and the clearly defined primary colour." [1].

In 1938 Mondrian moved to London, partly due to the imminent threat of the Second World War. When in 1940 he emigrated to New York, he took some of his paintings with him and decided to rework them. These so-called Transatlantic paintings are thus double dated [2]. Other works, such as *Broadway Boogie Woogie* (1942–1943, MoMA, New York) and *Victory Boogie Woogie* (1942–1944, Kunstmuseum Den Haag, The Hague), in which he experimented with coloured lines, are entirely conceived and painted in New York, where Piet Mondrian died on the 1st of February 1944.

Paint brands

During his long career Mondrian made use of a large range of paints, but, unfortunately, there is little known about which brands he purchased and when and where these were employed. In his letters Mondrian rarely wrote about the materials he used nor mentioned the paint manufacturers; and in the photographs taken in his studios (mainly in New York) no paint tubes can be identified [7]. Janssen reports that: "… many painters of De Stijl movement used Rembrandt paint [Royal Talens, The Netherlands]. It seems logical that Mondrian would have used this brand too, and that he would have continued to do so well into the 1920s, until he had finished the tubes he had and was ready to buy more." [1, p. 443].

From 1919 onwards, Mondrian purchased his materials from various suppliers in Paris. César Domela, a Dutch artist who knew Mondrian very well in his Paris period, reported that Mondrian bought his colours at Lefebvre-Foinet. This art supply firm made its own colours which were available in tubes, according to Domela [2, 8]. Around 1928 in fact, Mondrian advised artist Michiel Seuphor to go to Lefebvre-Foinet, from where he himself liked to buy his red paint [9]. On the reverse of many canvases from 1920 to 1931 a stamp of Lefebvre-Foinet or Robinot Frères can be found. In the latter shop Mondrian also might have bought his paints [10].

In 1936 he wrote in a letter to his friend and artist Winnifred Nicholson, who at that moment was in England: "The blue is magnificent and I should very much like it if you would buy a big tube for me and bring it. The colours interest me a lot: that is to say the red, yellow and blue. I am still not altogether happy with those of Foinet and Cambridge. Can you find me also a red and yellow? I prefer it if you bring them, because otherwise perhaps I have to go to the customs"[1] [11]. The colours Mondrian referred to might be Winsor and Newton paint. However, according to Nicholson [12] Cambridge Colours were favoured by Piet Mondrian while working in London:

[1] 'Cambridge' colours were produced by the English manufacturer of artists' paints Madderton & Co and had a high worldwide reputation. They ceased to operate during the Second World War. https://www.npg.org.uk/research/programmes/directory-of-suppliers/.

"Mondrian bought Cambridge colours not because they were less expensive than others, but because he thought that Oxford and so also Cambridge was the most reliable English commodity." [13, 14].

When Mondrian lived and worked in New York he tried to find a good American paint [2]. From a letter he wrote to his close friend Charmion von Wiegand[2] (13 October 1942) it appears that Mondrian certainly did not prefer 'Newton's' [Winsor & Newton], and that he believed Schmincke and Rembrandt are in fact better for some colours [1, 15]. In New York he often bought his paint at Friedrichs, which offered different brands, paying attention that the paint tubes of the same colour had the same series number [2].

Studies of Mondrian's materials and techniques

Recently, all seven Mondrian paintings from the collection of Fondation Beyeler (Basel, Switzerland) were extensively examined during the 'Piet Mondrian Conservation project (2019-2021), which was performed by the museum in close collaboration with the Cultural Heritage Agency of the Netherlands (RCE) [16–23]. This project gave a new momentum to the studies of Mondrian's painting technique and materials, which began in the late 1970's and until now mainly concerned Mondrian's neoplastic period. Previous technical studies, such as the extensive examination of *Victory Boogie Woogie* (1942–1944, Kunstmuseum Den Haag), which was carried out by an international, interdisciplinary team in 2006–2008 [24], as well as Hans Janssen's comprehensive biography on Mondrian [1, 25], were invaluable sources of information, as were the insights that were gained during the Mondrian Conservation Project (2009–2017) at Kunstmuseum Den Haag (previously known as Gemeentemuseum).[3]

These projects built on the work of others of which Ron Spronk gives a comprehensive overview [26]. Spronk discusses the early studies carried out by Carmean and Leisher in 1979 on the occasion of the exhibition of Mondrian's diamond-shaped paintings [27], and also refers to the work of Van Asperen de Boer, who was the first to perform technical analyses on ten European works that were painted between 1917 and 1933 [28]. Spronk and his team also carried out technical examination of five of Mondrian's Transatlantic paintings. The results of this study were published in the catalogue accompanying the exhibition of these important works [2]. Two other conservation projects also involved detailed technical examination. In 2011, five early abstract paintings from the collection of the Stedelijk Museum in Amsterdam were examined and analysed in collaboration with the Cultural Heritage Agency of the Netherlands [9]. Other in-depth technical studies were done on the collection of Mondrian paintings at the MoMA [5, 29–33], including *Broadway Boogie Woogie* [34].

More recent research focused on specific degradation phenomena in Mondrian paintings, such as delamination caused by zinc soap formation [35, 36], and instability of cadmium yellow paints [37, 38].

In 'The working methods of Piet Mondriaan', Pien van der Werf makes an important remark: "as long as it was in his studio he kept working on it" [39]. This observation is illustrated by the paint built-up in the rectangles and squares, where the sequence of paint layers reveals how Mondrian was constantly trying to find the 'right' balance between the planes. He also frequently adjusted the positioning of the black lines and, if necessary, even scraped away the paint in the adjacent planes to enable the changes [16, 18, 24, 28, 35].

Mondrian also regularly touched up his paintings when they returned from exhibitions. In a series of letters from 1927, for example, Mondrian mentioned that he had to repair a group of twenty paintings that had been damaged during a show at 'De Klomp' in Paris [25]. Seuphor recalls that "sometimes a painting would come back with fingerprints along the edges from handling. When this happened Mondrian would repaint the whole picture rather than trying to clean it" [2, p. 78]. Moreover, Nicholson reports on an incident with ink in a yellow field after which the painting in question was 'restored' by the artist himself: "… he had finally cleaned it off with sand paper himself and would soon finish the job by adding new coats" [40, p. 98].

Mondrian's white paints

Mondrian certainly started to use zinc white paint around 1917. In that year in a letter to his friend and painter Henk Bremmer he wrote: "Unfortunately here and there the white background has cracked, due to the extensive searching but also because the white wouldn't dry with the cold and the impossibility to sufficiently

[2] Charmion von Wiegand (1896–1983) was an American journalist, critic and painter. She was a very close friend of Mondrian during his stay in New York; she interviewed him, wrote about his art and helped him to translate his essays into English. She regularly watched Mondrian work in his studio [15].

[3] Gemeentemuseum Den Haag, Mondriaan restauratieproject, Restauratie van een wereldcollectie, Den Haag 2017.

stoke; maybe also because for the first time I took zinc white instead of Cremnitz white."[4] [10, p. 256].

Zinc white is used in oil paint from the mid-nineteenth century up to now. It is appreciated for its brightness, as compared to lead white. However, it has a lower covering power, requires longer drying time and yields a more brittle paint, especially if used pure [41]. Various degradation phenomena are indeed related to the use of zinc white and numerous studies have been devoted to the formation of zinc soaps. The amorphous or crystalline zinc carboxylates may cause delamination [35, 36, 42, 43].

Based on the examination of paintings from 1917 to 1921, Van Asperen de Boer reports that Mondrian's whites were typically built up in two or three layers, with a surface layer containing zinc white painted over one or two lower layers with lead white. Mixtures of the two pigments were presumed to be likely, but could not be ascertained. He also states that "As yet, no scientific data from paintings of between 1917 and 1920 is available, in this respect, but it is not impossible that Mondriaan only gradually achieved a two-layer structure with lead white in the bottom layer and zinc white (whether or not mixed with lead white) in the top layer." [28].

In the literature, the use of both lead white and zinc white is reported for various paintings dated between 1920 and 1937,[5] as well as for several Transatlantic paintings.[6] Spronk [2] describes that in these paintings a lower, lead white-containing layer was found, which was often mixed with a small portion of zinc white, whereas additions of other pigments were identified in the surface layers. On one occasion lead white with some zinc white was found to be present as a surface layer, while titanium white mixed with blanc fixe and some zinc white was found in *Picture no. II* (1936–43, Moderna Museet, Stockholm, no. NM 6080) [2]. The white paints that Mondrian applied in New York are usually relatively X-ray transparent, indicating that he rarely used lead white in that period. Mondrian was obviously searching for a good white, but the war caused shortages in materials. Charmion von Wiegand noted in her diary entry for September 17, 1941, that the "cream paint was all cracked" in *Boogie Woogie*: "I thought he should remove all that bad paint before painting it over-he had bought Permalba. 'I must find a good American white' he said. 'Holtzman said that this too was titanium.' It seems that most all the supply of Winsor Newton paint is now exhausted in NY." [15].

Broadway Boogie Woogie (1942–1943, MoMA) was examined with different techniques [29], including a combination of macro XRF mapping and multivariate image analysis [34]. A titanium oxide/barium sulfate composite pigment mixed with some zinc white and barytes was found. These pigments are likely related to Permalba White. Between 1921 and 1944 this paint contained different types of titanium dioxide composite pigments [44, 45]. Laver describes Titanox A as an anatase titanium white and Titanox B as a composite of anatase (25%) and barium sulfate [48].

Finally, during the in-depth technical study of *Victory Boogie Woogie* (1942–1944, Kunstmuseum Den Haag) it was discovered that Mondrian used two, or possibly even three, different types of white paint for the white squares: anatase with two different concentrations of blanc fixe and zinc white, and maybe also a rather pure zinc white. It was hypothesized that the latter paint might have been applied by Mondrian himself in a later phase, but only locally; however, the occurrence of zinc white retouches could be not excluded, based on the fluorescence behaviour and on the fact that Van Asperen de Boer had not found pure zinc white in his investigations [3]. As in *Broadway Boogie Woogie*, the anatase-zinc white-barium sulfate paint in *Victory Boogie Woogie* has been related to Weber's Permalba white.

Aim and methodology of this study

The aim of this study is to gain insight into the zinc white paints used by Mondrian in his neoplastic period. The examination of a series of paintings, dated between 1921 and 1935, is presented, with a focus on three paintings in the collection of the Fondation Beyeler in Basel: *Tableau I* (1921–1925), C*omposition with yellow and blue* (1932) and *Composition with double line and blue* (1935). These paintings were first studied with non-invasive techniques

[4] De witte fond is helaas hier en daar gebarsten, door 't vele zoeken maar ook omdat het wit niet drogen wilde met de koude en men niet voldoende stoken kon; misschien ook omdat ik voor 't eerst zinkwit in plaats van Cremswit nam.

[5] *Composition C* (257.48, 1920, MoMA) [30], *Tableau No. IV* (1924/25, National Gallery of Art, Washington) [Restoration report National Gallery of Art, Washington], *Composition with red, yellow and blue* (1927, A1931, Stedelijk Museum Amsterdam) [9], *Composition with red, blue and yellow* (1929, A9916, Stedelijk Museum Amsterdam) [9], *Composition with yellow* (1930, Kunstsammlung Nordrhein-Westfalen, Düsseldorf) and *Composition with blue and white* (1934/1936, Kunstsammlung Nordrhein-Westfalen, Düsseldorf) [47], *Composition in yellow, blue and white* (1937, 637.67, MoMA) [2, 33, 46].

[6] *Composition No. 12 with Blue* (1937-42, no. 15911, National Gallery of Canada, Ottawa) [2, 26], *Composition (with Red and Blue?)/No.7* (1937-42, no. 54.7, Munson-Williams-Proctor Insitute Museum of Art, Utica NY) p. 162 [2], *Composition with blue, red and yellow* (1937/1942 Kunnstsammlung Nordrhein-Westfalen, Düsseldorf) [47], *Composition with yellow, blue and red* (1937-42, T00648, Tate) [https://www.tate.org.uk/art/artworks/mondrian-composition-with-yellow-blue-and-redt00648], *Composition with yellow and red* (1938-42, B287/316, no. 1374, The Philips Collection Washington) [2], Composition with yellow, blue and red (1939-42, B279/308, no. T648, Tate Gallery London) [2].

Table 1 Investigated paintings by Piet Mondrian

Label in Fig. 1	Inv. no.	Title	Collection[a]	Dating	Dimensions (H x W in cm)	NDT[b]	No. of samples	Techniques
a	94.3	*Tableau I*	FBB	1921–1925	75.5 × 65.5	x	2	OM, SEM, FTIR, Raman
b	0333163	*Composition with red, black, yellow, blue and grey*	KMDH	1921	80.0 × 50.0	–	1	OM, SEM
c	0334328	*Composition with red, blue, black, yellow and grey*	KMDH	1921	39.5 × 35.0	–	2	OM, SEM
d	0334327	*Tableau I*	KMDH	1921	103.0 × 100.0	–	2	OM, SEM
e	O00201	*Composition I*	MoMAK	1929	40.5 × 32.5	–	4	OM, SEM
f	1542MK	*Composition II*	MBvB	1929	52.0 × 52.0	–	2	OM, SEM
g	78.3	*Composition with yellow and blue*	FBB	1932	55.5 × 55.5	x	4	OM, SEM, FTIR, Raman
h	0332044	*Lozenge composition with yellow lines*	KMDH	1933	80.2 × 79.9	–	3	OM, SEM, FTIR
i	90.12	*Composition with double line and blue*	FBB	1935	72.5 × 70.0	x	3	OM, SEM, FTIR, Raman

[a] FBB: Fondation Beyeler (Basel, Switserland); KMDH: Kunstmuseum Den Haag (The Hague, The Netherlands); MoMAK: The National Museum of Modern Art, Kyoto (Kyoto, Japan); MBvB: Museum Boijmans van Beuningen (Rotterdam, The Netherlands); [b]NDT (non-destructive techniques): pXRF/pRaman

(portable X-ray fluorescence and Raman spectroscopy). Then, samples were taken in order to gather more detailed information on the build-up and composition of the paint layers. Optical microscopy (OM), scanning electron microscopy with energy dispersive spectroscopy (SEM–EDX), Fourier transform infrared spectroscopy and micro-Raman spectroscopy were used. These results were compared with previous research data regarding *Lozenge composition with yellow lines* (1933, Kunstmuseum Den Haag) [49] and with the outcomes of the reexamination of cross sections from other paintings in the same collection and from a work of the Kyoto Museum of Modern Art. Those samples were taken and previously studied by Van Asperen de Boer in the early 1990's [28]. The white paint of *Composition II* (1929, Museum Boijmans van Beuningen) was studied as well.

All investigated paintings are listed in Table 1 and their images are reported in Fig. 1. The analytical techniques that were used are specified. The sampling areas are indicated in the Additional file 1.

Materials and methods

Corpus of paintings

Nine paintings were studied (Table 1 and Fig. 1). Information on the three paintings in the collection of Kunstmuseum Den Haag dated 1921 (Fig. 1b–d) is given in the Additional file 1. The other six paintings are briefly discussed in this section.

Tableau I (1921–1925, inv. 94.3, Fondation Beyeler) (Fig. 1a) is a key work in the development of the neoplastic style in the 1920s. Its present-day appearance is the result of a reworking of the painting by Mondrian in 1925. It bears the double date of 1921 and 1925, written as "21–25", next to the signature (the initials "PM"). Mondrian did not mean to indicate that the picture had taken shape over a prolonged, continuous period. On the contrary, he wanted to emphasize that the painting had been worked on two times and considered it finished twice, with a gap between the two phases, and hence a break in terms of time and style.

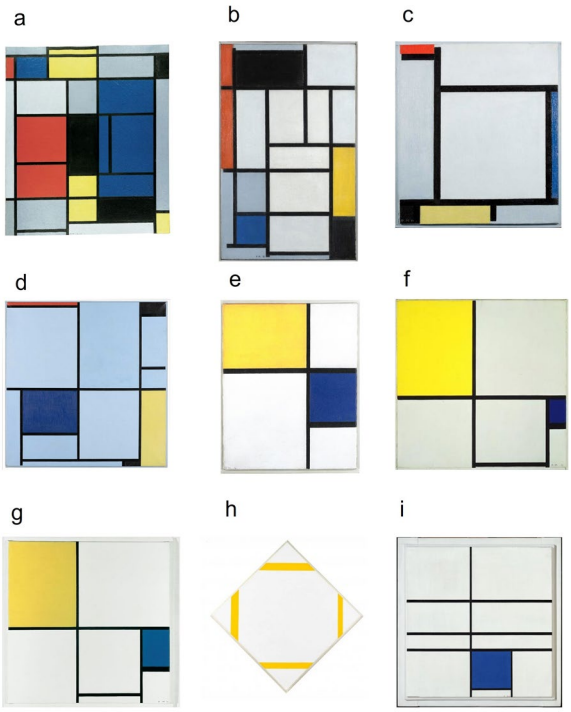

Fig. 1 Images (not in scale) of the paintings by Piet Mondrian that were investigated (see details in Table 1)

Surprisingly, recent investigation with infrared reflectography evidenced that, lying beneath the signature visible today, is an earlier one, of which the lettering "PM '2" can be clearly made out (Fig. 2). Unfortunately, it was not possible to reveal the important second digit after the two. This discovery nevertheless provides valuable clues: *Tableau I* was dated three times and thus considered finished three times by Mondrian. The dates are all likely related to its exhibition history, since Mondrian signed his works only when they were to go on show or be put up for sale [1]. Mondrian added the date of 1925 to *Tableau I*, as well as to three other pictures, after he had reworked these for the exhibition 'Mondrian, Man Ray', held in September 1925 at Kunsthandlung Kühl und Kühn in Dresden [50].

Composition no. I (*Composition with yellow and blue,* 1929, inv. O00201, The National Museum of Modern Art, Kyoto) (Fig. 1e) was previously studied by Van Asperen and Langendijk, while it was part of the private collection Paul Arthur Müller-Lehning, Amsterdam [51].

Composition II came in the collection of the Museum Boijmans van Beuningen as a gift of the artist's friends (1542MK, 1929) (Fig. 1f). It has been relined and put on a new stretcher. This painting has a very similar composition as *Composition with yellow and blue* (1932, Fondation Beyeler).

Composition with yellow and blue (1932, inv. 78.3, Fondation Beyeler) (Fig. 1g) was painted in Paris. It was owned by G. Wallbrink-Oud (Haarlem, The Netherlands) and until the 1970s remained in the ownership of the family. The painting was wax-lined and treated, probably in the 1970s. The original frame and subframe construction were overpainted in this process. In 1978 the painting was acquired by Ernst and Hildy Beyeler.

Lozenge composition with yellow lines (1933, inv. 0332044, Kunstmuseum Den Haag) (Fig. 1h) had been given in 1933 to the Municipality of The Hague by Charley Toorop and a group of artist friends on the occasion of Mondrian's 60th birthday. In 1935 the work was exhibited at the Gemeentemuseum Den Haag (now Kunstmuseum Den Haag) when the new building was opened. Possibly, Mondrian reworked the white planes between 1933 and 1935.

Piet Mondrian painted *Composition with double line and blue* (1935, inv. 90.12, Fondation Beyeler) (Fig. 1i) in Paris. It was directly sold to George Lovett Kingsland Morris, but changed different ownerships before it was bought by Ernst and Hildy Beyeler in 1990. The painting is in a very authentic condition. The original mounting has not been removed since its completion and it still shows the originally applied subframe and strip frame.

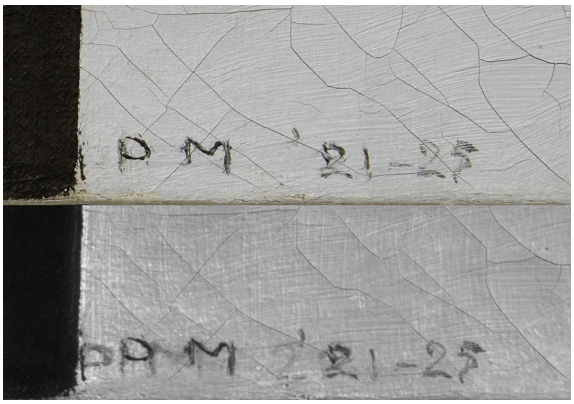

Fig. 2 Detailed images of the dating of *Tableau I* (1921–1925, FBB) in visible light (top) and infrared reflectography (bottom)

Samples

Twenty-three samples were studied. Cross sections from various paintings in the collection of Kunstmuseum Den Haag and one in the Kyoto Museum of Modern Art were available for reexamination (Archive of the Netherlands Institute for Art History (RKD) and Kunstmuseum Den Haag). These samples were taken, embedded and studied by Van Asperen de Boer in the early 1990's [28, 50], whereas samples from *Lozenge Composition with yellow lines* were previously examined by one of the authors in 2015 [49].

Recently, various samples were taken from *Tableau I* (1921–1925), *Composition with yellow and blue* (1932) and *Composition with double line and blue* (1935) in the collection of Fondation Beyeler (Basel), and from *Composition II* (1929, Museum Boijmans van Beuningen).

All samples were studied with OM and SEM–EDX, and some also with FTIR and micro-Raman spectroscopy (see Table 1). The sampling areas are indicated in the Additional file 1.

Analytical techniques

Portable X-Ray fluorescence (pXRF) spectroscopy

Analyses of the three paintings in the collection of Fondation Beyeler were performed with a portable Bruker Tracer 5i X-Ray fluorescence spectrometer, that is equipped with a low power Rhodium X-ray tube and a Silicon-Drift energy dispersive X-ray detector. The measurements were carried out in the spectrometer mode, using a 3 mm collimator, a tube voltage of 15 kV or 40 kV (to bring out better light and heavy elements, respectively) and a current of 6 μA. The acquisition time was 200 and 60 s.

Portable Raman (pRaman) spectroscopy

The handheld Raman measurements of the three paintings in the collection of Fondation Beyeler were conducted with a Bravo Spectrometer (Bruker). The device works with two excitation wavelengths, recording spectra in two separate spectral ranges of 300–2200 and of 1200–3200 cm^{-1} with a DUO Laser system (785 nm and 853 nm). The near infrared lasers (NIR) aid in reducing fluorescence. Furthermore, using two lasers enables to obtain better quality data in the overlap region of 1200–2200 cm^{-1} and lowers fluorescence interference. The energy at the paint surface is about 45 mW, conducting measurements at a distance of about half a millimeter with a spot size of 1 mm.

Optical microscopy (OM)

All cross sections were examined using a Zeiss AxioImager A2m optical microscope with incident polarized light from a VIS-LED lamp for bright field and dark field illumination, and incident UV light from the Solid-State Light Source Colibri 7, type RGB-UV, LED 'UV' (385 nm) for UV-induced fluorescence. The filter set used for UV fluorescence consists of these filters: excitation G 365, beam splitter FT 395, and emission LP 420 (filter set 02).

Scanning electron microscopy with energy dispersive X-ray analysis (SEM–EDX)

SEM–EDX analysis of the cross sections was performed using a Jeol JSM 5910 LV SEM with a Thermo Scientific SDD EDX detector. The primary electron beam energy used was 20 kV. The cross sections were examined in the low vacuum mode (30 Pa).

Micro-Raman spectroscopy

The micro-Raman spectra of some spots in the cross sections were obtained with a Perkin-Elmer Raman Micro 300 (Raman microscope) and a Raman Station 400F (Raman spectrometer) with a diode laser ($\lambda_0 = 785$ nm), in combination with a Olympus BX51M microscope. Exposure time, laser power and accumulations were selected for each measurement to obtain optimal spectra. The laser spot has a diameter of ca. 20 µm (50× objective) or 10 µm (100× objective) and the laser power (10–100%) varies in the range of 7–70 mW (50× objective) and 4–40 mW (100× objective) with a 600 lines/mm grating. Raman scattering is filtered with a double holographic notch filter system and is detected with an air-cooled charge coupled device (CCD) detector.

FTIR spectroscopy

A Perkin Elmer Spectrum 100 FTIR—Spectrum Spotlight 400 FTIR microscope was used. Attenuated total reflection Fourier transform infrared (ATR-FTIR) measurements of the inclusions in the zinc white paint were carried out with a Perkin Elmer ATR imaging accessory; FTIR transmission spectra were acquired with a Miniature Diamond Anvil Cell.

Results

Zinc white paint with aluminum phosphate

Composition with yellow and blue (1932, Fondation Beyeler) (Fig. 1g) was first analysed with XRF spectroscopy. This indicated the extensive use of zinc white in the white areas, and the presence of lead in the lower layers. It could also be verified that Mondrian applied extra layers of paint excluding the edges of the squares near the black lines [9, 24].

The occurrence of lead white and zinc white is confirmed by the cross sections. Sample 78.3-X3, taken at the edge of a white rectangle in the lower part of the painting, shows five white layers (Fig. 3). The first (layer

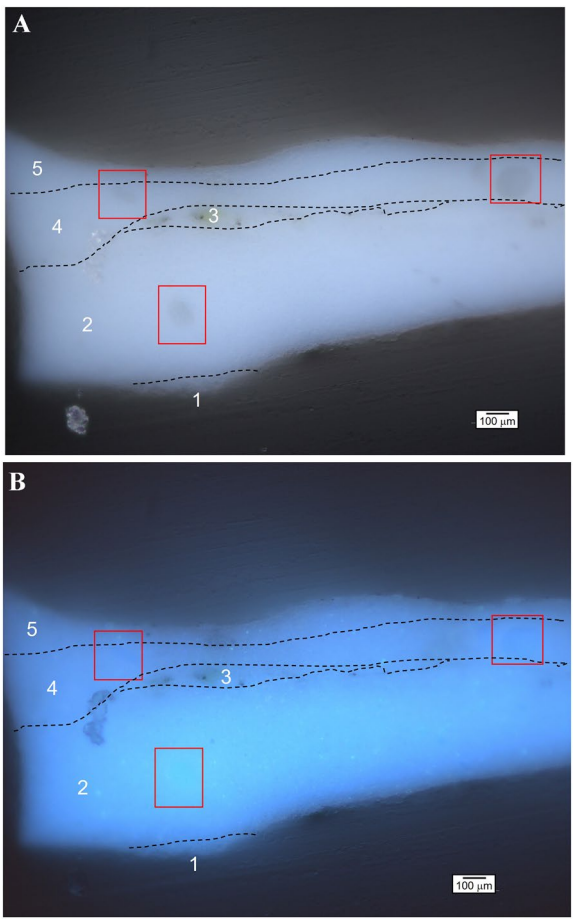

Fig. 3 Cross section of sample 78.3-X3 from *Composition with yellow and blue*. **a** Incident polarised light; **b** UV induced fluorescence. The following layers can be observed. 1: zinc white and lead white; 2–3 and 5: zinc white with aluminum phosphate (ZW-Al/P); 4: zinc white containing sparse lead white particles. Three aluminum phosphate inclusions are evidenced with a red rectangle

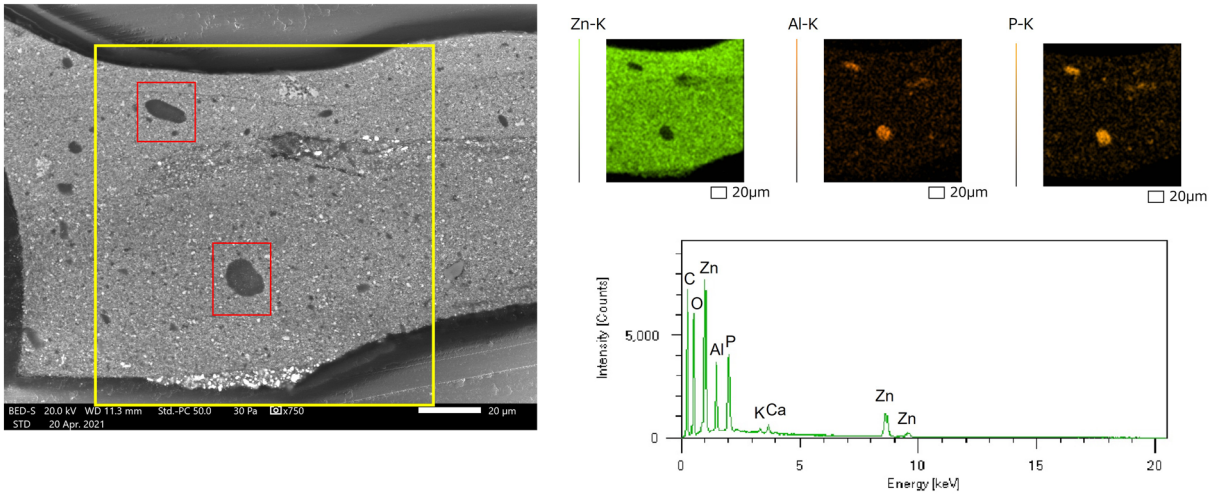

Fig. 4 SEM–EDX analysis of the cross section of sample 78.3-X3 from *Composition with yellow and blue*. Elemental mapping (zinc Zn, aluminum Al and phosphorous P) of a detail and EDX spectrum of one of the aluminum phosphate inclusions. Two aluminum phosphate inclusions are evidenced with a red rectangle

1) is the ground layer and is composed of a mixture of zinc white and lead white. Then, four paint layers are observed (layers 2–5). In layers 2, 3 and 5, a very specific type of zinc white paint was identified. It contains large and small rounded semi-transparent inclusions, showing a light blue fluorescence in UV and appearing dark grey in the SEM-BEI (Figs. 3, 4). The EDX spectra present distinct features with equally intense peaks of aluminum (Al) and phosphorous (P), as well as small amounts of potassium (K) and calcium (Ca) (Fig. 4). The composition of these inclusions is rather constant and characteristic. ATR-FTIR spectroscopy confirmed the occurrence of phosphates (Fig. 5). The broad band at around 1040 cm^{-1} suggests an amorphous or low-crystalline state. Between two of the zinc white paint layers a discontinuous paint layer with zinc white and lead white particles (layer 4) was found. The interpretation of this layer is not clear because it is only partially present.

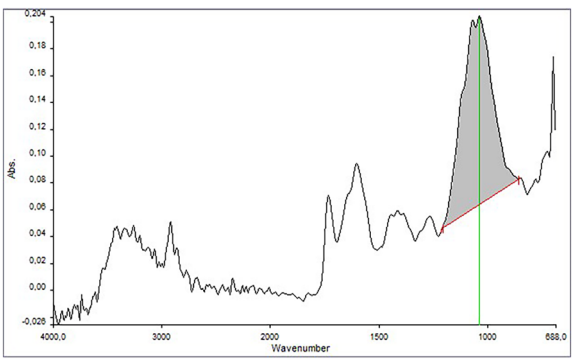

Fig. 5 FTIR spectrum of one of the aluminum phosphate inclusions in the cross section of sample 78.3-X3 from *Composition with yellow and blue*

Zinc white paint with aluminum sulphate

Composition with double line and blue (1935, Fondation Beyeler) (Fig. 1i) was first examined with XRF spectroscopy. In all the spectra of the white planes mainly zinc, but also some lead was found in the lower layers. The cross sections of the white areas of this painting reveal a more complex layering as compared with *Composition with yellow and blue*: similarly, a few layers of zinc white/lead white paint precede the ZW-Al/P paint layers; however, a different type of zinc white paint was found on top. This paint contains zinc white with aluminum-sulphur inclusions (ZW-Al/S), which can likely be ascribed to aluminum sulphate. The ATR-FTIR spectrum presents bands which are compatible with this material (data

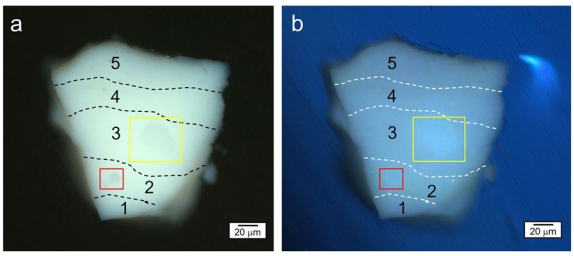

Fig. 6 Cross section of sample 90.12-X5 from *Composition with double line and blue*. **a** Incident polarised light; **b** UV induced fluorescence. The following layers can be observed. 1–2: ZW-Al/P; 3–5: ZW-Al/S. An aluminum phosphate and an aluminum sulphate inclusion are evidenced with a red and yellow rectangle, respectively

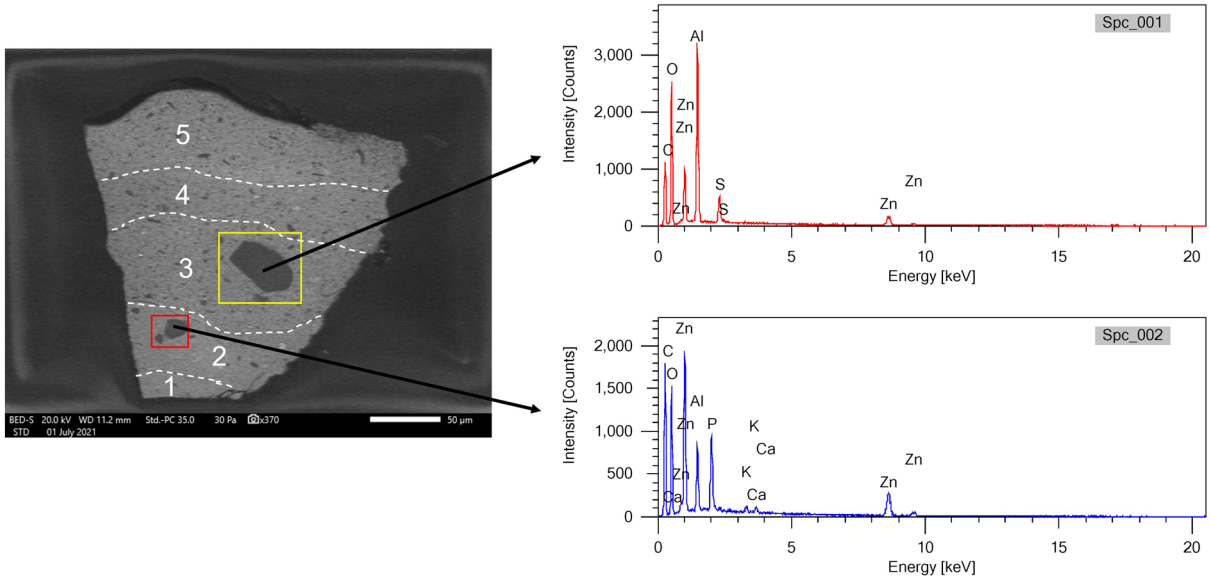

Fig. 7 SEM–EDX analysis of the cross section of sample 90.12-X5 from *Composition with double line and blue*. EDX spectra of an aluminum phosphate and an aluminum sulphate inclusion

not shown). Both the aluminum phosphate and aluminum sulphate inclusions show a bluish fluorescence in UV and appear dark grey in the SEM-BE image. The Raman spectra that were acquired with a portable instrument on the white planes show spectra with a peak at ca. 979 cm^{-1}, which might be related to aluminum sulphate.

The number of layers of the two types of zinc white paint seems to vary. In one white rectangle (sample 90.12-X4, data not shown) only one layer of each type (ZW-Al/P and ZW-Al/S) is present, whereas in another white plane (sample 90.12-X5) (Figs. 6, 7), respectively, two (layers 1–2) and three (layers 3–5) layers were detected.

FTIR spectroscopy evidenced the presence of amorphous and crystalline zinc carboxylates in the white paint layers in the cross sections.

Working phases

In some instances the presence or not of the ZW-Al/P and ZW-Al/S marker paint can provide information on the working phases.

In 2015 four samples of *Lozenge composition with yellow lines* (1933, Kunstmuseum Den Haag) (Fig. 1h) were taken in order to study the composition and buildup of the white planes and yellow lines, with a focus on the extensive overpainting of both the painting and the frame. A cross section (A370/2) that had previously been prepared and investigated by Van Asperen de Boer was reexamined as well. In the study carried out in 2015, the occurrence of zinc white paint with aluminum phosphate inclusions was ascertained, but no comparative data were available at that time [49].

The reworking Mondrian did between 1933 and 1935 (see "Corpus of paintings" section) seems to be confirmed by studying two cross sections (A370/2 and 0332044/3) from the white plane (Figs. 8, 9). On a lead white ground containing small amounts of yellow ochre and black pigment, Mondrian applied four paint layers with a similar composition, which are based on lead white and some ZW-Al/P (layers 2a–d). These layers are followed by two layers of pure ZW-Al/P paint (layers 3a–b). In the cross section taken from the upper edge (0332044/3) (Fig. 9), it can be observed that layer 3a penetrates to the bottom along layers 2a–d and the ground layer; on the right side of the sample a residue of a lead white/ZW-Al/P (layer 2d) is visible. This means that the pure ZW-Al/P paint was applied, most likely by Mondrian himself, after the formation of ageing cracks. Furthermore, in layers 3a–b zinc carboxylates were detected with ATR-FTIR imaging. These may have formed by reaction of the pigment and free fatty acids of the oil, or could be attributed to zinc stearate, which was sometimes added by paint manufacturers to enhance the pigment dispersion in oil. Indeed, some cracking (horizontal and vertical) can be observed in layers 3a–b. Later, to mask these cracks and even out the surface, overpaints were applied, most likely *not* by Mondrian himself (layer 4 and 5 in cross section

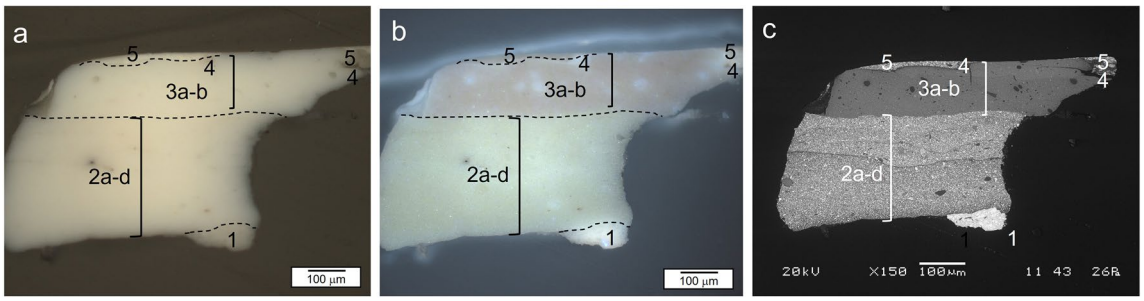

Fig. 8 Cross section of sample A370/2 from *Lozenge composition with yellow lines*. **a** Incident polarised light; **b** UV induced fluorescence; **c** SEM-BEI. The following layers can be observed. 1: lead white ground with some yellow ochre and black pigment; 2a–d: lead white and some ZW-Al/P; 3a–b: ZW-Al/P paint; 4: barium sulphate, calcium carbonate, (alumino)silicates and likely zinc white; 5: lead white and titanium dioxide

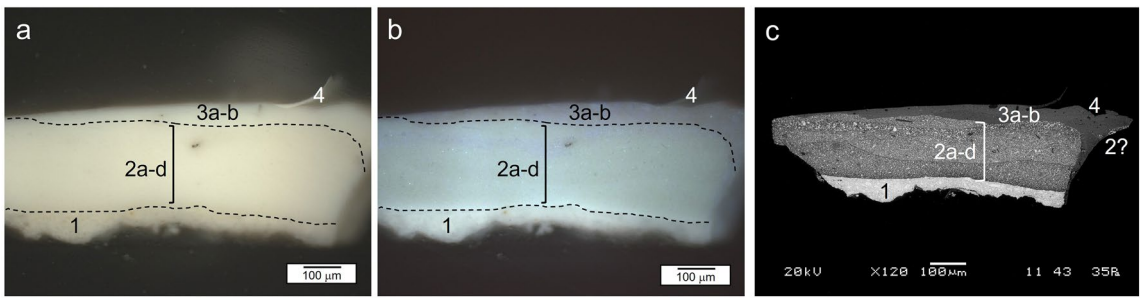

Fig. 9 Cross section of sample 0332044/3 from *Lozenge composition with yellow lines*. **a** Incident polarised light; **b** UV induced fluorescence; **c** SEM-BEI. The following layers can be observed. 1: lead white ground with some yellow ochre and black pigment; 2a–d: lead white and some ZW-Al/P; 3a–b: ZW-Al/P paint; 4: titanium dioxide and zinc white

A370/2).[7] The other cross section shows a thin layer of titanium dioxide/zinc white overpaint (layer 4 in sample 0332044/3) (Fig. 9).

By investigating *Tableau I* (1921–1925, Fondation Beyeler) (Fig. 1a) with the microscope, and by comparing its current appearance with the X-ray photograph, it became clear that Mondrian had made a number of changes to the black lines and to the coloured rectangles. At least two earlier layers of paint lie beneath almost every rectangle, some of them a very different colour to the present composition (see "Corpus of paintings" section).

This is illustrated by a sample taken at the upper edge on the left side of the painting (sample 94.3-X2, Fig. 10). Here, a complex buildup of ten layers was found. On a very thin chalk ground (layer 1), two blue paint layers (layers 2 and 3) were applied. Both contain lead white and ZW-Al/P paint, mixed with Prussian blue and cobalt blue. The field is now appearing grey and, indeed, the following layers are all greyish or slightly bluish. The lowest grey layer (layer 4) shows a mixture of lead white and ZW-Al/P paint, with some quartz, very fine black pigment, ultramarine and maybe some cobalt blue. The ZW-Al/P inclusions are clearly observed here. The second grey layer (layer 5) is based on very small black pigment particles with lead white, coarse and fine, calcium carbonate, and some zinc white. Then, two light-blue coloured paint layers (layers 6 and 7) are observed, both containing very fine ultramarine, lead white and zinc white. A second ground layer (layer 8) contains rather coarse barium sulfate particles with lead white, zinc white and chalk, followed by a thin blue paint layer (layer 9) with ultramarine and zinc white. The uppermost layer (layer 10) is based on ultramarine, gypsum, chalk, lead white and zinc white. The ZW-Al/P paint is present in the first four layers. Maybe these (layers 1–4) could be related to the first phase (1921?), layers 5–7 to the second phase (1921?), whereas in 1925 Mondrian might have applied a 'new ground' and the upper bluish paint layers (layers 8–10). ZW-Al/P paint was also detected in the second cadmium yellow paint layer of one of the yellow squares (sample 94.3-X1, data not shown), indicating that this painting phase was likely related to the first working phase of the previously described grey rectangle.

[7] Conservation report where it is mentioned that Minderman (restorer) has repared the white background. Archive Kunstmuseum Den Haag.

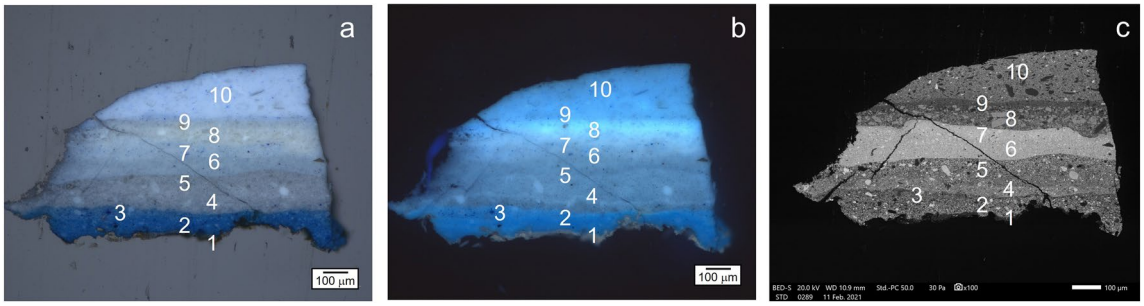

Fig. 10 Cross section of sample 94.3-X2 from *Tableau I* (1921–1925, FBB). **a** Incident polarised light; **b** UV induced fluorescence; **c** SEM-BEI. The following layers can be observed. 1: chalk ground; 2–3: blue paint layers with lead white and ZW-Al/P, Prussian blue and cobalt blue; 4: lead white, ZW-Al/P, some quartz, very fine black pigment, ultramarine and maybe cobalt blue; 5: very small black pigment particles, lead white, calcium carbonate, and some zinc white; 6–7: light-blue paint layers with very fine ultramarine, lead white and zinc white; 8: second ground layer with coarse barium sulfate, lead white, zinc white and chalk; 9: blue paint layer with ultramarine and zinc white; 10: ultramarine, gypsum, chalk, lead white and zinc white

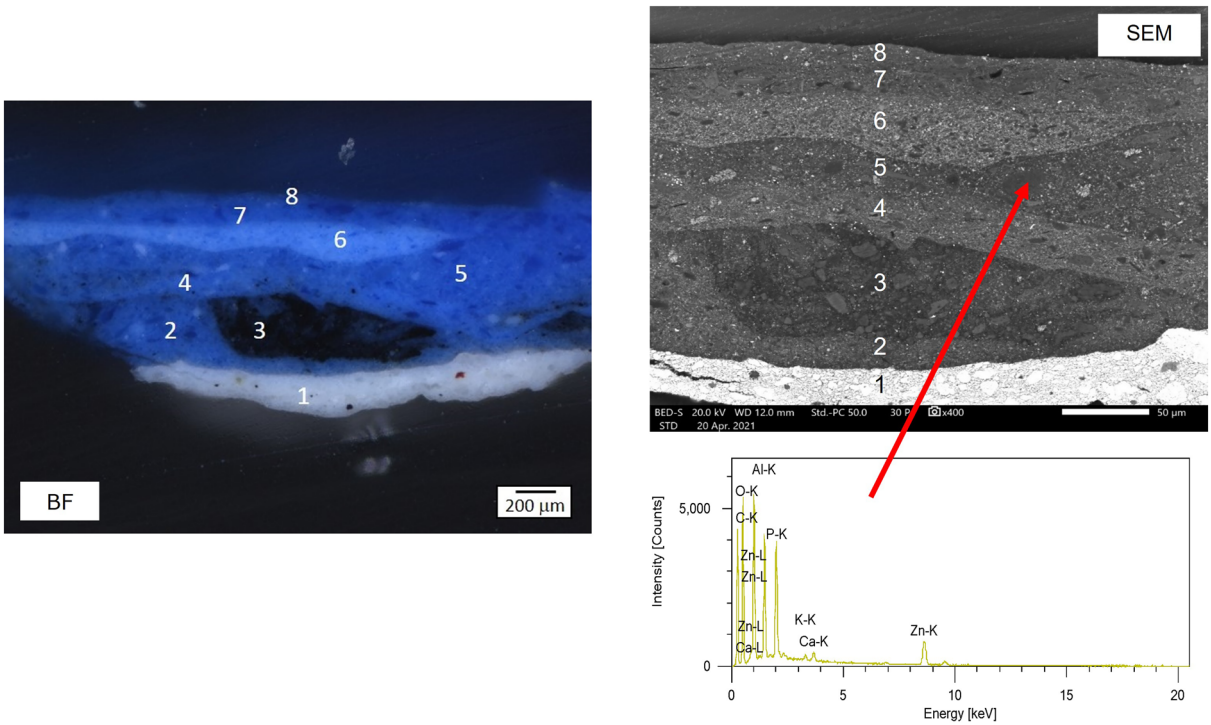

Fig. 11 Cross section of sample 78.3-X2 from *Composition with yellow and blue* in bright field (BF) incident polarised light and SEM-BEI. The EDX spectrum of a large aluminum phosphate inclusion is reported. The following layers can be observed. 1: white layer containing lead white with some zinc white and aluminum (hydroxide) and black and yellowish earth pigment particles; 2, 4–8: six blue paint layers with cobalt blue, zinc white and ultramarine (except for layer 8 regarding ultramarine); 3: discontinuous black paint layer from the black line, based on bone black. In paint layer 5 roundish inclusions with Al, P and low amounts of Ca and K were detected (EDX spectrum)

In any case, the changing colors of *Tableau I* correspond to the evolution taking place in Piet Mondrian's palette, as the artist moved away from the mixed tones found in his work up till around 1920/21, and towards increasingly pure primary colors.

Mixing with other paints

As also shown in the "Working phases" section, the characteristic ZW-Al/P paint was also mixed with other white or coloured paints. This is confirmed by other findings.

For instance, in *Composition with yellow and blue*, in the blue square (sample 78.3-X2, Fig. 11), six blue

paint layers were found on top of a white layer comprising mainly lead white with small amounts of zinc white (likely the ground layer). All blue layers contain cobalt blue, zinc white and ultramarine, except for the upper layer where no ultramarine was found. Due to the extensive use of cobalt blue, yielding ED spectra with peaks of Al, cobalt (Co) and P, the detection of zinc white paint containing aluminum phosphate is not easy. The original cobalt blue (Thénard blue) was made by the heating of cobaltphosphate and alumina [52, 53]. However, in one of the paint layers roundish inclusions with Al, P and low amounts of Ca and K could be clearly distinguished, indicating that here the specific ZW-Al/P paint was mixed with the blue paint. In the other paint layers—except for the upper two—the amount of phosphorous seems somewhat high to be only ascribed to cobalt blue, so the use of ZW-Al/P paint cannot be excluded. Mondrian also used the ZW-Al/P paint in mixture with cadmium yellow in a light yellow paint layer (the fifth yellow layer out of six) in the yellow square (sample 78.3-X9, data not shown).

A mixture of ZW-Al/P and cadmium yellow was also ascertained in the yellow lines of *Lozenge composition with yellow lines* (sample 0332044/2, data not shown).

In *Composition with double line and blue* both types of zinc white paint (ZW-Al/P and ZW-Al/S) have likely been mixed with other colours. Specifically, fluorescent Al/S inclusions could clearly be detected in two of the black paint layers of a black line (data not shown), indicating that at a certain point in the working process Mondrian mixed the Zn-Al/S paint with bone black paint; likely in the same phase when he applied this paint on the white planes.

After having found the ZW-Al/P paint in the paintings in the collection of Fondation Beyeler and in *Lozenge composition with yellow lines*, it was decided to verify whether Mondrian had used it in other paintings as well. Therefore, samples from *Composition II* (1929, Museum Boijmans van Beuningen), as well as the existing cross sections of paintings in the collection of Kunstmuseum Den Haag (dated 1921) and the Kyoto Museum of Modern Art (*Composition no. I*, 1929), previously prepared and analysed by Van Asperen de Boer [28, 51], were studied.

Reexamination of the cross sections from the paintings in the collection of Kunstmuseum Den Haag dated 1921 (Fig. 1b–d; Additional file 1) revealed that in the paint layers of the grey planes, Mondrian generally mixed the ZW-Al/P paint with lead white. Only in one sample ZW-Al/P was used alone.

SEM-EDX analysis of the cross sections of *Composition no. I* (1929, The National Museum of Modern Art, Kyoto) (Fig. 1e) allowed to ascertain that the ZW-Al/P paint had been mixed with cadmium yellow paint in the yellow area (samples 246/4–6, data not shown), and with lead white in the white underpaint of the blue plane (layer 2 of A246/3, Fig. 12). Here, the lead white shows a characteristic morphology with small platelets (Fig. 13a). Curiously, zinc white with Al-S inclusions was found in a black line paint layer on top of the edge of the blue plane (sample A246/2, data not shown).

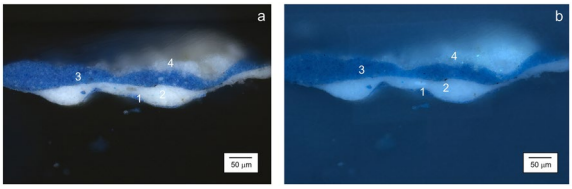

Fig. 12 Cross section of sample A246/3 from *Composition no. I* in **a** Incident polarised light and **b** UV induced fluorescence. The following layers can be observed. 1: thin blue paint layer with lead white and ultramarine; 2: lead white with ZW-Al/P; 3: cerulean blue, lead white, ultramarine, zinc white and quartz; 4: lead white, zinc white and calcium carbonate

Another sample could be taken from the edge of the biggest white area of *Composition II* (1929, Museum Boijmans van Beuningen) (Fig. 1f). The cross section (sample 1542MK-02) shows three paint layers (the ground layer is not included) (Fig. 14). The lowest paint layer (layer 1) is mainly based on lead white, but it also contains some ZW-Al/P paint. A particle of cobalt blue was identified as well, likely conferring a slightly blueish hue. Then, in a second phase, two more paint layers (layers 2–3) were applied, containing 'simple' zinc white and lead white in varying relative amounts. The lead white of layer 1 shows a different morphology (small platelets) as compared to that of layers 2 and 3 (chunks of various dimensions) (Fig. 13b), confirming that Mondrian reworked the painting by using different paints. This time the ZW-Al/P paint, mixed with lead white, was used in the first working phase. The ZW-Al/P paint has also been mixed with cadmium yellow in the yellow square (sample 1542MK-01b, data not shown).

Frames

Mondrian painted the frame—even multiple times—while he was still working on the composition, using the same zinc white paints as for the rectangles. This is clearly shown by the presence of the 'zinc white marker paints'.

In *Composition with yellow and blue* the ZW-Al/P paint, as well as the zinc white-lead white layer underneath, were also found on the frame (Sample 78.3-X10, Fig. 15). These were later covered by a thick layer of

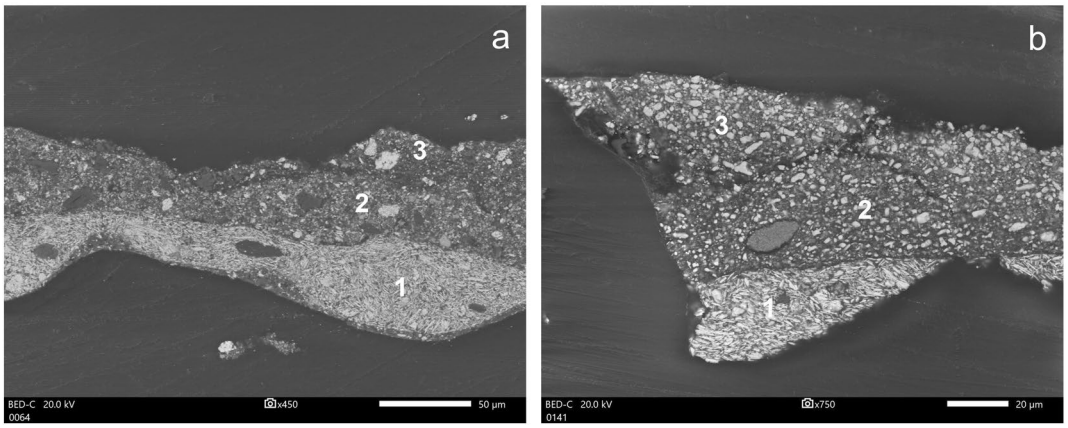

Fig. 13 SEM-BEI of the cross sections of samples **a** A246/3 from *Composition no. I* and **b** 1542MK-02 from *Composition II*

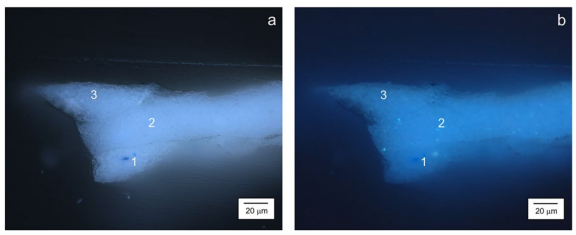

Fig. 14 Cross section of sample 1542MK-02 from *Composition II* in **a** Incident polarised light and **b** UV induced fluorescence. The following layers can be observed. 1: lead white with ZW-Al/P and cobalt blue; 2: lead white and zinc white; 3: lead white and zinc white

natural chalk and various white layers containing anatase and rutile (later overpaints of the 1970s).

On the nail of the frame of *Composition with double line and blue* (sample 90.12-X3; Fig. 16), on top of a zinc white/lead white layer (layer 1), a thin ZW-Al/P layer was applied (layer 2). Then, a rather thick chalk layer (layer 3), probably applied to fill the gap of the nail, forms the basis of a second ZW-Al/P layer (layer 4), followed by two ZW-Al/S layers (layers 5–6; layer 7 is an overpaint).

Discussion

Occurrence of aluminum phosphate and aluminum sulphate

The use of aluminum phosphate in 1920–1930's paint formulations has, as far as we know, never been reported before. Careful examination of both existing and newly prepared cross sections of nine paintings by Mondrian dated between 1921 and 1935 showed the presence of a zinc white paint containing aluminum phosphate. The composition of these inclusions with low amounts of calcium and potassium is fairly constant and characteristic (see EDX spectra in Figs. 4, 7, 11), indicating that we are dealing with the same type of paint.

This ZW-Al/P paint seems to have been used rather pure in *Composition with yellow and blue*, *Composition with double line and blue* (Fondation Beyeler) and *Lozenge composition with yellow lines* (Kunstmuseum Den Haag), all painted between 1932 and 1935.

In the two Beyeler paintings the ZW-Al/P paint was also found on the frame. This is a very important result, once more confirming that the frame was really conceived as part of the painting [54]. To this end Mondrian first attached the frames and then painted them, also before the painting was finished [9].

In the earlier paintings (1921–1929), as well as in the lower layers of *Lozenge composition with yellow lines*, Mondrian generally mixed the ZW-Al/P paint with different amounts of lead white paint. In *Composition no. I* and *Composition II*, both made in 1929, comparison of the morphology of the lead white particles in these lower white paint layers (Fig. 13) reveals that the same lead white paint, mixed with ZW-Al/P, was used. When comparing the paintings dated from 1921, no clear morphological link of the lead white particles could be observed. This suggests that the ZW-Al/P paint is to be considered a distinct paint with its own tube, which Mondrian then eventually mixed with lead white paint.

In most works the ZW-Al/P paint was also interspersed with specific cadmium yellow and blue paint, shedding light on the working stages within the same painting. This finding again confirms that Mondrian did not apply his paint directly from the tube. Van Asperen reports: "Admixtures of white to blue paints can also be observed in paint cross-sections, so it is difficult to see how Mondrian could have obtained such different tones by only using paint straight from the tube." [28] The

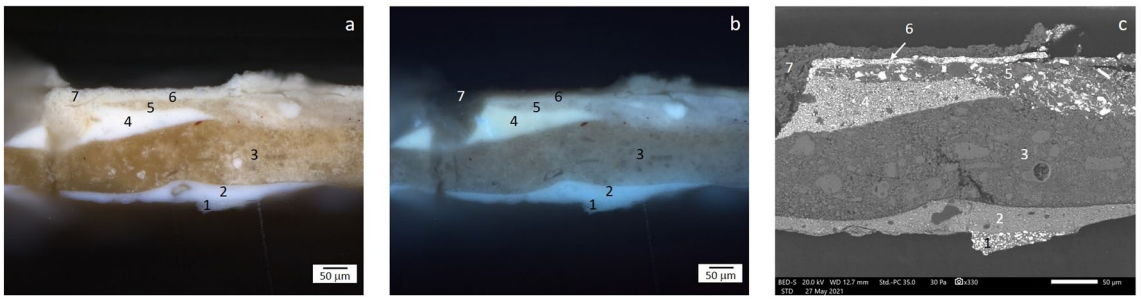

Fig. 15 Cross section of sample 78.3-X10 from *Composition with yellow and blue*. **a** Incident polarised light; **b** UV induced fluorescence; **c** SEM-BEI. The following layers can be observed. 1: zinc white with lead white and some chalk (ground layer); 2: ZW-Al/P paint; 3: second ground layer with natural chalk; 4: barium sulphate, anatase, zinc white and some chalk; 5: barium sulphate, anatase, zinc white, chalk and aluminosilicates; 6: lead white with anatase and some chalk; 7: rutile, chalk, needle-shaped magnesium–aluminum-potassium silicates and some coloured pigments

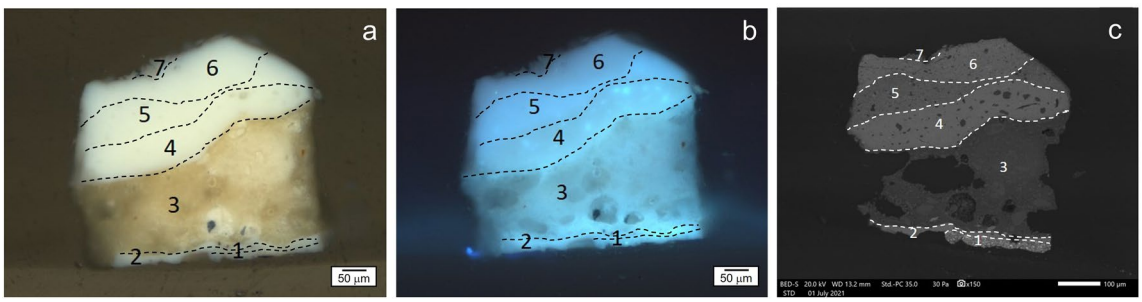

Fig. 16 Cross section of sample 90.12-X3 from *Composition with double line and blue*. **a** Incident polarised light; **b** UV induced fluorescence; **c** SEM-BEI. The following layers can be observed. 1: lead white and zinc white; 2: ZW-Al/P; 3: natural chalk (maybe to even out the depression created by the nail); 4: ZW-Al/P; 5–7: ZW-Al/S. The uppermost layer is rather crumbly at the surface

mixing of paints is also clearly shown by the palettes of Mondrian in the collection of Kunstmuseum Den Haag (inv. 0333339, dated ca. 1938) and in photographs taken in his studios [7]. One of the palettes was evidently only used for mixing the whites.

In *Composition with double line and blue* ZW-Al/S paint was found on top of the ZW-Al/P paint layers. This paint also seems to be rather distinct. It was likely also mixed with black paint in *Composition no. I*.

Nevertheless, as already observed in the paintings of this study, in the 1920s and 1930s Mondrian also used 'pure' zinc white paint, or lead white paint without any zinc white. This applies as well for *Composition with red, yellow and blue* (1927, KM101.213) in the collection of the Kröller-Müller Museum. Here, the white paint on top of a black line consists of a layer of lead white and some calcium carbonate followed by a layer of lead white mixed with 'simple' zinc white [55].

Detection of aluminum phosphate and aluminum sulphate

The occurrence of the specific ZW-Al/P and ZW-Al/S paint in Mondrian's artworks, and in paintings by others, is probably more widespread than currently known. It may have been overlooked in similar case studies by contemporaries, since its identification can only be accomplished with detailed SEM–EDX analysis of cross sections. At present very often sample taking is precluded and only XRF spectroscopy is carried out to identify the pigments of the different areas. Yet, if ZW-Al/P is present, with this technique only zinc, and possibly some phosphorous, can be detected, since aluminum is a light element. However, in the XRF spectra of the white fields of *Composition in yellow and blue* only small peaks of aluminum, and no phosphorous, were found, despite the rather large Al-P inclusions in the upper zinc white paint layers. Similarly, low amounts of aluminum sulphate are difficult to detect with XRF spectroscopy.

Nonetheless, even when studying a cross section with optical microscopy and SEM–EDX, the presence of aluminum phosphate might be overlooked, especially if diffusely present, or if used in a mixture with cobalt blue, which yields ED spectra with rather intense peaks of Al, and often also P.

Finally, even if Al and/or P are detected in a zinc white paint layer, the interpretation might be difficult in lack of reference data. For instance, when *Composition with red,*

blue, black yellow and grey (1921, inv. 154.57, MoMA) was examined at the MoMA [30], it was observed that the paint along the borders of some of the forms was significantly different from that of the adjacent paint: the retouching paint was mainly based on zinc white, with associated small peaks of P and Cl, instead of the lead white that was largely used. This difference pointed to retouching by a conservator, although other observations suggested that the zinc white paint had more likely been applied by Mondrian himself. This was somehow confirmed by the results of *Composition with red and blue* (1933, inv. 635.67, MoMA) [31]. The white and dark blue areas of this painting were found to contain very similar pigments to the retouched areas of the 1921 painting, specifically, the zinc white with the P and Cl peaks. No aluminum was however mentioned for the 1921 painting. Nevertheless, the MoMA report cautiously states that: "Finding paint used in a 1933 painting on a 1921 painting does not mean that the latter work was retouched in 1933. Not enough paintings have been studied to determine when Mondrian started using this type of zinc white paint." [30].

Indeed, based on the results of our study it appears that Mondrian made use of the ZW-Al/P paint already in 1921, both in lower and upper 'reworking' layers, albeit in mixtures with large or small amounts of lead white paint and other colours.

Synthesis and characteristics of aluminum phosphate

Understanding the purpose of adding aluminum phosphate (Al-P) to the zinc white paint from the 1920–1930s is a difficult task. Only modern patents and publications were found referring to the use of Al-P as a (partial) substituent of titanium dioxide white pigment. The inclusion of Al-P yields a matte and very white paint, increasing the tinting strength. This can be ascribed to amorphous structures which show unique physical and chemical characteristics forming closed voids after drying, resulting in hollow particles that are capable of scattering light [56]. Various formulations of aluminum phosphate can be prepared by changing the fabrication process and thus the final product composition [57].

In Mondrian's zinc white paint, the Al-P inclusions do not appear void. They look rather transparent in visible light and light bluish in UV. In the SEM-BEI they show rather uniform and no crystalline structures can be observed. This is somewhat confirmed by the broad phosphate band in the FTIR spectra (Fig. 5). The occurrence of calcium and potassium—with constant relative amounts (Figs. 4, 7, 11)—is likely related to the synthesis process which may involve alkaline solutions [57].

Conclusions

For the first time, the occurrence of a specific zinc white paint, containing an aluminum phosphate additive, was evidenced in several paintings made by Piet Mondrian between 1921 and 1935, and, as far as we know, it has never been identified in any artwork or paint tube from that time. This paint, with its characteristic composition, appears to be a useful marker for a specific period of Mondrian's career and enables to relate and date certain (re)working steps.

In the white, light grey or bluish planes of the paintings dated between 1921 and 1929, the ZW-Al/P paint is generally mixed with lead white paint. It can be found both in lower layers, as in *Tableau I* (1921–1925, Fondation Beyeler) and *Composition with red, black, yellow, blue and grey* (1921, Kunstmuseum Den Haag), or in the upper layers, when Mondrian seems to have reworked certain areas within a short time period. This applies for *Composition with red, blue, black, yellow and grey,* and *Tableau I* (both 1921, Kunstmuseum Den Haag). In *Composition no. I* and *Composition II*, both dated from 1929, the ZW-Al/P paint was admixed in small quantities to the same lead white paint in the first working phase.

In the early 1930s Mondrian made use of 'pure' ZW-Al/P paint, which is possibly related to the 'immaterial' whites he seemed to prefer in this specific period. However, in *Lozenge composition with yellow lines*, dated 1933, he first applied a mixture of lead white and ZW-Al/P, and a few years later he 'repaired' the cracks in the white planes with pure ZW-Al/P paint.

Besides the ZW-Al/P paint, another type of specific zinc white paint was identified. It was extensively used in *Composition with double line and blue* (1935) in a second working phase and contains an aluminum sulphate additive. Small amounts of ZW-Al/S were also found in the black paint of *Composition no. I* (1929). In our study the finding of ZW-Al/S paint is thus limited to these two works. Other paintings might be (re)examined, especially those made at the end of his stay in Paris, around and after 1935.

Both the ZW-Al/P and ZW-Al/S 'marker paints' were found to be mixed with yellow, blue or black paint in specific paint layers of the yellow and blue squares, and black lines respectively. This might help to delineate the chronology of his working process. The identification of these 'marker paints' is also important for the interpretation of overpaints in the course of a treatment when removal is considered.

Moreover, the detection of the 'zinc white marker paints' on the frames of *Composition with yellow and blue* and *Composition with double line and blue* enabled to establish that Mondrian used the same paint for the frames as in the white planes and that the frames were

painted while still working on the composition, and not only when he considered the work completed.

It has not yet been possible to identify the brand of the specific zinc white paints; Mondrian might have bought them at Lefebvre-Foinet or Robinet Frères. Unfortunately, patents of aluminum phosphate additives only concern contemporary paint formulations.

The occurrence of the zinc white marker paints is most likely more common in Mondrian's neoplastic paintings and in other paintings made in the 1920–1930s; however, it has probably so far been overlooked or could not be interpreted, in lack of reference data.

Abbreviations

Al-P	Aluminum phosphate
ATR-FTIR	Attenuated total reflection Fourier transform infrared
CCD	Charge coupled device detector
EDX	Energy dispersive X-ray
FBB	Fondation Beyeler Basel
FTIR	Fourier transform infrared
OM	Optical microscopy
KMDH	Kunstmuseum Den Haag (The Hague)
MBvB	Museum Boijmans van Beuningen (Rotterdam)
MoMA	Museum of Modern Art (New York)
NIR	Near infrared
RCE	Cultural Heritage Agency of the Netherlands
RKD	Netherlands Institute for Art History
SEM-BEI	Scanning electron microscopy back scattered electron image(s)
SEM–EDX	Scanning electron microscopy with energy dispersive X-ray spectroscopy
XRF	X-ray fluorescence
ZW-Al/P	Zinc white paint with aluminum phosphate inclusions
ZW-Al/S	Zinc white paint with aluminum sulphate inclusions

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-023-01127-8.

Additional file 1. Supplementary material. 1. Locations of the samples taken from the nine paintings. 2.Reexamination of the cross sections from the paintings dated 1921.

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Author contributions
IvdW carried out most of the OM and SEM–EDX analyses and wrote the manuscript. RH was involved in the study of the paintings in KMDH. LK was concerned with the study of the paintings in KMDH and MBvB. FS, MGr, CH and KJvdB were involved in the study of the paintings in FBB. SdG performed the ATR-FTIR analyses. MG carried out the analyses of *Lozenge composition with yellow lines*. All authors read and approved the final manuscript.

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Availability of data and materials
The locations of the sampling and the detailed results of the reexamination of cross sections from three paintings dated 1921 in the collection of Kunstmuseum Den Haag are reported in the Additional file 1. The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

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

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References

1. Janssen H. Piet Mondrian a life. London: Ridinghouse; 2022.
2. Cooper H, Spronk R. Mondrian: the transatlantic paintings. Cambridge: Cambridge University Press; 2001.
3. Van den Berg KJ, Miliani C, Aldrovandi A, Brunetti BG, de Groot S, Kahrim K, de Keijzer M, Van Keulen H, Megens L, Sgamellotti A, Van Bommel M. The chemistry of Mondrian's paints in Victory Boogie Woogie. In: Van Bommel M, Janssen H, Spronk R, editors. Inside out Victory Boogie Woogie. A material history of Mondrian's masterpiece. Amsterdam University Press: Amsterdam; 2012. p. 147–68.
4. Janssen H. Piet Mondriaan. The man who changed everything. Uitgeverij De Kunst.; 2017:128–151.
5. Janssen H, editor. Mondrian and cubism: Paris 1912–1914. Ridinghouse; 2016.
6. Janssen H, White M. The Story of De Stijl. Harry N. Abrams; 2011.
7. Coppes W, Jansen L, editors. Mondrian and Photography, Picturing the Artist and His Work. Hatje Cantz Verlag GmbH & Co KG; 2023.
8. Langendijk E. Interview of Eugène Langendijk with César Domela, Paris, January 13, 1988. Translated from the Dutch by Barbara Fasting. RKD Archive (The Netherlands).
9. Blok V, Bracht E, Wijnberg L. Mondrian in the Stedelijk Museum Amsterdam: Research and conservation of five early abstract paintings. Zeitschrift für Kunsttechnologie und Konservierung. 2011;25:187–222.
10. Joosten JM, editor. Piet Mondriaan, Catalogue Raisonné: The works of 1911–1944, vol. II. Blaricum: V+K Publishing; 1998.
11. RKD, Archive werkgroep Mondriaancorrespondentie project, inv.nr 62
12. Gabo M, Gabo N, Hepworth B, Nicholson B, Nicholson W, Read H, Harrison C. Mondrian in London reminiscences. Stud Int. 1966;172:285–92.
13. Janssen H. Working at a table. In: Manacorda F, White M, editors. Mondrian and his studios Colour in space. Tate Publishing; 2014.
14. https://www.npg.org.uk/research/programmes/directory-of-suppliers.
15. Brauen M. The Sameness Between Us. The Friendship of Charmion von Wiegand and Piet Mondrian in Letters and Memoirs. Arnoldsche. 2020.
16. https://www.fondationbeyeler.ch/en/pietmondrianconservationproject.
17. Baier U. Das Piet Mondrian Conservation Project. Restauro; 2021;6.
18. Van der Werf ID, de Groot S, Gross M, Hürlimann, Smulders S, Steckling F, Van den Berg KJ. Early Mondrian (1912–1914) painting technique and materials. Int J Conserv Sci. 2022;13:1509–20.
19. Van den Berg KJ, de Groot S, Smulders S, Van der Werf ID. Mondrian research—Part 1: materials and techniques of P. Mondrian. RCE Research Report No. 2019-132. 2019, Ministry of OCW, Cultural Heritage Agency of the Netherlands, Cultural Heritage Laboratory. Amsterdam; 2023.
20. Van der Werf ID, Van den Berg KJ, de Groot S, Smulders S. Mondrian research—Part 2.1 Materials and techniques of P. Mondrian (1921–1938), Tableau No. I (1921–1925). RCE Research Report No. 2020-157. Amsterdam: Cultural Heritage Agency of the Netherlands, Cultural Heritage Laboratory; 2023.

21. Van der Werf ID, Van den Berg KJ, de Groot S, Pause R, Van Rietschoten E, Smulders S. Mondrian research—Part 2.2 Materials and techniques of P. Mondrian (1921–1938), Composition with yellow and blue (1932). RCE Research Report No. 2020-157. Amsterdam: Cultural Heritage Agency of the Netherlands, Cultural Heritage Laboratory; 2023.
22. Van der Werf ID, Van den Berg KJ, de Groot S, Pause R, Van Rietschoten E, Smulders S. Mondrian research—Part 2.3 Materials and techniques of P. Mondrian (1921–1938), Composition with double line and blue (1935). RCE Research Report No. 2020-157. 2023 Amsterdam: Cultural Heritage Agency of the Netherlands, Cultural Heritage Laboratory.
23. Van der Werf ID, Van den Berg KJ, de Groot S, Pause R, Proaño Gaibor A, Van Rietschoten E, Smulders S. Mondrian research—Part 2.4 Materials and techniques of P. Mondrian (1921–1938), Lozenge composition with eight lines and red (1938). RCE Research Report No. 2020-157. Amsterdam: Cultural Heritage Agency of the Netherlands, Cultural Heritage Laboratory; 2023.
24. Bisschoff M, van Bommel M. *Victory Boogie Woogie* up close: A study of the large colour fields. In: van Bommel M, Janssen H, Spronk R, editors. Inside out Victory Boogie Woogie. A material history of Mondrian's masterpiece. Amsterdam University Press: Amsterdam; 2012. p. 203–24.
25. Janssen H. Piet Mondriaan. Een nieuwe kunst voor een ongekend leven. Een biografie. Hollands Diep. Amsterdam. 2016: 405–459.
26. Spronk R. Technical studies of paintings by Piet Mondrian. In: Van Bommel M, Janssen H, Spronk R, editors. Inside out Victory Boogie Woogie. A material history of Mondrian's masterpiece. Amsterdam University Press: Amsterdam; 2012. p. 101–17.
27. Carmean EA Jr. Mondrian, The diamond compositions. Washington; 1979.
28. Van Asperen de Boer JRJ. On the scientific examination of some Mondriaan paintings. KM. 1994;12 winter:26–30.
29. Ordonez E. MoMA conservation department records; 1990–1993.
30. Ordonez E. MoMA conservation department records; 1995.
31. Ordonez E. MoMA conservation department records; 1996.
32. Ordonez E. Looking at art, Mondrians composition C. Art News. 1920;1997:120–2.
33. Albertson C, Martins A. Piet Mondrian in the collection of the Museum of Modern Art. AIC Paint Spec Group Postprints. 2014;27:87–101.
34. Martins A, Albertson C, McGlinchey C, Dik J. Piet Mondrian's Broadway Boogie Woogie: non invasive analysis using macro X-ray fluorescence mapping (MA-XRF) and multivariate curve resolution-alternating least square (MCR-ALS). Herit Sci. 2016;4:22.
35. Raven LE, Bisschoff M, Leeuwestein M, Geldof M, Hermans JJ, Stols-Witlox M, Keune K. Delamination due to zinc soap formation in an oil painting by Piet Mondrian (1872–1944). In: Casadio F, Keune K, Noble P, Van Loon A, Hendriks E, Centeno SA, Osmond G, editors. Metal soaps in art. Cultural heritage science. Springer: London; 2014. p. 343–58.
36. Van Loon A, Hoppe R, Keune K, Hermans JJ, Diependaal H, Bisschoff M, Thoury M, Van der Snickt G. Paint Delamination as a Result of Zinc Soap Formation in an Early Mondrian Painting. In: Casadio F, Keune K, Noble P, Van Loon A, Hendriks E, Centeno SA, Osmond G, editors. Metal soaps in art. Cultural heritage science. Springer: London; 2014. p. 259–373.
37. Kolkena L. Degradatieverschijnselen van gele cadmiumolieverven in de schilderijen van Piet Mondriaan, MSc thesis. University of Amsterdam; 2013.
38. Kolkena L, Blok V, Megens L, Keune K, van Loon A, Hoppe R, Leeuwestein M, van der Werf ID, van den Berg KJ. A phenomenological atlas of degraded cadmium yellow oil paint in paintings by Piet Mondrian (1872–1944) and some of his contemporaries. To be submitted to Zeitschrift für Kunsttechnologie und Konservierung; 2024.
39. Van der Werf P. The working methods of Piet Mondriaan. KM. 1994;12 winter:31–35.
40. Green C, Wright B, editors. Mondrian Nicolson in parallel. London: Courtauld Gallery&Paul Holberton Publishing; 2012.
41. Kühn H. Zinc white. In: Feller RL, editor. Artists' Pigments: A Handbook of their History and Characteristics. Vol. 1. National gallery of Art. 1986:169–187.
42. Helwig K, Poulin JA, Corbeil M-C, Moffatt E, Duguay E. Conservation issues in several twentieth-century Canadian oil paintings: the role of zinc carboxylates reaction products. In: Van den Berg KJ, Burnstock A, de Keijzer M, Krueger J, Learner T, de Tagle A, Heydenreich G, editors. Issues in contemporary oil paint. London: Springer; 2014. p. 167–85.
43. Osmond G. Zinc white and the influence of paint composition for stability in oil based media. In: Van den Berg KJ, Burnstock A, de Keijzer M, Krueger J, Learner T, de Tagle A, Heydenreich G, editors. Issues in contemporary oil paint. Springer: London; 2014. p. 263–83.
44. Van Driel B. White, Friend or Foe? Understanding and predicting photocatalytic degradation of modern oil paintings. PhD. Delft University of Technology; 2018.
45. Phenix A, Soldano A, Van den Berg KJ, Van Driel B. The Might of White' 1: Formulations of titanium dioxide-based OIL paints as evidenced in archives of two artists' colourmen, mid-20th century. In: ICOM committee for conservation 18th triennial meeting Copenhagen Denmark 4–8 September 2017; 2017.
46. Ordonez E. MoMA conservation department records; 1997.
47. Ackermann M, Dalrymple Henderson L. Kandinsky Malewitsch Mondrian - Der weiße Abgrund Unendlichkeit. Catalogue K20 Kunstsammlung Nordrhein-Westfalen; 2014.
48. Laver M. Titanium dioxide whites. In: West FitzHugh E, editor. Artists' pigments: A handbook of their history and characteristics. Vol. 3. Washington DC/Oxford. National Gallery of Art/Oxford University Press:295–355.
49. Geldof M, Compositie Metgelelijnen. Piet Mondriaan, 1933. RCE Research Report No. 2015-066. 2015. Ministry of OCW, Cultural Heritage Agency of the Netherlands, Cultural Heritage Laboratory. Amsterdam.
50. De Visser E, Coppes W, Geerts T. Piet Mondrian: catalogue raisonné. RKD. https://rkd.nl/nl/explore/library/335135.
51. Langendijk E. Verslag van het bijvak: Methoden en technieken van materieel onderzoek van kunstwerken. Archive RKD (The Netherlands); 1988.
52. Roy A. Cobalt blue. In: Berrie BH, editor. Artists' pigments—a handbook of their history and characteristics, vol. 4. New York: Archetype Publications; 2007. p. 151–77.
53. Gettens RJ, Stout GL. Painting materials—a short encyclopaedia. New York: Dover Publications; 1966.
54. Joosten JM. De grenzen van Mondriaan. Openbaar Kunstbezit; 1977.
55. Geldof M. Mondriaan, Compositie met rood, geel en blauw, 1927, Kröller Müller Museum. RCE Research Report No. 2016-061. 2016. Ministry of OCW, Cultural Heritage Agency of the Netherlands, Cultural Heritage Laboratory. Amsterdam.
56. Beppu MM, de Oliveira Lima EC, Sassaki RM, Galembeck F. Self-opacifying aluminum phosphate particles for paint film pigmentation. J Coat Technol. 1997;69:81–8.
57. https://www.freepatentsonline.com/y2016/0046782.html.

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