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Hyperspectral Imaging Analyses of Cleaning Tests on Edvard Munch's Monumental Aula Paintings

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ABSTRACT
The development of innovative applications of imaging technologies for monitoring change in cultural heritage objects is central to the CHANGE-ITN project. Within this framework, the authors' ongoing work targets the harnessing of hyperspectral imaging (HSI) for the documentation of cleaning treatments on the monumental University of Oslo Aula unvarnished oil paintings on canvas (1909–1916) by Edvard Munch (1863–1944). This is applicable to unvarnished paint surfaces in general. Particularly, this paper evaluates HSI techniques for the investigation of cleaning tests carried out in 2008, which targeted the removal of visible, ingrained particulate matter from Munch's unvarnished oil paints and exposed grounds on *Kjemi* (1914–1916). An exploratory *in situ* HSI campaign using visible to near-infrared (VNIR) and short-wave infrared (SWIR) cameras was undertaken to capture the soiled or previously cleaned areas on the painting's surface, with comparisons to analogous mock-ups. Principal component analysis (PCA) was used to extract information about possible trends with respect to the soiling. Results indicate that in both VNIR and SWIR ranges, the intensity of reflectance can be used to discriminate statistically between soiled and unsoiled/cleaned areas, whereas in SWIR, combination and first overtone bands of oil peaks can also serve as markers.

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Hyperspectral imaging; principal component analysis; unvarnished oil paintings; cleaning tests; conservation documentation; Edvard Munch

Introduction

Hyperspectral imaging in the field of conservation

Hyperspectral imaging (HSI) is becoming an increasingly integrated tool for non-invasive and non-contact analyses of artworks. Although not yet immediately accessible to all conservators due to the high cost of the equipment, HSI has found a strong foothold for its affordance of pigment identification on a relatively large scale, given that it scans areas quickly and collects a wealth of information from across the visible and infrared (IR) regions (Delaney et al. 2016; Knipe et al. 2018). Other important strengths of HSI are documenting objects with accurately reproducible colour, mapping artists' materials, and identifying previous interventions (Deborah, George, and Hardeberg 2019; d'Elia, et al. 2020). For example, visible and near-infrared (VNIR) and short-wave infrared (SWIR) hyperspectral images can elucidate preparatory drawings, *pentimenti*, signatures, and traces of the working process. The SWIR range is of further interest for the identification of selected binders, and some inorganic components, in the ground layer (Ricciardi et al. 2012; Amato, Burnstock, and Michelin 2021).

However, HSI cannot act as a stand-alone analytical technique *per se*, and used in isolation does not provide straightforward nor definite identification of surface materials (Sandak et al. 2021, 9, 11–12). To extract information useful to the conservator, complementary analyses – such as portable X-ray fluorescence (pXRF), portable Raman (pRaman) and portable Fourier transform infrared (pFTIR) spectroscopies – are required. In a similar fashion, HSI does not replace, but complements, the initial observations made by the conservator's own eyes at the commencement of any artefact's investigation. Used in this manner, HSI then becomes a powerful tool for the rapid capture of an object's condition, affording large datasets, termed hypercubes, for accurate mapping of visual and chemical information, which has hitherto not been easily achievable.

The work presented here builds upon the exploration of such datasets and forms part of an ongoing European project (CHANGE-ITN, www.change-itn.eu) that targets the evaluation of HSI as a documentation

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technique for cleaning treatments on monumental unvarnished oil paintings, using the artworks of Edvard Munch (1863–1944) in the University of Oslo (UiO) Aula, painted between 1909 and 1916, as a case study (Figure 1(a,b)). Within this context, the development of innovative applications of spectral imaging technologies for monitoring change as a result of treatment on artworks is a primary driving force in the CHANGE-ITN project. An overarching objective is to provide a more accurate and reliable scientific grounding for the documentation of heritage objects in support of conservation research and treatments.

Documenting cleaning treatments using hyperspectral imaging

Diagnostic, non-invasive techniques are desirable to document an object's surfaces before, during, and after a conservation treatment to serve as a record for future reference. However, instrumental

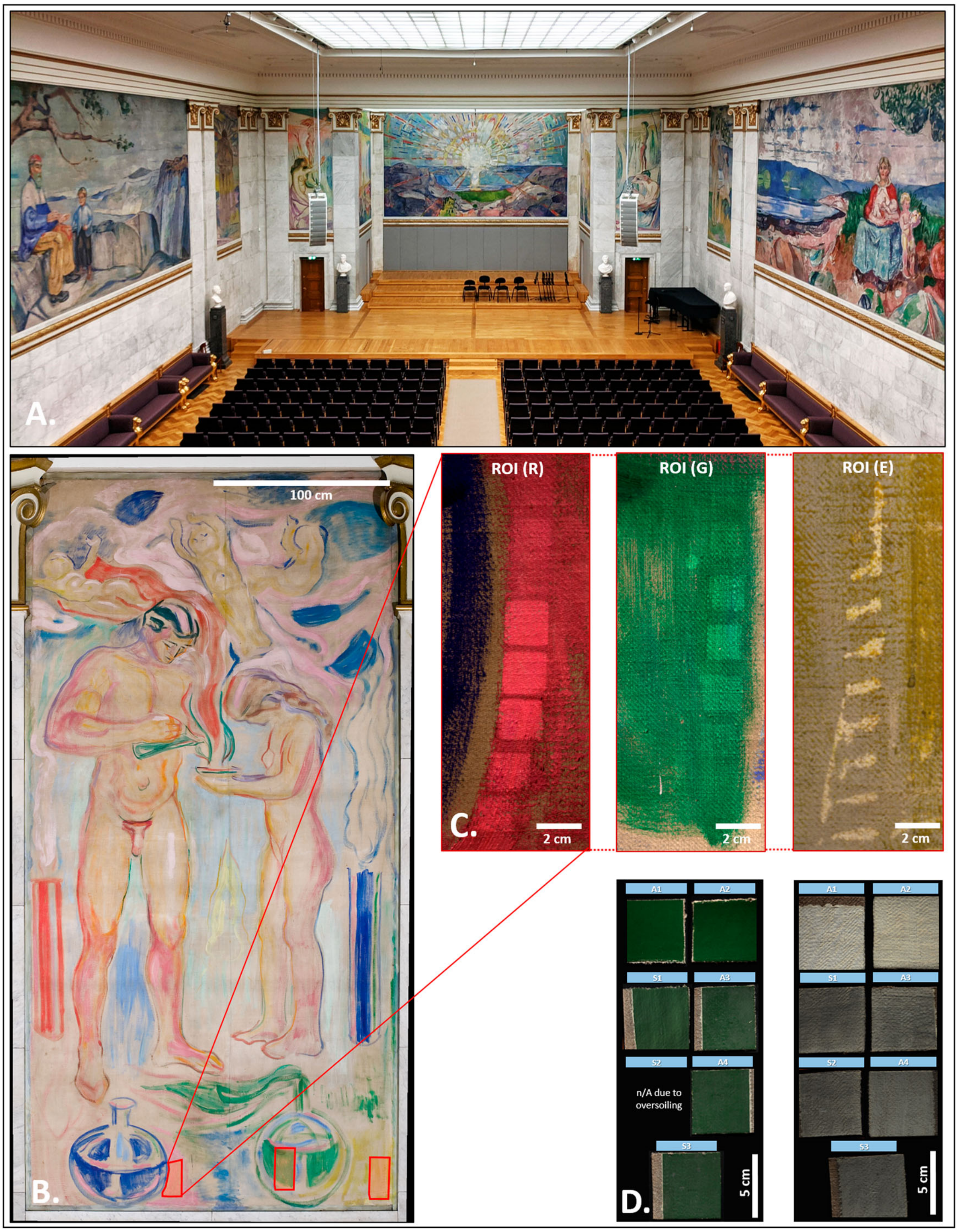

Figure 1. (a) The UiO Aula which hosts the 11 monumental unvarnished oil paintings on canvas by Edvard Munch. (b) *Kjemi/Chemistry*, 1914–1916, Woll no. 1227, 450 × 225 cm, UiO). (c) ROIs scanned for un/soiled red oil paint mixture (R), green oil paint mixture (G), and exposed ground (E). (d) The analogous oil paint and exposed ground mock-ups used in this study (labels correspond with Table 2). All J. D. Cutajar.

monitoring is not always straightforward to implement: innovative techniques are not always accessible, and moreover, monitoring can inevitably slow down, or even arrest, the conservation activities altogether. The need for more accurate and efficient techniques for documenting cleaning treatments is evident.

The application of HSI in this domain is yet in its infancy and has scarcely been attempted for the monitoring of degradation patterns or the accumulation/removal of secondary surface accretions (Bonifazi et al. 2019, 22). Interestingly, such studies have mentioned briefly that soiling might have an effect on spectral analyses.

The 11 monumental UiO Aula paintings under investigation (covering over 220 m^2 of canvas) have undergone at least seven cleaning campaigns during their lifetime (Frøysaker 2007, 249–252; Stoveland et al. 2019, 86–87), which targeted the removal of visible, ingrained particulate matter from their unvarnished surfaces. One of the latest campaigns took place during the *Munch Aula Paintings* (MAP) refurbishment project between 2008 and 2011. Several cleaning tests were carried out on two paintings (*Kjemi* and *Høstende kvinner*) in order to determine a feasible cleaning technique (Frøysaker, Miliani, and Liu 2011). Some trials on *Kjemi* are shown in Figure 1(c) and described in Table 1. Since then, new cleaning studies have also been undertaken on mock-ups of these paintings, as the continued deposition of airborne particulate matter in the Aula will warrant future cleaning treatments (Grøntoft, Stoveland, and Frøysaker 2019; Stoveland et al. 2021).

This paper describes the results from preliminary analyses of hypercubes of sections from one easily accessible Aula painting, *Kjemi/Chemistry* 1914–1916, Woll no. 1227, and related analogous mock-ups (Figure 1(d)). The aim was to determine whether a significant spectral difference could be detected between unsoiled and soiled areas on unvarnished oil paints and grounds, so as to allow their mapping.

Exploratory analyses of hyperspectral data for conservation

The hypercube can be interpreted as having a dual nature, that is, firstly as being a collection of images (one image per spectral band), and secondly as being a collection of reflectance spectra (one spectrum per pixel). Since it is a statistically meaningful dataset, hypercube interpretations are often based on principal component analysis (PCA), a common tool in multivariate statistics, which has been successfully used in recent applications of spectral imaging in conservation (Amato, Burnstock, and Michelin 2021; Sandak et al. 2021).

PCA is a mathematical transformation of the hypercube that reduces the number of images from hundreds to tens, hierarchically ordered according to their degree of variance, so as to confine meaningful information within a small set of principal component (PC) images (Figure 2(a)). By evaluating minute spectral variations chemometrically, a PCA approach can enable monitoring of changes in surfaces, with the possibility of detecting slight modifications (e.g. in the form of soiling or material degradation). This would be particularly useful in monitoring monumental artworks and their conservation interventions over time.

Materials and methods

Preparation of mock-ups

A set of analogous exposed ground and unvarnished oil paint mock-ups was prepared, based on material analyses of the ground and oil paints found on *Kjemi* (Frøysaker and Liu 2009; Frøysaker et al. 2019), as detailed in Table 2. The mock-ups served as points of reference between unsoiled and soiled areas for comparison to similar regions on *Kjemi*.

HSI acquisitions

Hyperspectral scans of the analogous mock-ups were carried out at the NTNU Colour and Visual Computing Laboratory in Gjøvik, Norway. HySpex™ VNIR-1800 and SWIR-384 pushbroom hyperspectral scanners (Norsk Elektro Optikk AS) were used. Spectral acquisitions were carried out following methodologies established by Deborah, George, and Hardeberg

Table 1. Cleaning tests on the green areas (ROI (G)) and toned red areas (ROI (R)) on *Kjemi* as shown in Figure 1, from Frøysaker, Miliani, and Liu (2011).

Cleaning tests			Test areas and related effect	
Reference	Application	Cleaning agent	Green areas (ROI (G))	Toned red areas (ROI (R))
1 (SSw)	Swab	Saliva	Some effect, mostly change in gloss	Average effect, but somewhat uneven
2 (MSp)	Sponge	2% w/v Marlipal	Good effect, changes in colour and gloss	Good and even effect
3 (BBr)	Brush	Brij 700	Good effect, increased change in colour and gloss than test 2	Average and somewhat uneven effect
4 (TBr)	Brush	Triton X100	Good effect, increased changes of colour and gloss than test 2	Good, quick and even effect
5 (TSw)	Swab	1% w/v TAC	Good effect, changes in colour and gloss	Average and somewhat uneven effect
6 (TSp)	Sponge	1% w/v TAC	Average effect, some changes in colour and gloss	Good and even effect
7 (SSp)	Sponge	Smoke sponge	Some effect, mostly change in gloss	Some effect, some change in gloss
8 (BRo)	Roll	Bread dough	Good effect, increased change in colour and gloss than test 2	Some effect

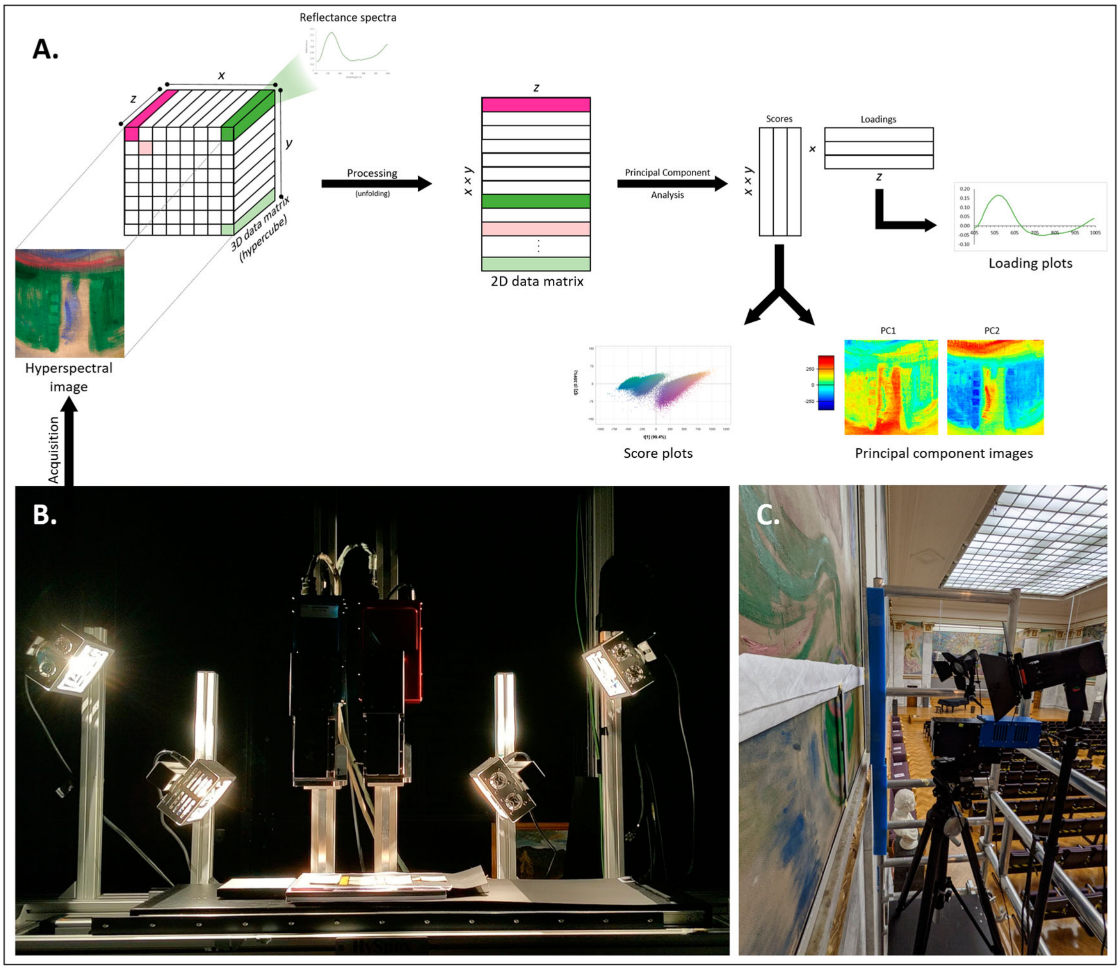

Figure 2. (a) Schematic for PCA process, adapted from de Oliveira et al. (2018). (b) HSI acquisition setup and (c) HSI cameras *in situ* on scaffolding in the Aula. All J. D. Cutajar.

(2019) and Pillay, Hardeberg, and George (2019), as described in Table 3 and Figure 2(b).

Within the Aula, the two cameras were used with a 1 m focal distance lens to capture three accessible sections with cleaned areas on *Kjemi*, as shown in Figure 1 (c) and Table 4. Since the painting is marouflaged and hung starting at a height of approximately 3.4 m, the HSI lab setup and acquisition conditions necessitated modification for *in situ* work upon a 6 m high scaffolding (Figure 2(c)).

Pre-processing of the hypercube was carried out using the manufacturer's acquisition software, and the associated HyspexRadV2.0® software package. Post-processing workflows were followed as described by Pillay, Hardeberg, and George (2019). These calibration processes were carried out manually using the FIJI (ImageJ) image processing package. The resultant hypercubes provided functions in absolute reflectance and were used further for the exploratory analysis by PCA.

Table 2. Ground and oil paint mock-ups for *Kjemi*.

Mock-up	Stratigraphy	Application	Rationale	Ageing	Soiling
Ground	Canvas: washed linen, twill weave Size: rabbit skin glue Composite half-chalk ground: chalk, zinc white, lead white in rabbit skin glue and boiled linseed oil emulsion	Hog's hair brushes for all applications	pDRIFTS, pXRF; also FTIR, Raman, SEM-EDS analyses on donated sample from *Kjemi* This ground not yet studied for Aula paintings	A1: six months natural drying A2, A3,A4: three campaigns of accelerated ageing in a Memmert™ chamber under visible light and fluctuating RH (15–65%) to simulate harshest Aula conditions	S1, S2, S3: three campaigns of artificial soiling adapted for the Aula
Oil paint	Canvas: *ibid*. Size: *ibid*. Composite half-chalk ground Paint: undiluted chromium oxide green in linseed oil paint		pDRIFTS, pXRF analyses on *Kjemi*. Water-sensitive and mechanically fragile paint found in abundance on Aula paintings		S1 and S3: two campaigns of artificial soiling adapted for the Aula. S2 skipped due to excessive soiling

Table 3. HSI acquisition and lighting conditions.

HSI camera	*VNIR-1800*	*SWIR-384*	**Lamps**	Tungsten-halogen	
Spectral range (nm)	407–998	951–2505	Quantity	4 (2 on each side of camera)	
Spectral bands	186	288	Spectral coverage (nm)	400–2500	
Spectral interval (nm)	3.26	5.45	Mount	Fixed at 45°, at two heights	
Spatial resolution (µm)	50	220	Reflectance standard used	Spectralon® grey diffuse 50% standard	
Focal length (cm)	30		Room lighting	Darkness	
Field-of-view (cm)	8.6				
Mount	Fixed, perpendicular to stage		**Acquisition software**	HySpex™ Ground 4.8	
			HSNR	2	
			Integration time (µs)	15,000	5200

HSNR = high signal-to-noise ratio.

PCA for exploratory analysis

The aim of the PCA was twofold – to determine whether there were any visual and chemical spectral differences between unsoiled and soiled areas on the mock-ups and *Kjemi's* cleaned areas, and then to evaluate whether statistically relevant maps of these areas could be achieved, based on the PCs generated. PCA is a powerful tool that might prove challenging for the practising conservator without training in coding languages, such as R, Python®, or MATLAB®. For this reason, the Evince™ application was selected based on its user-friendliness, and its simple data import utility, as well as its interactive outputs. The PCA was carried out using Evince™, an application developed by Prediktera® specifically for PCA analyses of hyperspectral images.

Using the Math function in FIJI, the hypercube was multiplied by a value of 255 before import, to ensure correct conversion to the data type required by PCA (hypercubes are typically represented in 'float' data type, with values ranging between 0 and 1. Most image processing algorithms, however, assume a 'uint8' data type, with values ranging from 0 to 255). To facilitate the speed of analysis by reducing memory usage, the number of rows and columns was reduced by a factor of 2, and only regions of interest (ROIs) were selected for computation. The image data were pre-processed *via* mean centring (also known as column auto-scaling). Up to 10 PCs were calculated for each model, and the PC images, loading plots and score plots (Figure 2(a)) were explored using the software's user interface.

The loading plots reflect the importance of each variable defined by a given PC and indicate which bands in a spectrum are contributing to the variance observed. The score plots compare one selected PC against another and provide insight into the clustering and trends of the data points which are found as pixels in the PC images. The joint interpretation of these PCA outputs allows comparisons and contrasts to be drawn on the captured data based on both spatial and spectral observations.

Results and discussion

The results for the PCA in this study are displayed in Figures 3–6. Most of the variance was typically explained by the first three PCs, and so the relevant PC images are shown in greyscale and pseudocolour to aid in visualisation, together with their associated

Table 4. Soiled and cleaned areas scanned by HSI on *Kjemi*.

ROI	Description	Materials in ROI	Identification[a]
(E) Exposed ground	Area on bottom right of the painting. Traces of rye paste glue deposited by tooth-edged spatula in 1946, cleaned in 2008. Soiled ground surrounds them.	Cadmium yellow oil paint; composite half-chalk ground (chalk, zinc white, lead white) with oil binder	Pigment: pXRF, VNIR-HSI Binder: pDRIFTS, SWIR-HSI Ground: SEM-EDS, FTIR, Raman
(G) Green mixture	Area on green-coloured round-bottomed flask. The cleaning tests are found on a diluted application of oil paint.	Emerald green (copper (II) acetoarsenite) oil paint; chromium oxide green oil paint; composite half-chalk ground (chalk, zinc white, lead white) with oil binder	Pigment: pXRF, VNIR-HSI Binder: pDRIFTS, SWIR-HSI Ground: based on above
(R) Red mixture	Area to the right of the blue-coloured round-bottomed flask. The cleaning tests are found on a thick, undiluted application of paint with some impasto.	Vermilion oil paint; lead or flake white oil paint; composite half-chalk ground (chalk, zinc white, lead white) with oil binder	Pigment: pXRF, VNIR-HSI Binder: pDRIFTS, SWIR-HSI Ground: based on above

[a]Analyses by Frøysaker and Liu (2009) using pXRF, by Cutajar in 2020 and 2021 using pXRF, pDRIFTS, and HSI, and in collaboration with SciCult KHM laboratories in 2020 using SEM-EDX, FTIR, and Raman.

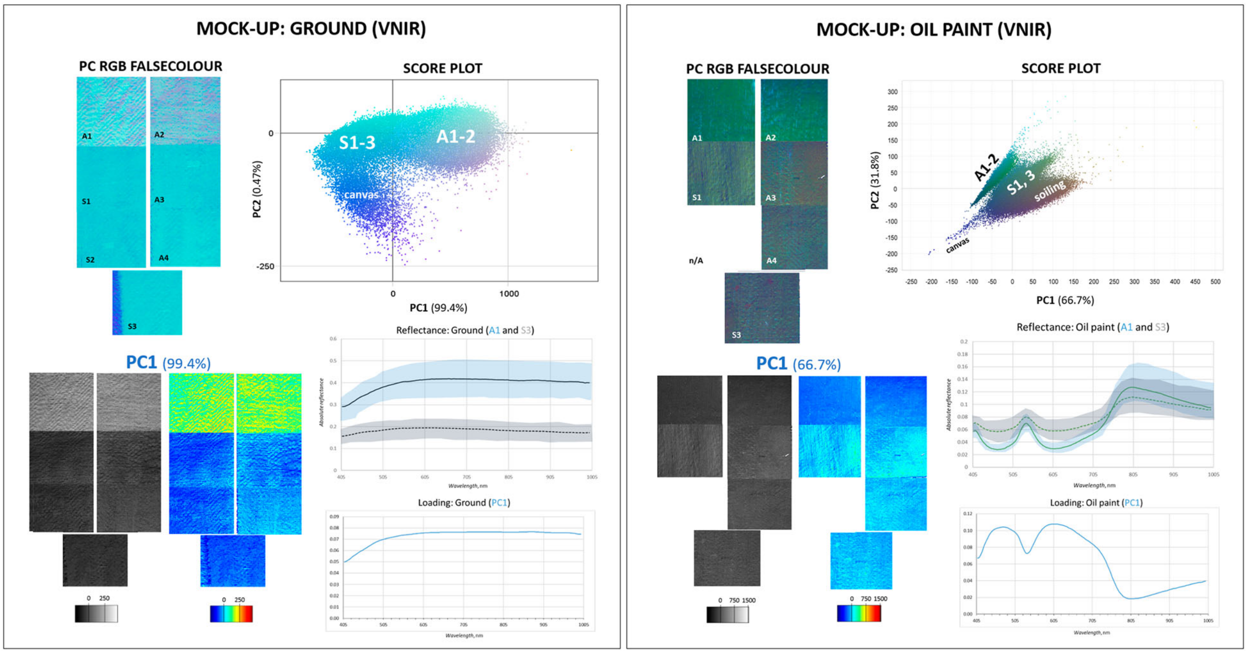

Figure 3. PCA results for ground (left) and oil paint (right) mock-ups, in the VNIR, with average reflectance spectra for unsoiled (A1) and soiled areas (S3). J. D. Cutajar.

score and loading plots to provide anchored, contextual understanding.

The data from the VNIR range relates to visually appreciable information on the surface of the mock-ups and sections on *Kjemi* and thus provide insight into spectral differences in the colorimetric properties of the pixels. The composite PC false colour images (which display all three PCs together as a function of RGB) indicate two to three distinct clusters, also reflected in the score plots (Figure 3). The major sets relate to the unsoiled (A1 and A2) and soiled surfaces (A3–A4, S1–S3), respectively.

These observations can be further rationalised by considering the separate PC images and their related loadings (Figure 3). For the ground mock-ups, their entire reflectance spectrum is positively correlated to PC1. The areas of unsoiled ground give the highest intensity reflectance spectra and are therefore highlighted, as opposed to the soiled areas which are marked as having negative values for this loading. For the oil paint mock-ups, the soiling is also mapped in PC1, but as an inverse of the chromium oxide green's spectrum (Figure 3). Although the whole spectrum is positively correlated, the peaks in

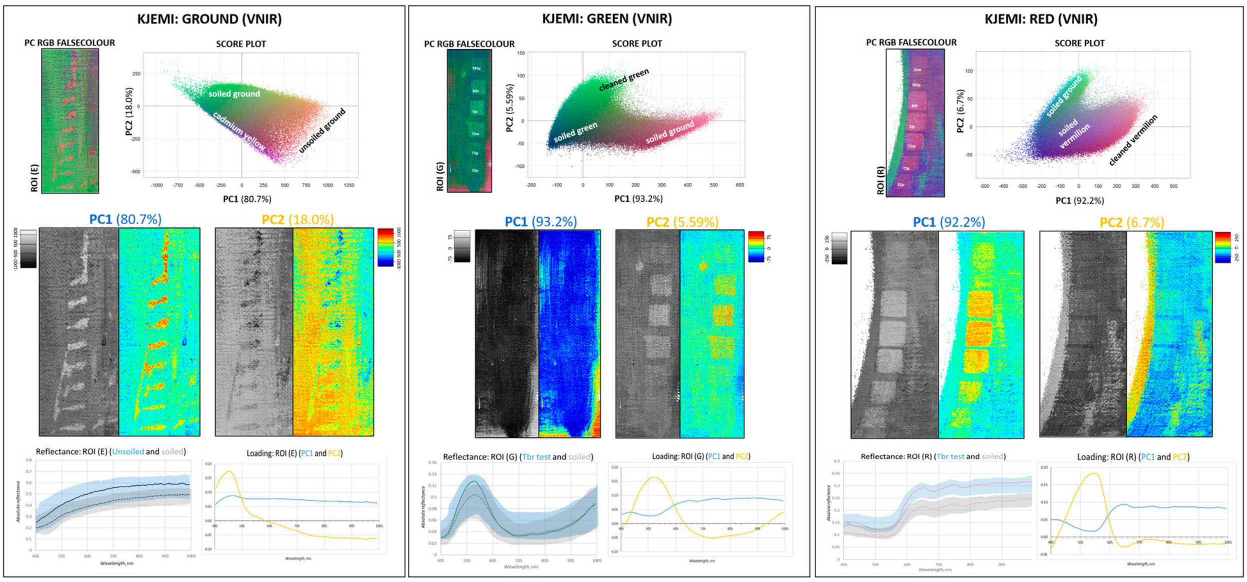

Figure 4. PCA results in the VNIR for the exposed ground (ROI (E), left), green mixture (ROI (G), centre), and red mixture (ROI (R), right) oil paints on *Kjemi*. PC1 and PC2 are shown, together with their corresponding loadings and average reflectance spectra for soiled and unsoiled/clean areas, respectively. For ROI (R), PC images have masked pixels. J. D. Cutajar.

the green region are found as minima instead of maxima, and therefore the areas of lower intensity reflectance for the green pigment, i.e. the soiled areas, are highlighted. In both examples, PC1 alone has been sufficient for mapping unsoiled/soiled areas.

These results hence indicate the major distinguishing feature between unsoiled/soiled areas is the variation in the intensity of the reflectance spectrum. This is satisfactorily reported for the VNIR scans of the cleaned areas on *Kjemi* (Figure 4). Their composite PC false colour images and score plots successfully mark out regions of unsoiled/soiled paint and ground as statistically varied sets. For the exposed ground (E) and red mixture (R) regions of interest (ROIs), the trend in PC1 is explained similarly as with the ground mock-ups.

Notably, the degree of cleaning by the tests is mapped out on the basis of observed colorimetric change i.e., areas cleaned with stronger cleaning agents are mapped out more intensely than others. For future cleaning trials, these differences could be used to help in deciding and documenting which is the most-desired treatment result.

Contrarily, for PC1 on the ROI (G) green mixture, it is the spectrum of the ground which seems to be positively correlated in the loading plot (Figure 4), and therefore it is mapped out with the highest intensity in the corresponding PC1 image. On larger areas of paintings with more pigments, this exercise can be expected to be more complex to interpret due to pigment mixtures, which will make reading loading plots more challenging (Sandak et al. 2021, 15). PC2 clearly contains information about the cleaning tests. The loading plot represents the green pigment's spectrum, where the maximum in the green region between 435 and 635 nm is the most positively correlated, and therefore similarly to ROIs (E) and (R) in PC1, the cleaner areas give a stronger signal for the green pigment.

PC2 for ROI (E) and ROI (R) demonstrates a similar trend. The loading plots indicate a positive correlation for a maximum placed between 400–500 nm and 500–600 nm, respectively, which coincide with regions of the lowest intensity reflectance in the ground and pigment's reflectance spectra (Figure 4). If these regions are associated with soiled areas, as observed in the oil paint mock-ups, then the respective PC2 images can be interpreted as maps of soiled ground in both cases. Concurrently, unsoiled/cleaned areas are mapped inverted – the reflectance peaks at higher intensities are negatively correlated, thus these areas get marked with negative values.

The chemical information collected in the SWIR range pertains to spectroscopically distinguishable vibrational transitions (known as overtones and combination bands) of organic materials, such as binding

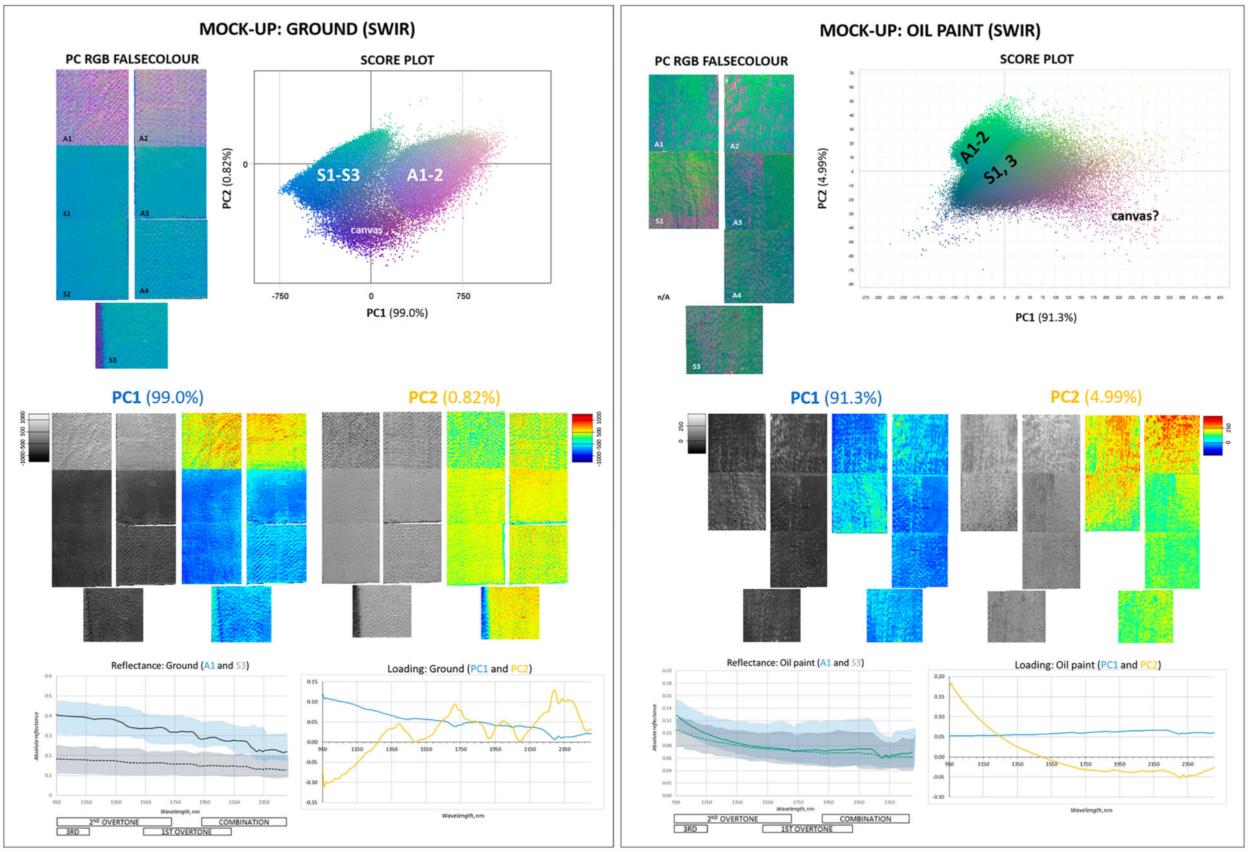

Figure 5. PCA results for the ground (left) and oil paint (right) mock-ups, in the SWIR. The average reflectance spectra for unsoiled (A1) and soiled areas (S3) are provided for comparison to the loading plot (both PC1 and PC2). J. D. Cutajar.

media. The data thus provides insight into spectral differences in the characteristic peaks for, e.g. lipid components of oils and waxes and amides in proteinaceous adhesives.

The composite PC false colour images and score plots for the mock-ups (Figure 5) indicate that although the unsoiled (A1 and A2) and soiled ground (A3–A4, S1–S3) sections are notably distinguishable, the same cannot be implied for the oil paint, where the two groups seem to be more a subset of one another rather than distinctly marked. This can be rationalised by looking at the PC1 images for each mock-up (Figure 5).

On one hand, the loading of PC1 for the ground is somewhat equally placed upon the entire SWIR spectrum, which shows the characteristic peaks of drying oil (Amato, Burnstock, and Michelin 2021, 4). Similarly to the VNIR range, the un/soiled grounds are clearly distinguished based on the intensity of the reflectance signal – this time of the binder – which is more detectable in unsoiled regions than soiled ones.

On the other hand, although a similar loading is found for PC1 of the oil paint mock-ups, the observations are somewhat different. No distinction is made between different stages of ageing and soiling, as indeed, the reflectance spectra for unsoiled and soiled regions are found at very similar intensities (Figure 5). Instead, the troughs in brushstrokes are marked out across the PC1 image, which is where oil deposits might be more concentrated, and therefore give the strongest signal irrespective of soiling.

These results indicate that the detection of soiling can be made indirectly in the VNIR and SWIR ranges as a function of the intensity of reflectance registered *when such a difference exists* between unsoiled and soiled areas. It is possible that the direct presence of the soiling might be instead detectable in the mid-infrared (MIR) region (2500–15,000 nm).

The PC2 for the mock-ups have loading plots that relate to the oil peaks, and as a result, might reflect nuances in the chemical composition of the binder through different stages of ageing. PC2 for the ground seems to lightly distinguish gradually between naturally aged and increasingly artificially aged samples, where the positively correlated combination bands for CH_2 methylene groups (at 2102, 2304, and 2347 nm) seem to be more marked as ageing increases. The oil paint mock-ups seem to corroborate a similar trend, whereby the aforementioned CH_2 combination bands and overtone stretching bands (1700 nm region) are negatively correlated, and thus the less aged samples are being marked out more strongly in the PC2 image.

The PCA results for the sections on *Kjemi* build upon the results for the mock-ups. In each ROI, the pixels for unsoiled/cleaned areas are grouped together in their respective score plots (Figure 6) and are clearly marked out in the composite PC false colour images. Contrary to the oil paint mock-ups, a sufficient difference in the intensity of the reflectance spectra (the entirety of which have a positively marked loading for PC1) for the unsoiled/soiled materials on *Kjemi* resulted in their satisfactory mapping based on PC1 alone.

Applying this to a treatment context, the respective oil binder signals for each material being cleaned could

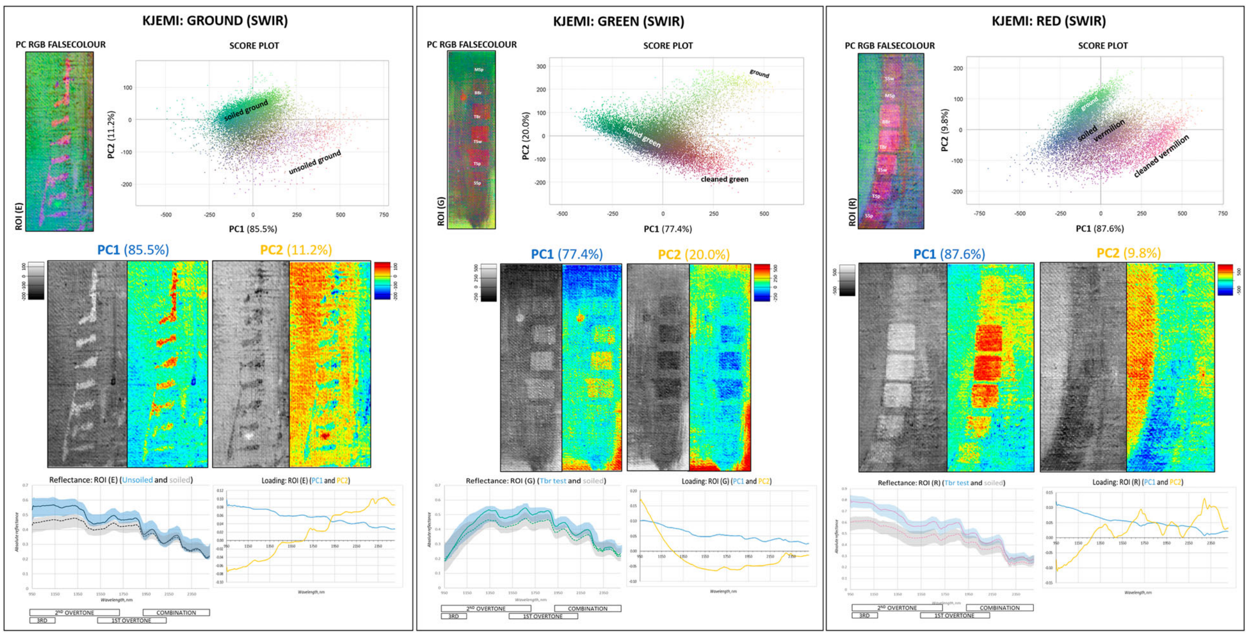

Figure 6. PCA results in the SWIR for the exposed ground (ROI (E), left), green mixture (ROI (G), centre), and red mixture (ROI (R), right) oil paints on *Kjemi*. PC1 and PC2 are shown, together with their corresponding loadings, and average reflectance spectra for soiled and unsoiled/clean areas, respectively. J. D. Cutajar.

therefore be monitored until a sufficient predetermined intensity is reached for what would be considered an appropriately cleaned area. Such a monitoring protocol could be coupled with readings in the VNIR range to guarantee documentation of both visual and chemical measurements. However, it must be noted that in ROI (G), the ground in PC1 gives off a stronger signal than the oil binder – to mitigate against this, the pigments that are not of interest could be masked out. This is easily achieved in Evince™, by selecting visually distinct pixels in the score plots, and is standard practice in PCA methodologies.

Similar to the mock-ups, the PC2 images here illustrate variance in the ROIs scanned as a result of different contributions from different oil peaks. In each ROI, the soiled ground is mapped preferentially over unsoiled ground or paint, as a function of the same CH_2 combination band doublet for stretching and bending (2304 and 2347 nm), and the ester carbonyl stretching (1934 nm). For ROI (E), these bands are positively correlated for soiled areas in the loading plot (unsoiled areas, therefore, mapped with negative values), whereas for ROI (G), they are negatively correlated for clean areas, resulting in the unsoiled and cleaned areas being marked out respectively.

It could therefore be of interest to use the combination bands for drying oils as a marker for documenting cleaning in the SWIR range, but further research would be necessary to investigate this. The determination of characteristic bands for monitoring is of further interest as such knowledge can contribute to the mapping of materials *via* normalised difference images (Lugli et al. 2021) which use characteristic spectral bands for the differentiation of materials, or by end-member classification, which separates materials based on known spectral libraries (e.g. Deborah, George, and Hardeberg 2019).

Conclusion

Hyperspectral imaging (HSI) is increasingly becoming more established in conservation research for the non-invasive, non-contact investigation of artworks. This paper lays the groundwork for the assessment of HSI in the documentation of surface cleaning treatments on monumental unvarnished oil paintings, using one of Edvard Munch's Aula paintings, *Kjemi*, as a case study.

Principal component analyses (PCA) of the acquired hyperspectral datasets indicated that unsoiled/cleaned areas are statistically diverse from soiled areas on the painted surfaces. These differences could be mapped accurately according to the principal component, where often the first principal component was sufficient for this purpose. Both VNIR and SWIR ranges can be used to mark these areas digitally, providing spectral information on the pigments (VNIR) and binders and adhesives (SWIR) employed in the artwork. The intensity of the reflectance measured was the major determining factor between soiled and unsoiled surfaces.

Capturing in the SWIR range has allowed for a more in-depth understanding of the spectroscopic properties of the drying oil binder. The stretching and bending of the methylene CH_2 groups in the combination and first overtone bands, as well as of the carbonyl ester stretching, seemed responsible for the distinctions being made in the PCA maps and merit further investigation for the discrimination of unsoiled/soiled areas using other chemical mapping techniques for hyperspectral data. A series of cleaning tests will be carried out on the analogous mock-ups, and their analysis by HSI will be the subject of a forthcoming publication. Additionally, although MIR-HSI cameras have not been used in this study, further works will attempt to detect the spectral signature for the soiling itself to essay its chemical mapping by HSI.

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Disclosure statement

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