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Understanding Multispectral Imaging of Cultural Heritage: Determining Best Practice in MSI Analysis of Historical Artefacts

Abstract

Although multispectral imaging (MSI) of cultural heritage, such as manuscripts, documents and artwork, is becoming more popular, a variety of approaches are taken and methods are often inconsistently documented. Furthermore, no overview of the process of MSI capture and analysis with current technology has previously been published. This research was undertaken to determine current best practice in the deployment of MSI, highlighting areas that need further research, whilst providing recommendations regarding approach and documentation. An Action Research methodology was used to characterise the current pipeline, including: literature review; unstructured interviews and discussion of results with practitioners; and reflective practice whilst undertaking MSI analysis. The pipeline and recommendations from this research will improve project management by increasing clarity of published outcomes, the reusability of data, and encouraging a more open discussion of process and application within the MSI community. The importance of thorough documentation is emphasised, which will encourage sharing of best practice and results, improving community deployment of the technique. The findings encourage efficient use and reporting of MSI, aiding access to historical analysis. We hope this research will be useful to digitisation professionals, curators and conservators, allowing them to compare and contrast current practices.

Highlights:

- A range of approaches are undertaken for multispectral imaging of heritage.
- An Action Research methodology was used to characterise the current pipeline.
- A set of recommendations for best practice and documentation are provided.

Keywords:

Digitization, Cultural Heritage Imaging, Multispectral Imaging, Advanced imaging analysis, best practice, workflow.

1 Introduction

Multispectral imaging (MSI)[1] is a non-invasive imaging technique in which images are captured of an object that is assumed to be predominantly flat. The object is illuminated using ultraviolet, visible and infrared light, allowing the identification of features that are imperceptible to the naked eye. However there is no current standard regarding application of MSI to heritage artefacts using systems with narrowband light sources, and the reporting of this activity in published literature lacks cohesion. Here, we aim to understand, analyse, and improve the process of using MSI for objects such as documents, manuscripts and paintings. We focus particularly on using digital cameras to capture images of the object with wavelength selection provided by narrowband sources and camera filters. We aim to better understand what is meant by multispectral imaging of historical material, and to establish best practice. Our approach uses a mixed method approach of Action Research, including: a literature review; unstructured interviews and dialogue with practitioners; and reflective practice. This research will offer new insights to those working in imaging in heritage institutions, such as curators, conservators and collection managers, allowing them to review, compare, and contrast current practices, and to better understand how and where MSI may be most appropriately used.

We found that the documentation of current MSI applications to cultural heritage objects is often inconsistent, which means it is often difficult to interpret, compare, reuse, or reproduce

[1] We distinguish here between multispectral imaging and hyperspectral imaging: the latter divides the spectrum into many more finely defined bands (see [90] for an overview). The camera-based systems we focus on typically capture 10-20 images at discrete wavelengths whereas hyperspectral (or ultraspectral) scanning systems capture hundreds to thousands of images in a continuous range of wavelengths [188]. Hyperspectral imaging systems have higher spectral resolution but lower spatial resolution than multispectral imaging systems. There is a compromise between spatial resolution, spectral resolution and imaging and processing time. Camera-based MSI tends to prioritise spatial resolution and capture time but gives relatively poor spectral resolution whereas scanner-based HSI tends to give excellent spectral resolution but require more time to acquire the data. Furthermore, MSI systems use a camera to capture the entire scene in each image, building the spectral dimension of the dataset as the illumination changes in each image. In contrast, HSI systems use a grating or prism to acquire the full spectral resolution for a single line in the scene and build the spatial dimension of the dataset for each scan. Scanning systems have been excluded from this study because the pipeline for scanning systems (such as those in [189]) differs widely from that for camera-based systems.

results. We identify and characterise the most commonly used pipeline for MSI in cultural heritage, including the consideration of the object, the imaging environment, the setup of equipment, capturing the sequence, image processing, data management, and management of metadata documenting each aspect of the method. We identify further research that is required to improve the current techniques used to analyse multispectral images, particularly regarding flat field correction, registration, and image processing. We recommend that thorough metadata are recorded to allow interpretation, interoperability, and dissemination of results. We advise that researchers in this area should be assiduous in detailing their methods when publishing results, whether in peer-reviewed journals or through the media, and provide an overview of which documentation should be captured.

2 Research Aim

This research aims to characterise the process of MSI in cultural heritage with the objective of understanding, analysing, and improving the process for objects such as documents, manuscripts and paintings.

3 Multispectral Imaging

Multispectral Imaging (MSI) was originally developed for remote sensing applications [1], such as environmental monitoring [2], [3], but has since been used across a variety of scientific applications including medical imaging [4–7], agriculture and horticulture [8–10], food science technology [11–14], and astronomy [15–17]. A major advantage of MSI for cultural heritage is that it does not require samples to be taken from the object. Materials such as inks and parchment interact with different wavelengths of light in various ways, for example, iron-gall ink reflects infrared light whereas carbon-based ink absorbs it [18]. MSI can differentiate between different inks and pigments [18–20], recover hidden features [21–24] and provide information on the current condition of an object [25-26], which can be useful for conservation practice.

Light with wavelengths invisible to the human eye was first used to enhance faded text in the early 1900s by Raphael Kögel [27-28] who used ultraviolet light to increase the contrast between the background and the text. Since then images have been captured for a range of historical artefacts in order to recover lost text and features, such as the Dead Sea Scrolls [21], [29], Petra and Herculaneum scrolls [22], the Archimedes Palimpsest [30], and the letters of David Livingstone [31]. It has been widely used to recover undertexts in palimpsests ([23], [31]–[34]) as well as to locate watermarks in paper documents [35-36] and underdrawings in paintings [25], [37–39]. However, research into the optimal application of MSI in cultural heritage is still relatively scarce, and where it exists it tends to be specific to reporting the results of a particular artefact (see [30-31], [34], [40-41]). Reports often focus on the results of the technique rather than the method which allowed those results to be created ([21], [24], [31], [38], [41–46]).

Systems have progressively developed from illuminating the artefact under broadband illumination and selecting wavelengths using external filters fixed to the camera lens (see [18–20], [47-48]), to illuminating the artefact directly with narrowband light emitting diodes (LEDs) (see [23], [31], [35], [49–51]). The latter systems use filters to exclude the illumination light, allowing images to be acquired of the fluorescence (see [23], [34], [45], [52]). Although the systems themselves have developed (and the costs reduced) over time, the same processing techniques are still applied. Indeed, techniques such as Principal Component Analysis[2] used in the Dead Sea Scrolls project continue to be used (see [34], [47], [53]–[55]).

Furthermore, the systems used, processing techniques applied, the metadata recorded, and even the data management change depending on the user, artefact and institution. This is an unfortunate consequence of working with unique items, which all have different research challenges, making comparisons and standards more fluid. Emery et al. [56] and France et al. [57] wrote reports that described advanced digital imaging in museums and libraries. Although the reports included MSI, the latest was published in 2010 and technology has since advanced. Another report was created in 2013 as part of the CHARISMA (Cultural Heritage Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to conservation and restoration) project, which described MSI using camera-based systems that use wideband illumination and external filters, but did not include the process for more expensive, narrowband systems [19]. Therefore, the current pipeline for MSI needs to be overviewed.

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[2] Principal Component Analysis is a statistical procedure commonly used to reduce the dimension of a set of data [190]–[194] covered more fully below.

While literature concerning the application of MSI to specific artefacts provides insight into the objects, it can be difficult to ascertain its effectiveness when applied to other objects. Inadequate documentation means that efficiencies cannot be identified, best practice is not shared, and it can be challenging to reproduce or reanalyse results obtained elsewhere. Furthermore, academic and heritage institutions tends to have different objectives: academia is motivated by peer-reviewed publications [58], whilst heritage institutions are interested in increasing access and conservation [59]. Therefore, documentation can be inconsistent due to the focus of the publication, and the objectives of the authors and institution carrying out the research. Furthermore, although many papers describe the imaging process for particular artefacts, such as palimpsests [23], ostraca [60], paintings [25] and carbonized papyri [22], collections usually contain a variety of artefacts. Consequently, a pipeline describing techniques is required to better understand what is currently meant by multispectral imaging in cultural heritage. This will allow MSI to be undertaken efficiently, to high quality, and encourage better and more systematic documentation of method and approach in project management and future published work.

4 Method: Action Research

Action Research seeks to "build a body of knowledge that enhances professional and community practice". It is an established method in Information Studies to involve researchers within methodological processes to understand and document their nuances ([61], p1 and [62–65]). For our purposes, this included gathering information in the following ways: a review of published literature using MSI within cultural heritage; unstructured interviews and dialogues with practitioners who regularly operate and supply MSI systems for cultural heritage; and reflective practice using the system ourselves (for example, see [52], [66–68]), with diaries, case studies, transcripts, and reports being gathered before analysis and synthesis.

The literature reviewed in this research involved papers that appeared in electronic searches of federated publication portals, such as Web of Science[3], Scopus[4], Google Scholar[5], and UCL's Library Services[6] catalogue, using the search terms: multispectral/multi-spectral/multi

[3] http://webofknowledge.com
[4] https://www.scopus.com
[5] https://scholar.google.co.uk/
[6] http://www.ucl.ac.uk/library

spectral imaging, and heritage imaging. Additional papers were found using chaining [69]. Papers were excluded if they were duplicates, if the systems were scanning-based rather than camera-based, if the papers concentrated on imaging of buildings or sites, and if the papers were not in English. The resulting corpus contained 66 papers, mostly published in the last 8 years (although the earliest was from 1996) from European and North American institutions. These papers showed how MSI was undertaken by practitioners in the heritage sector, using an approach based on content analysis methods [70].

Sixteen practitioners who regularly capture, analyse and manage multispectral images at major institutions such as the British Library, Library of Congress, Duke University, University of Manchester, University of Wisconsin-Madison, the University of Pennsylvania, UCL and the Metropolitan Museum of Arts, and industry organisations (R. B. Toth Associates[7] and Equipoise Imaging[8]) provided insight about their systems and workflows. These practitioners used different systems including R. B. Toth Associates, MegaVision and that of their own in-house design. Unstructured interviews were carried out in person, over online video-chat, and via email: the iterative process of Action Research resulted in drafts of this pipeline being shared and annotated by colleagues to further include their input (which is a standard and crucial part of the methodology [65]). The practitioners agreed to take part in the research but their names are not included so as to focus on the overall workflow rather than that of individuals. Grey literature was also included in the corpus, including training manuals and system documentation (e.g. [19], [71], [72]).

Information was consolidated into a general MSI pipeline. This identified users' understanding of MSI in cultural heritage, best practice, and areas requiring further research and development. By using the Action Research framework, we have been able to "review the relationship between theory and practice, and the role of the participant as researcher, subject, and actor" ([73], p.606) in order to fully understand what is meant by multispectral imaging of historical artefacts.

5 Findings: The Multispectral Imaging Pipeline

[7] http://rbtoth.com/index.html
[8] www.eqpi.net

We found that MSI involves a variety of stages starting with the consideration of the object and the imaging environment, the setup of equipment, capturing the sequence, image processing, data management, and management of metadata (Figure 1).

[FIGURE 1]

Figure 1. Current pipeline for multispectral imaging of historical artefacts.

5.1 Considering the Object

A critical initial step is for the imaging scientist and the heritage practitioner to discuss the object and the imaging requirements. This conversation can reveal any misunderstandings and lead to agreement on handling the object and determining the most efficient imaging protocol. Research that focuses on multispectral imaging of a particular artefact or class of artefacts (such as carbonized papyri [22], [33], palimpsests [23], ostraca [60], [74] and paintings [25] and exposure to damage [47] enables heritage practitioners to determine whether MSI in general is appropriate. The optimal combination of wavelengths and filters depends on the research question and the artefact itself, however, little research is available [19], [20], [47]. The object's condition may affect the success of MSI, including whether it is framed or mounted [75], has undergone previous conservation treatment [25], [57] or has experienced any damage (such as fire [22], [29], water, mould, deliberate abrasion [47], [52], etc). Large objects that do not fit within a field of view may be captured in sections and reassembled using mosaicing [26], [45], [76], [77]. Objects that have uneven surfaces can cast shadows which obscure surface areas and make it difficult to focus on differing depths, potentially requiring multiple sequences, a process sometimes referred to as z-plane imaging [57]. Background, supports, and weights may be required to prevent object movement, in consultation with curators and conservators.

5.2 The Imaging Environment

Imaging must be undertaken in a darkened room. The imaging environment should follow heritage imaging studio standards, including neutral grey walls for accurate colour reproduction [78-79]. The environmental conditions of the room (humidity, temperature) should be set to levels that best preserve the artefact [80] and monitored throughout the study. Furthermore, as hygroscopic materials are highly sensitive to changes in humidity and temperature, ensuring these conditions remain stable during imaging will limit any object movement.

5.3 The Multispectral Imaging System

Multispectral imaging systems comprise a camera body, lens, lights, filters, and computer. Image quality is largely dependent on the camera sensor and lens, the choice and setup of filters, and the spectral output and power of the lights. Documentation of the system setup is inconsistent, and photographs of the system rarely feature. The R-CHIVE (Rochester Cultural Heritage Imaging, Visualisation, and Education) group in the United States and the European COSCH (Colour and Space in Cultural Heritage) network have compared the results from different multispectral and hyperspectral imaging systems for heritage applications [83–85] and found that the results "showed a considerable variability in the image data" due to the differences in "their measurement geometries, the methods of data processing, the personnel operating the imaging systems, and the guiding purpose for application" [84]. Those that do include images of the system setup [23], [35], [47] or diagrams [81-82], provide a visual understanding of the system and enable the comparison of different systems and setups. We recommend including a labelled image alongside a detailed description of the system as an essential part of the metadata, providing readers with information needed to repeat the experiment.

5.3.1 Camera Sensor

To detect near infrared light with a commercial camera, the infrared filter must be removed from the sensor ([19-20], [41], [45], [86-87]), however, some cameras are now designed specifically without an infrared filter for MSI [68], [88–90]. Monochrome camera sensors ([35], [57], [68], [91-92]) are more common than colour sensors [93-94], although the colour filters on the sensor used to image the Archimedes palimpsest enchanced the writing by revealing fluorescence [76]. Silicon Charged Coupled Devices (CCD) or Complementary Metal-Oxide Semiconductors (CMOS) sensors are commonly used for MSI [20], [60], [87], [95–97], giving wavelength sensitivity from approximately 350 nm (ultraviolet) to 1100 nm (near infrared) [19-20], [28], [41], [60], [74], [87], [98], although the CHARISMA manual states that the sensitivity is actually wider than this range but is restricted by the choice of lens [19]. Camera sensors are typically described according to pixel resolution (typically between 30 megapixels [23], [31], [74], [99] and 60 megapixels [34], [45], [100]) and sensor sensitivity although newer systems incorporate 100-150 megapixel backs with 15 bit depth [101], [102], [103]. Additionally, the dimensions of the sensor, the bit-depth and the sensor type (i.e. CCD or, increasingly CMOS) were sometimes recorded.

5.3.2 Camera Body

A digital Single-Lens Reflex (SLR) or medium format monochrome[9] camera is typically used to capture multispectral images [23], [35], [49], [105], [106]. Reports do generally state the make and model of the camera. The camera is typically attached to a copy stand, but can be attached to a tripod for horizontal capture of items such as paintings [91], [107]. Portable MSI is necessary for imaging fixed objects such as rock art and wall paintings [108]–[110].

5.3.3 Camera Lens

The lens affects focus, field of view, depth of field, chromatic and spherical aberration [111] and wavelength transmittance. Calibration targets can be used to ensure the images have sharp focus [19]. The aperture of the lens determines the depth of field and must be small enough that the entire region of interest is in focus, although a small aperture can extend the exposure time. The aperture and the exposure times of the images should be recorded in the metadata for each image.

As MSI uses wavelengths outside of the visible range, an apochromatic lens should be used in which ultraviolet, visible and infrared wavelengths are focussed to the same point [111]. Apochromatic lenses are widely used [23], [60], [68], [87], [97], [112], [113].

Lenses used for general photography have low transmittance in the ultraviolet region. Therefore, quartz lenses, which allow shorter wavelengths of light to pass to the sensor, are useful for capturing reflected ultraviolet illumination [23], [42], [112]. It is uncertain whether a quartz lens is required for MSI as the silicon camera sensors are less sensitive at these wavelengths [19], [20]. However, if ultraviolet reflectance images are to be acquired, using a quartz lens is best practice. Details of the camera lens were included in some publications (e.g. [35], [91]).

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[9] See Adams and Baker [111] and Langford et al. [195] for definitions and descriptions of the different camera terminology.

5.3.4 Lights

The artefact can be illuminated using narrowband LEDs ([23], [31], [34], [45], [52], [74], [99], [100], [112]) or broadband light ([20], [114-115]). LEDs only illuminate the object with specific wavelengths and so reduce the exposure and risk of damage compared to broadband illumination [76], [112]. Light panels typically contain 10-20 LEDs from 365 nm to 1050 nm [23], [66], [100], [112], [116]. The peak wavelength for each individual LED is sometimes specified ([23], [99]). Recording the spectra of each LED using a spectrometer can be useful, especially when verifying the system specifications or when the wavelength range can be used for advanced image processing.

The lights should be positioned around the copy stand to uniformly illuminate the imaging plane. Extra light panels at a lower angle can capture raking light images of the artefacts, highlighting surface features [23], [26], [43], [100]. Transmission imaging, where the source of illumination is beneath the artefact, has been used to successfully detect watermarks [26], [35], [36]. Diffusers attached to the light panels soften the lighting and disperse shadows, ([35], [50], [100], [112], [113], [117]), but can also soften details and edges [80]. Information regarding the lights is often omitted [41], [48], [89].

Exposure of ultraviolet radiation can cause objects to become brittle, yellow, bleached or fade [75], [118], [119], depending on the intensity and duration of the radiation [98], [120]. Therefore, researchers have investigated the risk of light-induced damage [98], [121]–[123]. In one study, a 30 second exposure using ultraviolet LEDs was calculated to “result in the same delivered UV dose as 1.04 days on display” ([123], p. 2). Researchers planning to undertake MSI can repeat the methods in these reports and compare to standards ([120], [124]) to provide conservators with a quantified measure of damage that the object would be exposed to if the imaging were to be undertaken. It is recommended to minimise exposure to ultraviolet light to reduce any risk to the object.

5.3.5 Filters

Filters are used to reduce the range of wavelengths from the light source [20], [41], [47], [48], [89], [104], [115] or to exclude illuminating light when imaging fluorescence [23], [34], [45], [52], however the make and model are rarely described. When filters are used in conjunction with a broadband light source, the spectral ranges are often stated ([41], [47], [48], [115]), whereas when used to capture fluorescence, often only the region of the spectrum is documented [23], [34], [45]. As these filters are usually broad bandpass[10] or longpass[11] filters, simply stating the region is often sufficient, however, it would be good practice to document the boundary wavelengths for a bandpass filter and the lower bound for a longpass filter.

5.3.6 Computer

The specifications needed for a computer used for capturing multispectral images are different to one used for image processing. Adequate RAM and a powerful Central Processing Unit (CPU) are required for image processing, while for capture, adequate data storage is more important (10-20 GB is often required for each study including multiple image sequences). A large, high-resolution, calibrated monitor is needed to show colour accurately. These parts of the system are rarely documented, except where bespoke processing algorithms are developed [81].

Software used to acquire the multispectral images includes Spectral XV (produced by Equipoise Imaging LLC [66], [68]) and Photoshoot (produced by MegaVision USA [45], [99]). Such software often automatically records relevant metadata, such as wavelengths, filters, and camera settings [125].

5.3.7. System Set Up, Calibration and Maintenance.

Regular calibration must be undertaken to correct for lens distortion [126–128], assure colour management processes [50], [88], [129], and to be certain of the repeatability of results [84], [100]. The importance of scheduling time for quality assurance is rarely mentioned [20], [113], [80]. US Federal Agencies Digitization Guidelines Initiative (FADGI) technical guidelines for digitizing cultural heritage materials recommend weekly calibration [80]. Time must also be set aside for preventative maintenance, including cleaning of lens and filters, and bi-annual replacement of calibration equipment.

5.4 The Capture Process

[10] Bandpass filters allow a specified band of wavelengths to pass through.
[11] Longpass filters allow any wavelengths longer than a specified lower bound to pass through.

For high quality results, it is essential that images are correctly exposed, have sharp focus and a high signal-to-noise ratio, and are calibrated before any subsequent analysis is undertaken. The image quality is dependent on the exposure, aperture, and ISO, however these imaging parameters are often not reported. The optimum exposure depends on the position and wavelength of the lights, presence of filters and the object itself and is different for each imaging project. It is critical to record metadata regarding all aspects of the capture process. It would also be beneficial to document the spectra and strength of each LED, which could be incorporated into the image header files and used for calibration.

To identify whether unexpected errors, such as movement, have occurred, capturing identical images at the start, middle and end of the sequence can be considered. A calibration target and a ruler should be in the field of view of each image, however, if this is not possible, an additional sequence of images can be captured of the targets under the same conditions [19], [54] for colour and luminance calibration. Targets used in the literature include colour targets [19], [35], [54], [83], [130] and Spectralon reflectance targets [19], [54], [130], [131]. Some of the colour targets are only calibrated for visible light, whereas Spectralon has uniform reflectance over ultraviolet, visible and infrared wavelengths [19], [54].

Images should be captured in the camera's RAW format and then converted into a high-resolution lossless TIFF, the recommended archive format [78], for storage and further image processing [23], [35], [45]. A linear gamma correction[12] is used to ensure that the intensity values are the same in the saved file as the corresponding pixel response on the camera sensor. Dark Frame Correction (when an image is captured with the shutter closed to record any noise from the camera sensor which is then subtracted from the original to improve signal to noise ratio) is sometimes used [23], [112], [132–135].

Flat Field Correction (where a uniformly-reflecting surface is captured under identical conditions to the capture of the object to remove the non-uniform illumination or camera sensitivity) is commonly described [19], [21], [112], [113], [133], [135–137], [23], [25], [34–36], [38], [45], [82]. The material used should be flat, uniformly reflective, with minimal surface texture and no fluorescent brighteners. Therefore, many modern papers are not

[12] Gamma correction is a power-law transformation applied to images. When gamma<1, darker areas become brighter and vice versa for gamma>1. When gamma=1, pixel values remain unchanged.

suitable. Some of the literature minimally describes the material, stating only "paper", a "whitecard" or a "blank, white target" was used [34], [38], [97]. To prevent any artefacts on the material being transferred to the multispectral images, the camera is often defocussed when capturing the flat field images [19], [138]. Alternatively, the flat field images can be digitally cleaned [71].

Before image processing, any signification misalignments in the sequence of images must be corrected. This typically involves aligning the images either using their features (feature-based registration) or intensities (area-based registration) [68]. Although the need for registration is mentioned in the literature where external filters are attached to the camera lens (meaning that light refracts as it passes through the filter, and thus reaches the sensor in a different position than when there is no filter present ([25], [76], [88], [126], [139]), it rarely appears in papers using the newer systems with narrowband LEDs, even when filters were used to acquire fluorescence images [34], [41], [115]. However, as the number of pixels in camera sensors increase, they become increasingly sensitive to misalignment.

Finally, documented quality assurance processes should be implemented to ensure that images are correctly exposed and focussed, with no imaging artefacts, calibration targets are in the field of view, and that any labels and file names are correct. For example, Webb et al. [87] used the FADGI Digital Imaging Conformance Evaluation (DICE) target to assess noise, sharpness and resolution. Images with errors must be recaptured. This quality assurance step is rarely noted in the literature [35], [76], [87].

5.5 Image Processing

Various image processing techniques have been used to facilitate the identification of individual features and attributes of artefacts by highlighting differences and similarities between images in the capture sequence. The approach taken depends on the user, artefact and institution, and includes: Contrast Stretching [41], [88], [94], [116], [140], Spectral Curves [37], [49], [81], [91], [98], [114], [135], [141], Principal Component Analysis [21], [38], [74], [110], [126], Independent Component Analysis [34], [89], [139], [142], Linear Discriminate Analysis [55], [143]–[146], Spectral Mixture Analysis [30], [89], [98], [104], [139], Mosaicing [35], [45], [77], [91], [100], Clustering [22], [37], [47], [104], [147], [148], Spectral Angle Mapper [55], [149]–[153] and Colour Image Processing [22], [34], [37], [52],

[82], [100] including: Pseudocolour Rendering, False Colour Image Creation, and True Colour Image Creation. It would be good practice to record any processing techniques used in data analysis, including a brief description of the method as the terminology often varies between papers.

Contrast stretching increases the contrast in an image, or area of an image, by redistributing the pixel values to cover the whole range of greyscale values. This can be done in many ways, such as by mapping the minimum intensity value to 0% and the highest to the 100% and linearly scaling between or with histogram equalisation, which evenly redistributes the grey levels to flatten the histogram. These methods are simple yet effective [41], [42], [88], [94], [116].

Spectral Curves (or reflectance curves) show the reflectance of a pixel at each wavelength, with the resulting unique "signatures" assisting the identification of materials [37], [49], [81], [91], [98], [114], [135], [141], [154]. As multispectral images are captured using discrete wavelengths, reflectance values between must be interpolated and so are not as accurate as the curves produced by hyperspectral imaging or spectrophotometers. Nevertheless, spectral curves generated by MSI have been successfully used to distinguish between materials and identify any changes from exposure to different conditions [114], [154]. The spectra can be directly compared to reference pigments and materials that are placed alongside the object in the images [155], or they can be converted to relative reflectance by dividing the pixel intensity by the intensity values of a calibrated reference standard, such as 99% reflectance spectralon, and compared to a reference library [114], [141], [154], [155]. This reference library may be made with the same imaging system [98], [114], [154] or a different technique, such as spectrophotometry [91]. France et al. [154] developed an open-source tool that enabled researchers to create spectral curves through a standardised procedure that used white reference material to calibrate the spectra which could then be compared to a reference library [154]. Kubik [155] increased the signal-to-noise ratio by averaging spectra over three points. Registration may not be required if the neighbouring pixels contain the same material as the pixel of interest. However, to compare spectral curves from an object generated at different times, image cubes must be registered [88].

Mosaicing is used to stitch together multiple images of an object [156-157] that is too large to be imaged with a single photograph. It was widely used in MSI of historical artefacts, such as large paintings [45], [96], maps [57], [158] and curved paintings [159], but is less necessary with newer high resolution sensors. The process involves image registration (to align images), reprojection, stitching and blending (to smooth errors that can occur at the seams of stitching) [157]. Mosaicing algorithms can be computationally complex and time consuming [35], [37], [76], [126] and either use bespoke interfaces [33], or commercial software packages [35], [45], [48], [76], [82]. Some authors describe mosaicing algorithms [45], [91], [96], [98] whereas others simply state that mosaicing was used without stating which algorithm was used [23], [33], [56], [126], [160]. Fully explaining the approach taken would assist others in their application of mosaicing algorithms and software.

The crux of MSI image processing is the use of techniques that can enhance features of cultural heritage objects such as multivariate statistics. Principal Component Analysis (PCA) is a statistical technique used for data compression and feature extraction. It creates a new set of images called 'principal components', which can show features that are enhanced compared to the original images[13]. The images that are created, which we refer to here as principal component images, are linear combinations[14] of the original images and are ordered so that the first principal component image contains the largest variance, and later principal component images contain decreasing variance. Typically, the first few principal component images show the main features of the object and later principal component images show dependencies in the data that may have not been noticed and can be useful for revealing faint features, such as undertext [28], [161]. Later principal component images may also contain noise, and the selection of appropriate principal component images is often subjective.

PCA is one of the dominant image processing methods used in MSI image analysis, however, the justification and implementation of PCA is rarely described. For example, Comelli et al. [107] simply state that "principal component analysis (PCA) was considered", and other papers (see [24]) discuss the results from PCA but do not describe the implementation.

[13] It involves orthogonally diagonalising the covariance[13] matrix of a data set thereby creating the matrix of eigenvectors that are used as the basis to project the original data into new, uncorrelated data [3], [167]. For definitions and more information on orthogonal diagonalization, eigenvectors and basis see any linear algebra textbook such as [196].
[14] A linear combination of images involves adding and subtracting weighted versions of them to create a new image.

Terminology is used inconsistently, demonstrating an uncertain application of the process. For example, the term ‘principal components’ is used to define the eigenvectors of the covariance matrix in [36], [126], [133], [137], [162], but is used to define the new, uncorrelated images in [23], [38], [160], [47], [76], [82], [92], [110], [116], [135], [142]. The latter definition is used in the original 1933 paper by Hotelling [163] and so is the recommended terminology. These images are sometimes referred to as ‘PCA bands’ [34], [164], and ‘principal component scores’ [99], [107], [116] as well. This deviation from the standard, widely-accepted mathematical and statistical use of the terminology of PCA [161], [165]–[167] suggests that the approach is not well understood in the MSI cultural heritage community and makes it difficult for those who have not previously come across PCA to understand the process. We recommend using the terminology from Hotelling’s original paper [163], which uses ‘principal components’ to describe the new uncorrelated images. To avoid ambiguity, we call the images ‘principal component images’.

Likewise, Independent Component Analysis (ICA) transforms a data set into a new statistically independent set [168]. It is similar to PCA, except the new components resulting from the process are independent rather than uncorrelated, and the independent components are not ordered like the principal components [139]. ICA has been used for feature extraction such as recovering ink [47] and separating layers of text [139]. It is difficult to know *a priori* which multivariate statistical analysis technique will produce the desired results and thus multiple techniques are often applied to the images. Research which compares different processing techniques, such as [37], [47], [139] can assist optimisation of resources, and open discussion and comparison will inform the choice of image processing methods in future research.

Linear Discriminant Analysis (LDA) is a dimension reduction method that, unlike PCA and ICA, is supervised and thus requires a subset of labelled data [55], [143–146]. This can be provided by experts with knowledge of the materials and inks in the sample, or by applying an exploratory technique, such as clustering, to the multispectral images [169]. LDA classifies the pixels in the images according to the labelled set of reference spectra by maximising the differences between the categories. False colour images can be created by combining the results from LDA [143].

Pixels with similar properties can be grouped together using a clustering algorithm such as K-means clustering [44], [47], [104], [147], [148], fuzzy C-means [37], [44], [147], Gaussian mixture models [148], and the Linde, Buzo and Gray clustering algorithm [22], [170]. Since clustering methods are unsupervised techniques, they do not require labels and instead cluster the data based on some distance measure. When applied to multispectral images of historical manuscripts, different inks and materials can be separated into distinct clusters based on their spectra.

Spectral Angle Mapper (SAM) is a classification method that measures how similar two spectra are by calculating the angle between them [55], [108], [149–152]. SAM can generate similarity maps that show pixels with similar spectra, identifying materials with similar characteristics. This technique is an effective and computationally efficient method for segmenting multispectral images into areas with different chemical compositions [150], [151]. However, unlike spectral mixture analysis, SAM cannot be effectively used for mixtures of pigments and materials. Clodius et al. stated that SAM is often used to guide "whether other, more numerically intensive, methods may be useful" ([149], p. 1411).

Spectral Mixture Analysis separates the spectral response of a pixel that contains a mixture of substances into the individual spectral responses of the materials [171]. It is occasionally applied to MSI [30], [42], [47], [76], [98], [104], [139], [172] to separate a mixture of different materials, such as pigments or inks (such as for palimpsests). The spectral contrast between the separate materials must be large enough in order to distinguish between them: it is therefore more suited to hyperspectral than multispectral imaging due to its higher spectral resolution [172]).

Other image processing methods have been applied to multispectral images including Multivariate Spatial Correlation [32], Minimum Noise Fraction Transform [54], Self-Organising Maps [55], [173], and others [55], [81], [109], [143], [146], [174].

Colour Image Processing is commonly used to display and enhance differences by artificially creating colour images from greyscale images. The terms 'pseudocolour' and 'false colour' are used interchangeably in the literature even though they are distinct. A pseudocolour image is created by mapping different intensity values or features in a greyscale image to a range of colours [38], [175]. For example, in order to distinguish between the different clusters in the data set, a colour can be assigned to each of the separate clusters, thereby forming a pseudocolour image [22]. In contrast, a false colour image is created by placing several greyscale images into different colour channels combining the features from all of the images into one [176]. False colour images are often created by combining multispectral images captured in visible light with those captured under ultraviolet or infrared [19], [20], [92], [94], [139], [140], [177]–[179], [30], [31], [34], [37], [42], [43], [76], [82] and by combining the results from various image processing techniques such as PCA, ICA, and LDA [31], [34], [82], [139], [143]. They have also been created from combinations of multispectral images and the results from the different statistical techniques [28], [54]. True colour images are created using the multispectral images captured under visible light, and authentically portray the colours if all images captured under narrowband visible lights are used and weighted appropriately [26]. A calibrated colour target, such as the X-rite colourchecker, is used to calculate the weightings for each wavelength [100].

Image processing may be carried out using commercial software, such as ENVI [48], [92], Photoshop [45], [90], and MATLAB [97], [116] or open-source software, such as ImageJ [86], [110] and HOKU [180]. Academic institutions are more likely to have licences for commercial image processing software than heritage institutions. Using and developing open-source alternatives ensures any MSI researchers can produce high-quality results.

Research that compares different image processing techniques (for example, [47], [144], [146]) is useful to identify methods that yield the best results for different classes of objects. To maximise the applicability of these results, it is necessary to document reasoning, choice of image processing technique, application, and comparison of results when applied to individual MSI cultural heritage case studies. However, the motivation behind the choice of image processing techniques is rarely described. We recommend that a more critical approach is taken to this part of the method, with fuller documentation and discussion of results provided in published research.

5.6 Data Management

MSI data management is challenging, due to the large volume of images created, which require data-storage facilities to be available. The challenges of dealing with large data sets are discussed in the literature [24], [33], [35], [47], [56], [126], [181], with Christens-Barry et al. emphasising how managing the data “proved critical to the project” ([35], p. 5). A storage plan and process must be established which describes the resources, what information to discard, whether to preserve all images at each stage of the capture and image processing pipeline, file formats, retention of calibration information, and the establishment of data back-up procedures. With certain file formats (such as TIFF) it is also possible to capture metadata into each individual image file header [78], [182] and it is recommended that at least minimal metadata requirements are saved with each image capture [78]. To maximise future research and analysis, data should be shared, although this requires a systematic approach and access to resources that allow storage and distribution of large volumes of image data, with financial implications [26], [56]. The absence of a data standard which would allow interoperability of MSI image data and documentation is frequently mentioned (see [24], [26], [35], [56], [181]), although this requires access to appropriate programs to display, organize and analyse large sets of image data. Although many teams develop bespoke viewing software [20], [33], [44], there is increased interest in exploring how the International Image Interoperability Framework (IIIF) [183] can facilitate MSI image distribution and inspection and compatible storage of metadata in .json files. Documentation must be maintained to ensure data can be subsequently retrieved and reused, and open discussion of these issues is necessary to building common community approaches to address this issue. We recommend the FAIR (Findability, Accessibility, Interoperability and Reusability) principles [184]: a set of guidelines that encourage a rigorous management plan for data (and the algorithms, tools and workflows used to create that data), encouraging findability and reuse.

5.7 Metadata

Metadata is data concerning acquired and processed data [185]. In MSI, metadata must be recorded for the object, system, acquired images, processed images, data management and the metadata itself. It is widely acknowledged in the cultural heritage industry that detailed metadata is necessary for the management and preservation of digital images [78]. As described above, documentation regarding MSI processes, methods, and results is often lacking in published research, however, detailed metadata is required if the results are to be reused or repeated. The requirement to record metadata following a standard is mentioned in several papers [35], [56], [23], [24], [113], [47]. However, it is recognised that metadata for images in art conservation research is often lacking, and cannot be assumed to be thoroughly recorded [186]. Furthermore, MacDonald et al. stated that “the recording of metadata was generally found to have been neglected” rendering the assessment and comparison of data impossible ([84], p.15). Metadata standards have been written for MSI of heritage artefacts, such as the Archimedes Palimpsest Metadata Standard (APMS) [125] which is built on the Dublin Core Metadata Initiative [187]. This standard recommends recording the identification information of the image, spatial data reference information relating the image to the object, the imaging and spectral data reference information, data type information, data content information, and metadata reference information, and provides information on how to record and manage the metadata [125]. The FAIR principles contain recommendations for metadata such as “clearly and explicitly include the identifier of the data it describes” and ensure that “metadata are accessible, even when the data are no longer available” ([184], p. 4). We discuss our recommendations for metadata capture, for both project management and publication, below.

6. Recommendations

Our research resulted in a description of the MSI pipeline as well as a list of recommendations for best practice (Table 1) and for documentation (Table 2). These recommendations are intended to ensure that MSI results can be reused by other researchers regardless of the system. We recommend that the following metadata is recorded: the reasoning for performing MSI; measurements of the setup; a description of the object; the settings for the capture process; any calibration; software and algorithms of image processing methods; where and when the metadata was recorded, who recorded it and the standard followed. All of this information should be captured as part of a project management system. As much of this as possible should be published, for transparency and effective sharing of approaches and results.

[Table 1]

Table 1: The recommendations for best practice of the pipeline of multispectral imaging in cultural heritage

[Table 2]

Table 2: The recommendations for documenting the pipeline of multispectral imaging in cultural heritage

7. Conclusion

MSI is increasingly being applied to cultural heritage objects. However, there is a lack of documentation regarding what this process actually entails. We garnered information of different MSI pipelines using a camera-based system with narrowband light sources. This enabled the overall process to be better understood and highlighted areas that require further research. This was done using a standard Action Research methodology: reviewing the current literature; interviewing and visiting expert practitioners, and personal experience with multispectral imaging, which allowed us to engage both with the process, its practitioners, and its documentation. This varied approach, undertaken over a year long investigation, allowed us to synthesise the different information and expertise encountered into a full understanding of the MSI pipeline, which will be a useful reference for both experienced practitioners and those new to the technique.

Within the pipeline, we identified various areas that require further research and improvement. For example, the stage of flat field correction is a time-consuming process that varies across the literature, and further research is required to understand how effective it is, and when, if ever, it can be omitted. In addition, we established that the requirement for registration of MSI images is poorly understood, and that more effective methods could be established for alignment of images to allow accurate processing, given feature-based registration methods often fail with MSI captures. Blind Source Separation methods (such as PCA and ICA), Linear Discriminant Analysis, Spectral Angle Mapper, clustering techniques and Spectral Mixture Analysis are the most common methods used for feature enhancement and classification. It is likely that image processing techniques used in other fields of research, such as medical imaging and remote sensing, will also achieve good results. To ensure optimal results are achieved, the effectiveness of these techniques should be assessed to assist others wishing to understand how to undertake imaging of specific cultural heritage objects and media in an effective and cost-efficient manner.

We found that published documentation of the MSI pipeline in cultural heritage is inconsistent. As the cost of MSI systems using narrowband light sources decreases, technical capabilities accelerate and access to these tools increases, understanding the pipeline is necessary to encourage best practice in both implementation and reporting, and to encourage reproducibility of results via the comparison of approaches and their resulting datasets. Each stage of the pipeline should be fully documented to enable researchers to reuse and repeat results produced by others. Our recommendations provide a reference for MSI researchers to ensure that all of the essential details are recorded throughout the process, for project management, reporting, reproducibility and comparison of experiments, and to better inform those who are considering utilising MSI to answer research questions related to historical artefacts.

The current MSI pipeline is rarely well documented. We hope that our attempt to understand and document the optimal method for capturing and processing multispectral images of heritage artefacts using a camera-based system with narrowband light sources will help others to consider their method, produce the best quality results in their approach, and document and share results and data in a way which will benefit the wider cultural heritage imaging community.

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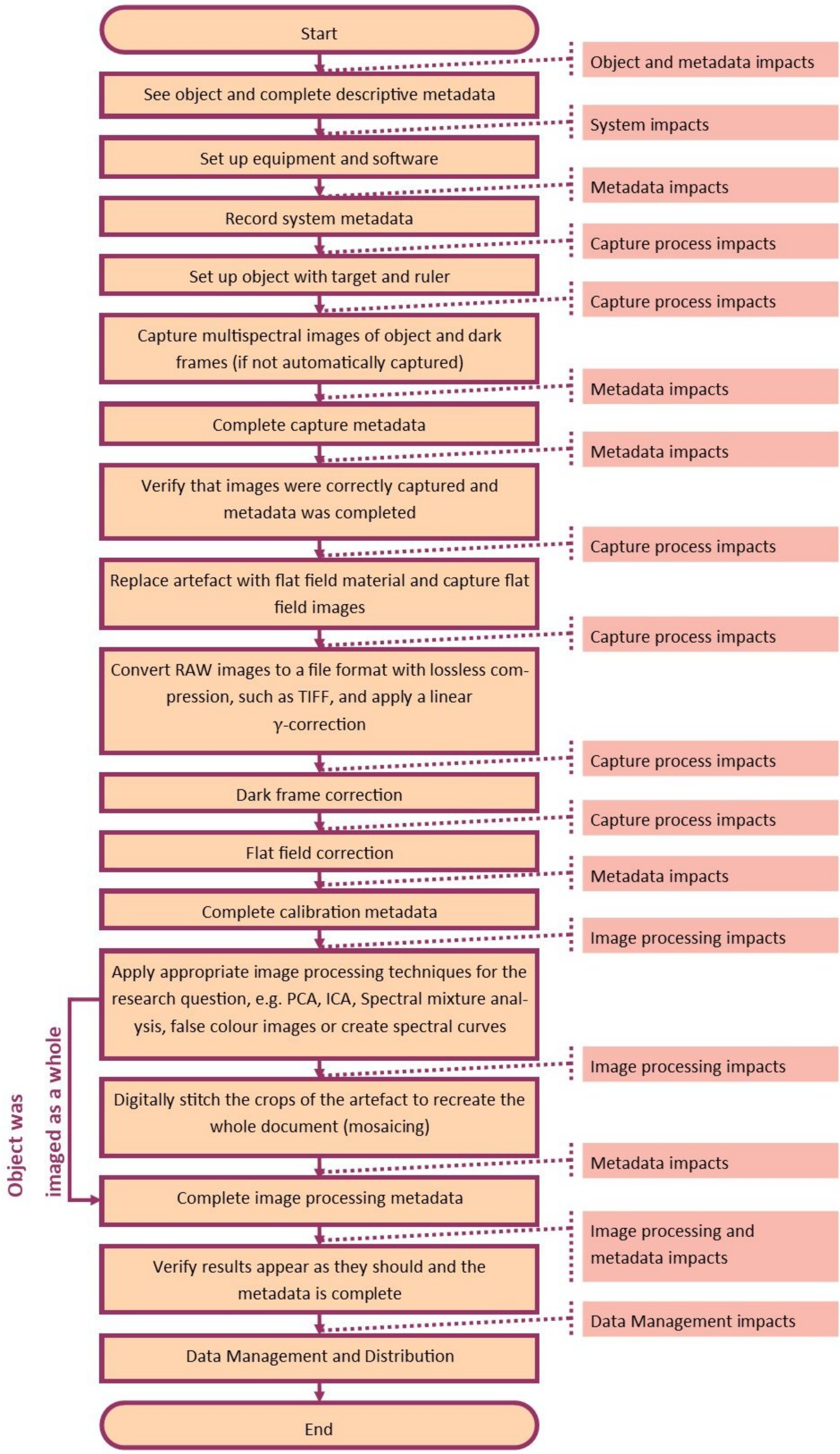
Section for Figures

Figure 1. Current pipeline for multispectral imaging of historical artefacts.



Section for Tables

Table 3: The recommendations for best practice of the pipeline of multispectral imaging in cultural heritage

Table 4: The recommendations for documenting the pipeline of multispectral imaging in cultural heritage

Table 1: The recommendations for best practice of the pipeline of multispectral imaging in cultural heritage

Stage of Pipeline	Best Practice
System	Frequent calibration, including correcting for lens distortions, colour management of the camera and monitor, checking the spectra of lights and replacement of the calibration targets. Ensure there are dark-room conditions Use an apochromatic lens corrected over the range of wavelengths to be imaged Use a quartz or extra-low-dispersion glass lens to keep sharp focus across all wavelengths Use narrowband LEDs to limit the use of filters to capture the fluorescence images only so that the requirement for image registration is reduced Record the spectra of the LEDs using a spectrometer
Object	Ensure room ambient conditions (temperature and humidity) are optimal for the artefact Consult with the heritage practitioner to discuss the imaging requirements
Capture Sequence	Use a linear gamma correction Use a lossless image format, such as TIFF Capture flat field images in the same imaging plane as the object and using a material with uniform reflectance, minimal surface texture and no fluorescent brighteners Capture a new sequence of flat field images whenever the system setup is altered Defocus the camera when capturing flat field images or digitally clean the images prior to correction so that artefacts are not transferred onto the multispectral images Apply flat field correction to all images Acquire a dark image with the lights off to capture the ambient light using the longest exposure of the image sequence Register any misalignments in multispectral images that may arise from the use of filters, chromatic aberrations, or movement of the object

Processing	Stretch the contrast in the images to the full bit-depth prior to PCA to give equal weightings to the darker images Subtract the appropriately weighted dark image from the multispectral images
Data Management	Complete frequent back-ups of the data to a different system (e.g. a server or hard drive)
Metadata	Follow a metadata standard consistently throughout the whole process from acquisition and analysis to distribution. The standard should be designed for multispectral imaging rather than standard photography. One such standard is the Archimedes Palimpsest Metadata Standard Use checksums to detect errors that may have arisen during transmission or storage

Table 5: The recommendations for documenting the pipeline of multispectral imaging in cultural heritage

Stage of Pipeline		Essential Documentation	Preferable Documentation
System	System	Make, model, software	
	Camera	Make, model, sensor size and type, bit-depth, modifications, lens make and model	
	Lights	Make, model, halogen/LED, wavelengths, quantity, diffusers	Spectra of the lights
	Filters	Make, model, wavelengths, application, purpose, quantity	
	Computer	RAM, CPU, GPU (for algorithm specific literature)	Operating system
	Setup	Distance from lights to artefact and from artefact to camera.	Background material, room conditions, use of lead weights and supports
Object	Properties	Size and shape, material, provenance/age, damage and conservation treatment, catalogue number	

Capture Sequence	Properties	Quantity, wavelengths, filters, shutter speed, aperture f/stop, ISO, metadata recorded during capture, software, resolution	
	Calibration	Method of flat field correction and digitally cleaning flat field images, software, material for flat field correction, targets	
Processing	Normalisation	Method, justification, software	
	Spectral Curves	Method, justification, software, image coordinates of where the spectral curves were calculated	
	PCA	Implementation, justification, software, explicitly define terminology used: for example that employed in Hotelling, (1933) so that the new data is called the 'principal components' not the eigenvectors	Percentage of data contained in the eigenvalues
	ICA	Implementation, justification, software	
	LDA	Implementation, justification, software, reference spectra	
	Clustering	Method, implementation, number of clusters, centroids of clusters, software	
	SAM	Method, implementation, justification, software reference spectra	
	Spectral Mixture Analysis	Method, implementation, justification, software, endmembers	
	Colour Processing	Colour space, choice of image(s)	
	Mosaicing	Method, justification, software	
	Other Processing Methods	Method, justification, software	
Data Management	Storage	Where the images are stored, file structure of the storage, when the images were last modified	When the images were uploaded

	Distribution Interface	How the images are distributed, file structure, what the files contain The viewing platform used, any standard or framework it is built on (e.g. if it is IIIF compliant)	File Size
Metadata		Metadata standard, who recorded the metadata, what they recorded, where it was recorded, the date it was recorded and date it was last modified	