Colour Management Protocols and Recommendations for Digitisation and Visualisation

Deliverable 5.1

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COLOURS Consortium

No	Short Name	Institution Name	Country
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2	FhG	FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV	Germany
3	FORTH	IDRYMA TECHNOLOGIAS KAI EREVNAS	Greece
4	NTNU	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU	Norway
5	FBA	FUNDINGBOX ACCELERATOR SP ZOO	Poland
6	FBC	FUNDINGBOX COMMUNITIES SL	Spain
7	ECE	ERASMUS CENTRE FOR ENTREPRENEURSHIP BV	Netherlands
8	ZVKDS	JAVNI ZAVOD REPUBLIKE SLOVENIJE ZA VARSTVO KULTURNE DEDISCINE	Slovenia
9	BCS	Brakebush Börries	Germany
10	GMB	GALERIA MESTA BRATISLAVY	Slovakia
11	MIC	MINISTERO DELLA CULTURA	Italy

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Executive Summary

This deliverable (D5.1) is part of Work Package 5 of the COLOURS project and defines colour management protocols and recommendations for the digitisation and visualisation of coloured heritage objects, as specified for Task 5.1 and, for their application to the Internal Pilot case studies, Task 5.3 in the Grant Agreement (No. 101233413). It reviews the principles of colour management, from ICC profiles and the CIE colorimetric system to scene-referred and output-referred data, rendering and colour encoding, and the limits of conventional tristimulus approaches. It sets out the constraints specific to cultural heritage, the existing standards (FADGI, Metamorfoze and ISO 19264-1) and current practice, and explains the role of hyperspectral imaging and the data preprocessing required for RGB and hyperspectral acquisition.

The report then documents how colour is handled in the COLOURS tools for digitisation, processing and visualisation, including the sRGB limit imposed by glTF delivery, and summarises a survey of 49 conservators, restorers and photographers that reveals a gap between the effort invested in physical calibration and its digital exploitation. Two project case studies, a 19th-century oil painting acquired with RGB and hyperspectral cameras in Düsseldorf and polychrome statuary acquired by photogrammetry in Bratislava, are used to derive eleven practical colour management recommendations (R1–R11) that can be followed without colour-science expertise. The deliverable concludes that the protocols will be validated on the Internal Pilots, including psychovisual experiments with stakeholders of Task 5.3, which are designed in D5.2 and will be run once the Internal Pilot datasets are available in WP10, with results reported in D10.2 (M24), and D5.2, submitted together with this deliverable, specifies the spectral-based colour management protocols that build on these recommendations.

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1. Introduction

Deliverable 5.1 lays out the definitions and requirements for colour management protocols applicable to the digitisation and visualisation of coloured heritage objects, as specified for Work Package 5 in the COLOURS Grant Agreement (No. 101233413). Its objective is to define protocols that ensure consistent colour appearance across devices, tools and platforms throughout the workflow from data acquisition to presentation on the ECHOES/ECCCH research platform. While this document lays the ground for spectral-based colour management to be considered, Deliverable 5.2 addresses spectral-based colour management protocols for both digitisation (input) and visualisation (output, covering 2D desktop imagery, 3D models, and AR/VR environments) that build on by extending the state-of-the-art methods standardised by the International Color Consortium (ICC). Besides serving as a general recommendation, the implementation of these protocols is described and explained in detail for two project case studies, a painting (2D) and polychrome statuary (3D), ahead of its validation on the Internal Pilots and its deployment in later work packages.

The protocols aim at ensuring that colour is reproduced consistently and accurately throughout the digitisation-to-visualisation pipeline, which is a long-standing challenge in cultural heritage imaging (Molada-Tebar et al., 2019; Gaiani, Apollonio, & Ballabeni, 2021). A survey of practitioners conducted within the project (Chapter 7) shows that this challenge remains largely unresolved in everyday practice (Deborah et al., 2026). This deliverable responds to that gap by defining colour management protocols for the digitisation and visualisation of coloured heritage objects and by demonstrating their practical application.

The document is organised as follows. Chapter 2 introduces colour management and the limitations of conventional tristimulus-based approaches. Chapter 3 reviews existing standards, the constraints specific to cultural heritage, and current practice. Chapter 4 presents hyperspectral imaging and its role in colour management, and Chapter 5 the data preprocessing required for RGB and hyperspectral acquisition. Chapter 6 describes the digitisation and visualisation tools and the ICC colour management pipeline developed so far, and Chapter 7 summarises a survey of user workflows. Chapter 8 presents two case studies and the resulting colour management recommendations (Table 8.1), and Chapter 9 concludes with how the protocols will be validated on the Internal Pilots.

2. Colour management

Colour management is the set of processes and technologies that ensure a colour is reproduced consistently as it passes between devices, media and viewing conditions. Every acquisition/input device (camera, scanner or spectrophotometer) and every output colour reproduction device (monitor, projector, display or printer) has its own device-dependent colour response, governed by factors such as sensor or display technology, spectral sensitivity or

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emission, white point, gamut and tone-reproduction curve. Which means identical RGB or CMYK values will produce visibly different colours on different devices. Also, the same physical colour is encoded with different numerical values by different acquisition devices. Colour management addresses this by characterising each device against a common, device-independent colour space expressed as tristimulus values e.g. CIEXYZ or CIELAB and applying the transforms needed to preserve an object's perceived colour throughout the capture-to-display pipeline. This is especially critical for cultural heritage documentation, where colour is itself part of the scientific and historical record and must remain accurate, reproducible and comparable across acquisition campaigns, institutions and display systems (Molada-Tebar et al., 2019; Barbero-Álvarez et al., 2023).

Colour values in this document follow the CIE colorimetric system (CIE, 2018). The CIE 1931 standard colorimetric observer (2°) provides the colour matching functions from which the tristimulus values X, Y and Z of a stimulus are computed for a given light source. CIE standard illuminants defined light sources are D65 that represents average daylight with a correlated colour temperature of about 6500 K, and D50 a warmer phase of daylight of about 5000 K. CIELAB (CIE 1976 L*a*b*) expresses XYZ relative to the white point of the chosen illuminant in an approximately perceptually uniform space, in which the colour difference ΔE_{76} is the Euclidean distance between two colours. The CIEDE2000 formula, abbreviated ΔE_{00}, improves on it by weighting the lightness, chroma and hue differences and is specified in ISO/CIE 11664-6 (ISO/CIE, 2014). ΔE_{76} and ΔE_{00} values are not interchangeable, because the two formulas weight lightness, chroma and hue differences differently, so a value computed with one cannot be compared with a limit or result defined with the other. The protocols of this deliverable therefore report both: ΔE_{00} as the primary measure of colour accuracy, because it is the CIE-recommended formula developed to agree better with perceived colour differences, and ΔE_{76} for comparability with the heritage studies and tools that use it, such as the camera characterisation of Molada-Tebar et al. (2019), who consider the laboratory reference conditions of CIEDE2000 unsuitable for archaeological fieldwork and this will be tested. Unless stated otherwise, XYZ and CIELAB values in this document refer to the CIE 1931 2° observer, ΔE_{76} denotes the CIE 1976 colour difference and ΔE_{00} denotes CIEDE2000, and the illuminant, such as D50 for the ICC Profile Connection Space or D65 for visualisation, is stated where it matters.

The dominant framework for implementing colour management is provided by the International Color Consortium (ICC), an industry standards body whose ICC.1 specification defines a common, vendor-neutral colour profile format (ICC, 2022). An ICC profile describes the relationship between a device's native colour space and a device-independent colour space also called a Profile Connection Space (PCS) e.g. CIEXYZ or CIELAB referenced to the D50 illuminant (ICC, 2022), together with one or more rendering intents. There are four rendering intents, namely, perceptual, relative or absolute colorimetric, and saturation that

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determine how out-of-gamut colours are handled when converting between devices. ICC profiles also describe standard RGB colour spaces such as sRGB or Adobe RGB (1998). These are defined by their primaries, white point and transfer function and are used as working spaces for editing, viewing and storing images, but they are not the PCS; a conversion between any two profiled spaces passes through the PCS (ICC, 2022). Thus, by chaining an input profile (camera, scanner or spectrophotometer), a standard working colour space, and an output profile (display, projector or printer), the ICC colour management workflow carries colour consistently along the full imaging pipeline, from acquisition to reproduction (ICC, 2021a). The specific design of the ICC's Profile Connection Space has direct consequences for how well conventional profiles serve the more demanding requirements of cultural heritage colour reproduction.

In practice, colour management should be applied at every stage of the digitisation-to-visualisation pipeline, for both 2D/flat and 3D digitisation/ visualisation workflows. In 2D workflows, a camera or scanner is first characterised, typically using a calibrated colour target imaged under controlled or measured illumination, to derive an ICC input profile that converts raw sensor values into a device-independent colour space. This input profile results in an image that is processed in a defined working colour space. The input profile in this workflow estimates the colorimetric values of the object under the capture illuminant within a measurable tolerance (for example ΔE_{00} and ΔE_{76}, as defined above), and the output profile then converts these values to the colour space of the display, with colours inside the display gamut being reproduced colorimetrically and colours or tonal ranges outside it being handled by the chosen rendering intent (ICC, 2021a).

These camera-derived colorimetric values are scene-referred data. Scene-referred data usually cannot be shown directly on a display or print, because the scene's dynamic range and gamut usually exceed what the output device can reproduce, and a colorimetrically accurate reproduction often looks dull. The data must be fitted to the output device, which is called rendering. Therefore, in conventional photography, the result is output-referred data, whose colours express how the image should appear on an idealised output device rather than the measured colour of the scene. Rendering is performed either in the camera defined by the manufacturer, when a colour encoding such as sRGB is selected, or by the photographer when working from RAW. Hence, it is not standardised as manufacturers or photographers tend to create output referred data that are visually pleasing (ICC, 2005).

After rendering, the output-referred data are colour-encoded, for example into sRGB. This step is standardised and unambiguous i.e. identical renderings give identical encodings (ICC, 2005). A colour space only specifies colour coordinates, whereas a colour encoding also specifies a reference medium, such as the reference display and viewing environment assumed by sRGB. sRGB data are therefore output-referred and do not represent the colorimetry of the scene (ICC,

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2005). In cultural heritage applications a scene-referred record of the object is preferable, but it cannot be shown with colorimetric accuracy on a display. HDR encodings such as PQ and HLG extend the luminance range and use the wide-gamut BT.2020 primaries, but they describe what is intended to be shown on a reference display and not the measured colour of a scene and displays with lower peak luminance still need tone mapping (ITU-R, 2025; ITU-R, 2021; Lang & Robinson, 2021).

The same principle extends to 3D digitisation, where photogrammetry or structured light/laser scanning combines geometric reconstruction with colour or texture information captured across many images taken under varying, often uncontrolled, illumination. Consistent colour management is required both to harmonise colour between the individual source images blended into a single texture atlas and to ensure that the reconstructed 3D model, once rendered and relit in a visualisation reproduces the object's true appearance (Simon Chane et al., 2013; Barbero-Álvarez et al., 2023). Conventional colour management workflow can be extended with multispectral and hyperspectral imaging, which captures many narrow spectral bands beyond conventional RGB and provides an illuminant-independent, physically based colour reproduction. Such spectral based colour management approaches that go beyond the standard three-channel ICC model can now be encoded into an ICC profile using the ICC.2 specification, also known as iccMAX, which enables spectral data and programmable transforms through Calculator Elements (ICC, 2023). Its Spectral Reflectance Interoperability Conformance Specification defines profiles in which spectral data, instead of tristimulus values, form the device-independent space (ICC, 2021b).

3. Colour management in Cultural Heritage

Colour management in cultural heritage differs from colour management in graphic arts or consumer photography in multiple ways which constrains the standard colour management protocols. This Chapter reviews the existing standards (Section 3.1), the constraints specific to cultural heritage (Section 3.2), and current practice, its limitations and the resulting requirement for standardised workflows (Section 3.3).

3.1. Existing standards

A common, standardised basis is required on which to build a colour management workflow. The ICC profile framework and the CIE colorimetric system introduced in Chapter 2 already provide the accepted industry standard for characterising devices and converting between device-dependent RGB/CMYK values and a device-independent reference space (ICC, 2022; Molada-Tebar et al., 2019). The cultural heritage digitisation community has in addition developed sector-specific technical guidelines that define concrete calibration and quality targets for imaging workflows. The Federal Agencies Digital Guidelines Initiative (FADGI) publishes tiered technical guidelines for digitising cultural heritage materials, specifying

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requirements for colour targets, tonal response, noise and resolution across different quality levels (FADGI, 2023). In the Netherlands, the Metamorfoze Preservation Imaging Guidelines define comparable image-quality requirements specifically for the preservation imaging of paper-based and photographic heritage collections (van Dormolen, 2025). At the international level, ISO 19264-1:2021 provides a standardised methodology for the quality analysis of imaging systems used in archiving, defining objective, device-independent metrics, such as colour accuracy, resolution and noise, against which a digitisation system's performance can be evaluated (ISO, 2021). These three frameworks are a few cited formal standards among cultural heritage imaging practitioners. The practitioner survey in Chapter 7 shows that their adoption remains limited (Deborah et al., 2026). The protocols proposed in this deliverable should therefore remain compatible with, and where possible build on, these existing standards rather than introducing an entirely separate framework. Conventional tristimulus or colorimetric profiles are, however, not sufficient for every application in cultural heritage, which motivates the spectral extensions discussed in Chapters 2 and 4.

3.2. Heritage-specific constraints

Cultural heritage also imposes constraints that standard workflows do not address. First, heritage objects are unique and often irreplaceable, so colour documentation cannot simply be repeated once conditions change and for fragile surfaces such as old paintings, direct-contact colour measurement with colorimeters or spectrophotometers is usually prohibited to avoid damaging them. This pushes practitioners towards imaging-based, non-invasive methods instead (Molada-Tebar et al., 2019; Liang, 2012). Second, heritage surfaces are frequently non-planar, glossy, varnished, transparent or otherwise optically complex such as varnished paintings, metal and glass artefacts, bas-reliefs etc., which violates the simplifying assumptions that form the basis for conventional flat-target colour characterisation and 3D texture digitisation methods (Simon Chane et al., 2013). Third, the materials themselves (aged and mixed pigments, binders, patinas) exhibit strong metamerism and narrow-band spectral behaviour that a three-channel RGB sensor cannot always resolve, since conventional colour sensors violate the Luther condition required to reproduce human colour discrimination (Simon Chane et al., 2013). Finally, in cultural heritage colour is not merely a matter of visual likeness but part of the scientific and historical record, for instance, to compare an object's condition before and after conservation treatment, or to identify/classify pigments and materials. Therefore, the colour measurements through image acquisition must remain valid, traceable and comparable over years or decades, and across multiple acquisition campaigns and institutions.

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3.3. Current practice, limitations and requirements

In current practice, colour is handled quite differently across cultural heritage scenarios. Documentation of archaeological and rock-art sites has historically relied on subjective, perceptual comparison against physical colour-chip collections such as Munsell charts and is only gradually being replaced by rigorous colour managed camera workflows (Molada-Tebar et al., 2019). Museum photography of paintings, sculptures and other movable objects commonly places a physical reference colour target in the field of view and produces colour managed photographs that form part of formal condition-assessment reports, for example prior to loaning an object to another institution (Simon Chane et al., 2013). For material and pigment analysis, multispectral and hyperspectral imaging is used to capture reflectance information beyond the visible RGB bands, supporting non-invasive pigment identification, detection of underdrawings or past restoration, and condition monitoring of paintings and manuscripts (Liang, 2012; Pei et al., 2023). Moreover, photogrammetry and other 3D digitisation techniques increasingly combine geometric reconstruction with colour or texture capture to document statues, wall-paintings and archaeological sites, blending colour information from many images into a single textured 3D model (Barbero-Álvarez et al., 2023; Simon Chane et al., 2013) without taking into consideration the colour management of the pixels at various angles of the light falling on it or its 3D appearance. The simplest way to define the surface appearance of an object is by capturing its bidirectional reflectance distribution function (BRDF) which includes both diffuse and gloss behaviour of the surface (Guarnera et al., 2016).

These varied practices also reveal significant issues and limitations. There is, at present, no single accepted standard procedure covering the whole pipeline from acquisition to flat or 3D colour appearance modelling in cultural heritage. Within photogrammetry pipelines specifically, the blending of colour values from multiple source images during texture generation remains a largely uncontrolled step that can introduce colour artefacts even when every other stage of acquisition is carefully calibrated (Barbero-Álvarez et al., 2023). This calls for standards that are adapted for a 3D digitisation and visualisation case where using a flat colour target for colour management is not enough. Conventional RGB/ICC colour management is further limited by device and illuminant dependence and by metamerism, meaning two differently pigmented surfaces can appear identical under one illuminant and mismatch under another (Simon Chane et al., 2013). Multispectral and hyperspectral imaging mitigate this but introduce limitations of their own (Chapter 4). Finally, colour workflows in the field still frequently rely on subjective, perceptual judgement, which is inherently observer-dependent and difficult to reproduce or validate scientifically using metrologically accurate quantification (Molada-Tebar et al., 2019). As such, there is a need to share colour and spectral data between different institutions and tools for consistent colour reproduction of objects (Simon Chane et al., 2013).

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These limitations show clearly that there is a requirement for standardised colour management workflows for cultural heritage scenarios, spanning digitisation and visualisation, that can be adopted without requiring its users to be colour scientists. Restorers, conservators and heritage photographers need methods and tools that are practical to apply in daily documentation and conservation work, and that are developed together with the conservation community rather than imposed from computer science or industrial imaging alone (Simon Chane et al., 2013). Such a workflow should allow these practitioners to reliably capture, characterise and compare colour across data acquisition campaigns, treatments and institutions. Therefore, defining and validating exactly this kind of colour management protocols, for both digitisation and visualisation across the project case studies (Chapter 8) ahead of validation on the Internal Pilots, is the objective of the present deliverable.

4. Hyperspectral imaging in Cultural Heritage

Hyperspectral imaging, and its coarser spectral resolution counterpart multispectral imaging, captures an image with higher number of channels than three broad red, green and blue channels that is common in digital cameras. Hyperspectral imaging captures hundreds of narrow bands that are continuous while multispectral imaging captures a few discrete broad wavelength bands, so that every point in the scene is associated with an approximation of its full spectral reflectance curve rather than a single RGB triplet. First developed for remote-sensing applications such as planetary science and astronomy, the technique has been applied in art conservation and art history since the early 1990s, precisely because, as a non-invasive imaging method, it can be used on any object that is fragile without damaging its surface (Liang, 2012).

The dense spectral sampling in hyperspectral imaging makes it valuable for cultural heritage specifically for colour management in many ways. First, because a full reflectance spectrum is captured rather than a colour rendered under one specific illuminant, the resulting data forms an illuminant-independent colour archive. The same spectral cube can be used to compute how an object would appear under any illuminant or observer, long after the acquisition campaign is over (Liang, 2012). Second, the fine spectral resolution supports material and pigment identification, since many pigments and materials have distinctive absorption or reflectance features that are not distinguishable in three-channel RGB but are readily resolved spectrally, and can be compared against spectral libraries such as the open-access INFRA-ART database (Pei et al., 2023). Third, extending acquisition beyond the visible range, for example, using ultraviolet-fluorescence or infrared bands, allows the detection of features such as underdrawings beneath the paint layers, damaged areas that have been restored or retouched, or degradation processes (Liang, 2012). A further example is the virtual removal or reapplication of varnish from hyperspectral reflectance, which helps conservators to decide before touching the painting (Habib et al., 2026;

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Sections 6.3 and Chapter 8). Finally, because hyperspectral data is tied to physical reflectance rather than to a specific sensor's colour response, it can serve as a metrological reference for an RGB image against which conventional camera-based colour capture and ICC camera profiles can be validated or corrected.

These uses make hyperspectral imaging play an important role in colour management for both flat (2D) and 3D reproduction and visualisation. For digitisation of flat objects, spectral reflectance data can be rendered into a colorimetrically accurate image under a chosen standard illuminant and observer, providing a reference against which the sRGB or other ICC-profiled output of conventional cameras can be checked and corrected. This increases the colour accuracy compared to the tristimulus value-based camera characterisation discussed in Chapter 2 (Liang, 2012; Molada-Tebar et al., 2019). Moreover, a scene-referred colorimetry is also possible using hyperspectral data that is a true colour representation of the object under the scene lighting. For 3D reproduction, combining spectral or multispectral data with photogrammetric or scanned geometry allows a reconstructed model to carry a physically based, illuminant-independent colour or material record rather than a single texture baked in under one lighting condition. Such a model can be relit and rendered consistently under different virtual illuminants in a visualisation, AR/VR or web-based viewer. Moreover, colour discrepancies introduced by photogrammetric texture blending can be identified by comparing the finished texture with known reference values, as done with a colour target by Barbero-Álvarez et al. (2023), and registering spectral data with the 3D model (Simon Chane et al., 2013) would extend such a check from the target patches to the whole surface.

Some limitations of using hyperspectral imaging are its high dimensionality which demands substantial storage and computation. Spectral libraries of heritage pigments and materials, while growing, are still incomplete for many classes of object. Fully integrated and portable acquisition systems suitable for in-situ fieldwork are still rare and the resulting high-dimensional datasets are difficult for non-specialist conservators and restorers to use and interpret without dedicated analysis tools and visualisation interfaces (Pei et al., 2023; Simon Chane et al., 2013).

5. Data Preprocessing

Colour-accurate digitisation with a conventional RGB camera requires a defined sequence of preprocessing steps before an image is suitable for either flat visualisation or as an input to 3D reconstruction. Working from the camera's raw sensor data, rather than an in-camera JPEG that has already been compressed and enhanced, preserves the greatest fidelity, and this raw output must first be debayered – reconstructed from the camera's colour filter array (commonly a Bayer pattern) into a full three-channel RGB image, using an interpolation strategy such as adaptive homogeneity-directed demosaicing or bilinear interpolation, each of which trades off spatial resolution against the risk of interpolation artefacts

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(Barbero-Álvarez et al., 2023). Because the resulting camera RGB is expressed in a non-standard, device-specific colour space and is subject to variations in white balance, black level and non-neutral illumination between shots, a calibration step follows: black-level and dark-current offsets are removed, the image is white-balanced to correct for the colour temperature of the illuminant, and the camera RGB is transformed – typically via the colour matrix stored in the image's EXIF metadata plus a gamma compression – into a standardised digital RGB space such as sRGB (Barbero-Álvarez et al., 2023; Molada-Tebar et al., 2019). Only once every image in a batch has been brought into this common reference space, with consistent white balance and colour rendering, can colour be compared reliably between pictures or used consistently as input to a photogrammetric reconstruction (Barbero-Álvarez et al., 2023).

Hyperspectral and multispectral cameras require an analogous, but more extensive, sequence of corrections before raw counts can be treated as measurements of an object's colour or material properties. A dark-current image, captured with the same integration time as the object frame but with no incident light, is subtracted from every frame to remove thermal and readout noise; a flat-field correction, derived from images of a uniform white target, then compensates for pixel-to-pixel gain variation and any spatial non-uniformity in the illumination (Liang, 2012). The dark and flat-field-corrected counts are then normalised, band by band, against images of a calibrated spectral reflectance standard, converting raw sensor response into true spectral reflectance, with further corrections often needed for scattered-light cross-talk between bright and dark regions of the scene and for the specific illumination-collection geometry used (Liang, 2012). Because many hyperspectral and multispectral systems acquire each spectral band sequentially, or through optical paths that differ slightly between channels, the individual band images generally also require geometric registration such as shifting, and in some cases rescaling, each channel so that all bands are correctly aligned into a single spectral data cube, before being used for any analysis (Liang, 2012; Simon Chane et al., 2013).

These preprocessing stages, applied consistently across both RGB and hyperspectral acquisition, are the practical precondition for the colour management protocols described in Chapters 2–4: without dark-frame subtraction, flat-fielding, white balance and geometric/spectral registration, neither camera characterisation nor any comparison of colour across devices, illuminants or acquisition campaigns can be considered reliable.

6. Digitisation and Visualisation

Colour enters the COLOURS workflow during acquisition and may then be handled in different software environments before the final result is displayed. These operations do not necessarily form a single linear workflow, and not every tool or use case passes through all of them. This Chapter therefore looks at colour management in three main contexts and explains, for each tool, what is

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documented about colour handling and what remains unclear. The tools themselves are described in D3.1.
The first context is acquisition, where colour information is captured from the physical object. The second is processing and simulation, where software tools may digitally reconstruct colour, simulate its degradation or alteration over time, or predict the possible effects of restoration. The third is visualisation, where the digital twin and its colour information are rendered and displayed on a monitor.
These three contexts represent different points at which colour may be captured, transformed, simulated or displayed, depending on the specific tool and application.

Table 6.1: Summary of the position of each tool.

Tool	Domain	TRL at project start	Documented colour handling
doLCE 2.0	2D-lenticular film	5	Colour reconstructed from encoded silver densities to RGB, informed by the known spectral characteristics of Kodacolor. Output colour space not stated.
Neg2Pos	2D -negative film	2	None implemented. Scanner profile characteristics, spectral capture bands, optical filtration and calibration-target integration are listed as expected features.
VarnishLab	2D - Paintings	3	Physics-based models on hyperspectral captures; output specified as side-by-side sRGB. spectral-to-sRGB transformation for visualisation only.
StyleShade3D	3D	4	Region-aware shading and material assignments over a semantic atlas. Appearance is assigned, not measured. No colour space or ICC handling described.
ATON	3D	7	PBR rendering; colour and material channels transported via glTF and Cesium 3D Tiles. No colour-managed rendering path is described. See the discussion of glTF below.
MuLaX	3D and 2D	6	Comparative display of previously acquired VIS, UVL and VIL layers and of point analyses. No colour management is described.
CKR	Cross-cutting	7	Over 60 resource types with E-RIHS-based metadata. No field dedicated to ICC profiles, colour space or acquisition targets.
LDE	2D - Paintings	5	Colorimetric values derived from calibrated hyperspectral reflectance via CIE 1931 (2°) observer and D65 illuminant, converted to CIELAB (1976); colour change quantified using ΔE_{76} Spectralon (white) and black (dark) reference calibration required for all acquisitions.

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Degreening	2D – autochrome plates	5	Removes greening defects from digitised autochromes with a deep-learning model; no colour space handling described. No further algorithmic development is planned; the tool is integrated and the pilot in which it is validated is defined in WP10 (D2.1, Section 4.1.8).

6.1. Acquisition

Acquisition is the stage where colour information first enters the workflow, rather than being transformed or processed further. What is captured here sets the ceiling for everything downstream: information missing at acquisition cannot be recovered later. Within COLOURS, two acquisition routes are considered: photography and scanning of flat originals, and photogrammetric capture of three-dimensional objects.

2D acquisition: photography and scanning

Within COLOURS, the acquisition of 2D/flat originals such as paintings follows the hyperspectral acquisition protocol followed in Habib et al. (2026). The object is illuminated using two halogen light sources positioned on either side at oblique angles, a configuration chosen specifically to minimise specular reflections from the painting's surface, and a plain whiteboard is captured alongside the painting to allow later flat-fielding of the acquired images. Apart from that, a conventional Canon digital camera is used to capture RGB images under the same lighting, positioned along the same imaging plane as, and capturing simultaneously with, the hyperspectral scanner, so that the resulting high-resolution RGB images and the lower-resolution hyperspectral reflectance cube refer to the same viewpoint and illumination conditions (Figure 1). As with the hyperspectral session, the RGB capture also includes the whiteboard and a physical colour target, together with the painting itself, providing the reference material later used to flat-field and colour-characterise the RGB images respectively. This combined RGB and hyperspectral acquisition routine, first applied in the Düsseldorf case study described in Chapter 8, forms the basis of the general 2D acquisition procedure recommended for paintings and other flat originals digitised within the project.

3D acquisition: photogrammetry

Three-dimensional models in the pilots are created through photogrammetry: a set of overlapping photographs is used to reconstruct geometry by feature matching, camera orientation, a sparse and then a dense point cloud, which is then meshed, unwrapped into a UV layout, and finally textured.
For colour purposes, the ordinary visible-light (VIS) photographs need to be kept separate from the diagnostic layers. In multi-band photogrammetry, ultraviolet-induced luminescence (UVL) and visible-induced luminescence (VIL) record how

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the object glows under a specific light source, not how it looks under normal light, and the two behave differently: UVL can still carry some colour-like information channel by channel, while VIL is read mainly as an intensity rather than as a hue. Even a paper specifically about colorimetric characterisation of multispectral systems leaves this band out: Amiri et al. calibrate their reflectance bands colorimetrically but explicitly exclude the UV-fluorescence band from that process (Amiri et al. 2024 p.138). Neither UVL nor VIL should be treated as ordinary colour data unless someone has specifically established how it was excited, recorded and converted into a defined colour value.

Colour control is harder in photogrammetry than in flat-original photography. When photographing a flat original, a colour target can sit right next to the object, under the same light, in the same shot and the correction it gives is valid for that one image. A photogrammetric set is tens to hundreds of images taken from different positions, and the light hits the surface differently from shot to shot. This does not mean a target has to appear in every single frame: one correction, worked out from a target photographed under stable conditions (same camera settings, same raw development, same light condition) can reasonably be applied to a whole batch, which is exactly what Gaiani et al. (2017, p.9) do, applying one calibration to groups of images captured in the same session. What that single correction cannot fix is what changes across the object itself: shadows, the angle of each surface to the camera and the light, and the fact that many materials don't reflect light the same way in every direction. Those remain separate problems.

So, what a target realistically gives in photogrammetry is a set-level reference, one correction, worked out once, applied consistently across the set, rather than the shot-by-shot control flat-original photography allows. That is a real difference from 2D reference practice, but it follows from how multi-view capture works, not from careless practice. And because building the texture averages information across overlapping photographs, keeping the set consistent matters more than getting any single frame perfectly accurate: an inconsistent set produces a patchy texture regardless of its average colour error.

It is worth looking at what published cultural-heritage photogrammetry actually does about colour. Different recent workflows were examined, all multiband or polychromy studies on objects comparable to the COLOURS pilots. A consistent partial practice emerges: a target is almost always photographed, and almost always used for white balance, exposure or a luminance reference rather than to characterise the camera. Grifoni et al. white-balance from a Kodak Color Control Patches Q14 target (2018); Triolo et al. photograph an X-Rite ColorChecker Classic grey scale together with a Kremer Egyptian blue tab and use it to set the reflectance value in Lightroom to 95%, that is RGB 243,243,243, to avoid clipping the white pixels (2019, p. 5003); Uueni et al. list "calibration" and "colour information" among their capture steps and mention "colour calibration checking" before photogrammetric processing, using a combination of natural and coded targets (2017, p. 135 and Figure 3); Ferdani et al. photograph a ColorChecker and

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a Spectralon standard at every set-up (2025, p. 78); Uccheddu et al. keep a Spectralon panel in every set and normalise against it and compute a numerical correction from the measured target values (2025, p. 8). The others use the target to set the image, not to characterise the device. This is not the whole story for cultural-heritage photogrammetry, though: other work has gone further, explicitly modelling how the camera responds to colour and checking how well colour survives the pipeline (Gaiani et al., 2017; Barbero-Álvarez et al., 2023).

Raw capture, development in Lightroom, and export to JPEG or TIFF before reconstruction is common practice. Uueni et al. use Lightroom for "minimal image processing" before photogrammetric processing (2017, p. 135); Triolo et al. use "*Adobe Lightroom software … in color correction and sorting tiff and JPEG files from the raw original acquisition image*", then process maximum-quality JPEGs in Agisoft Photoscan (2019, p. 5003); Ferdani et al. develop in Lightroom and export to JPEG before structure-from-motion (2025, p. 79); Lanteri et al. state it explicitly: frames *"were saved in .Jpg format with a resolution of 24 MP, sRGB 24-bit depth*" (2019, p. 210). The light source is declared in only one of the six: Grifoni et al. cite the CIE recommendations, record a standard illuminant A source with the ISO reference given.

Taken together, this points to two different levels of colour control in cultural-heritage photogrammetry. In most application-oriented multiband studies, the target and raw capture mainly keep exposure, white balance and consistency under control before reconstruction. A smaller, more demanding body of work goes further: modelling how the camera itself responds to colour, controlling the conversion from raw sensor data to RGB, and checking colour differences quantitatively through the pipeline (Gaiani et al., 2017; Barbero-Álvarez et al., 2023). So, the presence of a target alone does not say how much colour management is really being done — what matters is what the reference values are used for, and whether the resulting corrections and errors are documented.

This gap makes sense given what photogrammetry was built to do. Its main job is reconstructing geometry from overlapping images, where consistency between photographs matters for matching features and building a coherent-looking texture. A workflow that produces a stable, plausible surface appearance is doing exactly what it is designed to do, even without a colorimetrically characterised camera or a fully traceable colour pipeline. The problem only appears when the model is asked to carry colour as evidence, not just as appearance: internal consistency and a convincing look do not by themselves prove colour accuracy, since a texture can be seamless and still differ systematically from the real object. Making colour genuinely assessable requires a documented colour reference, controlled and recorded transformations, and a way to quantify how well the recorded values match that reference, which is the additional requirement COLOURS is introducing.

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6.2. From raw capture to finished texture

Photographing a ColorChecker and developing the whole set consistently in software like Lightroom, as the workflows above show, is a real and useful step: it fixes a common white balance, reduces differences between photographs and prevents visible colour shifts in the texture. It should not be confused, though, with full ICC camera characterisation. The profile a raw converter builds from a ColorChecker is not the same as a proper ICC input profile, it belongs to the raw-processing pipeline and may include choices meant to make the image look realistic and well balanced, not to be colorimetrically accurate. Photoshop, on the other hand, does support proper ICC colour management, but only once colour spaces, profile assignment and conversions are set deliberately and simply using it does not make a workflow colour-managed.

The difference becomes clearer next to a workflow built specifically for camera characterisation. Molada-Tebar, Marqués-Mateu and Lerma (2019) process raw camera data through a fully controlled colorimetric pipeline, fitting a second-order model that relates the camera's raw values to a standard colour representation; colour differences (CIE76) stayed below about three CIELAB units in their rock-art case study for all exposures except the overexposed image, which shows that exposure conditions matter for how valid the characterisation stays. Their work concerns photographic documentation rather than photogrammetric texture, but it tackles the same underlying problem a colour-critical set of input photographs has to solve: turning what the camera records into a colour value that means the same thing regardless of which camera recorded it. (Molada-Tebar et al., 2019).

Another important point is the file format used before the images enter the photogrammetric reconstruction. At the handoff from RAW development to photogrammetric processing, preservation of image information depends not only on file format but also on bit depth, compression, colour encoding/profile and transfer function. These parameters should therefore be documented explicitly. Uccheddu et al. follow a different approach. Their images are acquired as 12-bit-per-channel RAW DNG files, processed at 16 bits, and finally stored in 32-bit-per-channel EXR textures (2025, pp. 6–7). This preserves much more of the original image information during processing. The approach is similar to recommendations for 2D digitisation, where high bit depth should be maintained for as much of the workflow as possible and conversion to eight bits should be left until the final delivery stage (FADGI 2023, pp. 85 and 87).

A further problem, noted in Section 3.3, arises during texture generation itself. Photogrammetric software often processes texture pixels without tracking which colour space they came from, blending values from different photographs without properly accounting for gamma or colour-space conversion (Gaiani et al., 2021). In practice, building a texture means merging many overlapping photographs into one continuous surface, an averaging process, and if the transformations behind each source photograph are not known, the resulting colour is hard to interpret reliably.

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Barbero-Álvarez et al. (2023) tested this directly across a full photogrammetric colour pipeline: they controlled the conversion from raw sensor data to RGB, applied target-based calibration, and only then used the calibrated images for reconstruction. Because texture generation blends several source photographs in a way the software controls rather than the user, they treated it as the one step they could not directly control, and checked its effect afterwards — measuring the colour difference between the calibrated source images and the matching areas of the finished texture with CIEDE2000, using the ColorChecker patches, still visible in the reconstructed model, as known reference points (2023, §3.3–3.4).
In the documented workflow in Ferdani et al. (2025), no working colour space, camera characterisation or ICC profile is considered (see Section 6.5). This is not unusual in photogrammetry, and the same gap between recording colour references at capture and implementing a complete colour-management workflow is seen in current 2D practice (Chapter 7; Table 8.1, R2, R4 and R11). It is one of the areas that COLOURS needs to address.
This loss of accurate colour information is not inevitable as Uccheddu et al. show a way around it. They align the whole multiband set onto one shared 3D reference and build a single mesh whose three textures share one UV layout, so the visible, UV-fluorescence and infrared-reflectance textures share one UV map (Uccheddu et al. 2025, 6-7). The key difference is when they correct: instead of correcting each photograph before reconstruction, they correct the finished texture directly, pixel by pixel, against a Spectralon reference panel of known reflectance (p. 8). It works well enough for real analysis, a six-band dataset built on these corrected textures is used to classify materials automatically straight off the 3D surface (pp. 11-12). This shows two things: a quantitative colour correction can survive texture building if it is applied afterwards, and working at high bit depth works just as well in 3D. What it does not show is colour management in the full ICC sense.

6.3. Processing and Simulation

This section covers tools that modify or generate colour information within software. Depending on the application, they may recover colour from degraded or encoded data, simulate changes in the physical state of an object, or assign a reconstructed appearance that was not directly recorded during acquisition. These operations do not necessarily occur in every workflow. From a colour-management perspective, this is the context in which colour transformations should be performed in a defined working space and documented clearly, so that the origin and meaning of the resulting colour remain traceable.

doLCE 2.0

doLCE 2.0 reconstructs colour from digitised lenticular films, including early Kodacolor, through automated processing and user-guided corrections. It builds on the original doLCE work and the human-in-the-loop approach developed within PERCEIVE (Sinha et al., 2026), with further development in COLOURS. Details of

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the tool are provided in Deliverable D3.1; this section focuses on the colour-management procedure required for visualisation.

The procedure described below is adapted from Pfluger, Garmsen and Trumpy (2022), Modern methods for the visualization of lenticular film colors. It establishes a source RGB colour space from the physical characteristics of the historical projection system and converts the reconstructed colours into a defined output colour space.

To represent the colours of analogue Kodacolor lenticular-film projection, reconstructed RGB values must first be interpreted in the appropriate source colour space. Assigning a conventional RGB space directly would not account for the spectral characteristics of the original projection filter. The source space, named Kodacolor1928, was therefore defined from the measured transmittances of that filter and the spectrum of a film-projector light source.

In the study by Pfluger et al. (2022), filter transmittances were measured using a double-beam spectrophotometer (Shimadzu UV-1800), and the projector spectrum was measured using a spectroradiometer (Konica Minolta CS-2000) with a Kinoton FP38 projector. Colorimetric calculations followed CIE recommendations (CIE, 2005), using the CIE 1931 2° standard observer (CIE, 2019). The resulting specifications characterise the filter and illumination combination used in the study. Figure 6.1 compares Kodacolor1928 with DCI-P3 in the CIE 1976 uniform chromaticity diagram (Hunt and Pointer, 2011).

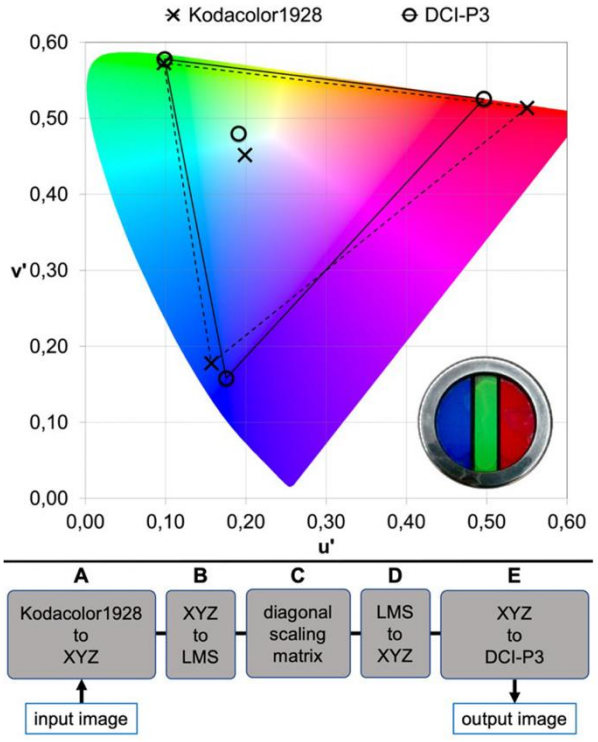


Figure 6.1: Kodacolor 1928 chromaticities derived from the measured projection filter transmittances and projector spectrum, compared with DCI-P3. Bottom: the five-step conversion from reconstructed Kodacolor 1928 RGB value to destination RGB values including chromatic adaptation. Adapted from Pfluger, Garmsen and Trumpy (2022).

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For colour-managed visualisation, the reconstructed values must subsequently be converted from Kodacolor1928 to the intended output RGB colour space. The source white point, expressed as normalised XYZ values [0.991, 1, 1.315], differs from standard output white points. The conversion therefore includes a chromatic adaptation transform.
Following the linear von Kries approach (Brill, 1995), adaptation is performed by scaling values in an LMS adaptation space. The procedure comprises five steps:

Source RGB to XYZ: convert linear Kodacolor1928 RGB values to CIE XYZ using the matrix derived from the source primaries and white point.
XYZ to LMS: transform XYZ values into the LMS adaptation space using the CAT02 matrix associated with CIECAM02 (Moroney et al., 2002).
Chromatic adaptation: scale each LMS component by the ratio between the corresponding destination and source white-point values.
LMS to XYZ: apply the inverse CAT02 matrix to obtain adapted XYZ values.
XYZ to destination RGB: convert the adapted XYZ values into the selected output RGB colour space.
Pfluger et al. (2022) used DCI-P3 as the destination space, with its colorimetric specifications defined by SMPTE (2011). For other visualisation contexts, the destination space should match the intended display or delivery requirements. The matrix operations apply to linear RGB values; the appropriate output encoding must subsequently be applied, and the resulting files should carry an explicit colour-space identification.

Neg2Pos

Neg2Pos converts digitised colour negatives into positive images with the aim of reproducing the colour and tonal qualities of analogue photochemical printing. Details of the inversion workflow are provided in Deliverable D3.1; this section focuses on the colour rendering and visualisation.
Following negative inversion, Neg2Pos simulates print-film appearance using the spectral-density curves of cyan, magenta and yellow dyes. Their combined absorption determines the simulated print's spectral transmittance, accounting for the spectral overlap between the dyes. The resulting colour rendering is therefore linked to the characteristics of the selected film/paper stock for printing.
The simulated transmittance is evaluated under a defined illuminant using standard colour-matching functions. The current prototype uses CIE D50 and the CIE 1931 2° standard observer to calculate XYZ tristimulus values, which are subsequently converted into an output RGB representation. Colour-managed delivery requires an explicit definition of the destination RGB space, its encoding and any chromatic adaptation between the simulated illumination and the destination white point.

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In case of motion pictures, any additional white-balance adjustment should be established for a coherent film section and applied consistently across its frames to avoid temporal colour fluctuations. Exported images should carry the appropriate colour-space identification, while processing metadata should record the print-film dataset, illuminant, observer and rendering adjustments. This documentation supports reproducible visualisation and preserves the relationship between the digital result and the simulated photographic process.

VarnishLab

Building on the physics-based model developed and validated by Habib et al. (2026), a dedicated varnish removal & revarnishing tool called VarnishLab will be prepared to make this capability directly usable by restorers and conservators, rather than remaining a research-only algorithm. The tool will take a hyperspectral reflectance cube of a painting, as captured with a portable scanner such as the Specim IQ (Chapter 8), and let the user interactively simulate the removal of the aged varnish or the application of a new one. Results are converted once, at the final rendering step, to sRGB for on-screen inspection (Chapter 8) and shown as a before/after or slider-based comparison of the original, virtually cleaned and virtually revarnished states, so that no colour science expertise is needed. Because the model was validated against a physically cleaned area of the same painting (Habib et al., 2026), the tool can support conservation decisions, but its interface should state its known limitations: virtual cleaning cannot reproduce the contrast enhancement of physically cleaned paint structures, and the revarnishing simulation has not yet been validated against a physical ground truth. The tool is intended as a fast, non-invasive preview of the likely visual outcome before an irreversible intervention.

StyleShade3D and StyleShade2D

Unlike imaging pipelines that aim to reproduce or archive the colorimetric appearance of a physical object, StyleShade3D operates exclusively on rendered representations of already-provided 3D assets. The application's purpose is to segment these assets into meaningful regions and apply downstream operations such as segment-wise material assignment and style transfer, rather than to capture, calibrate, or faithfully reproduce the object's true surface colour. Colour information in this context serves only as a visual and semantic cue to distinguish regions during segmentation and to render the final stylised output; it does not need to correspond to a colorimetrically accurate, device-independent, or spectrally grounded representation of the original object. Since no comparison to ground-truth object colour, no cross-device colour matching, and no scientific colour reproduction is required, a formal colour management workflow (e.g., ICC profiling, illuminant/observer control, or spectral calibration) is unnecessary for

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StyleShade3D's intended use case. Colour is treated as a relative, task-specific rendering attribute rather than a metrologically meaningful quantity.

Light Damage Estimator (LDE)

The Light Damage Estimator is a tool developed to predict photodegradation in coloured heritage 2D objects, primarily paintings, on the basis of spectral data. The tool originated as a Tools and Services outcome of the PERCEIVE project (Ciortan et al., 2026) and is being extended within COLOURS under WP3. It is grounded in the spectral RGB band framework published by Siozos et al. (2025), which established an empirical relationship between light exposure, the spectral composition of illumination, and colour change in artists' pigments. Within the COLOURS platform, the LDE is designed to operate also on hyperspectral reflectance data rather than only the sRGB input used in its PERCEIVE predecessor, thereby replacing device-dependent colour capture with a metrologically grounded spectral input.

Within the COLOURS platform, the LDE keeps two input pathways. The sRGB-based pathway from the PERCEIVE project remains available. Alongside it, a hyperspectral pathway has been introduced for COLOURS and is described in this section. Both pathways produce colour values in the same CIELAB (1976) space This means outputs from either pathway can be compared directly.

The two pathways differ in how colour is derived. The sRGB pathway is device-referred: its accuracy depends on the capture device following the sRGB specification correctly. In cultural heritage imaging practice, this is not always verified. The hyperspectral pathway, by contrast, derives CIELAB from calibrated diffuse reflectance. Reflectance is illuminant-independent and can derive any preferred CIELAB under any chosen illuminant. In line with D2.1, the RGB pathway, based on calibrated RGB images and point spectral measurements, is the baseline input, because it uses data commonly acquired in conservation practice. However, its colorimetric outputs should be treated with lower confidence than those derived from calibrated hyperspectral data.

Where stronger accuracy is required from the sRGB pathway, the white and black reference should be supplemented with a multi-patch colour target such as a ColorChecker. A set of patches with known reflectance values allows a characterisation model to be fitted between the camera's RGB output and CIE XYZ. This characterisation narrows the accuracy gap between the sRGB and the hyperspectral pathway, since a three-channel sensor still cannot resolve the full reflectance spectrum.

The predictive relationship at the core of the LDE is fitted against colorimetric change; accurate and traceable colour management is therefore a precondition for the validity of the tool's outputs. Colour is introduced through a defined spectral-to-CIELAB derivation: a calibrated diffuse reflectance spectrum is obtained for each pixel of the hyperspectral cube is converted to CIE XYZ using the CIE 1931 (2°) standard observer under the D65 illuminant, and subsequently

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to CIELAB (1976), referenced to the D65 white point (CIE, 2018). Colour change over time or exposure is quantified using ΔE_{76}, consistent with the validated methodology of Siozos et al. (2025). The LDE relies on cubes provided by partner acquisition systems, typically Halogen or LED based. For the illuminant-independence property to be maintained, each delivered acquisition must include a Spectralon (white) reference and a black (dark) reference, captured under the same illumination and geometry as the object, to enable radiance-to-reflectance calibration independent of the acquisition light source. In line with the requirements of D2.1 (Section 4.3.4), the baseline input of the LDE is calibrated RGB imagery, characterised as in R4, complemented by point spectral measurements (Protocol B in D5.2); hyperspectral reflectance is an optional input that improves accuracy for pigment mixtures and varnished surfaces. Each result states which input was used and how it affects the accuracy of the prediction.

6.4. Visualisation

Visualisation is the final stage of the process. The tools described here are ATON, MuLaX and the visualisation of the Light Damage Estimator; ATON and MuLaX are developed by CNR. Both tools use colour information rather than generate it. What they can do depends on the data provided by the acquisition and processing stages, as well as on the limitations of the final delivery format.

ATON

ATON handles colour and material information through glTF and Cesium 3D Tiles standards (D3.1). ATON is built on Three.js (D3.1) and handles glTF assets, whose base-colour textures must be decoded from sRGB to linear values before shading (Khronos Group, 2021, §3.9.2). The working and output colour-space configuration of ATON will be documented in D4.1 (M14). Much of its colour behaviour is in any case set by the delivery format, which already imposes important constraints on how colour is handled.

Within the glTF standard, the encoding of base colour textures is sRGB, that is a defined colour space with a defined transfer function and an assumed reference display. First, it uses the BT.709 chromaticity coordinates, which correspond to the sRGB primaries. This means that wide-gamut colour spaces cannot be preserved directly in the format. Second, the base colour texture must use the sRGB transfer function. Third, and most importantly, embedded ICC profiles in PNG and JPEG images must be ignored by compatible glTF viewers (Khronos Group, 2021, §2.6, §3.4, §3.9.2)
This means that a conformant glTF viewer, including ATON, cannot use an ICC profile embedded in a texture as part of the colour-management workflow.
A more suitable approach is to preserve a colour-managed, wide-gamut version of the asset before conversion to glTF. This upstream version can be considered the reference or master asset. The transformation used to generate the glTF

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delivery version should then be documented and stored alongside the asset. In this context, the use of sRGB in the final delivery asset is not necessarily a problem, because it is required by the format. The more important issue is whether a separate wide-gamut master version exists upstream, as recommended by standards such as FADGI and Metamorfoze (FADGI 2023, pp. 19–21; van Dormolen, 2025).
Finally, the impact of the sRGB limitation depends on the type of object being represented. Some highly saturated heritage colours, including pigments such as cadmium yellow and cobalt blue, may fall outside the sRGB gamut and therefore cannot be fully reproduced. For objects whose colours already fall within the sRGB gamut, however, the practical impact may be minimal (Gaiani et al. 2021, §5.4).

LDE

A key aspect of the LDE tool is the accurate visualisation of its outputs. While the quantitative analysis of the hyperspectral data is performed in the CIELAB colour space, the results must also be rendered in sRGB, the standard display colour space, for visual interpretation. To this end, the CIELAB values are first converted to CIE XYZ tristimulus values, referenced to the D65 white point used throughout this derivation, and subsequently transformed to linear sRGB using the appropriate XYZ-to-sRGB matrix. The linear values are then converted to final display values through the sRGB transfer function (gamma encoding). This enables the LDE outputs to be displayed consistently on standard colour displays, in sRGB, while preserving the distinction between quantitative colorimetric analysis and visual representation.

MuLaX

MuLaX brings together previously acquired layers,such as VIS, UVL and VIL,and point analyses within the same spatially referenced environment. It provides tools such as lens and split views, texture-based masks and interactive semantic painting (D3.1).
MuLaX does not generate colour information itself, but displays the data produced by the acquisition and processing stages. For visible-light layers, ICC profiles are not managed by the application. This means that colour reproduction depends entirely on the processing carried out before the data are imported into MuLaX. The interface allows users to select and compare different layers, including VIS, UVL and VIL, but it does not apply an ICC-based colour-management chain to the visible data.
Uccheddu et al. provide a useful comparison from a different perspective: their workflow includes radiometric calibration to support quantitative comparison and classification of multispectral data. This is not equivalent to ICC-based colour management, but it highlights the importance of controlling image processing upstream when different layers are compared.

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MuLaX handles two-dimensional artefacts as well as three-dimensional ones (D3.1, Figure 10). Paintings are dealt with by mapping the image as a texture onto a plane, which means flat material travels the same route as everything else and inherits whatever happens on it, including the constraints the delivery format imposes

6.5. ICC colour management in 3D Visualisation

The limited use of ICC colour management in 3D Visualisation and in tools like ATON and MuLaX can be explained by three main factors, each of which requires a different response.

The first concerns visualisation and delivery formats. The ICC colour-management chain is effectively broken at the final delivery stage because glTF defines how colour must be handled: it uses fixed primaries, requires the sRGB transfer function for base-colour textures, and tells applications to ignore embedded colour profiles (Khronos Group, 2021, §3.4, §3.9.2). This means that even careful colour management earlier in the workflow cannot be fully preserved at this stage. This is a limitation of the interchange format, not a problem caused by a specific tool.

The second reason is that many 3D applications do not require exact colour reproduction. In some cases, the main goal is to compare or identify materials. What matters then is that pixel values are consistent and can be compared with each other or with a physical reference. For example, Uccheddu et al. successfully classify the distribution of materials on a 3D surface using radiometric normalisation, without applying a colorimetric workflow (2025, pp. 8–11). In this type of application, ICC characterisation is therefore not always necessary.

The third reason is related to how 3D software has developed. Photogrammetry software was mainly created for surveying and geometric reconstruction, where texture is generally treated as visual documentation rather than as a precise colour measurement. As Gaiani et al. note, colour procedures in this field have often been borrowed from other disciplines rather than developed specifically for photogrammetry (Gaiani et al., 2021). As a result, many software packages do not even allow users to specify a colour space.

These three cases should be kept separate in Chapter 8. The first is a limitation that cannot currently be removed and must instead be managed through workarounds. The second shows that ICC colour management is not necessary for every tool or task. Only the third represents a practical gap that can be improved through better workflows and practices within the project.

7. User Workflows and Analysis

To understand the colour management protocols required to be addressed or developed in this deliverable based on the realities of current practices, a dedicated survey of cultural heritage imaging practitioners was conducted within the COLOURS project and reported by Deborah et al. (2026) in ‘Surveying colour management practices in conservation/restoration of cultural heritage objects’

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that was presented in Association Internationale de la Couleur (AIC) 2026. The survey collected responses from 49 photographers, conservators and restorers, covering imaging equipment, lighting conditions, calibration, colour management software, photo-editing software and archiving practices, following a structure adapted from a related survey of 2D imaging workflows in the cultural heritage sector (Deborah et al., 2026; Eckertz et al., 2025).

The results reveal broad but uneven adoption of colour management practice. Dedicated camera equipment dominates over mobile devices (77.6% of respondents), and the use of physical colour targets during acquisition is high (73.5%), most commonly ColorChecker charts are used, with about 45% practitioners recalibrating on every capture rather than trusting a single fixed baseline. Lighting practice, however, is split by working context, such as institutional studio photographers tend to enforce a strict no-mixing policy to protect a stable colour profile, while practitioners working in situ e.g.: in galleries or historic buildings with fixed windows or house lighting, are frequently forced into conditional or intentional mixing of daylight and LED sources. Such a mixing practice respondents themselves associate with colour casts that are difficult to correct later (Deborah et al., 2026).

The survey's most significant finding, for the purposes of this deliverable, is a clear paradox between physical calibration effort and its digital exploitation. Although 73.5% of respondents photograph a colour target, only 45.8% use dedicated colour management software to process it, and just 14 of those 22 software users (28.6% of all respondents) build custom ICC or digital camera (DCP) profiles from their target captures. For the remainder, the target functions mainly as a manual white-balance and visual check rather than as the basis for a scene-referred colour profile. This is compounded by a heavy reliance on manual correction in post-processing where over half of respondents still colour-correct images by eye despite having captured a target. Flat-field correction which is described in high-end archiving guidelines as a non-negotiable step, is performed by only 18.4% of the total respondent group, largely restricted to institutional archivists with access to specialised equipment (Deborah et al., 2026).

At the level of formal standards, the survey exposes a genuinely polarised landscape where nearly half of respondents (47.6%) follow no international workflow recommendation at all and rely instead on custom, in-house or ad hoc protocols, while only a specialised minority systematically apply frameworks such as FADGI, ISO 19264 or Metamorfoze and consistently link their calibration data to descriptive metadata. This is mirrored in archiving practice, where raw and processed images are widely retained (around 80% and 75%, respectively) but only 32.7% of respondents retain the metadata and paradata needed to make that imagery scientifically usable in the long term, and only 16.3% achieve what the survey terms a ‘gold standard’ of retaining calibration data, metadata/paradata and workflow documentation together (Deborah et al., 2026).

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Taken together, these findings provide direct empirical support for the argument set out in Chapter 3 of this deliverable i.e. cultural heritage colour management is characterised not by a lack of willingness among practitioners as most already invest in colour targets and post-processing, but by the absence of a single, practical, well-communicated set of protocols that connects physical calibration effort to a rigorous, metadata-linked colour management workflow. The survey's authors report an active demand for baseline education in technical imaging workflows and conclude that these results should directly inform the design of a flexible, robust colour management workflow for the European Collaborative Cloud for Cultural Heritage platform which is precisely the aim of the protocols proposed in this deliverable (Deborah et al., 2026).

8. Colour Management Recommendations

This Chapter derives practical colour management recommendations from two project case studies, a 19th-century oil painting captured with RGB and hyperspectral cameras (2D, Düsseldorf) and polychrome statuary captured by photogrammetry (3D, Bratislava) and relates them to the published workflows reviewed in Chapters 3 and 6 and to the practitioner survey in Chapter 7. The case studies are dedicated exercises carried out by project partners to develop and test the protocols under realistic conditions. Case study 1d (Düsseldorf) is one of the paintings of case study 1d of Internal Pilot 1, and Case study 2a (Bratislava) is case study 2a of Internal Pilot 2; both were carried out ahead of the Internal Pilots. In the Internal Pilots, acquisition is normally carried out by the holding institution, and the protocols will be validated on the full set of Internal Pilot case studies (Chapter 9). Where a case study step underlies a recommendation, it is cross-referenced by its number (R1–R11, Table 8.1).

8.1. Case studies

Case study 1d (Pilot 1): RGB and hyperspectral image acquisition at BRAKEBUSCH restaurierungswerkstatt, Düsseldorf (2D/flat scenario)

The Düsseldorf case study was carried out at the BRAKEBUSCH Restaurierungswerkstatt conservation studio, where a 19th-century oil painting, Blick auf das Wetterhorn by August Wilhelm Leu, was imaged in a practical studio setting rather than a specialised imaging laboratory, following the general 2D acquisition procedure described in Section 6.1 (oblique halogen lighting, whiteboard for flat-fielding, co-registered RGB and hyperspectral capture; see R1 and R2) (Habib et al., 2026).

In this campaign the Canon RGB camera and the Specim IQ hyperspectral camera were mounted together on one tripod, with a ColorChecker placed below the painting (Figure 8.1), so that the RGB and hyperspectral data share viewpoint, lighting and reference material (R2).

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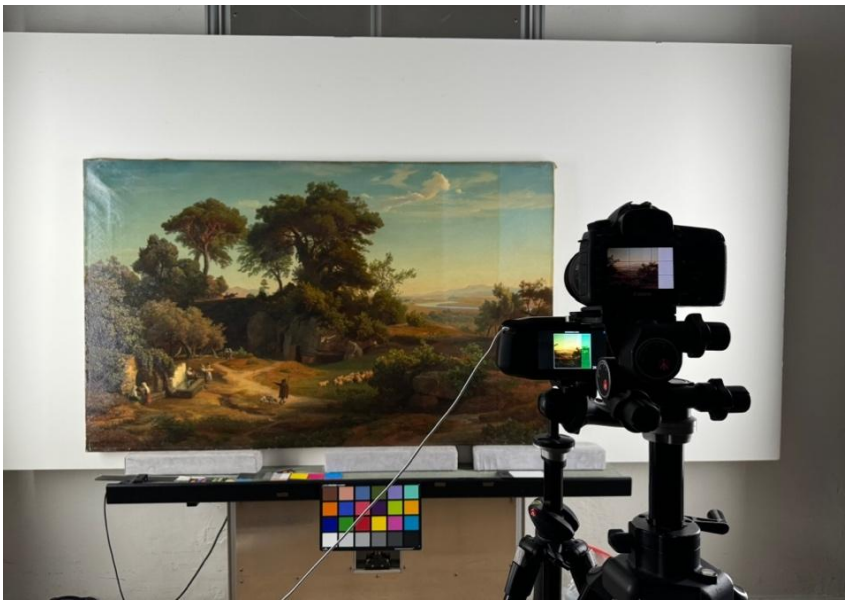


Figure 8.1: 2D/flat acquisition set up

The hyperspectral data and RGB data were acquired in two separate sessions: once before any conservation treatment, and again approximately one month later, after varnish removal had been completed on one third of the painting. Each hyperspectral image comprises 204 spectral bands spanning 397.32 to 1003.58 nm at 3.09 nm intervals; because the bands below about 400 nm and above about 780 nm showed increasing noise, particularly towards the near-infrared, only the first 140 bands (397.32–807.84 nm) were retained, covering the visible range with reliable signal quality (Habib et al., 2026). The Specim IQ outputs spectral radiance, which was converted to spectral reflectance following the procedure described in Chapter 5: dark-current subtraction, then normalisation by a secondary whiteboard whose reflectance had been calibrated against a primary white reference target with manufacturer-supplied reflectance factors (Habib et al., 2026; Figure 8.2; see R2).

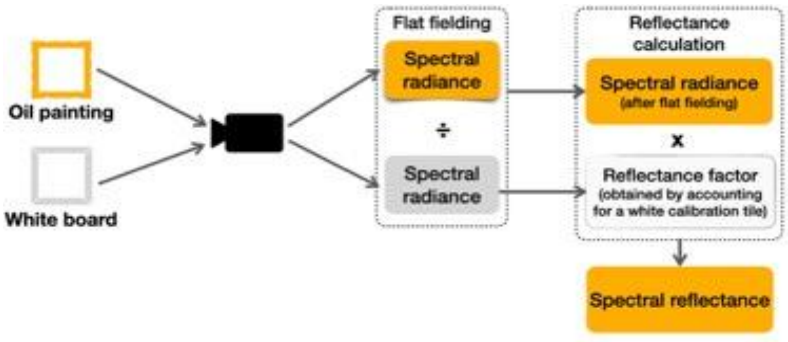


Figure 8.2: Illustration of the process of obtaining spectral reflectance factor of the case study painting from the acquired spectral radiance cube. Dark subtraction was performed during the flat-fielding step.

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This hyperspectral reflectance data was then used to simulate the virtual removal of the painting's aged varnish, using a physics-based model that decomposes the light reflected from the painting into an interface (surface) reflection component and a body (pigment) reflection component, and removes the wavelength-independent interface contribution associated with the aged varnish layer (Trumpy et al., 2015; Habib et al., 2026). Because this virtual cleaning operates directly on physical spectral reflectance values, rather than on an RGB image encoded in any particular device or display colour space, the computation itself required no colour management, as the algorithm's inputs and outputs are calibrated reflectance spectra, which are colorimetrically well defined independently of any camera or screen. The results were validated quantitatively, by comparing the virtually cleaned reflectance spectra against those of the physically cleaned painting using colour-difference (CIEDE2000) and spectral (RMSD) error metrics, and were only converted into sRGB images, via a standard colorimetric rendering step, at the very last stage, purely so that the outcome could be visually inspected and communicated to conservators (Habib et al., 2026; see R6).

In this acquisition scheme, the RGB and hyperspectral captures play complementary rather than interchangeable roles. Hyperspectral and multispectral sensors inherently trade spatial sampling for spectral resolution, so the RGB camera remains the practical source of the high-resolution image needed for documentation and display and should be colour-managed using an ICC workflow. The RGB images are converted from camera RGB into a standard working space via an ICC input profile derived from the colour target captured during the same session, following established camera-characterisation procedures (Molada-Tebar et al., 2019; see R4 and R5). The simultaneous hyperspectral capture, however, offers more than a parallel dataset, because it records the full spectral reflectance of the same colour target and painting under the same illuminant. It can be used as a physically grounded reference to build or validate a more accurate ICC/camera characterisation than a colour-chart regression alone can provide (R7).





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Figure 8.3: Case study 1d, before-cleaning capture rendered in sRGB. Left: Hyperspectral image. Right: colour-managed RGB image (captured illuminant, chromatically adapted to D65) for a selected area.

The use of the hyperspectral data as a colorimetric reference (R7) was tested for this case study. Both data sets were radiometrically corrected (dark and flat-field correction, normalisation to the white reference). The hyperspectral data were converted to reflectance and the raw RGB data were demosaiced linearly. The reflectance of each ColorChecker patch was converted to CIE XYZ (CIE 2° observer) under the captured illuminant, and a least-squares mapping from white-normalised camera RGB to XYZ was fitted on the patches. The mapping was applied to the whole RGB image, which was chromatically adapted (Bradford transform) to the D65 white point and encoded as sRGB. The fit to the chart patches gave a mean ΔE_{00} of 1.38 (median 1.26). After registration of the colour-managed RGB image to the pixel grid of the low-resolution hyperspectral image, a pixel-by-pixel comparison over a selected area as shown in Figure 8.3, with both images in chromatically adapted XYZ under the captured illuminant, gave a mean ΔE_{00} of 1.83. The fit error refers to the patches used to derive the mapping, and the comparison is made against the hyperspectral reference rather than an independent measurement (R5).

Case study 2a (Pilot 2): Photogrammetric acquisition at Galéria mesta Bratislavy (3D scenario)

Building on the state-of-the-art review and the workflow analysis presented above, this section illustrates how a colour-aware acquisition can be implemented in practice, through a real acquisition campaign carried out within the project. The approach described below is proposed as good practice for photogrammetric acquisition of reflective, oversized or otherwise challenging polychrome surfaces within COLOURS. This campaign is a 3D acquisition of part of the Galéria mesta Bratislavy (GMB) statuary collection, carried out in June 2026 by CNR ISPC, NTNU and GMB teams. It was a dedicated, CNR/NTNU-led acquisition exercise. Its purpose was to develop and test the colour-management protocols under conditions realistic enough, such as, reflective polychrome surfaces, large object size, mixed lighting constraints, ahead of validation on the rest of the Internal Pilots. The following practices were adopted to ensure rigorous digitisation and colour fidelity throughout the campaign. To optimise logistics and ensure consistent conditions, all statues were relocated to a single facility, where the complete imaging setup was mounted on the first day and used continuously for the remainder of the campaign. The space provided optimal dimensions (7 × 11 m) with pale white-grey walls, allowing for a controlled and uniform workflow. The campaign addressed two specific groups of sculptures from the collection: large-scale statuary (measuring 2.20–2.30 m in height) and smaller sculptures (measuring between 80–120 cm), plus various smaller fragments.

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Acquisition took place entirely indoors, in an environment free of ambient light pollution; the only light sources present were the two main studio lights used for cross-polarised illumination, both set to a known and fixed colour temperature (R1).
The acquisition setup utilised specific studio support equipment to specifically accommodate the scale of the large sculptures. The camera was mounted on a professional studio column camera stand, allowing to smoothly and precisely move the camera along the various axes, while keeping its position and distance to the object consistent. Between rounds, the camera was repositioned vertically along the column stand using the movable arm, reaching heights of up to approximately 3 m. This was necessary to cover the upper portions of the taller statues (2.20–2.30 m), which would otherwise have fallen outside the camera's field of view from a single fixed height.



Figure. 8.4: Pictures of the wooden polychrome statue taken with and without polarised filters

The illumination setup included studio lights and large soft-boxes, however, due to the polished reflective surfaces of the statues it was necessary to neutralise reflections using a cross-polarisation approach (Conen et al., 2018; Bartoš et al., 2023). To do so, a polarising filter was directly mounted on the camera lens, while two cross oriented polarised sheets were placed over the main light sources.
Well-distributed, diffuse lighting combined with cross-polarisation is necessary to avoid strong cast shadows and specular reflections in the source photographs; only under these conditions does the photogrammetric processing yield an albedo

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texture free of such artefacts, allowing an accurate rendering of the object's true colour and, where needed, supporting virtual relighting of the model or a photorealistic PBR simulation of its reflective behaviour, as shown in Figure 8.4

Because the statues were too large to fit inside available standard lightboxes, the standard photogrammetric alternative would have been to acquire each object by moving the camera and tripod around it. This would have required a colour reference picture at every camera position, which was highly impractical and time consuming. The camera and illumination setup was therefore kept strictly fixed, and the statues were rotated on turning pedestals, with alignment marks on the ground to keep them centered (Figure 8.5; R1, R2).



Figure. 8.5: 3D acquisition set up

The photogrammetric acquisition was carried out across 4 to 5 complete rotational rounds per statue. Between rounds, the camera was repositioned, moving primarily up and down along the vertical Z-axis on the column stand and adjusting the angle to capture the full geometry. To adhere to the calibration protocol, a ColorChecker reference target was photographed at the beginning of every round, after the camera set-up, giving one reference per round under the light and camera configuration used for that round (R2).

In summary, the GMB workflow (fixed camera and lighting, rotated object, cross-polarised illumination and a per-round reference target) is a practical, repeatable template for acquisition campaigns involving reflective or oversized objects (R1, R2, R8). The resulting textured model is shown in Figure 8.6.

The per-round ColorChecker captures support the image-level characterisation recommended in Table 8.1 (R4, R8), which is evidenced by published workflows. Calibrating the images against a target before photogrammetric reconstruction preserved colour through the pipeline, with texture blending as the only uncontrolled step (Barbero-Álvarez et al., 2023; Section 6.2). Colour inconsistency between the input photographs is a major source of visible texture seams (Coelho et al., 2022), and applying an ICC profile built from a target to scan textures significantly reduced colour error in the final 3D model (Felicísimo & Polo, 2022). A purpose-built colour chart with a multi-dimensional calibration outperformed

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generic chart-based calibration and is worth considering for future campaigns (Barbero-Álvarez et al., 2021).



Figure. 8.6: 3D Model of the statue after photogrammetric processing: specular reflection and cast shadow are not present in the textures.

A flat colour target samples colour under a single geometry of surface, camera and light, which is not sufficient for the reflective, polished GMB statues whose visible colour changes with viewing and illumination angle. In published work, colour-managed HDR imaging integrated into a BRDF-based appearance acquisition produced models in CIE XYZ that were compared with spectrophotometric measurements (Goesele et al., 2004), and dedicated systems measure 3D shape, multispectral colour and angular reflectance with the same detector (Sitnik et al., 2011). Colour correction has also been carried out directly on point clouds and meshes (Pepe et al., 2017; Coelho et al., 2022). A multi-faceted 3D target that samples the same reference colours at several known surface orientations, from which a BRDF-aware correction could be propagated over the point cloud, has not yet been tested in the project and is proposed in Table 8.1 (R9).
The 3D images of case study 2a have been captured; their characterisation and accuracy (R4, R5, R8) will be reported in D10.2 (M24).The colour management of these images will be carried out in the next phase, and the accuracy will be reported.

8.2. Colour management recommendations

The recommendations in Table 8.1 describe the practice that COLOURS proposes to follow. They may go beyond what the tools and workflows described in Chapter 6 currently do and will be refined as the Internal Pilots provide validated results.

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Display characterisation and viewing conditions for desktop and XR visualisation are specified in D5.2 (Sections 4.4 and 6.5), which also addresses the requirement of D2.1 on consistent colour representation across devices.
They consolidate what the case studies, the reviewed workflows and the survey show to be necessary for colour-managed digitisation of paintings and sculpture in a practical heritage setting, i.e. by restorers, conservators and photographers without colour-science expertise. Each is tagged by its evidence: *Tested* (used in a case study), *Literature* (supported by published work) or *To test* (proposed, not yet validated).

Table 8.1: Colour management recommendations for different scenarios.

No.	Recommendation	Basis	Applies to	Status
R1	Use one stable, known-CCT light source in a fixed geometry: two symmetric oblique lights for flat originals, cross-polarised diffuse light for glossy 3D objects. Avoid mixing daylight and LED. Where possible keep camera and lights fixed and move the object.	Case studies 1d, 2a; Chapter 7; Conen et al., 2018; Bartoš et al., 2023	2D/flat and 3D	Tested
R2	In every session or camera round, under the actual illumination, capture a uniform white/grey board (flat-fielding) and a multi-patch colour target (e.g. ColorChecker); for hyperspectral work add a calibrated white reference and a dark frame. In photogrammetry one target capture per round gives a set-level reference; the target need not appear in every frame.	Case studies 1d, 2a; Chapter 5, Section 6.1, Chapter 7; FADGI, 2023; ISO, 2021	RGB, hyperspectral and 3D	Tested
R3	Capture raw with fixed exposure, no auto white balance and no clipping. Apply identical raw-development settings to the whole set, process at 16 bit or higher and convert to 8-bit only for delivery.	Case studies 1d, 2a; Chapter 5, Section 6.2; Barbero-Álvarez et al., 2023; FADGI, 2023	RGB	Tested
R4	Characterise the camera, do not only white-balance. After black-level, flat-field and demosaicing, derive an ICC input profile or a matrix/polynomial model to CIE XYZ from the target. A raw converter ColorChecker preset is not an ICC characterisation. Re-derive it when light, exposure or camera settings change.	Case study 1d; Section 6.2, Chapter 7; Molada-Tebar et al., 2019	RGB	Tested
R5	Quantify and report accuracy: validate on patches not used for fitting and report both ΔE_{00} and ΔE_{76} (mean and 95th percentile), with illuminant and observer stated. Agree	Case study 1d; Section 6.2; Molada-Tebar et al., 2019;	All	Literature

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	acceptance thresholds for each metric before the validation.			
R6	Process spectral data in reflectance and render to sRGB only at the final visualisation step: analyses such as virtual varnish removal need no colour management, the rendered image does. State illuminant and observer and the chromatic adaptation used when exchanging with D50-referenced ICC profiles.	Case study 1d; Chapter 4, Sections 6.3, 6.4; Habib et al., 2026	Hyperspectral	Tested
R7	Where co-registered hyperspectral data exist, use their reflectance to compute target and painting colour under the actual illuminant, and use it to build or validate the RGB characterisation. Keep RGB for spatial detail.	Case study 1d; Chapter 4; Liang, 2012	RGB and hyperspectral	Tested
R8	In photogrammetry apply the per-round characterisation to all images of the round before structure-from-motion, keep rounds consistent, and use cross-polarisation so that the texture approximates diffuse albedo. After texturing, measure ΔE_{00} and ΔE_{76} of the visible target patches in the model to quantify the uncontrolled blending step.	Case study 2a; Section 6.2; Barbero-Álvarez et al., 2023; Coelho et al., 2022	3D	Literature
R9	For glossy or polychrome surfaces treat the flat-target correction as the diffuse baseline. Test a multi-faceted 3D target that samples colour against surface orientation, condition the correction on local normal, light and view direction, and propagate it consistently over the point cloud or mesh.	Case study 2a; Goesele et al., 2004; Sitnik et al., 2011; Pepe et al., 2017	3D (Glossy and Polychrome objects)	To test
R10	Archive a master (raw plus a characterised 16-bit file with profile, or EXR texture) and derive delivery versions by a documented transform. Expect sRGB 8-bit delivery in glTF-based viewers (embedded ICC profiles are ignored), flag colours outside the sRGB gamut, and keep luminescence bands (UVL, VIL) separate from visible colour.	Sections 6.1d, 6.4, 6.5; Gaiani et al., 2021; Khronos Group, 2021	All	Literature
R11	Record illuminant (type, CCT/SPD), geometry, camera settings, target identity and reference values, raw-development settings, profile or transform, software versions and accuracy results, and link them to the image metadata, in a form compatible with FADGI, Metamorfoze and ISO 19264-1.	Section 3.1, Chapter 7; Deborah et al., 2026; FADGI, 2023; van Dormolen, 2025; ISO, 2021	All	Literature

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R1–R5, R10 and R11 (plus R8 for 3D objects) form a minimum workflow that requires only a stable light source, a white board, one colour target and raw capture. Hyperspectral reference data (R6–R7) and BRDF-aware correction (R9) are optional extensions for institutions with the necessary equipment. These recommendations rest on one painting, one statuary collection and published workflows; the acceptance thresholds in R5 and the items marked *To test* will be validated on the Internal Pilots (Chapter 9).

9. Conclusions and future work

This deliverable defined colour management protocols from two case studies, published workflows, tools and a practitioner survey, consolidated in Table 8.1 (R1–R11). The next step is to validate these protocols under the real conditions of the project's Internal Pilots. The validation will include psychovisual experiments of Task 5.3, designed in D5.2 (Chapter 5), in which stakeholders of the Internal Pilots assess colour and appearance consistency across a controlled laboratory display setting, AR/VR viewing conditions, and uncontrolled everyday computer-display viewing; they will be run once the Internal Pilot datasets are available in WP10, and their results will be reported in D10.2 (M24). The items still to be validated are the acceptance thresholds for colour accuracy, set separately for ΔE00 and ΔE76 (R5), the extension of the use of hyperspectral data to build or check the RGB camera characterisation (R7, tested in case study 1d) to the Internal Pilot datasets, and the multi-faceted 3D target for glossy and polychrome surfaces (R9). In parallel, the spectral-based component of the protocols is formalised and extended for the ECHOES/ECCCH platform in Deliverable 5.2, submitted together with this deliverable, and will be carried into implementation and deployment under Work Package 6, where it will be tested against the additional, more critical cases of colour consistency across media and display platforms that arise once the protocols move from controlled acquisition campaigns into full operational use.

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