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Micro fading test for textile single yarns: a new methodology applied to the *Reformation Tapestry* to assess its sensitivity to light

Giulia Vannucci[1*], Salwa Joram[2], Anna Beselin[3] and Stefan Röhrs[1]

Abstract

Tapestries and especially pile carpets can be challenging objects for assessing their photosensitivity by microfading: they are often made of relatively thick yarns resulting in a non-flat airy surface. For this reason, focusing the light on the object's surface is difficult and the precision of the colour change measurement is hampered. In this study, an improved test methodology was developed to overcome the difficulties by analysing single yarns. The methodology consists in flattening the yarn between glass microscope slides tightly held together by means of 4 strong paired neodymium magnets. The results show that the newly-developed sample preparation together with the required instrumental adjustment allow to significantly reduce the standard deviation and variation coefficient which often characterize microfading measurements of textiles. The methodology for sample preparation is evaluated and had been applied to samples from the *Reformation Tapestry* dating to 1667 from the collection of the Museum Europäischer Kulturen (Museum of European Cultures) in Berlin.

Keywords MFT, Micro-fading test, Textiles, Fibres, Yarns, Tapestry, Dyes, Micro-fader, Colour change

Introduction

For artwork displays, museums have to meet the most adequate lighting conditions in order to minimise the risk of light damage and, at the same time, allow the visitor to visually experience artworks at adequate illumination. The dilemma in balancing visibility and safeguard ("seeing versus saving" [1]) is a well-known and discussed issue that challenges conservators, curators or museum professionals. Light damage is a consequence not only of the light´s intensity, but also of its duration. The relationship between exposure time and light intensity is described by the Reciprocity Law, or Bunsen-Roscoe Law, according to which the material response is a function of exposure (or dosage), which can be expressed as the product of intensity and time. If reciprocity holds, the same amount of damage is provoked whether facing high intensity for short exposure time or, conversely, long exposure times at low intensity. While this principle holds for the most stable artefacts, it has been demonstrated that highly fugitive colourants might not obey the reciprocity [2].

According to the objects' responsivity to exposure, the optimal light display conditions have to be assessed taking into account intensity, exposure duration, and spectral power distribution of light source [3, 4]. Textiles, tapestries as well as pile carpets and woven floor coverings, works on paper or parchment, dyed leather, painted or dyed wood are some of the materials well-known to experience colour change induced by light which may occur as fading, yellowing, change of hue, or darkening. In addition, the photochemical

*Correspondence:
Giulia Vannucci
g.vannucci@smb.spk-berlin.de
[1] Rathgen-Forschungslabor, Staatliche Museen Zu Berlin, Stiftung Preußischer Kulturbesitz, Berlin, Germany
[2] Museum Europäischer Kulturen, Staatliche Museen Zu Berlin, Stiftung Preußischer Kulturbesitz, Berlin, Germany
[3] Museum Für Islamische Kunst, Staatliche Museen Zu Berlin, Stiftung Preußischer Kulturbesitz, Berlin, Germany

change induced by light can also cause embrittlement, fraying of fibres and surface cracking. The knowledge of the identity of the pigment or dye alone is not sufficient for assessing the light sensitivity of a material, since this is affected also by other factors such as any interaction between the colourant and the substrate, the pH of the substrate, the other materials surrounding the colour (especially for a paint), concentration of the colourant, particle size of the colourant, and history of past exposures [5–7]. In addition, environmental factors such as oxygen availability or relative humidity influence the fading rates [8].

In absence of rigorous light sensitivity data, the general guidelines provided by museum professionals often restricted exhibit durations or light levels, limiting the public access, since "standard" rules are applied to broad classes of colourants and materials [9, 10].

Thanks to specific fading rate data, it is possible to assess the light sensitivity of a cultural heritage object prior to its exhibition and thus elaborate an ad hoc strategic plan to minimize its damage, by modifying the light conditions of the display, the rotation schedule, or perhaps the decision to exhibit or loan the artwork at all. The microfading tester (MFT), introduced in the field of heritage science by Paul Whitmore in 1999 [11] to address the aforementioned issues, meets the requirements of specifically obtaining rapid and sensitive measurements of colour change during a light exposure for a certain object. The MFT is a device capable of performing accelerated fading tests (with megalux values of incident radiation) on sub-millimetre areas as reflected spectra are continuously recorded in real-time and transformed into colour information. With these values, it is possible to correlate a change in colour to the light exposure in less than 30 min. The tests, which are almost non-destructive, can be performed direct on the object or on samples, without the need of characterizing the material beforehand. As with any accelerated aging method, the results are better evaluated if compared to a set of standards, which are tested under the same experimental conditions [12]. In MFT measurements, the reference materials employed are the three most light-sensitive examples of a set of eight blue dyed fabrics known as Blue Wool standards (BWs), conforming to ISO 105 [13].

Since its introduction, many museums and heritage institutions all around the world have started to employ this technique to study different materials and collections, such as photographic materials [13], Alaskan native artefacts [14], textile dyes [15], Japanese wood block prints [16], Australian indigenous objects such as feathers, natural fibres and natural dyes and resins [17], and many others (a general summary can be found in the article by Ford et al. of 2013 [5]).

Due to the relative slowness of the fading process and the lack of a colour reference to compare with, colour change often goes unnoticed. For tapestries and pile carpets, it is possible to observe the fading by comparing the colours on the front with the reverse side. In the case of pile carpets, the fading is also detectable by opening up the pile. Often the tips of the pile are much lighter than the inner part of the pile as the inner area is, like the reverse side of the carpet, protected from direct light. An adapted methodology applicable to yarn samples of tapestries and pile carpets was developed for assessing the photosensitivity of this type of object. Taking a sample, instead of direct measurement on the object, is generally not the preferred approach, but has in the case of tapestries certain advantages. In comparison to objects from other materials, tapestries and pile carpets can be more easily sampled because they are commonly rather large and sampling is often possible at the reverse side or from the pile. Additionally because of their size, they can be difficult to handle which can also favour the sampling approach. Tapestries and pile carpets are mostly made of thicker yarns than textiles or fabrics in general. This causes a very non-flat and bulky topography of the sample surface and "fluffiness" on a micro-scale level. These circumstances make a precise measurement of the colour change difficult because the incident light cannot be focused on a well-defined surface and the geometry for colour measurements is not respected [18]. Same considerations apply also to the finely woven BWs. As outlined by Lerwill et al. [19], small differences in the focusing plane can greatly affect the fading rate, and according to Tse et al. [18], this is indeed one of the major causes for erroneous results. In addition, special attention has to be given to slightest displacements of the tested area as this is also responsible for non-accurate and non-precise results. The use of small weights to fix the object is sometimes not enough to avoid micro movements of the tested materials, but Tse et al. found that objects could be well immobilized within neodymium magnets and a metal plate beneath. We use a glass slide to properly fix and flatten the sample. Microfading framed and glazed objects through glass has already been outlined in previous studies [20–22].

The new micro-fading methodology was used to study the photo-sensitivity of historic textiles from the collections of the Museum für Islamische Kunst ('Museum of Islamic Art) and Museum Europäischer Kulturen (Museum of European Cultures). Micro-fading results from the Reformation Tapestry (Fig. 1) in the Museum Europäischer Kulturen will be discussed in this article [23]. The *Reformation Tapestry* can be dated to the seventeenth century, as the date "31st October 1667" can be read in its outermost edge. It is believed to have been

Fig. 1 Panel 4 of the *Reformation Tapestry* (Museum of European Cultures, Berlin)

created to commemorate the 150th anniversary of the publication of Luther's ninety-five theses, which was the trigger for the Reformation process in northern Europe. The tapestry (length 350 cm height × 53 cm) was produced using a discontinuous weft in a technique known as *tapestry weaving* or *Gobelin* technique, that reflects Flemish and northern Dutch influences. It consists of five panels with inscription bands illustrating scenes from the New Testament. During an extensive conservation treatment in 1973–1976, original thread ends were sampled and preserved in the collection. These samples were then analysed for the last exhibition in the Museum of European Cultures in 2017/2018 in occasion of the 500 years anniversary of the Lutheran Reformation [24, 25].

The overall well preserved colours suggest that the tapestry did not see much light during its lifetime. Even though the colours are brighter on the reverse, they do not contrast very strongly with the front. Observation of the tapestry with respect to its colours revealed that this contains a large number of reds—many shades between scarlet and pink. Also, blues, yellows, and greens and their various shades and tones, all the way to beige are present. All the image panels are made with a dark brown background. In the inscription bands, the background colour changes: the first panel features exclusively dark blue wool, the second one green and the third one dark green. The last colour appears nowhere in the first panel. Such changes in colour are not uncommon in tapestries. This can be explained by the materials available, because the dyed yarns were produced in relatively small batches. Every batch could have a different nuance, due to variations in the natural raw materials as well as different hands following the same recipe [23–25]. This might also affect their sensitivity to light.

Methods

Samples

The tests were carried out on 10 samples in the form of yarns or bundles of threads from the *Reformation Tapestry* from the Museum of European Cultures, Berlin (Fig. 1). These had been characterized (type of fibre, colourant and mordant employed) in previous studies [24, 25].

Micro fading tester

The instrumentation employed resembles the original MFT developed by Whitmore. The intense light is focused on a micro-spot of the sample, from which reflected spectra are continuously recorded by a receiving probe, connected to a spectrometer and finally a computer. The reflected spectra are transformed into colour information employing CIELAB.

For the tests, an Oriel® Fading Test System (model 80,190) from Newport Oriel Corporation (California, USA), with a sampling head extended with an endoscope camera was employed. The light source is a UV and IR filtered Xenon arc lamp (Osram 75W Xe). The reflectance spectra were analyzed with a photodiode array detector (control development, model PDA-512). Optical fibres (Oriel P/N 78251 and 78367) were used to deliver a focussed beam of light to the sample.The geometry of illumination and detection is 0/45°. The diameter of the illuminated spot is 0.4 mm and the test duration was 15 min. The dimension of the MFT spot was estimated after exposing a sun-print paper to the intense MFT light for few seconds followed by measuring the so faded diameter spot under a microscope. The instrument is calibrated employing a LabSphere Spectralon® as white standard. The warming-up time of the instrument is of 1 h. Spectra were recorded in the wavelength interval of approximately 420–735 nm. The irradiating light had a measured intensity ranging between 5.28 and 5.33 Mlux. Illuminance was measured daily using an Almemo datalogger 8590-9A and a FLA623 sensor adapted to measurement of direct light.

The CIELAB system

The system used for colour notation is CIELAB, also known as CIELAB1976. This system defines a three-dimensional colour space within which the colour characteristics of a sample material are specified in terms of a lightness dimension L*, and two chromatic dimensions, a* and b*. The L* dimension indicates the lightness from black to white (0–100). The other two dimensions indicate the colour in terms of redness-greenness and yellowness-blueness respectively. The CIELAB colour space was defined in 1976 with the aim to provide a perceptually uniform space with respect to human colour vision, meaning that the same amount of numerical change in these values corresponds to about the same amount of visually perceived change.

In 2001 an improved colour difference equation for the CIELAB colour space has been introduced to better fullfill the perceptually uniformity in all areas of the colour space. This affects particularly differences of the blue hues and is therefore important for measurement of BWs. Results in colour differences are calculated as ΔE_{00} values.

Blue wool classification

The fading response of the tested material is categorized by comparing it to a reference material: the Blue Wool (BWs) standards, conform to ISO 105.

In total eight dyed BWs standards are available, with BW1 being the most photosensitive and BW8 the least. Each successive material is approximately from two [7] to three times [1] as lightfast as the previous one. Commonly for micro-fading only the BWs standards 1–3 are used. Colour change of materials that are less photosensitive are difficult to assess since their reaction might be too weak to be detected in a short measurement. In museums, objects are categorized by their light sensitivity. Recommended classifications of annual light exposure of objects related to the light sensitivity of Blue Wool Standards have been published in the CIE 157:2004 [4]. A limiting exposure in lux hours per year is attributed to each material class.

Publications on the subject of lighting policies [10, 27–29] separate highly sensitive objects into different categories. Based on the literature, the Rathgen Research Laboratory has produced the evaluation scheme shown in Table 1, which shows recommendations based on the microfading results. It is worth saying that other institutions also make different recommendations [30].

Methodology developed for single yarns MFT analysis

Bulky and voluminous fibres can be mounted in a way that enables to flatten the surface and can so be tested as single yarns in MFT. To compare results from different sample preparations, the colour change for BWs single yarns are compared to conventional measurements of BWs as a fabric. For each test, Blue Wools (1–3) were measured 10 times by MFT. The individual ΔE_{00} values were used for the calculation of average ΔE_{00}, and standard deviations. These values were used for evaluating the performance of the sample preparation in comparison to the conventional use of BWs.

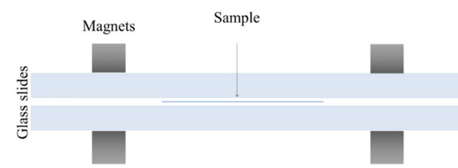

Fig. 2 Schematic representation of the flattened sample between two glass slides held together by means of neodymium magnets

Several ways of mounting the sample were tested. No satisfying results were registered when the yarn was simply prepared on a glass slide. Sandwiching between glass slides was tested subsequently. Fixing to the glass slides by adhesive tape or the use of neodymium magnets with the sample being sandwiched between a glass slide and a metal support as proposed by Tse et al. [18] was tested. Surprisingly, no improvement was observed, apparently the pressure was not high enough.

The mounting of the sample was optimized in such a way to flatten the single yarn between two glass microscope slides, tightly held together by means of 4 paired neodymium magnets (Fig. 2). Neodymium magnets (brand Maqna) were purchased from the Otom Group GmbH, and consist of Neodym magnets of 10×4 mm^2. They are nickel-plated and belong to the Class N42 (i.e. magnet with 42 MegaGauss-Oersted, Article number: SB-10 × 4-N42-N). The adhesive force is around 2 kg for an area of only 10×4 mm^2. The handling of these types of magnets can represent a risk of accidents due to their high magnetic force.

This arrangement as shown in Fig. 2 required a re-alignment of the MFT probes to compensate for the deviation of the light beam due to the introduction of the upper glass slide into the light path (Fig. 3 (a)).

The geometry of illumination and detection is 0/45°. A theoretical calculation, taking into account the upper glass microscope slide (soda lime glass) of 0.9 mm height and refractive index of 1.518, indicated that the illuminating probe had to be lowered by 0.43 mm

Table 1 Rathgen research laboratory evaluation scheme for micro-fading results

Classification	Suitability for exposition	Exposure limits		
		% of total exhibition time	exposure time in a decade	exposure in lux hours per year
BW1	*Very sensitive*; not recommended for exhibition	0%	–	–
BW2	*Sensitive*; not recommended for permanent exhibition at 50 lx	20%	2 years of 10 years	30,000 lx h/a
BW3				
BW4	*Less sensitive*; suitable for *permanent exhibition* at 50 lx	100%	10 years of 10 years	150,000 lx h/a

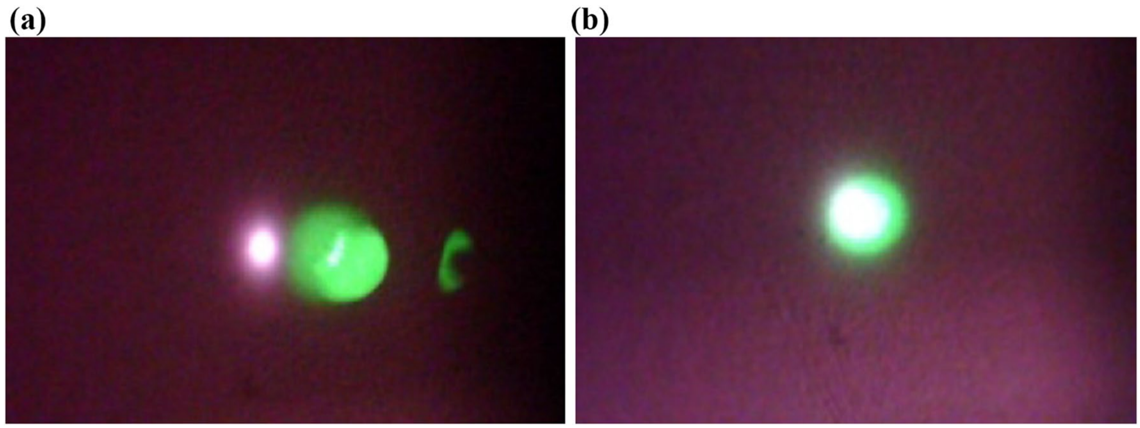

Fig. 3 Receiving and illuminating probes in presence of the upper glass microscope slide before (**a**) and after (**b**) modification of geometrical set-up. Green laser light is projected through the receiving fibre

(distance b in Fig. 4) to reach the required alignment (Figs. 3(b) and 4)—see Appendix for the calculations. Subsequently, the position of the illuminating probe was adjusted in order to focus in the interception point of the two beam paths. Alignment was carried out experimentally by projecting light through both probes and superimposing the light spot (Fig. 3).

The light absorbance of the glass slide was estimated. In presence of the glass slide, the light intensity registered by the Almemo measuring probe decreased of around 10%. This means a transmission of about 90%. The calibration with the white standard (Labsphere Spectralon®) was performed whileinterposing the glass slide. Because of the double passage of light through the glass, a decrease in maximum raw counts intensity of around 20% was registered when comparing these values from previous tests. Indeed, two transitions through the glass slide with 90% transmission would result in 80% of the initial intensity.

These results were confirmed by measuring the transmittance of the glass slide employed (Fig. 5). These measurements were carried out in the laboratories of Technical University of Berlin, Faculty of Electrical Engineering and Computer Science, Department of Lightening Technology. The spectrophotometers used are Omega 20 from Bruins instrument (Puchheim, Germany). Measurements were taken in the range 250–1000 nm (5 nm step); the software employed is Omega.

Analogous considerations and calculations were made in the study by Prestel [22], where the application of microfading technique through glass was evaluated.

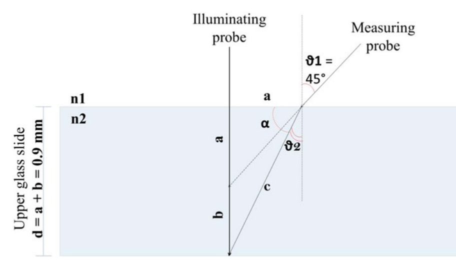

Fig. 4 Schematic representation of the light path with a glass slide interposed between the sample and illuminating/measuring probes. The upper glass slide has a thickness of d = 0.9 mm. n1 and n2 are the refractive index of air and the microscopic glass slide, respectively. ϑ1 is the angle formed by the normal to the surface and the receiving probe direction (45°); ϑ2 is the deviation angle inside the glass calculated through the Snell´s law. α is the complementary angle to the ϑ2 used to calculate the height necessary to the superimposition of the probes

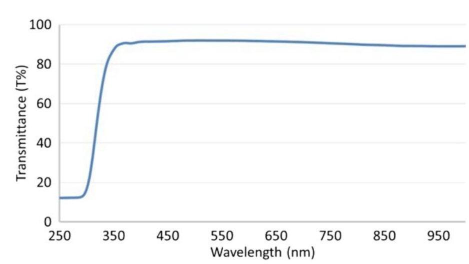

Fig. 5 Transmittance spectra (T%) of the upper microscopic glass slide

Results and discussion

Evaluation of the developed methodology of sample mounting techniques

Results of BW1 samples mounted in different ways are compared in Table 2. The results are given also for the

Table 2 BW1 measurements for method development given as average colour change (ΔE00, average), standard deviation (σ) and relative standard deviation (σrel)

	Material & Methods	ΔE_{00}, average $N \geq 10$	σ	σ_{rel} %
a)	BW1 fabric "Traditional set-up": no glass slides	3.51	0.49	14
b)	BW1 single yarn Without pressing glass slides	3.49	0.76	22
c)	BW1 threads Without pressing glass slides	2.69	0.58	22
d)	BW1 single yarn pressed between glass slides	4.30	0.12	3

conventional sample mounting, i.e. BWs analysed as a fabric, and for single BWs yarns without any further sample preparation. These provided relatively high standard deviation. The yarns were simply put on a glass slide and the extremities were fixed on it by adhesive paper. The results were less reproducible and for BW1 to BW3 not coherent with previous test results on BWs material as fabric sample.

The low reproducibility was in part attributed to *(i)* the irregular surface of the yarn itself, with undulating features (due to warp and weft) and *(ii)* the limited width of the yarn compared to the diameter of the illuminated spot, resulting probably in a "loss" of part of the reflected light portion reaching the measuring probe (Fig. 6).

To overcome the problems associated to size and form of the single yarn, some tests on yarn bundles, i.e. handmadethreads, from three yarns were made (Table 2, row c). These wider samples still gave high standard deviations and low values of ΔE_{00} compared to the traditional set-up.

Finally, the single yarn was placed between two glass microscope slides, tightly pressed and flattened by means of 4 paired neodymium magnets as shown in Fig. 2. This type of configuration gave significantly improved values of standard deviations (Table 2 row (d)). Such sample preparation fostered the additional advantage of increasing the yarns' width, as shown in Fig. 7. A general widening (roughly of more than 100 µm) is observed for all three standard materials, even if the averaged measured yarn diameters are not to be considered representative—these depend on the chosen yarn as well as the measuring position along the yarn. The observed enlargement of the yarn width allowed focusing the 0.4 mm spot size on the yarn.

BW1 single yarns pressed between glass slides interestingly provided an averaged value of ΔE_{00} higher than the one of the traditional set-up. This outcome was unexpected: the presence of glass, due to its absorption, reduces the amount of light reaching the sample (in this study the loss in intensity was evaluated being about 10%) and this would naturally result in a reduced ΔE_{00}. This phenomenon was observed in the study from Prestel [22]. Here, the interest was performing MFT measurements through glass in order to reproduce real case studies where the main part of a collection to be tested is already framed and glazed (for example paintings, photographs, paper collection). Indeed, the possibility of measuring through glass could help to save some precious time, avoiding dismounting the frame and the glazing for each piece of the collection. In the study from Prestel, the effect of glass with different thickness and refractive index on the colour change of several samples (some ceramic tiles, BWs, paper references and an historic watercolour on paper) was evaluated. The samples were not pressed, as the glass slides were simply "interposed" between the sample and the measuring head, after alignment, which lead to a reduced ΔE_{00}. A possible explanation of our results, apparently contradictory, can be found in the effect that the flattening may have on the yarns. Our data indicate that the increase in ΔE_{00} is not homogeneously distributed in the three coordinates L*a*b*. Rather, the main factor playing a role in colour change increase when the

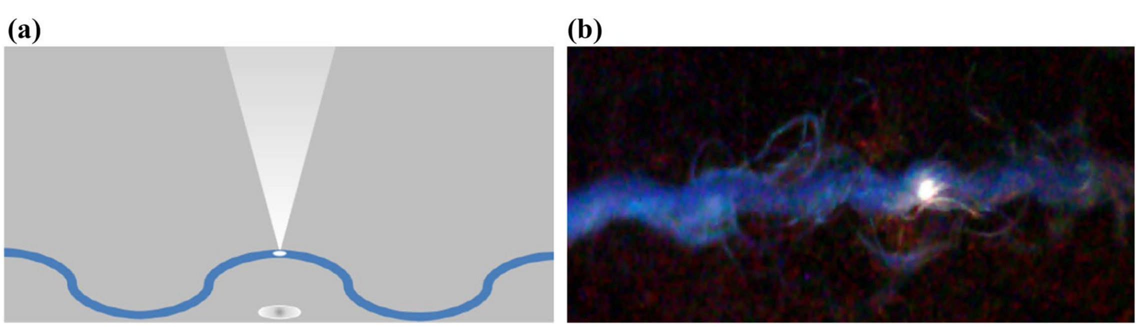

Fig. 6 Schematic representation (**a**) and photograph of a real sample (**b**) of the crimped yarn under the light beam

BW1		BW2		BW3	
Without glass slides	Between glass slides	Without glass slides	Between glass slides	Without glass slides	Between glass slides
x ≈ 296 µm	x ≈ 420 µm	x ≈ 298 µm	x ≈ 406 µm	x ≈ 470 µm	x ≈ 687 µm

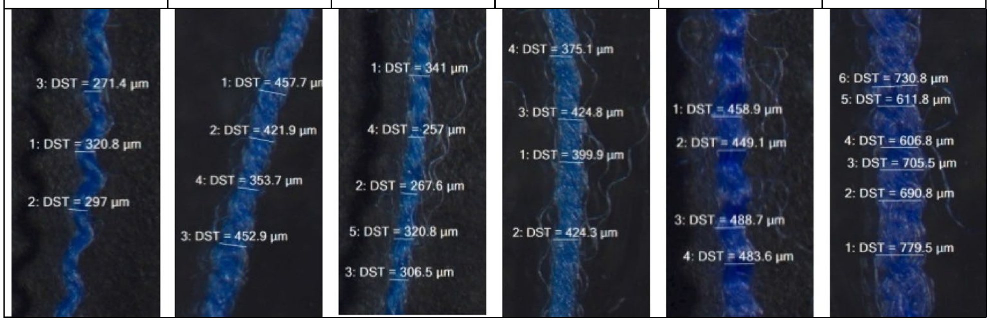

Fig. 7 Optical microscope images of BWs yarns in absence and presence of the upper microscopic glass slides. The average of yarns´width dimension is given as x̄. In the images, DST stays for distance and indicates the width of the fibre between two selected points

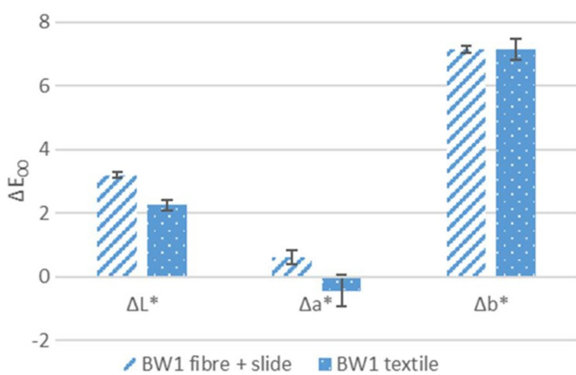

Fig. 8 ΔL*, Δa*, Δb* of BW1 for the single yarns pressed between the glass slides (oblique lines) and fabric with traditional set-up (dotted). The standard deviation is represented with vertical bars

yarns are pressed between glass slides is ΔL* (Fig. 8). L* represents the lightness and has values ranging from 0 (dark/black) to 100 (light, absolute white if a* and b* are 0). For BW1, either pressed or not, ΔL* is always positive, meaning that by the end of the experiment the colour has become lighter, as expected in a fading experiment. The averaged values for flatted yarns is ΔL* = 3.2 and ΔL* = 2.3 in the case of traditional set-up.

Also the average starting L* value of the pressed yarns is higher in respect to the non-pressed BW1 fabric, indicating that more light is reflected from the sample surface because of its flattening. Hence, the pressed sample provides more measurable area and less voids that contribute to the final measurable colour change ΔE_{00}.

An increase in the measured ΔE_{00} is advantageous: it signifies an increase of sensitivity of the method, helping to better discriminate the category of sensitivity such as the difference between BW1 to BW3 and possibly BW4. In addition, this conservative measurement helps in avoiding overestimating the light stability of the materials.

Validation of new sample preparation technique

To test that the results obtained from a single yarn are also representative for the fabric, results for a single yarn were compared with those obtained from the fabric. Colour fading measurements of BWs (1–3) were performed on fabrics and on yarns. In both cases, the reference materials were flattened between glass slides held by 4 paired neodymium magnets (Fig. 2). For each set of samples, 10 measurements were carried out per BWs and were all used for the calculation of average colour change ($\Delta E_{00,\ av}$), standard deviation (σ) and the coefficient of variation σ_{rel} (Tables 2 and 3). These BWs measurements on yarns were used as calibration for the *Reformation Tapestry*´s samples (R.T.).

As can be seen in Table 3, the obtained $\Delta E_{00,\ av}$ values are similar for the yarn as for the fabric within the uncertainty boundaries given by σ. This indicates that the MFT results obtained from single yarns are representative for the fabric and that sampling the fabric has no significant effect on the results.

The results of the colour changes of the BWs yarns are plotted in Fig. 9. An exponential regression function is

Table 3 BWs measurements employing new sample preparation and geometrical arrangement obtained under the same instrumental performances conditions. Results are given as average colour change ($\Delta E00_{av}$), standard deviation (σ) and relative standard deviation (σ_{rel})

BWs	Yarn				Fabric		
	$\Delta E_{00, av}$	σ	σ_{rel} %	BW_{eq}[a]	$\Delta E_{00, av}$	σ	σ_{rel} %
1	4.30	0.12	3	0.97–1.04 (Δ = 0.07)	4.56	0.40	9
2	1.91	0.15	8	1.90–2.08 (Δ = 0.18)	1.93	0.28	14
3	0.45	0.07	15	2.96–3.08 (Δ = 0.12)	0.46	0.12	26

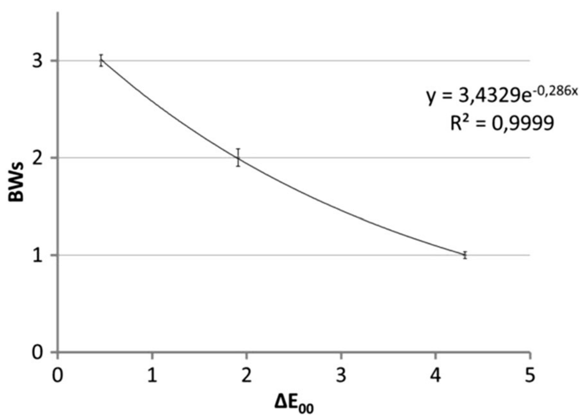

Fig. 9 Results of the BWs yarns measurements and regression function. Calibration used for samples of the *Reformation Tapestry*

obtained, which can be used to calculate BWs equivalent values (Table 3) for the test samples of the *Reformation Tapestry*.

Several values to express the uncertainty of the repeated measurement are given in Table 3. The σ-value of the single yarn is always improved in respect to that of fabrics: for BW2 and BW3 values of σ are lowered to about the half, while for BW1 up to a third. The σ_{rel} tends to increase from BW1 to BW3. This effect shows that smaller ΔE_{00} values are more challenging to determine with the given instrumental set-up. For this reason, BW4 samples are commonly not analysed.

In Table 3 also the minimum and maximum BWs equivalent values obtained from the $\Delta E_{00, av} \pm \sigma$ and the difference (Δ) are given. It is worth noting that the absolute error in BWs equivalent values (Δ) is not changing in the same way as the absolute error in σ, because the changing slope in the exponential function influences the error propagation.

Fading experiments on historic samples

Each yarn was measured 5 times and an average was calculated. The obtained relative standard deviations vary from 6 to 26%. Using the equations given in Fig. 9, the BWs yarn equivalent was calculated. The results for the samples from the *Reformation Tapestry* have been summarized in Table 4. The photosensitivity of the samples

Table 4 Summary of measurements of RT samples.

Material	Dyestuff	$\Delta E_{00, average}$	σ	σ_{rel} %	BW_{eq}
Sample 6 Red—Wool	American cochineal	0.19	0.05	26	3.2
Sample 8 Rose—Wool	American cochineal	0.58	0.07	12	2.9
Sample 13 Brown—Wool	Madder, tanning agent: gall	0.52	0.04	8	3.0
Sample 14 Faded red—Wool	Redwood, madder	0.46	0.04	9	3.0
Sample 15 Yellow—Wool	Flavonoid	0.46	0.07	15	3.0
Sample 17 Faded red—Wool	Redwood, Traces of Alizarin (Madder)	0.63	0.04	6	2.9
Sample 20 Yellow—Silk	Weld	0.50	0.09	18	3.0
Sample 24 Red—Wool	American cochineal	0.27	0.02	7	3.2
Sample 25 Faded red—Wool	Madder, redwood, tanning agent: gall	0.96	0.09	9	2.6
Sample 26, Dark green—Wool	Woad or Indigo Weld	0.38	0.02	5	3.1

Results are given as average colour change (ΔE00, average), standard deviation (σ), relative standard deviation (σrel), and BWs equivalent (BWeq) is quite homogenous. All results are ranging from half way between BW3 and BW2 to BW3. Samples number 17 and 25 have the highest photosensitivity. The colourants found in samples 17 and 25 were redwood and madder [24], while the third photosensitive sample 8 is American Cochineal. Sample 14, similarly dyed with redwood and madder, appears more stable than samples 17 and 25. It can be noted that the observed photosensitivity is not strictly related to the type of dyestuff, indeed several factors can affect the fading rate, as discussed in the introduction. However, redwood and madder dyed samples seem to be more vulnerable compared to American Cochineal.

Only natural colourants were used at the time of weaving. Green was created from mixing blue with yellow. In the German tapestry art craft of the 15th and 16th century, green hues were achieved by both single and doubled-baths procedures (where the latter could be "blue over yellow" or "yellow over blue" dyeing). Which dyeing technique was employed for the colours of the *Reformation Tapestry* is unknown.

Indigo dyes, used for blue, are much more lightfast compared to the yellows, which lose their intensity over time. Therefore, the fading green turns towards a more bluish olive tone. This is the case of sample 26, for which a special addressing should be made, containing blue indigotin and a yellow flavonoid (weld). The ΔE_{00} of sample 26 is in the range 0.3–0.4, and a BW_{eq} of 3.1. The ΔL*, Δa*, Δb* values of sample 26 were examined and compared to BW3 (made of only one colourant: CI Acid Blue 83) (Fig. 10 and Table 1). In general, the two materials show a different behavioral trend in the three colour coordinates, even if this must be considered with care, since the standard deviations for such small values are not negligible. The BW3 shows mainly a decrease in blueness (less negative b*) and the sample is lighter (increase in L*). For sample 26, the fading data after 15 min of exposure suggest that a*, representing the greenness-redness, becomes less negative (less green), while b*, representing the blueness-yellowness, decreases (it loses yellowness). From the data, one could suppose that sample 26 tends to the darkening (as ΔL* is negative) and to the decrease in the yellow component (Δb* is negative) (Table 5) This data seem to indicate that the decrease in yellowness is actually occurring, and this in turn could be the result of the lower light-fastness of flavonoids in respect to indigotin.

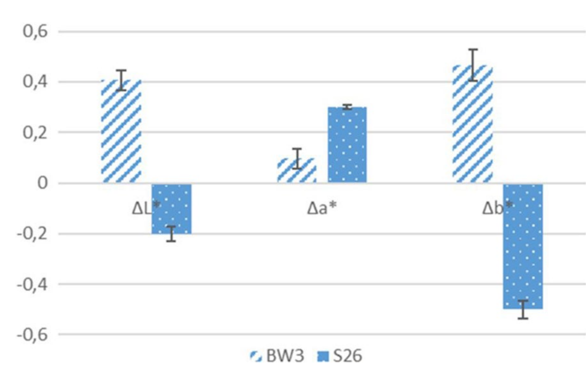

Fig. 10 ΔL*, Δa*, Δb* values of BW3 (oblique lines) and sample 26 (dotted). The standard deviation is represented with vertical bars

It is difficult to compare these results with other fading data in the literature, since each artwork is a unique piece with a unique history. Laboratory dyed test samples subjected to accelerated ageing might as well not represent the "real" conditions. At the Canadian Conservation Institute [1] materials were grouped by their light sensitivity into different categories. Cochineal falls for example into the "very sensitive" group, rated as ISO BW1-2–3. Alizarin-containing dyes (like madder) are rated as medium sensitive, in the range of BW4-5-6. This categorization is different from our results, since our findings suggest a sensitivity range of BW3 for all the tested samples.

Conclusions

The photo-sensitivity of the *Reformation Tapestry* in the collection of the Museum Europäischer Kulturen (Museum of European Cultures) in Berlin was investigated by MFT using a newly developed sample mounting technique. All samples were analysed as single yarns flattened between two microscope glass slides closely pressed by means of 4 paired neodymium magnets. The results of this method were compared to conventional measurements on BWs materials as fabrics. The developed methodology for sample preparation provided ΔE_{00} results of the BWs yarns characterized by greatly reduced standard deviations at least by a factor of 2. The improvement was attributed to the flattened surface, resulting in a more reproducible measurement geometry so that the correct focusing could be more easily obtained. Additionally, it was observed that the flattening helped to widen the yarns, increasing the area to the spot size of

Table 5 Average values of ΔE00, ΔL*, Δa*, Δb* of sample 26 and BW3 are given with the associated σ

Material	Dyestuff	ΔE_{00}, av	ΔL*, av σ	Δa*, av σ	Δb*, av σ
Sample 26	Woad or Indigo, Weld	0.38	ΔL*: − 0.2 σ: 0.06	Δa*: 0.3 σ: 0.02	Δb*: − 0.5 σ: 0.07
BW3		0.45	ΔL*: 0.4 σ: 0.08	Δa*: 0.1 σ: 0.08	Δb*: 0.5 σ: 0.13

the MFT. This flattening procedure applied to yarns samples could also be be adapted for *in-situ* use, directly on a textile, without removing a thread, when sampling would not be possible.

The results obtained for historic yarns of the *Reformation Tapestry* indicate that all samples fall into the same class of light sensitivity (Table 1). The Blue Wool Equivalent values are close to BW3 for most of the analysed yarns. The tapestry falls in the category for which it is suggested at the Rathgen laboratories not to exceed 2 years of display per decade. The most sensitive samples (25 and 17), half way BW2 and BW3, have both been dyed by redwood and madder.

Appendix

Here are shown the calculations employed to evaluate the distance (b in Eq. 3) for which the illuminating probe had to be lowered in order to have alignment. Considering a refractive index of 1.518 (typical value of a soda lime glass), ϑ_2 was calculated by the Snell´s Law. This ϑ_2 is the angle formed by the vector of the reflected light and the normal vector to the surface (Eq. 1). With this value, it was calculated in Eq. 2 the length of the path of the reflected light reaching the probe (c). Finally, from Eq. 3 the distance b is calculated. See Fig. 3 and Fig. 4 for the schematic representation.

From Snell´s Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

where: $n \approx 1$, $\sin\theta_1 = \frac{\sqrt{2}}{2}, n_2 = 1.518$; So that: $\theta_2 = 27.76°$.

For trigonometry applied to a triangle with one right angle:

$$d = c \sin\alpha \tag{2}$$

where: $d = a + b = 0.9\text{mm}$; and: $\alpha = 90° - 27.76° = 62.24°$; So that: $c = 1.017\text{mm}$.

From Pythagoras' Theorem:

$$a^2 + d^2 = c^2 \tag{3}$$

So that: $a = 0.47$ mm; and: $b = 0.43$ mm.

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Author contributions
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Availability of data and materials
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Declarations

Competing interests
The authors declare no competing interest.

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