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Development and application of a mathematical model to explain fading rate inconsistencies observed in light-sensitive materials

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Light fastness tests conducted on several areas of a light-sensitive material may sometimes show inconsistent fading rates. These different fading behaviours suggest that colorants are not evenly distributed over the substrate surface or may be attributed to texture variations of the material. A mathematical model has been developed to help explain these discrepancies. Micro-fade testing, a relatively novel technique, has allowed microspectroscopic detection of variations in the initial colour parameters of a sample, permitting assessment of its diverging fading rates. The method has been applied to fading data of various light-sensitive materials resulting in more consistent fading patterns. It has been demonstrated that micro-fading curves obtained for the same material are related by a constant value, which is the ratio of adjusted values of time and ΔE^*.

Introduction

The poor stability of some colorants found in museum artifacts is a topic of concern for conservators and museum curators as the colours of these objects are often noticeably different because of the action of light in conjunction with other environmental elements. Several factors, such as type of illumination, temperature, relative humidity and atmospheric contaminants, influence the fading rate of museum materials. Most light-sensitive colorants found in museum collections exhibit similar fading behaviours on exposure to light. Giles and co-workers classified these trends as Type II or Type III fading rates [1,2]. Materials with higher light sensitivity usually experience a rapid change in colour during the early stages of exposure, followed by a slower rate after maximum fading has occurred; this curve has been described as Type II. The dye is typically found in aggregate form inside the fibre substrate, with a small part of the colorant molecularly dispersed. Dyes exhibiting higher light fastness are characterised by a constant rate of fading, which is classified as Type III. This trend is mostly observed for dyes that form large aggregates inside the fibre, for which the surface area accessible to the environmental elements is reduced resulting in slower fading rates [3]. Although the light fastness of organic dyes is related to both their chemical structure and physical state, it is known that the physical state of the dye within the fibre has a greater influence on its stability [4].

Some investigations on the light fastness of museum materials have been conducted on laboratory specimens using traditional accelerated-ageing methods [5–7]. However, fewer studies have been devoted to evaluating the precision of fading rates observed for comparable zones of an actual artifact by contrasting the initial colorimetric parameters of each area considered [8]. The influence of the initial colour parameters on the fading of a material should not be ignored as it has a direct effect on the precision of the measurements. It has been reported that these variations may be attributable to the effect of surface texture, which produces alterations on the perceived colour of textiles [9–11]. These observations evidence the need for additional research on the effects of initial colour parameters and texture on the fading rate of a single material in the museum science field.

In this study, a micro-fading tester (MFT) has been employed for evaluating the light fastness properties of museum materials. This instrument was developed because of the necessity of identifying fugitive colours in museum artifacts, with the aim of establishing exhibition policies that take into consideration the light sensitivity of objects [12]. Micro-fading spectrometry is an important technique in museum research as it allows non-destructive accelerated testing of real objects, taking into account the significant and usually unpredictable contribution of preparation, application and previous exposure of colorants to the actual fading rates of materials [13]. Two main advantages of this device are the small diameter of the illuminated spot and a relatively short testing time when compared with other accelerated ageing methods. However, certain discrepancies have been observed after comparing the micro-fade testing results with those obtained using traditional accelerated ageing methods; especially for textiles and unevenly coloured surfaces [14]. Micro-fading tests conducted in similar adjacent areas of an artifact have occasionally shown poor precision, suggesting that the same colorant may have different fading rates. For example, Connors *et al.* [15] observed some inconsistencies in the micro-fading curves of dayflower blue and indigo blue areas after studying a series of Japanese woodblock prints. Nevertheless, a better

precision of the fading data would be expected after testing adjacent coloured areas of the same print because of the high stability of these two colorants.

Artificial weathering tests of museum materials have typically made use of Blue Wool (BW) standards as a reference scale [16,17]. The degree of fading of a Blue Wool standard can be qualitatively and quantitatively assessed using modern spectroscopic methods [18]. In the present study, different fading rates were observed after evaluating several areas of a Blue Wool 1 standard. However, the extent of this effect was not entirely understood. Therefore, an immediate interest for investigating this phenomenon arose considering that Blue Wool standards must show a more consistent fading pattern throughout their entire surface. These variations were also detected after examining equivalent areas of various reference materials.

The rationale for the mathematical adjustments is the establishment of a model of fading trend that minimises the deviations caused by material effects. This normalisation is particularly needed when equivalent zones of a light-sensitive material show diverging micro-fading curves. The advantage of using this mathematical treatment of the data is that it helps to explain the micro-fading rate of a material in a more precise way and allows understanding of any variation that may arise during the test. While the original fading curves may suggest that a material exhibits different light fastness properties throughout its surface, the adjusted curves give a more reasonable view of the colour change experienced. The research aim is to find a general fading curve that better represents the rate of the light-induced change at the micro-scale for highly sensitive materials.

In most cases, materials with moderate and low light sensitivity do not show large deviations after comparing the fading rates of several equivalent areas. Micro-fading tests conducted at different illumination intensities have revealed that highly sensitive museum materials exhibit diverging fading rates attributable to reciprocity failure [19]. However, a sample tested at the same intensity level should not present this type of deviation. The long-term goal of this work is to understand the fading behaviour of coloured museum materials under laboratory conditions in order to correlate the results with potential fading occurring in a museum environment. Understanding the fading behaviour of sensitive museum materials is of great importance for the establishment of exhibition lighting guidelines. Using such a theoretical model for describing the fading trends will be useful for understanding the long-term stability of cultural heritage materials.

Experimental

Materials

Blue Wool standard cards were purchased from Talas (USA) and were used as received. Blue Wool 1 was the only standard employed in the study as it exhibits the highest light sensitivity. The dye present in Blue Wool 1 is CI Acid Blue 104 (CI 42735). Silk samples dyed with turmeric were prepared and provided at the Smithsonian Museum Conservation Institute. Silk fabric was obtained from a commercial source in Washington DC (USA). Turmeric powder was purchased from Kremer Pigments Inc. (USA) and was applied as a direct dye. The main colouring agent in turmeric dye is curcumin, also known as CI Natural Yellow 3 (CI 75300). The dyebath was prepared by adding 100 g of turmeric powder to 6000 ml of distilled water. The mixture was heated at 80 °C for 1 h. The water was strained using grade 1 Whatman (UK) cellulose filter paper to remove particles of turmeric. Approximately 100 g of the silk was added to the coloured water and subsequently the temperature of the bath was gradually increased to 70 °C, where it was maintained for 1 h. Afterwards, the bath was allowed to cool for approximately 2 h until room temperature was reached. After dyeing, the samples were rinsed with distilled water and then air-dried. Finally, the dyed silks were cut into 10×15 cm fragments prior to the micro-fade testing.

Light fastness measurements

This research was carried out using the MFT developed by Whitmore *et al.* [12] from the Art Conservation Research Center at Carnegie Mellon University in Pittsburgh. Individual components of this instrument are manufactured by Newport Oriel Corporation (USA) and are sold as the Oriel 80190 Fading Test System. The device consists of a reflectance spectrophotometer coupled to an accelerated light fading micro-tester. The sensitivity of objects to high-intensity visible light can be determined by using short increments in exposure time to a 75-watt xenon arc light source. The instrument uses a 0/45 geometry for illumination of the sample and collection of reflected light. The illumination probe generates a spot of approximately 0.4 mm. The light reflected by the sample is collected by the second probe, which then focuses it onto the 0.1 mm slit of the spectrophotometer. The working distance measured from the external lens of the illuminating probe to the surface of the sample is approximately 1 cm. The intensity of the illuminated spot was measured with an ILT 1700 radiometer from International Light Technologies (USA) using a probe calibrated for point sources. These measurements were carried out at the beginning of each testing session as part of the calibration protocol.

A manual translation stage allowed positioning and aligning of every test specimen along the *XY* axes below the illumination fibre. Prior to the micro-fading measurements, an initial survey of each fabric is carried out with the aim of finding the areas that give higher reflectance. This assessment is performed, preferably under dark conditions, by slowly translating or rotating the sample until an intense speck is observed. Simultaneously, a gradual increase in the per cent of reflectance is detected as the illuminated spot is shifted from a valley to a high point of the weave. A high spot is typically associated with a position where a weft thread goes over a warp thread, or vice versa. Spectrocolorimetric data are recorded periodically and their change is evaluated over time using a PDA-512-USB spectrophotometer from Control Development Inc. (USA); with a diffraction grating slit of 100 μm and a 0.5 nm spectral resolution over the 400–700 nm range. The

integration time used was 6 ms and 10 spectra were averaged. The Commission Internationale de l'Eclairage (CIE) illuminant and observer combination used was D65 and 2°, respectively. Colour differences were calculated using the CIELab 1976 equation.

Estimating the amount of error in a micro-fading measurement is a difficult task involving several factors such as sample effects, instrumental parameters and colorimetric calibrations. As indicated by Whitmore, 'the validity of the test is not an intrinsic property of the test itself. It is rather a description of the performance of particular materials during the test and generalizations to describe the validity of the test are unlikely possible' [20]. With the purpose of verifying the repeatability of the measurements, the chromaticity coordinates, x and y, were recorded for a set of 10 ceramic tiles from Hale Color Consultants (USA). The MFT was set to single-scan mode and 10 readings from the centre of each tile were recorded. Each tile was removed from the focused beam of light of the instrument and repositioned between measurements. Expected and observed values are shown in Table 1. The data show good accuracy and precision besides some deviation obtained for the grey tile, which has a slightly higher error of 2.8 and 3.6% for x and y parameters, respectively. In addition, Whitmore *et al.* [12] observed that instrumental drift is accountable for ΔE^* values, which are less than 0.2 per hour. Lerwill *et al.* [21] determined an error which is less than 0.12 ΔE^* units during the first hour of operation using a similar instrument. These are considered acceptable values for reasonable sensitive determinations of colour changes with this apparatus.

Theoretical model

A descriptive model of a hypothetical system that shows diverging fading rates has been devised with the aim of explaining the variations observed in actual museum materials. The micro-fading behaviour of a light-sensitive material is usually governed by two main rates. The change initially proceeds in a rapid way, followed by slower fading at a constant rate. An analogous curve of loss of dye concentration with respect to time could be classified as Type II using the system of Giles *et al.* [2]. Johnston-Feller and co-workers indicated that the fading of a colorant usually takes place in this way and therefore the reaction follows first-order kinetics [22]. More recently, Daniels [23] has indicated that, although the kinetics of fading are exponential, the changes in visual appearance as measured by ΔE^* are not necessarily caused by a change in a proportionate amount of dye. For that reason, Daniels makes a distinction between fading rate constants and reaction rate constants. The former are related to the ΔE^* while the reaction rates constants are derived from changes in the concentration of the colorant. The proposed mathematical model follows Daniels' approach as it is based on colour changes measured using ΔE^*.

It has been observed that the fading rate of a light-sensitive museum material can often be described by a power function with the general form given by Eqn 1:

$$f(x) = kx^n \tag{1}$$

where $f(x)$ is the ΔE^*, x is the time, k is a constant and n is a real number. In general, n values may vary from 0.1 to 0.5 for micro-fading spectrometry curves of light-stable to light-sensitive materials, respectively. Two square-root functions have been selected as the model describes and compares micro-fading curves recorded on two imaginary spots of a light-sensitive material. The mathematical expression of this matching strategy is shown by Eqn 2:

$$\Delta E^* = a(t+b)^{0.5} + c \tag{2}$$

where a, b and c are constants and t is time in min. Two theoretical fading curves, namely plot 1 and plot 2, can be obtained by using the constants $a = 10$, $b = 0$, $c = 0$ (Eqn 3) and $a = 10$, $b = 1$ and $c = -10$ (Eqn 4):

$$\Delta E^* = 10t^{0.5} \tag{3}$$

$$\Delta E^* = 10(t+1)^{0.5} - 10 \tag{4}$$

Inspection of the two equations reveals that constants b and c represent adjustments to time and ΔE^*, respectively. A graphical representation of these two functions is shown in Figure 1.

The first derivative is typically used to evaluate the rate of change of a function with respect to time [24]. Hence, the use of the first derivative of ΔE^* with respect to time was considered adequate to evaluate the rate of colour change recorded during a micro-fading trial. A time

Table 1 Expected and observed CIExy values obtained for a set of 10 colour ceramic tiles and standard deviation corresponding to 10 measurements

	x		y	
Colour	Expected	Observed	Expected	Observed
Blue	0.1844	0.1828 ± 0.0013	0.1345	0.1314 ± 0.0014
Brown	0.4822	0.481 ± 0.004	0.3813	0.381 ± 0.003
Green	0.2806	0.278 ± 0.003	0.4028	0.399 ± 0.006
Red	0.6591	0.662 ± 0.003	0.3198	0.3207 ± 0.0014
Orange	0.6188	0.620 ± 0.002	0.3662	0.3669 ± 0.0012
Grey	0.3075	0.299 ± 0.003	0.3256	0.314 ± 0.003
Light green	0.3133	0.3103 ± 0.0013	0.3718	0.367 ± 0.002
Light blue	0.2828	0.2787 ± 0.0010	0.3239	0.315 ± 0.003
Yellow	0.4355	0.4247 ± 0.0010	0.4630	0.4611 ± 0.0012
Light yellow	0.3634	0.358 ± 0.014	0.3928	0.38 ± 0.005

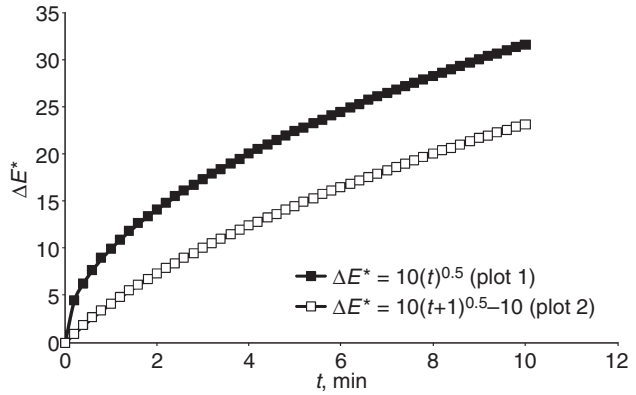

Figure 1 Plots of two hypothetical functions: (1) $\Delta E^* = 10t^{0.5}$ and (2) $\Delta E^* = 10(t + 1)^{0.5}-10$

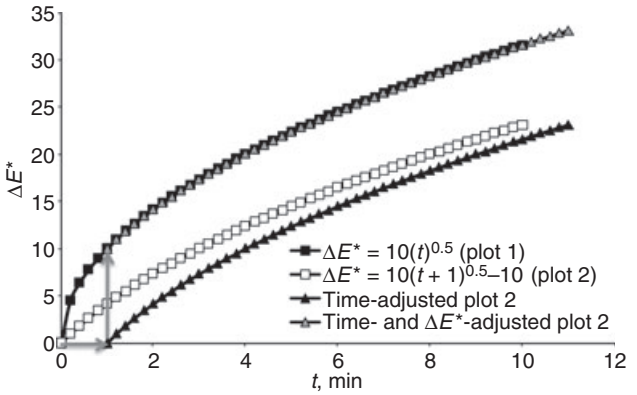

Figure 3 Plots 1 and 2 showing the full adjustments required to align the two curves. The horizontal shift was 1 min and the vertical shift was 10 ΔE^* units, which are the values of constants b and c, respectively

adjustment can be deducted after comparing the first derivative plots providing a way for normalising the data. The derivatives of equations of plots 1 and 2 are shown by Eqns 5 and 6, respectively:

$$\mathrm{d}(\Delta E^*)/\mathrm{d}t = 5t^{-0.5} \quad (5)$$

$$\mathrm{d}(\Delta E^*)/\mathrm{d}t = 5(t + 1)^{-0.5} \quad (6)$$

The derivatives are presented in graphical form in Figure 2. The derivative of plot 2 is adjusted by the time constant ($b = 1$). The final adjustment to plot 2 consists of a vertical shift of the time-adjusted plot 2 to plot 1. Adding 10 to every ΔE^* value completes this operation and demonstrates that plot 2 is essentially a segment of plot 1 (Figure 3). An evaluation of the model using experimental measurements was carried out and some results are presented below.

Results and Discussion

Application of the mathematical model to the normalisation of fading data

Evidently, knowing the exact mathematical function that governs the fading of a material attributable to exposure to light is not a straightforward task. However, it is still possible to estimate the adjustment necessary to normalise acquired fading data if multiple light fastness tests are conducted on different areas of the same material. The proposed model was applied to actual fading data with the aim of verifying the performance of the described method. The normalisation of light fastness data from reference materials has resulted in fading curves that show good correlation (Figure 4). This was performed by taking and contrasting first derivatives plots of ΔE^* with respect to time for all analysed coloured spots within a specific sample. It has been found that time and ΔE^* corrections are constant within a material and deviations in fading curve behaviour are observed primarily during the initial part of a micro-fading test.

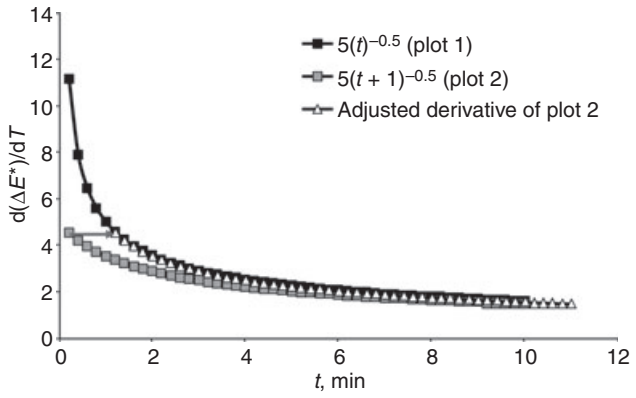

Figure 2 First derivative plots of the two hypothetical functions: (1) $\Delta E^* = 10t^{0.5}$ and (2) $\Delta E^* = 10(t + 1)^{0.5} - 10$. The time constant ($b = 1$) adjustment to the derivative of plot 2 is also shown

Blue Wool 1 standard trials

Figure 4a shows the results of nine micro-fading tests conducted on a fresh Blue Wool 1 sample using an illumination intensity of 7.0 Mlx. The separation between each tested spot was approximately 1 cm. After inspecting the micro-fading curves, it appears that there is a considerable amount of scatter in the data. As explained above, Blue Wool standards consist of various dyed fabrics and differences in reflectance of light are probably attributable to the texture of the textile. However, it is expected that a reference material that is carefully controlled during its manufacture would exhibit a more systematic pattern of variation between each data set.

Figure 5 shows the ΔE^* values at the 1-min point for each of the nine micro-fading trials on Blue Wool 1. Different initial $L^*a^*b^*$ values, which gave rise to these initial ΔE^*s, are probably the sources of scatter of the fading data (Table 2). Average initial L^*, a^* and b^* values and their standard deviations are 42 ± 2, 6.3 ± 0.9 and -45 ± 2, respectively. Initial ΔE^* values were normalised with the purpose of adjusting the remaining trials to a reference fading curve. Trial 8 was selected as the reference trial as it demonstrated the fastest fading rate, which is a conservative choice if one attempts to use this information to evaluate the light fastness of future trials. Initially, trials 5 and 8 were compared. In Figure 6, it can be seen that the micro-fading curves recorded for these two trials are different, indicating that the fading rate of trial 5 is slower than that of trial 8. Plots of the derivatives of ΔE^* with respect to time *vs* time from these two trials were

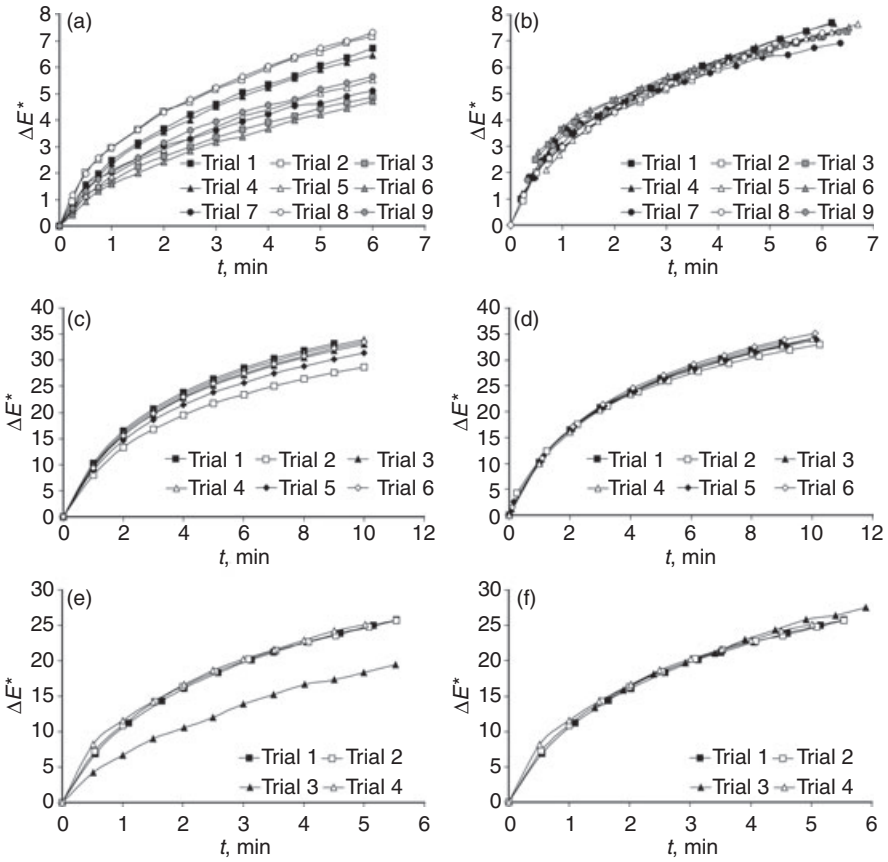

Figure 4 Application of the mathematical model to actual fading data: (a) micro-fading curves of nine areas of a Blue Wool 1 standard; (b) normalised Blue Wool 1 data; (c) micro-fading curves of six areas of a Bengal rose gouache sample; (d) normalised Bengal rose data; (e) micro-fading curves of four areas of a turmeric/silk system; (f) normalised turmeric/silk system data

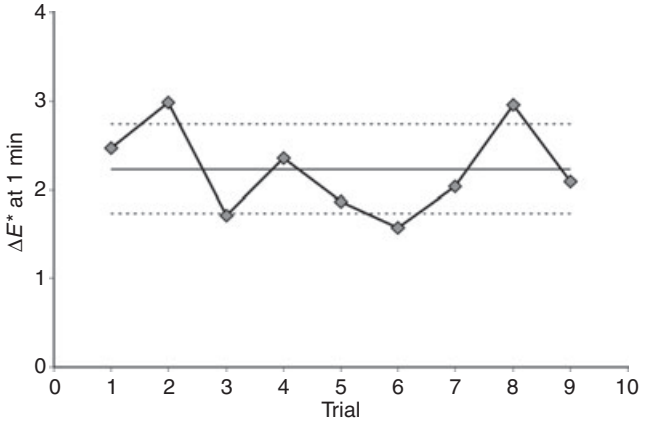

Figure 5 ΔE^* values at the 1-min point for nine trials of Blue Wool 1 using a light intensity of 7.0 Mlx. The mean ΔE^* value and the standard deviation are indicated by solid and discontinuous lines, respectively

compared, revealing that the two plots differ by approximately 0.69 min. The original micro-fading curve of trial 5 was then adjusted using the 0.69-min time shift. After 1 min, the difference in ΔE^* between trials 5 and 8 was −1.09. The ΔE^* correction used in adjusting these two plots was 2.18, which is equal to the difference in ΔE^* values times −2. After performing the adjustments, the fading rates for the two different locations on the same Blue Wool 1 sample are very similar.

A normalisation parameter of 0.69/2.18 = 0.3165 min was obtained from the corrections performed to trial 5. Afterwards, every Blue Wool 1 test was normalised to trial 8 using the normalisation parameter explained above, which allows calculating the time adjustments for all trials. Table 2 shows the normalisation results obtained for micro-fading tests conducted on nine areas of a Blue Wool 1 standard. Figure 4b presents the normalised micro-fading curves for the Blue Wool 1 trials. It can be seen that the adjusted micro-fading curves are fairly coincident. The results suggest that initial $L^*a^*b^*$ values are largely responsible for the apparent differences in the original fading curves observed in Figure 4a.

Bengal rose gouache data

The normalisation model was verified using some data published by Whitmore *et al.* [12] on the fading rate of a Winsor and Newton Bengal rose gouache paint sample. The colorant present in the Bengal rose paint is CI Pigment Red 169 (CI 45160:2), which is a fugitive colorant exhibiting higher sensitivity to light than Blue Wool 1. Figure 4c shows the original fading data reproduced for the full time duration of the tests. Micro-fading data were collected using an illumination intensity of 6.4 Mlx. Once more, it can be seen that light fastness tests conducted on equivalent areas of a light-sensitive material resulted in apparently different fading rates. However, these differences are probably attributable to slight variations in the initial $L^*a^*b^*$ parameters of each tested area.

The ΔE^* values at the 1-min point obtained for six areas of the Bengal rose gouache sample are shown in

Table 2 Initial CIELab parameters and ΔE^* values after 1 min, together with corrections required to normalise fading curves of Blue Wool 1 to trial 8

Trial no.	Initial values (L^*, a^*, b^*)	ΔE^* after 1 min	ΔE^* difference from trial 8	ΔE^* correction	Time correction (min)	Correction factor (min)
1	45.74, 5.37, −45.49	2.46	−0.5	1.0	0.3165	0.3165
2	40.12, 7.88, −48.44	2.98	0.02	−0.04	−0.01266	0.3165
3	42.78, 6.48, −46.60	1.71	−1.25	2.5	0.7913	0.3165
4	42.47, 6.80, −47.84	2.36	−0.6	1.2	0.3798	0.3165
5	41.84, 6.29, −43.27	1.87	−1.09	2.18	0.69	0.3165
6	41.18, 6.60, −44.78	1.58	−1.38	2.76	0.8735	0.3165
7	42.11, 6.42, −45.61	2.04	−0.92	1.84	0.5824	0.3165
8	45.52, 4.50, −45.71	2.96	0	0	0	0.3165
9	39.53, 6.08, −44.04	2.09	−0.87	1.74	0.5507	0.3165

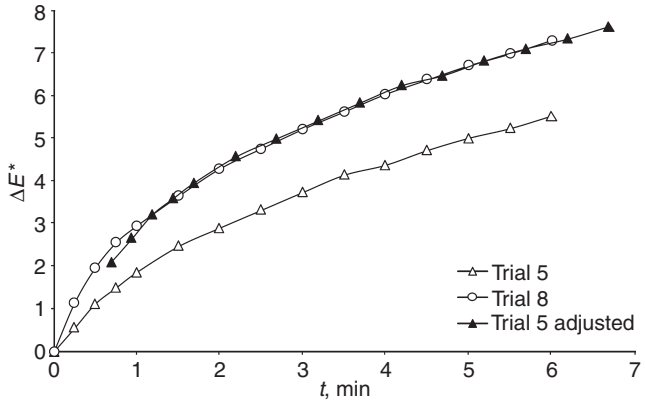

Figure 6 Deviation of micro-fading curves of Blue Wool 1: trials 5 and 8 are compared showing the adjusted curve of trial 5

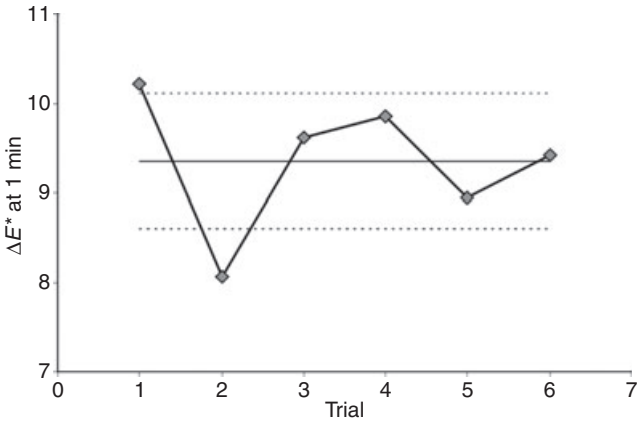

Figure 7 ΔE^* values at the 1-min point for six trials of Winsor and Newton Bengal rose gouache using a light intensity of 6.4 Mlx. The mean ΔE^* value and the standard deviation are indicated by solid and discontinuous lines, respectively

Figure 7. The average ΔE^* value and the standard deviation are indicated by solid and discontinuous lines, respectively. It can be observed that trials 1 and 2 exhibit greater deviation from the average ΔE^* of 9.4 and consequently these two tests show the fastest and slowest fading rate. Table 3 shows the variability in initial $L^*a^*b^*$ values for the Bengal rose gouache fading tests. Average initial CIE $L^*a^*b^*$ values and their standard deviations are 51.8 ± 1.1, 74 ± 3 and −30.9 ± 1.5, respectively.

The data were normalised using the proposed mathematical approach. After comparing trials 1 and 5, the ΔE^* and time corrections obtained were 2.56 and 0.15 min, respectively. The normalisation parameter was calculated as: 0.15/2.56 = 0.05859 min. Table 2 shows the ΔE^* and time adjustments applied to the Bengal rose gouache light fastness data. The results indicate that variations in the initial $L^*a^*b^*$ values are largely responsible for the apparent differences in the original micro-fading curves. These data adjustments show the fading rates as remarkably consistent (Figure 4d).

Silk sample dyed with turmeric

Micro-fading curves of four areas of a silk sample dyed with turmeric are shown in Figure 4e. The tests were conducted using an illumination intensity of 6.0 Mlx. It can be seen that trials 1, 2 and 4 exhibit identical curves, while trial 3 shows deviation from the rest of the plots, suggesting that this area has greater light fastness than its counterparts. A plot of initial and final chromaticity parameters of the four trials is presented in Figure 8. After inspecting the data, it becomes evident that subtle changes in initial colour coordinates are accountable for the different fading curve observed for trial 3. Similarities in initial CIE a^*b^* parameters are observed for three of the trials, enclosed by an oval in Figure 8, while trial 3 shows a clear deviation from its counterparts. The three tests showing similar fading rates can be differentiated from trial 3, which exhibited a slightly higher reflectance in the red region. This is evidenced by a redness value (a^*) that is *ca*. 2 units higher than the one registered by the other three areas. These results indicate that the MFT is capable of detecting slight variations in the sample, such as an uneven distribution of the colorant on the fabric. The changes experienced by the turmeric/silk system are mainly associated with a loss in chroma rather than a variation in hue. This was confirmed by ΔH^* values, which remained under 0.9, along with changes in the metric chroma that were in the range of −25 to −19 C^* units.

The micro-fading curve of trial 3 was normalised to that of trial 1 following the proposed mathematical model. The ΔE^* and time corrections were 13.4 and 1.4 min, respectively. A plot showing the adjustments performed to trial 3 is shown in Figure 4f. It can be observed that trial 3 is simply a segment of the other

Table 3 Initial CIELab parameters and ΔE^* values after 1 min, together with time corrections required to normalise fading curves of Winsor and Newton Bengal rose gouache to trial 1

Trial no.	Initial values (L^*, a^*, b^*)	ΔE^* after 1 min	ΔE^* difference from trial 1	ΔE^* correction	Time correction (min)	Correction factor (min)
1	51.60, 74.93, −31.96	10.22	0	0	0	0.05859
2	50.74, 70.35, −28.13	8.06	−2.16	4.32	0.2531	0.05859
3	51.77, 78.10, −31.27	9.62	−0.6	1.2	0.07031	0.05859
4	50.56, 75.76, −30.50	9.85	−0.37	0.74	0.04336	0.05859
5	52.32, 73.96, −31.23	8.95	−1.28	2.56	0.15	0.05859
6	53.61, 69.89, −32.40	9.42	−0.8	1.6	0.09374	0.05859

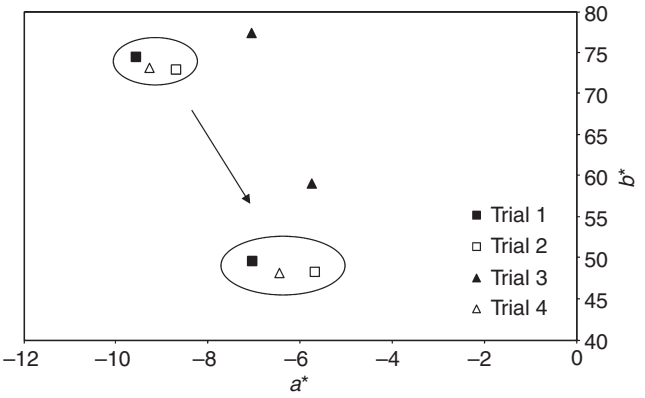

Figure 8 Initial and final CIE a^*b^* chromaticity coordinates from four areas of a silk sample dyed with turmeric. The arrow indicates the direction of the change observed during the micro-fading tests

three tests confirming the effectiveness of the proposed mathematical model.

Conclusions

A mathematical model that permits normalisation of micro-fading data by merging fading curves from different domains into a single domain correlation has been devised. This model helps to account for scattering of fading data observed after testing several areas of the same material. These deviations should be negligible but, in the case of light-sensitive museum materials, they can be significant, suggesting that the same material exhibits inconsistent fading rates. The influence of initial $L^*a^*b^*$ values on the fading rate has been investigated as it was found to be an important factor in producing these variations. Although preliminary results indicate this correlation, additional research is needed in order to confirm this effect.

Micro-fading curves of a museum material that exhibits Type II behaviour can be compared by taking and contrasting their plots of first derivative of ΔE^* with respect to time against time of exposure. Original fading curves show similar rates that may be displaced by a constant amount attributable to subtle variations in $L^*a^*b^*$ values. These variations along the surface of a material can be detected with the help of an MFT and therefore a mathematical correction that serves to normalise all fading curves is possible. The mathematical analysis indicates that fading curves have square-root form showing a displacement from the origin, which was found to be constant, permitting to normalise the data to a reference curve. The model was successfully applied to a series of micro-fading tests conducted on a variety of museum materials that fade in shade. This implies that colour changes are mainly attributable to a reduction in the concentration of the colorant with increasing exposure to light.

The number of cultural institutions around the world using micro-scale fading instruments to evaluate the light fastness of sensitive objects in their collections has increased in recent years. For this reason, there is an evident necessity for correctly and consistently interpreting the data through inter-laboratory comparisons and normalisation procedures. The methodology presented in this paper provides a tool for researchers to gain higher confidence in their micro-fading data. The results show that more uniform fading curves, which better represent the light fastness of a material, could be obtained. This provides a better approach for interpreting the data than just accepting the differences observed within a material as different fading rates. Although this study serves as an initial step for explaining apparent different fading rates observed in colorants that fade in shade, the authors recognise that other types of fading behaviours exist, which may result in micro-fading curves that deviate from the proposed square-root model. In that instance, a new mathematical fit of the fading data must be determined if deviations are still observed.

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