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The effect of prior exposure on the lightfastness of early synthetic dyes on textiles

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Abstract

Many studies have investigated light-induced damage to colourants in heritage collections using prepared samples of materials such as artist paints and dyed textiles. The body of research focuses primarily on the response of virgin materials, where colour change is assessed with respect to the original colour as light dose increases. From a practical perspective, most objects in museum collections have accumulated a significant light dose from illumination before acquisition, and subsequent years of exhibit lighting. When considering the risk of further degradation, it is often stated by heritage professionals that fugitive colourants with past light exposure are no longer as sensitive due to the slowing rate of visual damage. This is evident by studying 'fading curves', where the rate of colour change typically diminishes with increasing light dose. It remains unclear, however, to what degree the lightfastness of remaining colour changes with ongoing exposure. To address the issue, the light sensitivity of residual colour was investigated as a function of prior dose using a published dataset of colour measurements from textiles dyed with early synthetic colourants in the period of 1874–1905. The CIELAB colour values (D65/2°) for each material and dose increment were used to determine the future dose that causes a just-noticeable difference (JND), $\Delta E_{00} = 1.7$, starting at different amounts of past exposure. This involved resetting the reference CIELAB values to that of the residual colour after each prior dose. The analysis provides an extension of our earlier work, where only the initial lightfastness was reported. A summary of the findings illustrates the shifting distribution of lightfastness, toward higher Blue Wool (BW) ratings with increasing exposure. As the dose progresses, dyes that start at BW1 sensitivity progress to BW2, then BW3 and so on. The findings from this work may assist with boundary approximations of object sensitivity when prior light exposure is known, or a reasonable estimate is available. An analysis of experimental data is summarised as a tool for this type of decision-making process.

Keywords: Textiles, Synthetic dyes, Lightfastness, Prior damage

Introduction

Heritage professionals dedicate considerable amounts of time to managing the light an UV exposure of collections, by planning display conditions that provide access to the public while minimising damage. Michalski [1] describes three approaches that are applied in practice: (1) basic strategy for small museums; (2) traditional rule-driven strategy; (3) risk management strategy. The first eliminates extreme light and UV conditions in small museums, while the second involves fixed light levels for specific types of collections (e.g. 50 lx for textiles with UV below 75 mW/lm) [2]. The third requires assessing the light sensitivity, defining an acceptable rate of damage, and then managing the light dose within one just-noticeable change in a given number of years. Visitor demographics (visibility), institutional mandate, and significance [3, 4] may also be considered when selecting light levels. The approach maintains broad generalizations for different

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types of collection materials unless micro-fade testing (MFT) [5] is available for a direct assessment of light sensitivity for colourants on an object.

In the absence of specialized analytical techniques, the risk management approach benefits from knowledge of the object's history and information regarding the light sensitivity of related (reference) materials. Prior light exposure is an important component of the history since it is often stated that the light sensitivity of a degraded colourant is lower than that of the unexposed material [6–9]. Michalski [7] emphasises the point in a discussion of lightfastness data:

> *"Unlike a new pale shade, a pale remnant of an already faded colour can be much more durable than the original colour. This small mercy comes about since a colourant forms a range of lightfastnesses so that the most fugitive components fade first, leaving the least fugitive components as the remnant."*

Strict use of lightfastness ratings for virgin materials (mock-ups or historic samples), with negligeable prior exposure, may lead to an overestimation of light sensitivity for many objects in collections. The upside is greater protection from damage; however, the downside is reduced light levels (poor visibility) and less access to the public. Obvious exceptions include sensitive colourants in newly prepared materials, archival documents with little past exposure, objects stored and not used/exhibited, pages in books that were rarely opened, etc. In practical terms, museum collections contain a distribution of colourants, with a wide variety of light sensitivity, and varied exposure history. In consideration of this information, a better understanding of two factors would help to optimise risk assessment for exhibit lighting:

1. The exposure history of the object or collection: i.e. a boundary estimate for the prior light dose.
2. The influence of prior light dose on current light sensitivity of the residual colour—especially for highly sensitive materials starting in the Blue Wool 1–3 range.

To address the first issue, some studies have investigated the annual dose for collections, particularly with respect to daylight in galleries and historic buildings in the UK. In the 1960's, Thomson [10] measured ~ 1.5 Mlx·h on average for spaces within the National Gallery, London, and provided estimates for other world cities using weather data. Citing a review of measurements in historic buildings managed by English Heritage and the National Trust, Aronson et al. [11] used an average value of 0.83 Mlx·h/y to estimate prior dose for paintings in the Yale Center for British Art (YCBA) collection. For typical paintings with ~ 150y of prior exposure (UK) and 50y of YCBA exhibition, the cumulative dose estimates ranged from 145 to 265 Mlx·h for different gallery zones. A similar assessment could be considered for textiles in museum collections. It is easy to imagine that many older objects have a significant history of light exposure from their initial period of use (e.g. as interior furnishings or garments worn outdoors in daylight) before accumulating a further dose in exhibit conditions.

The focus of our present study relates to the influence of prior light dose on lightfastness, where we seek to identify the dose values where it becomes unlikely for the residual colour to exhibit BW1, BW2, or BW3 sensitivity. In the present literature, very little information is available to show the relationship between lightfastness of residual colours and prior light dose. Michalski [7] notes one study by Kashiwagi and Yamasaki [12] involving traditional Japanese vegetable dyes. In their work, the authors assessed lightfastness at the beginning and end of the experiments to highlight a decrease in light-sensitivity. In a more generalised analysis, Michalski [13] used theoretical fading curves for the ISO Blue Wool standards to illustrate the dose values where the colours are effectively gone. A similar investigation is presented here with two main differences: (1) the analysis uses a dataset of colour change measured for > 100 dyed textiles [14, 15] with increasing light dose; (2) calculations are performed in a manner that shows the changing sensitivity of the residual colour.

Methodology

A previously published dataset [14, 15] was used for the analysis, which contains tabulated colour measurements for historic samples of early synthetic dyes on textiles as a function of light dose. Approximately 30 measurements were available at dose intervals up to ~ 85–100 Mlx·h depending on the test batch. Raw data consisted of diffuse reflectance measurements for 107 dyed textiles, illuminated at 20 klx using an LED illuminant with a correlated colour temperature (CCT) of 3200 K and colour rendering index (CRI) of 95. Samples were obtained from period trade literature (1874–1905), and assumed to have negligeable prior light exposure due to their placement in the pages of books and remaining vibrancy of colour (e.g. the highly fugitive Erythrosin). For reference, the source dataset also includes a summary of information about the samples that were tested.

In previous work, visible reflectance spectra were converted to CIEXYZ colour space using colour matching functions for a 2° standard observer, and D65 illuminant (D65/2°). The colour values were then converted to CIELAB for colour difference calculations. Using measurements taken from samples over a black background, the light dose causing a just-noticeable difference (JND) was assessed in the present study at a threshold of $\Delta E_{00} = 1.7$. This relates to an ISO Grey Scale contrast value of 4 [16], which is a common benchmark for assessing a JND. Within the textile dataset, the calculated ΔE_{00} values can represent a change in lightness (lighter or darker) and/or hue shift with light exposure. At large colour difference (i.e. $\Delta E_{00} > 10$), this metric can be less accurate, and the HyAB method has been shown to better represent perceived differences [17]. The colour differences in the present study were assessed with respect to small changes; therefore, ΔE_{00} was used exclusively.

Measures of light dose were used in different contexts in the analysis, with the following variables defined in units of Mega lux-hours (Mlx·h):

d : future light dose.

p : accumulated light dose from prior exposure.

J_p : future light dose causing a JND ($\Delta E_{00} = 1.7$) for the residual colour after prior exposure, p. J_0 is the value at $p = 0$.

The method for assessing lightfastness as a function of prior exposure involved resetting the reference CIELAB values after different light dose increments, and calculating new colour difference curves. The dose causing a JND, J_p, was then determined by interpolation from each curve and tabulated with respect to the prior dose, p. This procedure is illustrated in Fig. 1a using data for Hofmann's Violet RRR on wool [18]. The solid bold line represents a fading curve where colour change is evaluated relative to the CIELAB values of the original colour prior to light exposure ($p = 0$). The dashed lines indicate colour change for the residual colour after prior doses of 1.4, 11 and 31 Mlx·h. In each case, the reference CIELAB values were reset to the colour remaining at the beginning of the next phase of light exposure. Figure 1b shows the same results on a magnified scale, highlighting the curves up to the point of a JND. The small circles indicate the intersection of each curve at $\Delta E_{00} = 1.7$, and the downward arrows point to values of J_p on the x-axis.

It was considered that an alternate approach might involve calculating the inverse slope of the fading curve, and multiplying by 1.7 to scale the values to a JND. Alternatively, the dose for each increment of $\Delta E_{00} = 1.7$ on the fading curve could be tabulated. One concern with applying this method was that, unlike ΔE_{76}, the ΔE_{00} colour difference formula compensates for perceptual non-uniformity and does not give a simple vector distance in CIELAB space. At large colour differences, the meaning of the rate of change of ΔE_{00} with light dose becomes unclear with a fixed reference to the original colour. To provide an example, a comparison is given for a single sample from the dataset. Figure 2a shows data from Hofmann's Violet RRR on wool, where the x-axis is the total ΔE_{00} referenced to the original colour, and the y-axis is the calculated cumulative steps of $\Delta E_{00} = 1$ with a shifting point of reference. In other words, we determine the actual 'steps of fading' that have occurred with respect to the ΔE_{00} values on a fading curve. The trend shows good

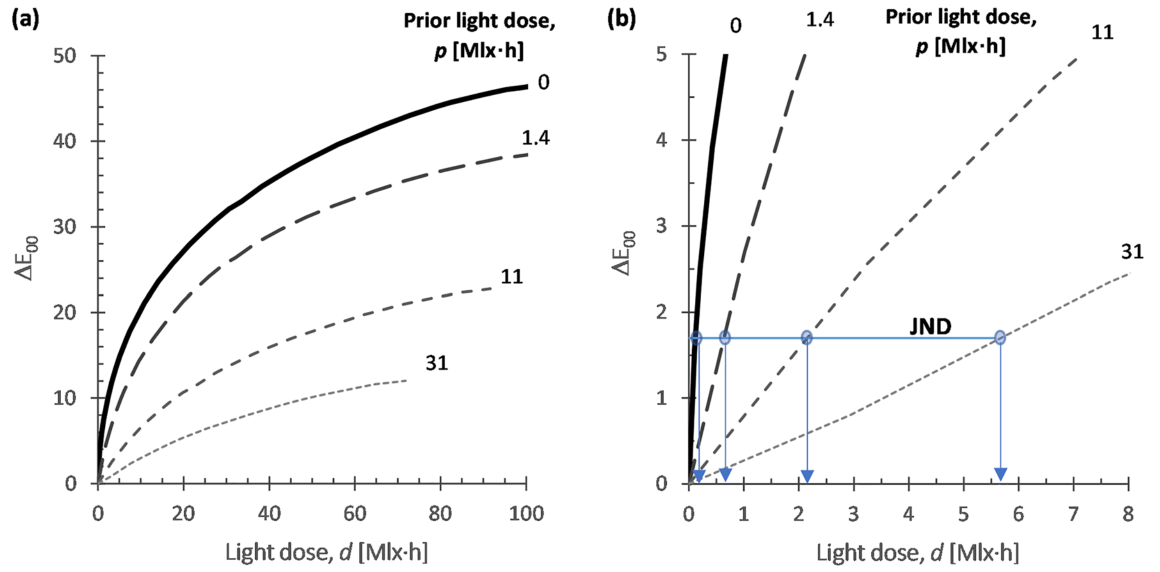

Fig. 1 **a** Colour change versus light dose for residual colour of Hofmann's Violet RRR after different amounts of prior light exposure; **b** Magnified scale showing the intersection of each curve with a JND at $\Delta E_{00} = 1.7$

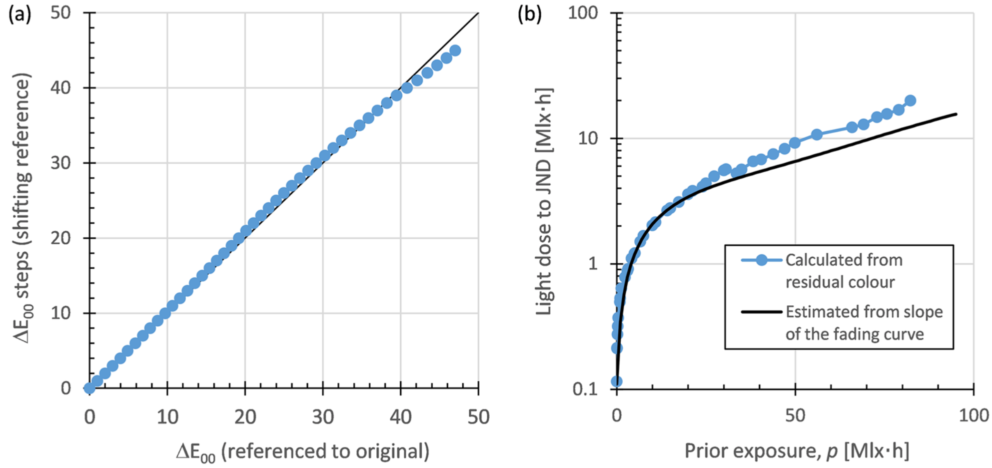

Fig. 2 Comparison of methods for interpreting the fading of Hofmann's Violet RRR: **a** Relationship between ΔE_{00} unity steps and ΔE_{00} from the fading curve (referenced to the original colour); **b** Comparison of methods for evaluating the future dose causing a JND as a function of prior exposure

agreement for this particular sample since the points are close to the black line — indicating that the two values are nearly equal.

The plot in Fig. 2b shows the relationship between prior light dose, *p*, and the future dose causing a JND for the residual Hofmann's Violet colour. The series with blue points represents values calculated with the method illustrated in Fig. 1b. The solid black line was calculated from the inverse slope of the fading curve (i.e. solid bold line in Fig. 1a), multiplied by 1.7. The results show good agreement at dose values up to ~20 Mlx·h, and then the curves begin to diverge. A greater discrepancy occurs for materials where the fading curve shows strong changes in slope between JND steps. As an example, this was particularly evident in the results from Methyl Blue for silk from Farbwerke vorm. Meister Lucius & Brüning [19]. The approach was abandoned early on in the research work; however, it is mentioned here as a consideration that was taken at the onset of the project.

Results and discussion

The procedure described in the "Methodology" section (Fig. 1) was performed for each of the textile samples, to determine the dose causing a JND as a function of prior exposure. From these calculations, a relationship between J_p and p was defined for each test material. Figure 3a shows the trend of increasing lightfastness for the residual colour as the prior dose increases for Hofmann's Violet RRR. In this example, the dose causing a JND at no prior exposure ($p = 0$) is 0.12 Mlx·h, while the value increases to 3.6 Mlx·h for the residual colour at $p = 20$ Mlx·h. This is approximately equivalent to a shift from BW1 to BW3 sensitivity, as shown by the horizontal lines denoting Blue Wools 1–4. Note that the Blue Wool comparisons use generalized values of dose to JND, J_0, in Mlx·h for a light source without ultraviolet (UV) energy, according to the CIE 157 Technical Report [20]. The transition between BW ratings was defined as the mid-point between dose to JND values on a plot of log(J_0) versus BW number. For reference, Table 1 gives the approximate dose to JND for BW1–3 exposed to a light source without UV, as listed in CIE 157. The calculated number of years to a JND is also given when the annual dose is limited to 0.015 Mlx·h/y for high responsivity materials [20, 5].

When interpreting the results in Fig. 3, it is important to also consider the condition of the colour with respect to the original. At a prior exposure of 16 Mlx·h, the residual Hofmann's Violet colour is at BW3 sensitivity; however, at this point the colour change from the original is quite large (i.e. $\Delta E_{00} = 25$ at a dose of 16 Mlx·h in Fig. 1a). Figure 3b shows the results for Erythrosin on cotton [21], which was the most fugitive colourant in the dataset ($J_0 = 0.028$ Mlx·h). The curve shows a sharp increase in J_p with prior exposure and very little colour remains when the lightfastness progresses to BW3 and higher.

Table 1 Approximate dose causing a JND for BW1–3 (no UV), and the corresponding years to JND (at 0.015 Mlx·h/y)

ISO BW#	~ Dose to JND, no UV (Mlx·h)	~Years to JND (at 0.015 Mlx·h/y)
1	0.3	20
2	1	67
3	3	200

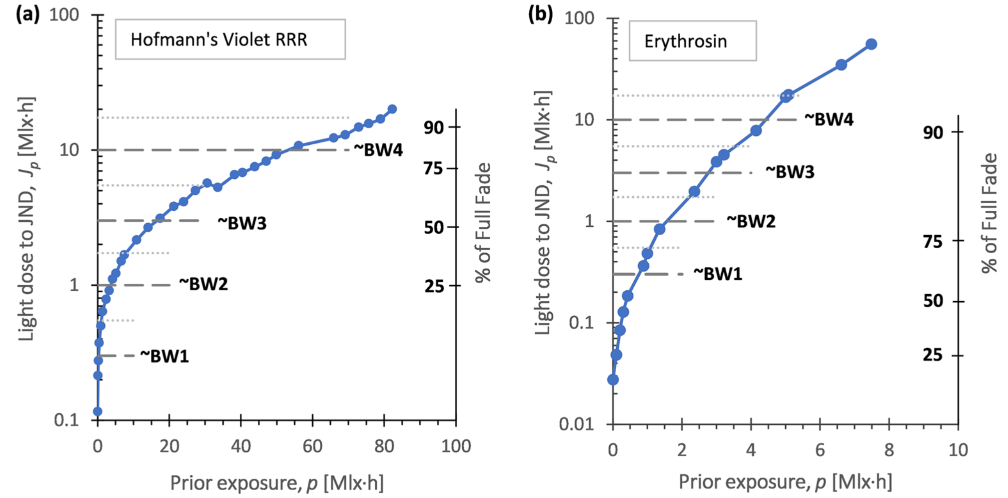

Fig. 3 Future dose to JND for residual colours as a function of prior exposure. Approximate Blue Wool (no UV) scale overlaid for reference. **a** Hofmann's Violet RRR on wool; **b** Erythrosin on cotton

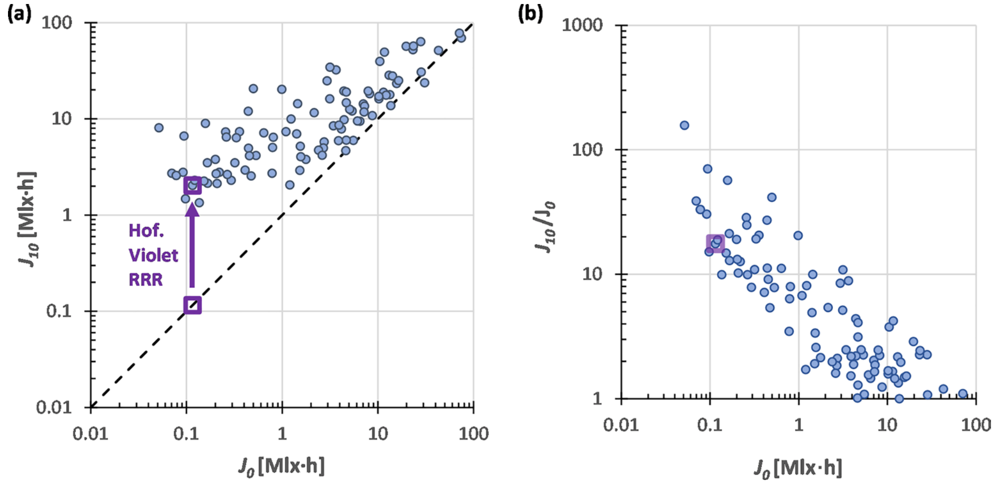

Fig. 4 **a** Light dose causing a JND for the residual colour after 10 Mlx·h of light exposure versus the value for the original colour; **b** Lightfastness enhancement of the residual colour after 10 Mlx·h versus dose causing a JND for the original colour

Figure 4 shows a summary of results for the full dataset. The plot in Fig. 4a gives the lightfastness of residual colour at $p = 10$ Mlx·h versus the initial value at $p = 0$. The angled dashed line indicates unity, where the values are unchanged. Points on the line reflect no change after 10 Mlx·h, while those above indicate an increase in lightfastness. An example is again highlighted for the Hofmann's Violet RRR sample, showing the transition from its initial sensitivity to the value after 10 Mlx·h. Note that some highly fugitive samples do not appear on this plot since they are highly faded at 10 Mlx·h and the value of J_{10} is beyond the experimental data (cf. Erythrosin data in Fig. 3b). The plot in Fig. 4b presents similar data; however, the y-axis is now the lightfastness enhancement at 10 Mlx·h, J_{10}/J_0. These data show the expected strong effect that 10 Mlx·h has on fugitive materials, while the influence is smaller for the less sensitive samples. The point for Hofmann's Violet is similarly shown for reference as the purple square.

A further analysis was performed to determine the degree of colour change that occurred for each sample once the light sensitivity of the residual colourant diminished to half the initial value. In other words, when the dose that will cause a JND, J_p, is twice the initial value, J_0. Figure 5 summarises the findings as a histogram showing the distribution of colour difference values (relative to

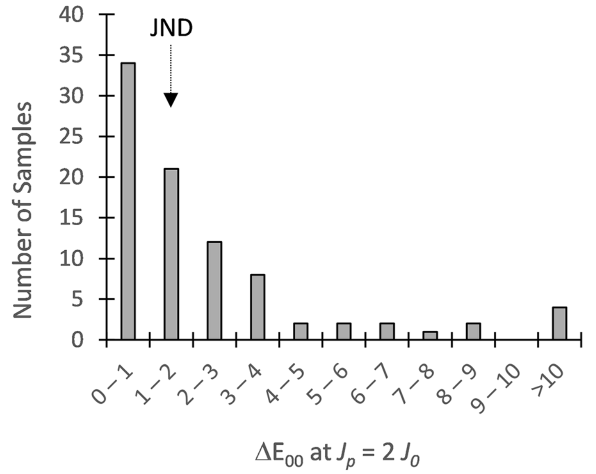

Fig. 5 Distribution of colour difference when the light dose causing a JND for the residual colour progresses to double the initial value

the original material) binned by ΔE_{00} values of one unit. The median value for the samples was $\Delta E_{00} = 1.4$, which is approximately a JND. The findings lead to an interesting generalization, or rule-of-thumb: when a dyed textile progresses to one JND from its initial color, the light sensitivity of the residual colour is roughly halved.

Blue wool ratings

The ultimate goal of this analysis was to determine at which prior dose values, p, the residual colourants are no longer in the higher sensitivity ranges (i.e. BW 1, 2, and 3). Figure 6a shows the number of samples that are less than or equal to each BW rating as a function of prior exposure. At $p = 0$, more than a third of the samples rank as BW1; however, none of the residual colours are in this category when prior dose approaches 3 Mlx·h. They have all progressed to BW2. Similarly, none of the samples rank ≤ BW2 when $p \geq \sim 17$ Mlx·h, or ≤ BW3 when $p \geq \sim 45$ Mlx·h. These data are also presented in Fig. 6b, where the number of samples is calculated for discrete BW bins. The curve for the number of samples rated as BW1 quickly decays to zero with a relatively small prior dose. As p increases, there is briefly a rise in the number of BW2 materials as the former BW1 samples degrade and progress to the next level of fastness. A similar trend is evident with the number of BW3 materials, showing an initial increase (former BW2 progressing to BW3) followed by a decrease to zero as they eventually progress to BW4. The overall results clearly show the shifting distribution of light sensitivity for the large collection of dyed textile samples. Similar trends are expected for other types of coloured materials in collections; however, this remains to be investigated in future work.

An additional consideration for the results in Fig. 6 is the effect of the illuminant spectral power distribution (SPD). The results specifically relate to irradiance from the LED light source used in the study, which is representative of modern indoor gallery lighting. Previous studies [22–24] have shown the influence of different spectral regions on fading, highlighting some trends in addition to a large degree of variability. For example, the work of McLaren [23] indicates a decreasing

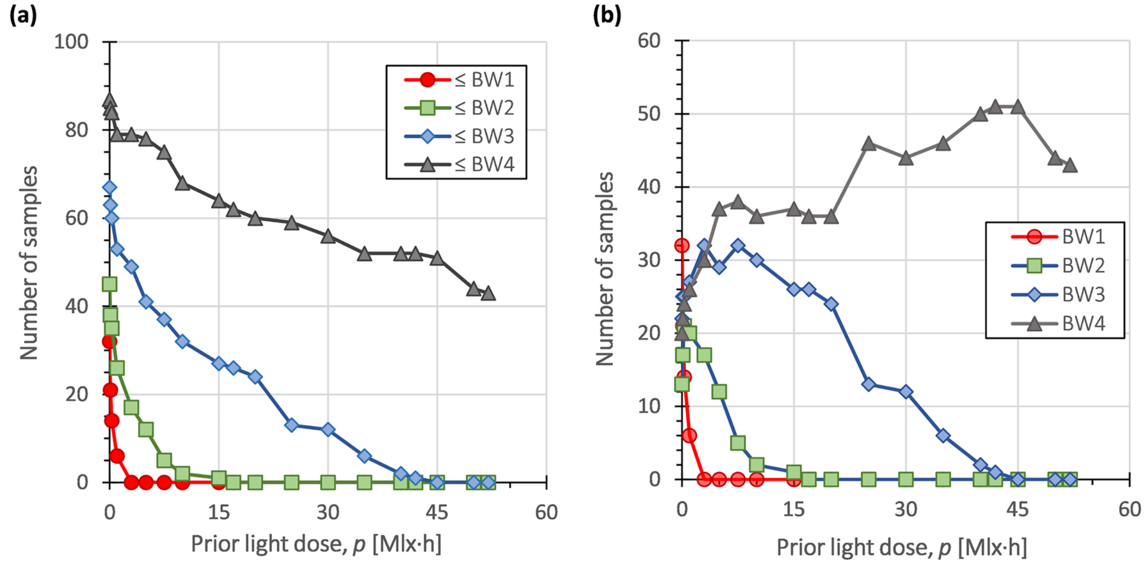

Fig. 6 Summary of results showing the number of samples with given lightfastness ratings as a function of prior dose. **a** results binned as values less than or equal to each BW rating up to BW4; **b** samples binned by discrete BW ratings

proportional influence of the UV region on total fading (with respect to visible) as the ISO BW rating decreases. There is, however, considerable scatter in the results. For the Blue Wools and a small selection of artist pigments, Saunders and Kirby [24] also show the varied influence of wavelengths through the visible range on colour change.

Of the many possible illuminant spectra, two comparisons are most relevant with the LED: (1) Traditional incandescent lamps at ~2700–3000 K; and (2) Daylight through glass (with/without UV filtered). Incandescent lamps have been in use since the early 20th century, and the importance of daylight does not need mention. In a discussion of LED lighting for museums, Michalski and Druzik [25] review lightfastness data and note a similar rate of colour change for a warm-white LED (high CRI, 3000 K, blue pump) source in comparison to incandescent. For daylight through glass, the rate of damage may be nearly the same or up to ~3X faster for some materials that were considered.

Practical considerations

In order to address the practical impact of this study, the results obtained from Fig. 6 were compared with published measurements of annual light dose for different exhibit settings. The cumulative dose versus time is shown in Fig. 7 for several conditions that were considered. These include the work of Thomson [10] at the National Gallery, London in 1967, and recent research at English Heritage and the National Trust [11, 26]. For the latter work, Fig. 7 shows the average annual dose for an English country house used in a study of the prior exposure of paintings at the Yale Center for British Art [11]. Also included is the logged annual exposure at an office exhibit space in Ottawa, which gave 1.85 Mlx·h/y (Irene Karsten, personal communication, 2022 June 16). For comparison, Thomson's proposed approximation of indoor daylight illuminance-hours gives ~2.4 Mlx·h/y for Ottawa on average. We calculated this value using daily NASA weather data (horizontal solar irradiance in kWh/m^2/d) from RETScreen [27] for the period of 1984–2021 and converted to illuminance hours by the factor 1 W/m^2 ≈ 120 lx [28]. Thomson's approximation involves multiplying this value by 1.5% for a representative indoor value.

Overlaid on the graph in Fig. 7 are horizontal lines indicating the dose values where residual colours ceased to exhibit sensitivities of BW1, BW2 and BW3 for textile samples in the present study. At larger exposure conditions (labelled a, b, and d), none of the residual colours would be classified as BW1 after approximately two years, and none would be ≤ BW2 after 10 years. The line labelled 'f' is shown to represent the modern conservative limit of 0.015 Mlx·h/y in the CIE 157 report [20] for preservation of high responsivity materials (BW1–3).

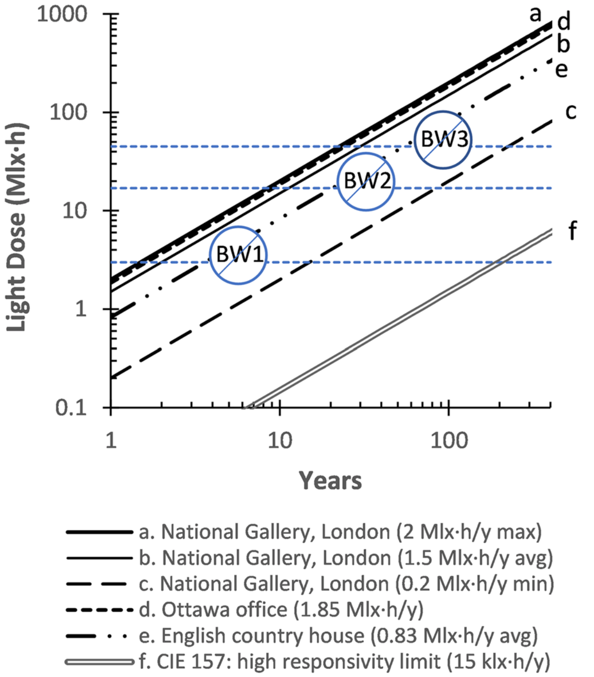

Fig. 7 Cumulative light dose for different exhibit scenarios. Horizontal lines show threshold values where BW1, BW2, and BW3 sensitivities were no longer present for residual colours in the present study (cf. Fig. 6)

Given the summary in Fig. 7, one may consider how likely it is for an object more than 100 years old to retain a sensitivity of BW1, 2 or 3 given its history. A similar plot could be constructed to illustrate the dose that would accumulate for a textile garment worn outdoors in daylight using general illuminance values: e.g., direct sunlight, midday (100 klx); daylight from clear sky (20 klx); overcast sky (10 klx); thick overcast, grey sky (5 klx) [29].

A particular scenario is worth considering with respect to the dose limit for 'high responsivity' materials in the CIE 157 document. The recommended limit is 0.015 Mlx·h per year for this class of material, which typically includes textiles dyed with early synthetic colorants [1, 8, 20, 30]. Classification of material sensitivity in grouped ranges (e.g. high: BW1–3, medium: BW4–6) is typically necessary due to the large degree of uncertainty in risk assessment unless specialized instrumental techniques are available. When a material is broadly classified as 'highly sensitive', Table 1 shows the years to JND (no UV) for the individual Blue Wools as: BW1 (20 years); BW2 (67 years); BW3 (200 years).

Now consider a hypothetical situation where the assessment of an object or collection history leads to the conclusion that the material(s) have experienced more than ~15 Mlx·h of light exposure. A review of the results in Fig. 6 indicates that it is unlikely that the residual colours are in the BW1–2 sensitivity range. It is now possible to use the risk-management strategy described by Michalski [1] to reassess the annual dose limits. For example, based on the significance [4] of the object or collection, and mandate of the institution (e.g. access), is 200 years to a JND appropriate? If 20 years to a JND were acceptable, it would increase the dose limit by a factor of 10 to give 0.15 Mlx·h per year. This value is roughly in-line with the requirements for full-year exhibition at 50 lx (8 h a day, every day of the year = 0.15 Mlx·h). Alternatively, higher light levels could be used for a shorter period to enhance visibility (e.g. for older visitors), while staying within a prescribed dose limit. Ford and Smith [3] give a related example that considers significance in the management of light exposure using MFT test results. For objects at about BW3–4 sensitivity, the authors explore an option that would allow illumination at 50–150 lx (lowest possible for good display) with an exhibition period based on significance: (a) five years per decade (high significance); (b) life of the exhibition, up to ten years (average significance).

Conclusion

To better understand the light sensitivity of heritage collections with prior light exposure, measurements of colour change were studied for more than 100 dyed textile samples containing early synthetic organic colourants from the period 1874–1905. In the analysis, the dose causing a JND was determined as a function of prior exposure for the residual colour of each material. Results highlighted the shifting distribution of light sensitivity for the sample set with light dose. An overall comparison was presented for the lightfastness of virgin colourants versus their respective values after 10 Mlx·h. A further analysis indicated that the light sensitivity is, as a general rule, halved once the material reaches a JND from the original. In other words, it takes roughly twice the dose to cause a JND for the residual colour that remains after the first JND.

The results were further interpreted to provide practical information for risk assessment in exhibit lighting applications. In this case, the dose to JND values were binned according to generalized BW responses when exposed to an illuminant without UV [20]. Results indicated the following:

- No samples ≤ BW1 after ~ 3 Mlx·h.
- No samples ≤ BW2 after ~ 17 Mlx·h.
- No samples ≤ BW3 after ~ 45 Mlx·h.

It is important to note that the spectral power distribution of the light source will also influence the results, since materials will have varied sensitivity to wavelengths through the visible range. This is an area to study in future work, in addition to performing similar analyses on other types of coloured materials in heritage collections.

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Author contributions
EH performed the data analysis and drafted the manuscript. JP reviewed and edited the manuscript. Both authors read and approved the final manuscript.

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Availability of data and materials
The calculated results are available on the Harvard Dataverse repository at https://doi.org/10.7910/DVN/O9PVXD [31]. Note that this is a continuation of two previous studies [14, 32]. Datasets from prior research provide context with respect to the dye industry [33], and summarise data regarding the sample materials (including original colour measurements) [15].

Declarations

Competing interests
The authors declare that they have no competing interests.

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