Natural Light Aging of furniture, textile, ivory and bone in historic environments.

David Thickett[1], Boris Pretzel[2], Bhavesh Shah[1], Naomi Luxford[1]

[1] English Heritage, London, United Kingdom. David.thickett@english-heritage.org.uk

[2] Victoria and Albert Museum, London, United Kingdom (retired) / Tokyo University of the Arts, Japan (retired)

Corresponding author: David Thickett (david.thickett@english-heritage.org.uk)

ABSTRACT

This study examines the sensitivity of historical objects to long-term light exposure in UK historic houses managed by the English Heritage Trust, using real objects under natural conditions. By monitoring light levels with Elsec sensors and Hanwell Luxbug loggers, and measuring colour changes with Minolta 2600d and Ocean Optics 2000 spectrometers, the research documents the effects on textiles, wooden furniture, and bone and ivory artefacts. Objects were periodically measured over several years to document colour changes, with measurements taken after 1, 2, 3, 6, and 11 years for furniture and textiles, and after 19 years for ivories, while bone objects were measured after over 70 years of display. Bone and ivory objects were not measured periodically, but by comparing exposed and unexposed surfaces. Results indicated that light doses in most rooms were approximately 60% of the maximum values specified in light plans. Wooden furniture showed minor changes, with the most fugitive area indicating perceptible changes ($\Delta E_{00} \geq 1.5$) after just over 21 years. Textiles exhibited varied colour change (ΔE_{00} ~1.7 to > 15 after 1 Mlux.h), with at least one colour on each textile showing high sensitivity, more sensitive than blue wool standard No. 1. Bone and ivory objects demonstrated relatively minor colour changes ($\Delta E_{00} < 1.5$). Results suggested that pollutant, especially ozone concentrations, could contribute to observed colour changes but, without specific dye analysis these effects remain inconclusive. The findings highlight the challenges in managing light exposure and the need for precise, long-term measurements to develop evidence-based conservation strategies for lighting. Results suggest that current guidelines may be overly conservative for bone objects.

KEYWORDS Light management, historic houses, bone, ivory, textiles, wood, colour change, pollution

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1. Introduction

Determining the sensitivity of objects to light is typically accomplished by making facsimiles of the object and subjecting these to exaggerated light levels whilst monitoring the resultant colour changes (Russel and Abney 1888, Brommelle 1964, Padfield 1964, Padfield and Landi 1966). Over the last 20 years or so, techniques have been developed to allow discrete, small areas of the actual objects to be exposed and changes to be monitored on the actual object itself, either very rapidly and very high illumination (Whitmore et al. 2000, Ford and Druzik 2013) or more slowly but at high precision (Pretzel 2000, 2008, 2021), to allow light sensitivity to be measured. In contrast, this paper presents results of long term (many years) assessments of colour change of objects on display in a number of day-lit and artificially lit spaces at UK historic houses managed by English Heritage Trust. Lighting historic interiors with daylight presents numerous challenges (National Trust 2011, Mardaljevic et al. 2009, Thorn 2013, Thickett 2017). Many institutions use UV films on windows, and double blinds manually adjusted to a light plan (National Trust 2011, Thickett 2007, Pretzel 1993). Typically, these involve measuring lux levels at selected points in a room, several times a day, and adjusting blinds to bring the lux levels to the value on the plan. At English Heritage Trust, management of light levels has been achieved by training two to four people from each property. This included perception demonstrations with increasing lux levels and representative objects. Evaluation of the light monitoring from 52 locations showed they were all illuminated well under their maximum planned dose (40% under the light plan level, Thickett 2007). One instance of calibration slipping on a light meter used for the light plans at Kenwood House, London, led to a large number (over 40 in a week) of visitor complaints due to low light levels. Before increasing the light plans, research was undertaken to examine the recent fading rates of several sensitive objects in situ. Textiles and wooden objects were selected for colour measurement. The objects were measured with a hand-held spectrometer periodically for 8 years with contiguous light measurements. A further set of colour measurement was undertaken 5 years later but by this time most of the light dose measurements had been discontinued. Although the collections on display include many easel paintings and works of art on paper, these were not included in the project as the measurements would not be entirely straight forward. Different varnishes and the thick layers on paintings would introduce uncertainty as to whether changes were due to the pigment or binder or varnish. Whilst most of the furniture objects were varnished, this is most likely a shellac-based varnish and a thinner layer. All paper art is in glazed frames or occasionally showcases, substantially increasing the effort to enable accurate colorimetric measurements.

The visual impact of modern light measuring equipment means recording sensor placement is extremely limited in historic interiors. Sensors are often placed at high level on door frames, on top of painting frames. The side-lit nature of most rooms means that readings will not necessarily be representative of the light doses experienced by the contents. This added another uncertainty and provided more impetus to undertake monitoring of actual objects.

The evidence for light induced changes to bone and ivory is very limited. Colour measurements were taken on the exposed and shaded sides of a number of objects that have been displayed for over 20 years. This was complimented by a years' worth of light monitoring to enable estimation of the light dose received by the exposed surfaces over time.

Most light management strategies consider light dose to be the predominant cause of colour changes. The presence of pollutant gases such as ozone and, to a degree, nitrogen oxides, can cause dramatic colour changes in some dyes on textiles.

2. Methods and Materials

Light levels were measured using either Elsec sensors incorporated in a Meaco radiotelemetry system or free-standing Hanwell Luxbug loggers. Previous research had shown the timings used (hour averages of 10-minute readings for Meaco and averaged 1-minute readings from the Luxbug), correlated well with integrating lux meters and readings at much shorter measurement intervals (Thickett 2017). The equipment was placed very close to the object surface and at the same orientation. Fourteen light doses were estimated by exposing pieces of blue wool standards and measuring the colour change. The colour change was converted to a lux dose using the calibration published by Bullock and Saunders (1999). That method was modified to measure the same 6mm area before and after exposure to reduce errors (Thickett *et al*. 2007), Light doses from an expanded set of 85 rooms were compared to the planned doses from light plans. Discrepancy in fading rates of blue wools 1-3 have been reported for microfading and more so for lightbox aging (Ford and Korenberg 2024). Greater batch to batch variations have been observed with UV filtered daylight aging by the authors. At English heritage, each new batch of blue wool is now tested when received to produce a new calibration curve, substantially removing the contribution to uncertainty from batch variations.

Colour measurements were mainly undertaken with a Minolta 2600d instrument. The parameters are shown

below, together with a summary of the equipment specifications given by the manufacturer;

- Illuminant D65 (most objects mainly day-lit).
- SCI (specular component included)
- 52mm integrating sphere
- 10nm resolution
- Range 360 to 740nm
- Spectral repeatability 0.1% (380-740nm)
- Inter instrument agreement, ΔE^*_{ab} (1976) 0.2 (MAV and SCI)

For some curved bone objects measurements were made with an Ocean Optics 2000 fibre optic spectrometer with a 1mm diameter measurement area. Parameters and instrument specifications are;

- SCI (specular component included)
- Range 300-1000nm
- Resolution 1nm
- Spectral repeatability (0.05% at 600nm, 0.1% at 450nm)

These objects were measured once only, with the exposed and unexposed surface compared. The colour differences were calculated for D65 light source and 10° observer.

For objects measured with the Minolta, the measurement points were aligned with patterns on the object, located with marked up photographs or using punched Melinex® masks (Pretzel 1992; Wilhelm and Brower 1993). The colorimeter orientation was controlled and the small area head (SAV - 6mm diameter) placed using the view port.

Colour measurements were taken after 1, 2, 3, 6 and 11 years for the furniture and textiles. Colour measurements of the exposed and unexposed surface of the 4 ivories were taken after 19 years of display. The 5 bone and single ivory object at Chesters Roman Fort were measured after more than 72 years on display.

For colours measured in the CIE system [ISO/CIE 2019] there are two (main) choices of "observer" for converting spectral power distribution of reflected (or transmitted) light to colour coordinates. The first, the so called "standard" or "2 degree" observer was agreed in 1931. The second, the so called "supplemental" or "10 degree" observer was agreed later in 1964. The choice of colour matching function is dependent on the colour variation in the visual field. In general, the 1931 observer is recommended when measuring colours of areas subtending a small angle to the eye whilst the supplemental observer is recommended where this is not the case. A brief summary of the reasons for the two choices of reference observer data is given below.

Different types of light sensitive cells are contained at the back of the eye (in the "retina"). Three classes of "cone cell" (with different maximum sensitivities, sometimes colloquially called the red, green and blue cones but more correctly referred to as the l – for long, m – for medium, and s – for short wavelength – cones) give rise to colour vision. These cones are spread in a very non-uniform manner across the retina and are heavily concentrated towards the centre of the visual field. The central part of the retina is called the fovea (approximately 1.5mm in diameter) and this is where most of the cone cells are located. At the centre of the fovea sits the foveola (approximately 0.35 mm in diameter) with the highest density of cones, where the eye performs visual tasks with the sharpest definition.

Colour sensation is derived in response to local contrasts across the mosaic of different cone cells in the retina. The three types of cone cells are not equally or similarly distributed across the retina. Indeed, the very centre of the foveola is effectively devoid of the s-cone so colour sensation from this very central high-resolution area of our eyes effectively only "dichromatic" and not "trichromatic" as we normally consider our colour vison to be. Given the complex distribution of the three classes of cone changes across the retina, it is not surprising that our colour sensation will depend on which areas of the retina are engaged with forming bits of the image.

The fovea (central portion of the field of view) covers approximately 2 degrees of view and is supposed to best be represented by the Standard Colorimetric observer. For colour analysis of complex scenes as found in many artworks, this might be considered a good representation for reference observers. However, in the course of the international adoption of this CIE standard observer, many compromises took place and mixed data sets were used so the colour matching functions and wavelength sensitivity function for this observer have been found to be somewhat wanting, especially in their short wavelength portions.

The 1964 supplemental observer colour matching functions were adopted some 30 years later and are recognized to be more consistent and experimentally better derived. A 10-degree field of view extends well beyond the foveal region, and this might be considered reasonable when assessing colour across larger objects of where variations are less detailed.

Although colour calculations will vary significantly if calculated with different observers, the effect on colour difference calculations is less pronounced – but it is of course paramount to remain consistent.

A 10° setting was used for the wood and a 2° for the intricate textile patterns. The colorimeter was regularly calibrated by the manufacturer and most measurements were taken within 3 months of such a calibration, with one of the sets taken within 6 months of calibration.

Initial trials with the Ocean Optic fibre optic spectrometer on bone surfaces indicated large errors (with five measurements the CIEDE2000 was 0.8 with uncertainty estimated at ± 3.5!) with manual positioning. A system with a clamp stand, stable lab jack, Zaber AXR X-Y automatic stage and Acuity AR 600 laser displacement sensor was used to accurately position the fibre optic head 2mm above the surface with an accuracy of 40µm. For the same bone object this approach determined a CIEDE2000 of 0.72 with a standard deviation of 0.07. This uncertainty includes any contributions from positioning error.

The objects measured are described in Table 1, which also gives the number of different areas measured and the total number of measurements (the product of the number of areas and the number of replicate measurements at each area) for each object.

Object	Location (property)	Room	Material	Col	Meas
A/Travelling Chest	Ranger's House	Introduction Room	Wood	3	15
B/Chair	Marble Hill House	Great Hall	Wood	1	5
C/Chest	Kenwood House	Housekeepers Room	Wood	3	15
D/Door	Kenwood House	Dining Room	Wood	1	5
E/Carpet	Osborne House	Council Room	Silk	13	39
F/Carpet	Audley End House	Saloon	Wool	4	8
G/ State Bed (bedspread)	Audley End House	Neville bedroom	Cotton	4	8
H/Banner	Audley End House	Great Hall	Cotton	3	6
J/Pin Open Head*	Chesters Roman Fort	Main Room Bone, Jet and Shale Case	Bone	1	10
K/Comb	Chesters Roman Fort		Bone	1	10
L/Plaque	Chesters Roman Fort		Bone	1	10
M/Brush*	Chesters Roman Fort		Bone	1	18
N/Textile Threader*	Chesters Roman Fort		Bone	1	10
O/Crozier Head	Battle Abbey	Inner Room Abbots Case	Walrus Ivory	1	16
P/Large Plaque	Ranger's House	Red Evocation Centre Case	Elephant Ivory	1	16
Q/Medium Plaque	Ranger's House		Elephant Ivory	1	16
R/Round Plaque	Ranger's House		Elephant Ivory	1	16

Tab. 1.: Objects used in this study, together with their location, material type, number of distinct colours measured ("Col"), and total number of colour measurements for each object ("Meas" – the product of number of areas and number of replicates). All colour measurements except for objects marked with an asterisk (*) were performed with a Konica Minolta CM2600d hand held spectrometer; objects marked with an asterisk were measured using an Ocean Optics 2000 spectrometer. The leading letter before each object is an arbitrarily (alphabetic in order of listing in the table) letter to aid identification in subsequent sections and tables.

Ozone and nitrogen dioxide were measured in the rooms containing the objects with diffusion tubes provided by Gradko Ltd. Measurements were taken for four-week periods determined likely to be the periods with maximum values either from previous measurements or results from the nearest automated continuous monitoring network station. Additionally, the ozone concentrations were measured monthly in the Great Hall at Audley End House for 12 months to produce an accurate annual dose figure. This location was selected as previous measurements had shown Audley End House to have the highest ozone concentrations of the properties considered. The Great Hall was thought likely to be most effected of the three rooms by pollutant infiltration; due to its large windows, proximity to the entrance door and lowest surface area to volume ratio.

3. Results and Discussion

3.1. *Measured light exposure*

The measured and planned light exposures for 85 rooms are shown in Figure 1.

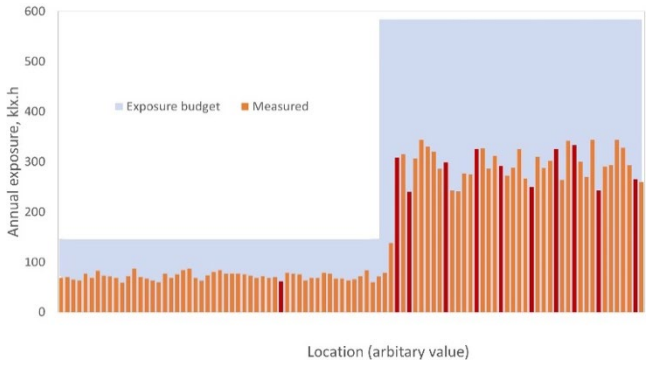

Fig. 1.: The measured and planned annual light exposure for 85 rooms. The dose specified by the light plan indicated by the light blue shaded areas for each location. Red bars are estimated exposures calculated from exposed blue wools; orange bars are calculated exposure using electronic monitors.

As can be seen, the results reflected the previous study and the measured doses are only approximately 60% of the maximum doses allowed for in the light plans.

3.2. *Fading of Furniture*

The discoloration of selected wooden furniture objects is shown in Figure 2. For each object, several (five) areas in each colour range were measured. For simplicity, only results for the fastest changing point in each colour are shown, as these will dominate the change in visual appearance for that object.

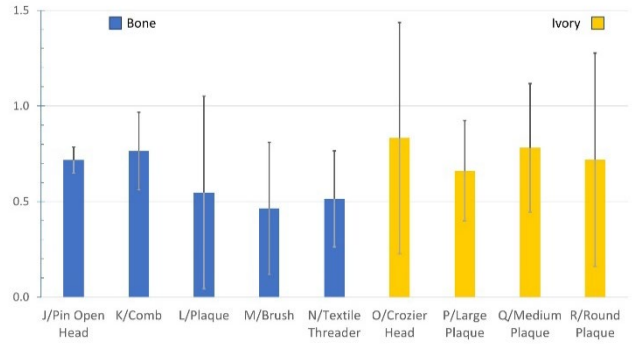

Fig. 2. : Colour changes versus light exposure for the area showing the largest colour change for four selected furniture objects. Uncertainty is estimated to be approximately 0.25 CIEDE2000 units.

The most reactive area, the black inlay on the travelling chest (A), indicates a perceptible change (*PC*, determined to be a CIEDE2000 colour change of 1.5) (Ashley-Smith et al., 2002) after just over 21 years. Terms such as 'just noticeable change' (j.n.c.) are frequently used by authors, but usually without experimental verification (e.g. Colby 1992; Derbyshire and Ashley-Smith 1999). The term *Perceptible Change* (*PC*) was introduced by Asheley-Smith and co-authors to distinguish their experimentally determined 50% likelihood of a colour difference being detected by trained observers (professional conservators) under ideal conditions (1000 lux illuminance, high colour rendering light source with 3000K colour temperature, neutral grey background with 20% reflectance) (Pretzel 2008). As luck would have it, the PC equated to a colour change approximately equal to grey scale 4 (expressed in CIEDE2000 units) and this is (typically) the value chosen for a j.n.c. The fading rate measured falls between two quoted time periods (10 and 30) years in the recommendations from Rijksdienst voor het Cultureel Erfgoed (RCE) (Rijksdienst voor het Cultureel Erfgoed 2016).

Unfortunately, an archiving error meant not all the underlying L*a*b* values were available for statistical analysis. The resultant colour differences however, were properly archived and are shown in Figure 2. In the absence of the underlying data, no formal uncertainty analysis can be undertaken at present, The uncertainty has been extimated at ± 0.25 CIEDE2000, in line with the uncertainty estimates given by Bullock and Saunders (1999) (albeit that their measurements were made using a tristimulus colorimeter rather than hand-held spectrometer and results were expressed in CIE94 colour difference, not CIEDE2000).

3.3. *Fading of textile*

The most affected and least affected colour from each textile is shown in Figure 3. Selecting the most and least rapidly changing colours on each object emphasizes the degree of differential change, as well as highlighting the most significant changes that will dominate the change in visual appearance.

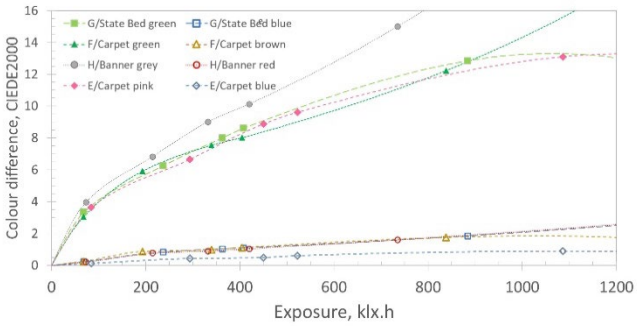

Fig. 3. Colour change on natural exposure of four textiles. Highest and lowest reactivity colour from the numerous colours measured is shown. Please note differences in scale compared to figure 2: the light levels for these objects are controlled to lower values, giving lower overall dose.

Uncertainties for this dataset were estimated at ± 0.4 CIEDE2000, based on the Bullock estimates, and considering the variable nature of the surface for embroidery (State Bed G and Banner H), and the effect of the pile on the two carpets (E an F – though, both carpets were selected as ones with no public access and site staff avoided the measurement areas).

Each textile had a number of low reactivity colours, generally changing at a rate reaching 1 PC (ΔE_{00} = 1.5) after approximately 650 ± 300 klx.h (Carpet F) to 680 ± 200 klx.h (Banner H) exposure. This falls between blue wool 2 and blue wool 1 on the blue wool equivalence scale (blue wool data from Bullock and Saunders 1999, recalculated to CIEDE200, and HERIE). One object (Carpet E) had a significantly more stable low reactivity colour, fading to 1 PC after approximately 2.3 ± 0.8 Mlx.h, putting the rating to between blue wool 2 -3 (Bullock and Saunders) or blue wool 3 (HERIE). All of the textiles had at least one highly responsive area, fading by 1 PC after only 23 ± 6 klx.h ((Banner H) to 30 ± 8 klx.h (Carpet F). These areas all remain significantly more reactive than blue wool 1 and the textile objects might therefore typically be categorized as vulnerable and not recommended for long-term display (Derbyshire et al. 2002).

The variability in light fastness of different textile dyes and colours has been reported in a number previous surveys (Padfield 1964, Padfield and Landi 1966, HERIE). Historic house collections rarely include significant reserve material for rotation and historical precedence limits the ability to change an object's location, so there is an acceptance that objects will undergo change at faster

rates than might be accepted for other heritage institutions. Nevertheless, the continued high reactivity observed for the fastest changing areas on the textiles is surprising, given the long periods for which the objects have been on display. The fastest change is occurring in a grey area in the Banner (H). This has been on display only since 2002, before that having been kept in dark storage, so the high sensitivity is perhaps less surprising, given the limited historical exposure, for this object.

3.4. *Alteration of bone and ivory*

Results are shown in Figure 4.

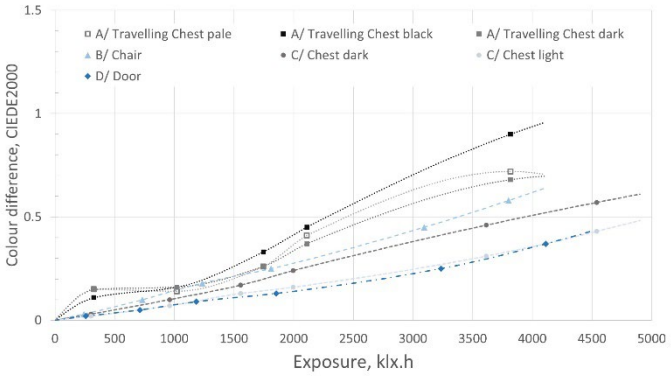

Fig. 4: Colour difference between exposed and unexposed face for ivory (in yellow) and bone (in blue) objects. NB although the colour changes shown are all of roughly the same magnitude, the ivory objects are estimated to have received roughly only 8 % (15% for the Crozier Head P) of the dose estimated to have been received by the bone objects.

For these objects, data for all five or eight repeat measurements at each point were available, so uncertainties in the colour differences were estimated by propagating variance in the CIELAB data through to the CIEDE2000 colour difference formula. The graphs show error bars equal to the calculated standard deviation. The uncertainties are large compared to the colour difference between the surfaces but the uncertainty was also calculated using the tristimulus data rather than the derived CIELAB coordinates. As both methods gave convergent results, the uncertainty estimates are considered robust. For further details the procedures used and of the nature and propagation of uncertainty in colour difference computation, see Pretzel et al. (forthcoming).

All colour changes for these objects are relatively small given the exposure periods, with none of them reaching 1 PC.

Table 2 shows the colour change versus accumulated exposure data plotted in Figure 4, together with a rough (linear) estimate of the years of exposure that might result in 1 PC.

	Colour change, ΔE_{00}	Light exposure, Mlx.h			Estimate of years to 1 *PC*	Material
		Measured over 1 year	Estimated total exposure	Estimate of dose to 1 *PC*		
J/Pin open head	0.72 ± 0.07	1.225	88.21	190 ± 20	151 ± 14	bone
K/Comb	0.8 ± 0.2	1.225	88.21	170 ± 50	140 ± 40	bone
L/Plaque	0.5 ± 0.5	1.225	88.21	240 ± 220	200 ± 180	bone
M/Brush	0.5 ± 0.3	1.225	88.21	290 ± 210	230 ± 170	bone
N/Textile threader	0.5 ± 0.3	1.225	88.21	260 ± 130	210 ± 100	bone
O/Large plaque	0.7 ± 0.3	0.096	6.92	4 ± 2	43 ± 17	Ivory
P/Crozier head	0.8 ± 0.6	0.181	13.04	8 ± 6	40 ± 30	Ivory
Q/Medium plaque	0.8 ± 0.3	0.096	6.92	4 ± 2	36 ± 16	Ivory
R/Round plaque	0.7 ± 0.6	0.096	6.92	4 ± 3	40 ± 30	ivory

Tab. 2.: Colour difference between exposed and unexposed surfaces of selected bone and ivory objects, together with measured annual exposure, estimated total exposure and a rough (linear) estimate of time at current exposure resulting in a colour difference of 1 PC.

The bone objects were exhibited at Chesters Roman Fort (see Table 1). The estimated light doses at Chesters are subject to large uncertainty as the exact exposure period can only roughly be estimated. A 1950s photograph shows the objects in place at that date, but the museum opened in the 1920s. Furthermore, there have been changes to the fabric of the building with a yellow glass skylight being replaced with clear glass. It is also not given that the two surfaces were the same colour to begin with. Nonetheless, the colour difference between the exposed surface and the unexposed is remarkedly small and much less than anticipated from several standard recommendations. RCE (Rijksdienst voor het Cultureel Erfgoed 2016) rate bone as sensitive with a limiting exposure of 10Mlx.h causing a visible change. The Canadian Conservation Institute (CCI) (Canadian Conservation Institute 2010) recommend that bone is illuminated at up to 150lux, limiting annual exposure to 440klx.h, but they do not give any indication of how quickly changes might become visible under this illumination level. The British Standards Institution (BSI) (British Standards Institution 2014) and CIE (2004) rate bone as low sensitivity or low responsivity (respectively). CIE giving an exposure of 300 – 1100 Mlx.h in uv free light for a “noticeable fade”. BSI do not give an exposure resulting in visible changes but recommend a maximum annual exposure of 600 klx.h for this class of objects. Our results would rate bone as medium to low responsivity under the CIE classification, with a limiting exposure to 1 PC ranging from approximately 100 to 400 Mlx.h.

The ivory objects are on display at Rangers House and Battle Abbey. The light exposures at Ranger’s House and

Battle Abbey can be estimated with a much smaller uncertainty. Our results for ivory objects fall in to the highly responsive under the CIE classification, with limiting exposure to 1 PC estimated to be 4 ± 3 Mlx.h. CCI (Canadian Conservation Institute 2010), BSI (British Standards Institution 2014) and CIE (2004) put ivory and bone in the same classification, with BSI and CIE rating them as low sensitivity or low responsivity (respectively) (and CIE rating their limiting exposure as 300 – 1100 Mlx.h). Derbyshire and Ashley-Smith (1999) rate portrait miniatures on ivory as sensitive and Derbyshire et al (2002) indicate a limiting exposure of 1.8 Mlx.h for this category. RCE suggests 1 j.n.c. in 1 Mlx.h (Rijksdienst voor het Cultureel Erfgoed 2006).

The rates of change of colour with exposure for ivory objects determined in this study are somewhat lower than the limiting rates indicated by RCE or Derbyshire et al. but are significantly faster than the rate indicated in the CIE document. In any case, this is a very small sample set and measurements of more objects would be required to produce concrete recommendations.

3.5. *Pollution*

The results of the pollution measurements are shown in Table 3.

Property	Room	Ozone		Nitrogen dioxide	
		Date (d/m)	Conc (ppb)	Date (d/m)	Conc (ppb)
Ranger's House	Introduction Room	3/4 - 1/5	2.5 ± 0.38	2/5 - 1/6	9.9 ± 1.98
Marble Hill House	Great Hall	3/4 - 1/5	1.8 ± 0.27	2/5 - 1/6	12.5 ± 2.50
Kenwood House	Housekeepers Room	1/4 - 31/5	3.6 ± 0.54	3/5 - 2/6	10.3 ± 2.06
Kenwood House	Dining Room	1/4 - 31/5	4.7 ± 0.70	3/5 - 2/6	11.4 ± 2.28
Osborne House	Council Room	14/4 - 13/5	11.1 ± 1.66	19/2 - 20/3	3.6 ± 0.72
Osborne House	Bedchamber	14/4 - 13/5	9.7 ± 1.45	19/2 - 20/3	2.9 ± 0.58
Audley End House	Saloon	5/7 - 3/8	11.3 ± 1.70	12/1 - 9/2	2.8 ± 0.56
Audley End House	Neville Bedroom	5/7 - 3/8	12.4 ± 1.86	12/1 - 9/2	2.5 ± 0.50
Audley End House	Great Hall	5/7 - 3/8	13.1 ± 1.96	12/1 - 9/2	3.2 ± 0.64

Tab. 3.: Ozone and nitrogen dioxide concentrations measured at the expected highest concentration periods for selected locations.

The concentrations measured are comparable to other data reported (Tetreault 2003, Kadokura et al. 1988). The rural properties (Osborne House, Audley End House) have higher ozone and lower nitrogen dioxide concentrations. Whilst the urban properties (Ranger's House, Marble Hill House and Kenwood House) have higher nitrogen dioxide (probably from traffic) and lower ozone concentrations. (Rozbicka and Rozbicka 2014). The annual dose of ozone in the Great Hall at Audley End house was determined to be 2954 ppb.day.

Unfortunately, most of the published data impacts of pollution impact on European natural dyes (28) is testing on paper (Whitmore and Cass, 1988 and 1989, Tetreault 2003) and the dyes present on the textiles were not analysed. Taking the highest values (worst case), 13.1ppb of ozone in Audley End Great Hall and applying that concentration value for 12 months would give an annual dose of 4781 ppb.day of ozone. Similarly for nitrogen dioxide the highest monthly concentration is 12.5 ppb (Marble Hill Great Hall), giving a worst-case scenario of 4562ppb days (ppb.day) nitrogen dioxide if present at those concentrations throughout the year. This calculation scales up the dose measured over 30 days to 365 days. The actual measured annual ozone dose (sum of 12 approximately monthly measurements) in the Great Hall was just under 64% of the estimated, worse case dose. For the most sensitive reported dyes, these doses would generate colour changes of 8.54, 13.66 and 27.32 for ozone (Whitmore and Cass 1988). and 0.33 and 0.22 for nitrogen dioxide (Whitmore and Cass 1989) over the 15-year measurement period. These values are much higher for the ozone than those measured in this work. The potential maximum effect of nitrogen dioxide is under 20% of the largest colour changes measurements. These estimates indicate it is important to consider pollution as a potential cause of colour change.

One issue with pollution measurement for cultural heritage is the lack of a method to measure long term doses. Whilst diffusion tubes are convenient and reasonably priced, the variability in concentrations across a year means 12 measurements would be required to assess an accurate dose, which greatly increases both cost and effort needed.

4. Conclusions

Light doses in these historic houses remain substantially below the anticipated and planned lighting budgets, suggesting that there is some flexibility to change the lighting designs. This will be particularly beneficial in any spaces that are regularly perceived by the public as gloomy or underlit. However, the colours on the textile objects measured should all be considered highly responsive (following the CIE classification) or vulnerable to sensitive under the V&A scheme (Derbyshire et al. 2002)

Long term measurements have shown only small colour changes (ΔE_{00}<1.5) for furniture, ivory, and bone. Bone objects, in particular, seem less sensitive than indicated by most schemes (but agree with the classification in CIE 2004).

From this data, for these specific objects at least, it appears that the lack of underpinning data has indeed possibly led to over-prescriptive guidelines for bone. The monitored textile objects, however, still have highly sensitive areas.

The verification of the fading rates, together with the relatively low actual average annual exposures, suggest light levels can be increased in some areas if needs be to improve the visual aspects of the situations, although any such change will need careful management and monitoring. However, textile objects may be already be fading at faster than anticipated rates even with the lower-than-expected annual light doses.

The measured ozone concentrations could be contributing to the colour changes observed. Without analysis of the dyes present, which was beyond the scope of this work, the changes are hypothetical. One issue with pollution measurement for cultural heritage is the lack of a method to measure long term doses economically.

This long term, natural ageing measurement approach has been extremely useful, but issues with long term calibration and uncertainty due to repositioning need addressing. Good inter-instrument repeatability is needed for robust results. A reasonable number of replicates are required for systematic and robust uncertainty analysis, which is particularly important for determining small colour changes with confidence. Five to eight replicate measurements (where available) appeared to produce colour difference and variance estimates that remained consistent regardless of whether the computation was carried out directly from the XYZ co-ordinates or using the derived CIELAB variables.

The early training courses for English Heritage staff appeared to have engendered over precautious attitudes to lighting levels and led to doses significantly under those anticipated in light plans. The training has been modified to reduce areas perceived by visitors as under luminated.

The utility of long-term measurements under actual exposure conditions has been demonstrated. Long term stability of the spectrometer and accurate repositioning for measurements are critical. These did not detract from usefulness or credibility of the data.

5. Conflict of interest declaration

The authors declare no conflicts of interest.

6. Funding source declaration

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7. Short biography of the author(s)

David Thickett (ORCID 0000-0001-9532-1517) is the senior conservation scientist at English Heritage. He specialises in the study of environmental preventive conservation and object response. He has a particular interest in pollution and his recent research has focused on epidemiology, sustainability, damage functions, acoustic emission, non-invasive testing and showcases. David is a directory board member of the Infra-red and Raman Users Group; UK Expert to CEN TC346, European conservation standards and editorial board member of Heritage Science.

Boris Pretzel (ORCID 0009-0008-8388-2737) was Materials Scientist (1989-2011) then Head of Science (2011-2021) at London's V&A, then invited Professor of Conservation Science, Tokyo University of the Arts, 2022-2024. His research interests include the perception and measurement of colour, and the propagation of uncertainty in measurements. He is European chair, former president, and founding directory board member of the Infrared and Raman Users Group, a Trustee of the National Heritage Science Forum, a Chartered Physicist, a Chartered Scientist, and Fellow of IIC.

Bhavesh Shah (ORCID 0000-0001-8673-0589) is a Conservation Scientist at English Heritage. His research primarily focuses on using environmental monitoring and data science to support preventive conservation and object preservation. He has an interest in machine learning, sustainability, lighting and colour change. Bhavesh is a member of the Royal Society of Chemistry and a member of the Institute of Conservation UK.

Naomi Luxford (ORCID 0000-0002-7751-7783) is a Conservation Scientist at English Heritage, working on environmental control and monitoring, including display cases, heating systems and light control. With an emphasis on how display requirements and indoor environmental conditions relate to building performance, particularly in historic buildings. Her research focuses on how materials in collections deteriorate as a result of the environmental conditions around them.

Licensing terms

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