RESEARCH PAPER

Determination of the Annual Light Exposure Received by Two-Dimensional Museum Objects Displayed on Vertical Surfaces using Photometric Measurements

Julio M. del Hoyo-Meléndez, Marion F. Mecklenburg and María Teresa Doménech-Carbó

Accurate estimates of cumulative light exposure are an important prerequisite for the assessment and limitation of photochemical damage to museum objects on display. The task is complicated because spotlights used to highlight particular features illuminate objects' surfaces unevenly, and also because indirect light sources, for example diffuse sunlight within exhibition spaces, result in changing total illumination levels throughout the day and seasonally. This paper presents a methodology for determining the annual light exposure of 2-D objects by combining the results of continuous light readings adjacent to the object and one-off point measurements over its illuminated surface, a method that allows a more accurate estimate of total exposure than either monitoring method alone. Two pieces of information are required to calculate cumulative exposure: first, the ratio of direct to indirect lighting, which is arrived at by quantifying the amount of visible light falling on the object relative to that received by its surroundings; and, second, the diurnal and seasonal variation in illuminance of indirect light sources, particularly diffuse daylight. Two paintings in different galleries exposed to different ratios of diffuse sunlight to direct artificial light – one low and the other high – were used to refine and test the method.

INTRODUCTION

The challenge of reaching an acceptable compromise between adequate exhibition lighting and minimizing light-induced damage is complicated both by the difficulty of accurately estimating cumulative exposures in exhibition spaces exposed to variable levels of indirect light, and predicting or measuring the different rates of light-induced change experienced by different components of museum objects. This paper deals with the first problem, while the second has usually been addressed by accelerated light exposure tests on surrogate samples of colorants known or suspected to be used in the construction of objects [1–3]. For some years museums have used guidelines proposed by Thomson [4], whose approach has been elaborated over time in schemes for which exposure periods are based on improved material responsiveness classifications and an estimate of an object's desired display lifetime [5–8]. A relatively recent innovation, micro-fade testing, improves this approach by allowing non-destructive accelerated testing of real objects, addressing the considerable and usually unpredictable contribution of preparation, application and prior exposure of colorants to the actual fading rates of light-sensitive materials [9–11]. Most museums, however, still make use of these recommendations without a systematic light-monitoring program to accurately quantify cumulative light exposures of individual works.

Received September 2009

Numerous investigations have been conducted on the interaction of light with museum materials [12–14], and on the use of electronic and chemical light dosimeters as a way of estimating exposures received by museum objects [15–17]. The high sensitivity of some materials typically found in museum collections have led to the development of more sensitive dosimeters [18, 19], for example one based on the color change of photosensitive dyes developed by Bacci et al. [20]. Although low-cost chemical dosimeters address the prohibitive expense of placing electronic dosimeters next to each object, the visual evaluation of dose-related color changes, calibrated against known laboratory exposures, is somewhat subjective. In addition, because the calibration is usually carried out at much higher light levels than typical museum lighting, the calibration may be intrinsically unreliable in particular cases where a failure of reciprocity, which assumes that the effects of 10000 lux for 1 hour and 10 lux for 1000 hours are equivalent, occurs [21–23].

Recently, there has been a trend towards the use of a combination of natural and artificial light in museums, particularly when lighting moderately light-sensitive and insensitive objects [24, 25]. Natural lighting may on occasions more faithfully reproduce the artist's intent, as well as provide energy-saving benefits; however, its ultraviolet (UV) component, which also varies with the weather, time of day and the seasons, is even more damaging than its visible counterpart [4]. For these reasons its quantity is usually deliberately limited and supplemented by artificial lighting, and because the natural light component is inherently variable, each must be quantified individually to arrive at a total exposure. The benefit of the proposed method is not only that an accurate determination of exposure may be made, but also that the balance between artificial and natural light may be set depending on the sensitivity of the objects forming the exhibit and the lighting effect required.

Two-dimensional objects hung on vertical surfaces are typically lit using a combination of direct sources and indirect, whether indirect artificial gallery lighting or sunlight. The former are used to highlight specific areas of an object while indirect lighting is used to enhance architectural elements in the exhibition space, to reduce contrast with strongly lit works, or to harmonize color throughout the exhibition space. A badly judged ratio of direct to indirect light can result in highly saturated or unsaturated colors depending on how the object reflects the light back to the observer [26]. The effect this ratio has on the perception of works has been summarized by Cuttle [27], who notes that typical ratios employed by museum lighting designers are 1.5:1 or 3:1, which he classifies as 'noticeable' or 'distinct', respectively. The terms 'object' and 'ambient' are sometimes used to refer to 'direct' and 'indirect' lighting respectively; however, for consistency the latter pair of terms is used throughout this paper.

Earlier contributions to the field include the work of Saunders [28] and Staniforth [29], which focused on measurement methodology and calculation of the cumulative exposure, respectively. Similar logging devices were employed for evaluating the light levels in models of the galleries at the National Gallery in London and at Clandon Park, an eighteenth-century house owned by the National Trust. Both authors mention some of the disadvantages of the instrumentation, which included the need for amplification of the signal, a limited amount of memory space, and a short battery life. Staniforth uses the average illuminances for a given recording period and recognizes that a very crude assessment of the annual exposure can be obtained by multiplying the daily exposure by the number of days of the open season. Other light-monitoring programs are based on estimating total exposures near objects without taking into account the effect of spotlights [30, 31], and conversely some authors have recommended annual light exposures based on the sensitivity of the object and spot readings, without evaluating the variable contribution of indirect lighting, particularly natural daylight [32, 33]. This work outlines a systematic approach for incorporating the contribution of both in total exposure estimates.

The goal of the research was to assess the feasibility of quantifying total light exposures in different locations by decomposing them into their natural and artificial lighting components and to compare the results with estimates in which only one or the other was considered. Continuous illuminance measurements and spot readings were taken in several areas of the Donald W. Reynolds Center (DWRC) for American Art and Portraiture in Washington, DC, from 1 November 2007 to 31 October 2008, as part of a comprehensive light levels monitoring program [34]. This building is shared between the National Portrait Gallery (NPG) and the Smithsonian American Art Museum (SAAM). A track lighting system combined with some natural light radiation is used throughout the museum to create specific lighting scenarios for individual works of art. These lighting settings typically include one or more direct light sources of higher illuminance value aimed towards the artifacts as well as indirect light sources which might include diffuse daylight, ambient lighting and floodlights. Most paintings in the museum galleries examined are illuminated with a combination of low-voltage (5.5–12 V) and line-voltage (120 V) halogen lamps employed for direct and indirect lighting, respectively. In this study, two paintings in different spaces within the NPG were chosen to represent different balances of direct and indirect lighting in order to examine the implications of each scenario for the calculation of annual cumulative exposures of paintings within them. Both galleries have the same invariant 12-hour gallery lighting schedule 364 days in a year; however, it is recognized that circumstances are not always that straightforward. Some museums are closed on particular days of the week and holidays, and host special events during the evenings, and cleaners and security staff require lighting after hours to work. The current project forms part of the development of new and comprehensive museum lighting policies and procedures for the Smithsonian Institution that take more fully into account the variations in lighting scenarios and light levels experienced by exhibits.

EXPERIMENTAL METHODS

A total of 25 ELSEC 764C recording environmental monitors (Littlemore Scientific Engineering, Dorset) were employed in the study. These meters record visible light in lux ($lm \cdot m^{-2}$) in the 400–700 nm range and the proportion of UV radiation in $\mu W \cdot lm^{-1}$ from 300 to 400 nm. They are cosine corrected for angular response and their stated accuracy by the manufacturer for the visible and UV ranges is 5% and 15%, respectively [35]. Data files were downloaded to a laptop via a USB2IR external wireless mini adapter (StarTech.com, Ohio, USA) into RView 3.8 for ELSEC monitors (Littlemore Scientific Engineering), from which they were subsequently exported to a spreadsheet for plotting and analysis.

Stationary monitors programmed to take readings at 10-minute intervals were installed next to 24 separate works of art on each of the three floors of the DWRC. They were installed in boxes, leaving only the sensors exposed, approximately 1 m from the center of the accent light beams, and a separate movable meter was used to take spot measurements across the surface of the paintings and drawings themselves. These measurements were taken as close as possible to the object without making any contact with its surface, and with the monitor held at the same orientation to the light source(s) as the corresponding stationary monitor. Because there were variations in illuminance across the surfaces of the spotlit paintings, a square grid of 10–20 cm^2 was imposed on printed photographs of the works, and five averaged measurements taken from the center of each square were used to find the maximum illumination, which was taken to be the direct light illuminance value. Using this value, and readings from the stationary monitors, the direct (movable) to indirect (stationary) lighting ratios could be calculated, and the total cumulative exposures for each of the works could be estimated from the integral of the illuminance versus time plots.

Calculation of lighting ratios and total light exposure

A similar approach to the one employed in photography and cinematography was used [36], where key and fill lights are analogous to museum direct and indirect lights. The direct to indirect lighting ratio R was obtained by dividing the direct illuminance value E_m (lx), by the indirect light component E_s (Equation 1) where the subscript 'm' denotes the movable and 's' the stationary light meter readings:

$$R = E_m / E_s{:}1 \quad \text{(for example 2.5:1)} \tag{1}$$

In some cases a direct light with a large beam angle directed towards a small painting can produce a spot large enough to overlap with the stationary monitor. Conversely, a large painting may be exclusively illuminated with floodlights. In both situations, the exposure experienced by the painting and the adjacent monitor would be similar since an approximated 1:1 ratio of direct to indirect artificial lighting is obtained. In the absence of natural light, the ratio of direct to indirect light (R) allows the total artificial light received by the object ($E_{v(artificial)}$) to be calculated from the value recorded by the stationary monitor as shown by Equation 2:

$$E_{v(artificial)} = E_{s(artificial)} \times R \tag{2}$$

It is known that all artificial light sources experience a loss in luminosity as they age. For example, halogen lamps are known to have lumen depreciation factors of approximately 0.9 [37]. Thus, lamp aging and its effects are a possible source of error in the calculation of the annual exposure. However, this estimation method assumes that deviations in illuminance caused by these losses do not alter the results significantly. Therefore, the total artificial light exposure for the object (H_a) in lux hours is obtained using Equation 3:

$$H_a = E_{v(artificial)} \times t \quad (lx \cdot h) \tag{3}$$

where t is exposure time in hours.

Because daylight levels experienced by the painting and those recorded by its corresponding stationary monitor are assumed to be equal ($E_{m(daylight)} = E_{s(daylight)}$), the total light received by the painting (E_v), including diffuse daylight, is the sum of the artificial light component striking the painting when the lights are on ($E_{m(artificial)}$) and changing diffuse daylight levels throughout the day ($E_{s(daylight)}$) as shown by Equation 4:

$$E_v = E_{s(daylight)} + E_{m(artificial)} \tag{4}$$

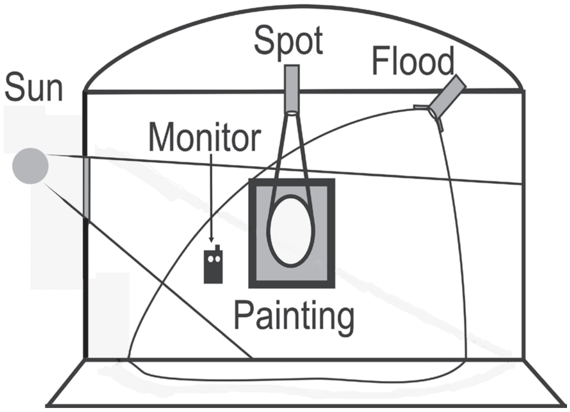

Figure 1 A hypothetical gallery in which direct and indirect light sources are used for illuminating a painting.

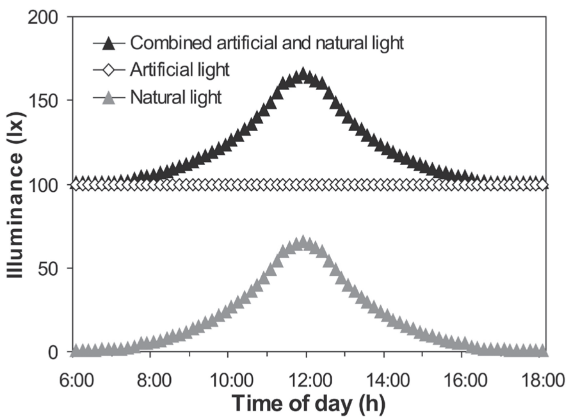

Figure 2 Illuminance measurements from a hypothetical museum gallery showing the total illuminance data separated into its artificial and natural light components.

If the exact sunrise and sunset times cannot be discerned from the data, an online calculator may be employed [38].

Figure 1 shows a painting in a hypothetical museum gallery illuminated by a direct source and two indirect sources. The light monitor located next to the work of art detects a mixture of diffuse daylight and radiation from a floodlight while the painting receives higher illumination from the two secondary sources plus the spotlight. The combined effect of various lamps acting upon the painting is obtained by adding the individual illuminances produced by each light source according to Equation 4.

Figure 2 shows illuminance measurements in a day for a hypothetical museum gallery with diffuse natural light as well as artificial lighting from 06.00 to 18.00 hours. A stationary light monitor registered a gradual increase in illuminance from 06.00 until 11.50 when it reached a maximum of 166 lx. This was followed by a gradual decrease from 12.00 to 18.00. The exhibition space had a 100 lx artificial light baseline in illuminance during the entire 12-hour period allowing the natural light component to be calculated by subtracting the latter from the total light recorded by the stationary monitor:

$$E_{s(daylight)} = E_{s(total)} - E_{s(artificial)} \quad (5)$$

The result can be used to generate hypothetical approximate annual light exposures for a gallery illuminated by a combination of daylight averaged over the year and direct light sources of any overall illuminance value, in this case 100 lx.

RESULTS AND DISCUSSION

Two case studies show the importance of accounting for natural light in determining cumulative exposures. The first is a setting in which the levels of artificial light were much higher than the natural light contribution throughout the entire year, and for the second, artificial and natural light dominated at different times depending on the month.

Calculation of the annual light exposure received by an object where artificial light dominates

The first case study involves a 69 × 56 cm oil on canvas portrait of Dorothea Lynde Dix painted by Samuel Bell Waugh in 1868 (NPG 97.38, Figure 3). The painting and its stationary monitor were located on an east-facing wall in gallery E112 on the first floor in the north-east corner of the building. The work was illuminated by a spotlight and ambient gallery lighting, and also exposed to diffuse daylight from the north and east windows at varying levels throughout the day and at different times of the year. Point measurements of ambient light at several locations away from the painting correlated well with continuous illuminance readings logged by the stationary meter, while the principle light level gradations moving out from the area of maximum illumination (without daylight) are illustrated in Figure 3.

In the absence of daylight, spot measurements within each of the 30 grid locations across the painting

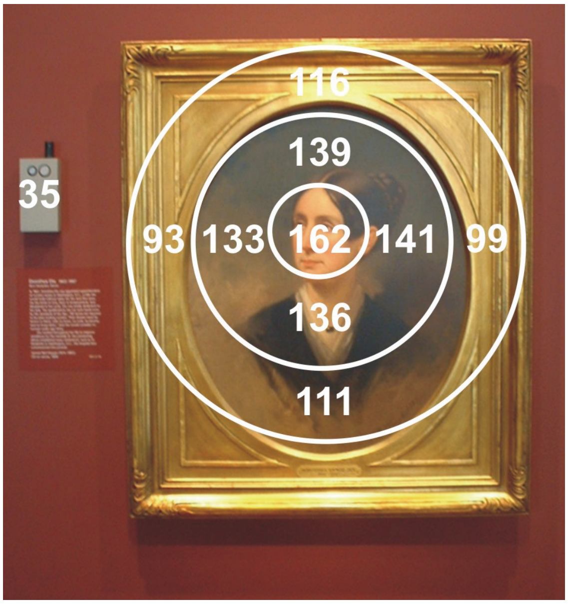

Figure 3 *Comparison of illuminance readings (lx) taken over the surface of a portrait of Dorothea Lynde Dix painted by Samuel Bell Waugh, located in gallery E112 of the DWRC. The adjacent light monitor registered an artificial light baseline in illuminance of 35 lx. Reproduced with permission.*

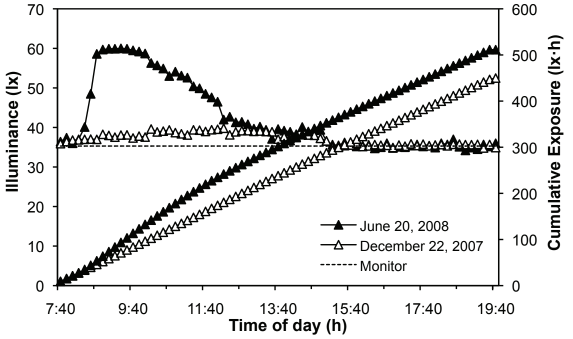

Figure 4 *Illuminance measurements (primary axis) and cumulative exposures (secondary axis) registered by a stationary monitor installed in gallery E112. The artificial light baseline registered by the stationary monitor is indicated by a discontinuous line (primary axis).*

showed that the sitter's face was the area most strongly lit at 162 lx (E_m), for a total cumulative exposure (H_a) of 1944 lx·h/day (Equation 3). The stationary monitor value was 35 lx (E_s), which subtracted from 162 lx (E_m) gave a spotlight contribution of 127 lx. The corresponding cumulative exposure contributions of the indirect lighting and spotlights were 420 lx·h and 1524 lx·h/day respectively (total of 1944 lx·h) and the direct to indirect lighting ratio (R) was 4.6:1 (Equation 1).

Illuminance data (E_s) recorded by the fixed light monitor installed in gallery E112 on 22 December 2007 and 20 June 2008 is shown in Figure 4 (primary axis). In December there is little variation due to daylight; however, the June data records a slow increase in diffuse daylight levels from 07.40 to 08.20 hours, followed by a more rapid increase in illuminance from 08.20 to 09.20 when it reached a maximum of 60 lx. From 09.30 to 12.50 the maximum light level dropped back to the constant artificial light level of 35 lx (no daylight).

Cumulative exposures (Figure 4, secondary axis) registered by the stationary meter (E_s) on 22 December 2007 and 20 June 2008, which are made up of the indirect artificial light and diffuse daylight ($E_{s(artificial)}$ + $E_{s(daylight)}$), were 450 and 511 lx·h respectively. Adding the constant spotlighting value $E_{m(artificial)}$ of 1534 lx·h (Equation 4 and Table 1) gives total cumulative exposures of 1974 and 2035 lx·h for the two dates, a difference of only 61 lx·h. It can be seen that the total exposure of the most strongly lit part of the painting, including diffuse daylight, is approximately five times the indirect light level recorded by the stationary monitor and that the added contribution of natural light on 20 June is relatively minor at 61 lx·h.

Monthly cumulative exposures calculated in the same way over a year show the same picture. They are illustrated in Figure 5, in which the columns (primary axis) represent a single month's exposure, and the lines (secondary axis) the running exposures for the stationary meter (E112M), the highest illuminated area of the painting (E112P) and the cumulative exposure which would have occurred if there were no daylight component (E112E). The total annual exposures for the stationary monitor and the central area of the painting including daylight were 170 and 726 klx·h respectively,

Table 1 *Estimated exposures (EE) for a stationary meter (M) and the highest illuminated area on a painting (P) of Dorothea Lynde Dix located in gallery E112 of the DWRC during December and June solstices*

Type of exposure	EE (lx·h) 22 Dec 2007		EE (lx·h) 20 June 2008	
	M	P	M	P
Total	450	1974	511	2035
Artificial light	420	1944	420	1944
Natural light	30	30	91	91

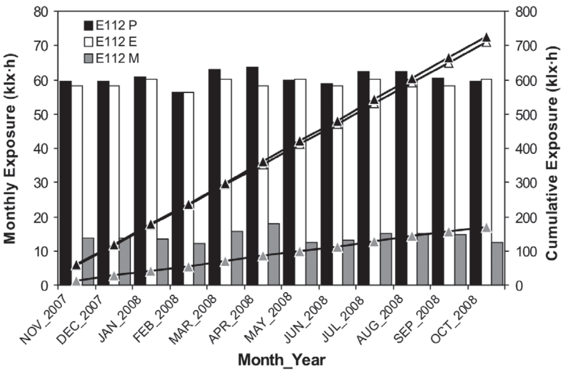

Figure 5 *Monthly light exposures (primary axis) and cumulative exposure trends (secondary axis) calculated for a stationary meter (E112M), an area of a painting exhibiting higher illumination (E112P), and extrapolated values from a point measurement (E112E).*

and the corresponding totals calculated solely from the ambient and spot artificial lighting (excluding daylight) were 153 and 708 klx·h. E112P and E112M are nearly linear because the daylight contribution is small, adding only 2.5% to the values calculated purely from spot readings of direct and indirect artificial light. Obviously because the painting was spotlit, values measured by the stationary monitor at only 23% of the total experienced by the painting itself would greatly underestimate its exposure.

Calculation of the annual light exposure received by an object where natural light levels are significant

The second case study is a 108 × 81 cm oil on canvas portrait of Martha Graham by Paul R. Meltsner from 1938 (NPG 73.41), which, for the purposes of determining the illumination distribution across its surface, was divided into a grid of 48 squares. The painting (and its stationary monitor), located on the south-facing wall of gallery S321, on the third floor, was spotlit and received indirect light in the form of ambient artificial gallery lighting as well as variable levels of diffuse daylight according to the time of day and year. Like the previous example in gallery E112, the artificial lighting is on for 12 hours per day; however, the skylights in this space admit much higher levels of natural light.

On 12 December 2007 at 18.45 hours, when there was no daylight, the stationary monitor level (E_s) was 77 lx and the highest illuminance value recorded at the surface of the painting itself (E_m) was 152 lx giving a direct to indirect lighting ratio (R) of 1.97:1 ≈ 2:1. Figure 6 shows the decreasing illumination in the cone of the spotlight moving out from its highest value on the face of the sitter. The much lower value of R (2:1) compared to the previous example (4.6:1) may be explained by a higher component of natural light in this space relative to gallery E112; thus, a lower amount of artificial ambient lighting is required for works exhibited in gallery S321.

Figure 6 *Comparison of illuminance readings (lx) taken over the surface of a portrait of Martha Graham painted by Paul R. Meltsner located in gallery S321 of the DWRC. The adjacent light monitor registered an artificial light baseline in illuminance of 77 lx. Reproduced with permission.*

Figure 7 (primary axis) is the illuminance data recorded by the stationary meter next to the painting on 22 December 2007 and 20 June 2008. Natural light intensities higher than the 152 lx 'no daylight' threshold value were registered on 20 June 2008 from 08.40 to 18.00. Estimated cumulative exposures (Figure 7, secondary axis) registered by the stationary meter and the highest illuminated area of the painting on 22 December 2007 were 1137 and 2037 lx·h, respectively, with the same measurements on 20 June of the following year yielding 3072 and 3972 lx·h. The increase in exposure as a result of natural light on these two days is approximately 2.0 klx·h for both the monitor and the highest illuminated area of the painting, a much greater impact than in gallery E112 (Table 2).

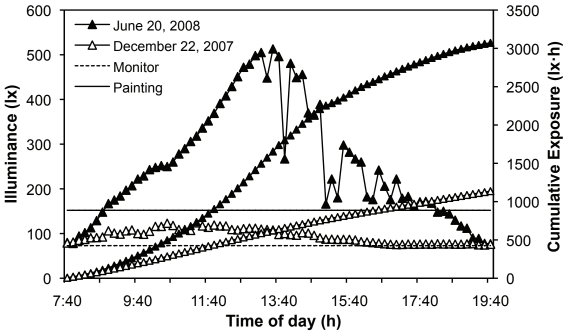

Figure 7 Illuminance measurements (primary axis) and cumulative exposures (secondary axis) registered by a stationary monitor installed in gallery S321. Artificial light baselines registered over the surface of the painting and on the adjacent wall are indicated by discontinuous lines (primary axis).

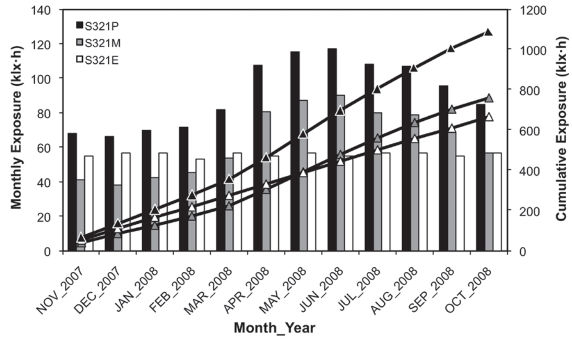

Figure 8 Monthly light exposures (primary axis) and cumulative exposure trends (secondary axis) calculated for a stationary meter (S321M), an area of a painting exhibiting higher illumination (S321P), and extrapolated values from a point measurement (E112E).

Table 2 Estimated exposures (EE) for a stationary meter and the highest illuminated area on a painting of Martha Graham located in gallery S321 of the DWRC during December and June solstices

Type of exposure	EE (lx·h) 22 Dec 2007		EE (lx·h) 20 June 2008	
	M	P	M	P
Total	1137	2037	3072	3972
Artificial light	924	1824	924	1824
Natural light	213	213	2148	2148

Figure 8 is a plot of monthly light exposures (primary axis) and cumulative exposure trends (secondary axis) at the stationary monitor (S321M). Also shown are monthly exposures and cumulative exposure curves obtained for the highest-illuminated area of the painting with natural light component included (S321P) and excluded (S321E). The natural light contribution increased for the painting and the stationary monitor from December 2007 to June 2008 to a maximum of 90 klx·h for the stationary monitor and 117 klx·h for the painting, and the trend reversed from June 2008 to October 2008 with the approach of winter. The stationary monitor and painting cumulative exposure curves show a more rapid increase from November 2007 to June 2008 with an inflection point in June that results from the decreasing total exposures registered in the subsequent months. Corresponding annual cumulative exposures for the painting and stationary monitor were 1090 and 761 klx·h (Figure 8). The annual cumulative exposure (S321E) extrapolated from only the artificial light values, ignoring the daylight component, increases linearly to 664 klx·h, 39% less than the actual value of 1090 klx·h. This highlights the importance of including the contribution of natural light in this situation and not simply estimating the exposure from one-off measurements of spotlight (E_m) and ambient gallery lighting (E_s).

CONCLUSIONS

A systematic method has been described for calculating more realistic annual light exposures received by two-dimensional museum objects that largely overcomes the limitation of not being able to log light levels on the surface of a work of art directly. It is particularly relevant to the situation where diffuse natural light is allowed to enter the display space. One-off illumination measurements taken at the surface of the work and adjacent to it at a distance of about 1 m permit the calculation of the direct to indirect artificial lighting ratio *R*. This value, in combination with the results of continuously logged total illumination from a permanent monitor oriented to the light sources in the same way as the work, but 1 m distant from it, permit the diffuse daylight component of light reaching the logger to be separated out from the overall illumination levels and added to the artificial light baseline earlier measured at the surface of the painting. The total cumulative visible exposure received by the painting can be more accurately estimated in this way than from either point measurements at the surface of a painting or continuous logging adjacent to it alone. If artificial illumination levels change for any reason, the new illuminance and *R* values will be the baseline for the same calculations from that time on.

ACKNOWLEDGEMENTS

The authors are greatly indebted to Bruce Ford for his helpful technical comments about this research and also for proofreading the final manuscript. This research was supported by the Smithsonian's Collections Care Pool Fund, administered by the Smithsonian Collections Advisory Committee and through a predoctoral fellowship from the Smithsonian Institution Office of Research and Training Services. The work proposal was jointly sponsored by the Smithsonian American Art Museum, the National Portrait Gallery and the Museum Conservation Institute. The authors would like to express their gratitude to staff from both museums for all their support, valuable discussions and recommendations concerning this work. Finally, special thanks to Magdalena Moskal for her valuable comments and suggestions concerning this paper.

SUPPLIERS

ELSEC 764C Environmental Monitors: Littlemore Scientific Engineering, Gutchpool Farm, Gillingham, Dorset SP8 5QP, United Kingdom.

USB to Infrared IrDA Adapters: StarTech.com, 45 Artisans Crescent, London, Ontario N6V 5E9 Canada.

RView 3.8 for ELSEC monitors: Littlemore Scientific Engineering, Gutchpool Farm, Gillingham, Dorset SP8 5QP, United Kingdom.

REFERENCES

1 Padfield, T., and Landi, S., 'The light-fastness of the natural dyes', *Studies in Conservation,* **11** (1966) 181–196.

2 Kühn, H., 'The effect of oxygen, relative humidity and temperature on the fading rate of watercolours: Reduced light damage in a nitrogen atmosphere', in *Contributions to the London Conference on Museum Climatology*, ed. G. Thomson, International Institute for Conservation of Historic and Artistic Works, London (1968) 79–85.

3 Saunders, D., and Kirby, J., 'Light-induced colour changes in red and yellow lake pigments', *National Gallery Technical Bulletin* **15** (1994) 79–97.

4 Thomson, G., *The Museum Environment*, 2nd edn, Butterworth-Heinemann, London (1986).

5 Feller, R.L., 'Control of deteriorating effects of light upon museum objects', *Museum* **17**(2) (1964) 57–98.

6 Colby, K.M., 'A suggested exhibition policy for works of art on paper', *Journal of the International Institute for Conservation, Canadian Group* **17** (1992) 3–11.

7 Ashley-Smith, J., Derbyshire, A., and Pretzel, B., 'The continuing development of a practical lighting policy for works of art on paper and other object types at the Victoria and Albert Museum', in *ICOM Committee for Conservation, 13th Triennial Meeting, Rio de Janeiro*, ed. R. Vontobel, James & James, London (2002) Vol. I 3–8.

8 *CIE 157: Control of Damage to Museum Objects by Optical Radiation*, Technical Report, Commission Internationale de l'Eclairage, Vienna (2004).

9 Connors, S.A., Whitmore, P.M., Keyes, R.S., and Coombs, E.I., 'The identification and light sensitivity of Japanese woodblock print colorants: The impact on art history and preservation', in *Scientific Research on the Pictorial Arts of Asia, Proceedings of the Second Forbes Symposium at the Freer Gallery of Art*, ed. P. Jett, J. Winter and B. McCarthy, Archetype, Washington, DC (2005) 35–47.

10 Ford, B., and Smith, N., 'The development of a significance and risk based lighting framework at the National Museum of Australia', in *Conserving Public and Private Collections: AICCM National Conference*, National Museum of Australia, Canberra, in press.

11 del Hoyo-Meléndez, J.M., and Mecklenburg, M.F., 'A survey on the light-fastness properties of organic-based Alaska Native artifacts', *Journal of Cultural Heritage* **11** (4) 493–499.

12 Michalski, S., 'Damage to museum objects by visible radiation (light) and ultraviolet radiation (UV)', in *Lighting in Museums, Galleries, and Historic Houses, Papers of the Conference, Bristol*, The Museums Association, London (1987) 3–16.

13 Ford, B.L., 'Monitoring colour change in textiles on display', *Studies in Conservation* **37** (1992) 1–11.

14 Saunders, D., Chahine, H., and Cupitt, J., 'Long-term colour change measurement: Some results after twenty years', *National Gallery Technical Bulletin* **17** (1996) 81–90.

15 Tennent, N.H., and Townsend, J.H., 'Light dosimeters for museums, galleries, and historic sites', in *Lighting in Museums, Galleries, and Historic Houses, Papers of the Conference, Bristol*, The Museums Association, London (1987) 31–35.

16 Bullock, L., and Saunders, D., 'Measurement of cumulative exposure using Blue Wool standards', in *ICOM Committee for Conservation, 12th Triennial Meeting, Lyon*, ed. D. Grattan, James and James, London (1999) Vol. I 21–26.

17 Bacci, M., Picollo, M., Porcinai, S., and Radicati, B., 'Evaluation of the museum environmental risk by means of tempera-painted dosimeters', *Thermochimica Acta* **365**(1) (2000) 25–34.

18 Lavédrine, B., 'The blue pink scale: A new light dosimeter for the exhibition of photographs and sensitive artifacts', in *Care of Photographic Moving Image & Sound Collections, York*, ed. S. Clark and L. Lodge, The Institute of Paper Conservation, Leigh (1999) 124–128.

19 Cohen, N.S., Odlyha, M., Campana, R., and Foster, G.M., 'Dosimetry of paintings: Determination of the degree of chemical change in museum exposed test paintings (lead white tempera) by thermal analysis and infrared spectroscopy', *Thermochimica Acta* **365**(1–2) (2000) 45–52.

20 Bacci, M., Cucci, C., Dupont, A.L., Lavédrine, B., Picollo, M., and Porcinai, S., 'Disposable indicators for monitoring lighting conditions in museums', *Environmental Science and Technology* **37**(24) (2003) 5687–5694.

21 Saunders, D., and Kirby, J., 'Light-induced damage: Investigating the reciprocity principle', in *ICOM Committee for Conservation, 11th Triennial Meeting, Edinburgh*, ed. J. Bridgland, James and James, London (1996) Vol. I 87–90.

22 Lavédrine, B., *A Guide to the Preventive Conservation of Photographic Collections*, The Getty Institute, Los Angeles (2003).

23 del Hoyo-Meléndez, J.M., and Mecklenburg, M.F., 'An investigation of the reciprocity principle of light exposures using micro-fading spectrometry', *Spectroscopy Letters* **44** (2011) 52–62.

24 Wilkinson, M.A., 'Lighting options, daylight and artificial lighting', in *Lighting in Museums, Galleries, and Historic Houses, Papers of the Conference, Bristol*, The Museums Association, London (1987) 58–65.

25 Wilson, M., 'The Hampton site extension: Lighting considerations', in *Lighting in Museums, Galleries, and Historic Houses, Papers of the Conference, Bristol*, The Museums Association, London (1987) 85–88.

26 Aguilar-Rico, M., and Blanca-Giménez, V., *Iluminación y Color*, Universidad Politécnica de Valencia, Valencia (1995).

27 Cuttle, C., *Light for Art's Sake: Lighting for Artworks and Museum Displays*, Butterworth-Heinemann, Oxford (2007).

28 Saunders, D., 'A portable instrument for the logging of light levels', *The Conservator* **13** (1989) 25–30.

29 Staniforth, S., 'The logging of light levels in National Trust houses' in *ICOM Committee for Conservation 9th Triennial Meeting*, ICOM-CC, Dresden (1990) 602–607.

30 Odlyha, M., Cohen N.S., Campana, R., and Foster, G.M., 'Environmental research for art conservation and assessment of indoor conditions surrounding cultural objects', *Journal of Thermal Analysis and Calorimetry* **56** (1999) 1219–1232.

31 France F.G., 'Lighting the treasures', in *Facing Impermanence: Exploring Preventive Conservation for Textiles, Proceedings of 6th Biennial North American Textile Conservation Conference, Washington DC*, ed. S. Thomassen-Krauss, North American Textile Conservation Conference, New York (2007) 119–130.

32 Van der Reyden, D., 'Paper documents', in *Storage of Natural History Collections: A Preventive Conservation Approach*, ed. C.L. Rose, C.A. Hawks and H.H. Genoways, Society for Preservation of Natural History Collections, Pittsburgh (1995) 327–353.

33 Daniel, V., 'Building management and maintenance in the new millennium', *Library Review* **50** (2001) 407–416.

34 del Hoyo-Meléndez, J.M., Mecklenburg, M.F., and Doménech-Carbó, M.T., 'An evaluation of daylight distribution as an initial preventive conservation measure at two Smithsonian Institution Museums, Washington DC, USA', *Journal of Cultural Heritage*, in press, doi:10.1016/j.culher.2010.05.003.

35 ELSEC, *Environmental Monitor User Manual*, Littlemore Scientific Engineering, Dorset (2007).

36 Musburger, R.B., *Single-Camera Video Production*, 4th edn, Focal, New York (2005).

37 Matthews, J.H., *Introduction to the Design and Analysis of Building Electrical Systems*, Van Nostrand Reinhold, New York (1993).

38 Cornwall, C., Horiuchi, A., and Lehman C., 'Sunrise/sunset calculator', www.srrb.noaa.gov/highlights/sunrise/sunrise.html (accessed 28 November 2010).

AUTHORS

JULIO M. DEL HOYO-MELÉNDEZ holds a PhD in science and conservation of cultural heritage from the Department of Conservation and Restoration of Cultural Heritage of the Polytechnic University of Valencia, Spain. He received his MS in chemistry from the University of Houston in 1997. An interest in the conservation of cultural heritage combined with a scientific background led him to work as an assistant conservator of paintings, objects and works of art on paper in both museum-based and private studios, from 1998 to 2004. He was a graduate intern in the Museum Research Laboratory of the Getty Conservation Institute in Los Angeles, USA from 2005 to 2006. In 2007, he was awarded a predoctoral fellowship at the Smithsonian Museum Conservation Institute in Maryland, USA for conducting research on the action of light on cultural heritage materials. *Address: Instituto Universitario de Restauración del Patrimonio, Universidad Politécnica de Valencia, Camino de Vera 14, 46022 Valencia Spain. Email: judeho1@doctor.upv.es*

MARION F. MECKLENBURG is a senior research scientist at the Smithsonian Museum Conservation Institute. He received a PhD in engineering from the University of Maryland, USA in 1984. He has a background in conservation acquired while working at the Corcoran Gallery of Art, Washington, D.C., USA, Smithsonian Institution, and various private studios. He has also served on the faculty of the University of Maryland, Johns Hopkins University, USA, South Valley University, Egypt, and the Polytechnic University of Valencia, Spain. His research interests include collections preservation and the mechanical properties of cultural materials. *Address: Museum Conservation Institute, Smithsonian Institution, Suitland, MD 20746-2863, USA. Email: mecklenburgm@si.edu*

MARÍA TERESA DOMÉNECH-CARBÓ is the director of the Heritage Conservation Institute of the Polytechnic University of Valencia and a professor in the Department of Conservation and Restoration of Cultural Heritage of the same university. She received a PhD in chemistry from the University of Valencia in 1989. A year later she took a lectureship in conservation science at the Polytechnic University of Valencia, and a Personal Chair in 1999. Her research interests include the development of new analytical methods for the study of cultural heritage materials with a focus on the characterization of constitutive materials of works of art, alteration processes, control and assessment of conservation treatments, and the development of new materials and methods for conservation. *Address: as del Hoyo-Meléndez. Email: tdomenec@crbc.upv.es*

Résumé — *Les estimations précises de l'exposition cumulée à la lumière sont des conditions préalables à la mesure et à la limitation des dommages photochimiques pour les objets exposés dans les musées. La tâche est compliquée par le fait que les lampes à éclairage ponctuel utilisées pour mettre en valeur certaines particularités éclairent la surface de l'objet de façon irrégulière, et aussi parce que les sources de lumière indirectes, comme par exemple l'éclairage solaire diffus à l'intérieur des espaces d'exposition, induisent des niveaux totaux d'éclairement changeants, de façon diurne ou saisonnière. Cet article décrit une méthodologie pour déterminer l'exposition annuelle à la lumière d'objets en 2D en combinant les résultats de la mesure d'une lumière continue adjacente à l'objet, avec une mesure de sa surface éclairée; une méthode qui permet une estimation plus précise de l'exposition totale que chaque méthode prise isolément. Deux éléments d'information sont requis pour calculer l'exposition cumulée : en premier, le rationentre éclairage direct / éclairage indirect, qui est obtenu en quantifiant la lumière visible tombant sur l'objet par rapport à la lumière reçue par son environnement ; et, en second lieu, les variations diurnes et saisonnières de l'éclairement par les sources de lumière indirecte, en particulier la lumière du jour diffuse. Deux peintures exposées dans des galeries différentes exposées à différents ratios lumière diffuse/lumière artificielles – l'un faible, l'autre élevé – ont été utilisées pour affiner et tester la méthode.*

Zusammenfassung — *Eine genaue Abschätzung der kumulativen Lichtexposition ist eine wichtige Voraussetzung für die Beurteilung und Begrenzung lichtinduzierter Schäden an ausgestellten Museumsobjekten. Die Aufgabe ist kompliziert, da die zum Beleuchten besonderer Eigenheiten verwendeten Punktstrahler die Oberfläche der Objekte ungleichmäßig erhellen, aber auch, da indirekte Lichtquellen, zum Beispiel diffuses Sonnenlicht, im Laufe des Tages und saisonal in den Ausstellungsräumen zu stark schwankender Beleuchtung führen. In diesem Artikel wird eine Methodik zur Bestimmung der jährlichen Lichtmenge für zweidimensionale Objekte vorgestellt, bei der die Ergebnisse kontinuierlicher Lichtmessungen im direkten Umfeld des Objektes mit einmaligen Punktmessungen an dessen beleuchteter Oberfläche miteinander kombiniert werden; die Methode erlaubt eine weit akkuratere Bestimmung der absoluten Lichtdosis, als eine der beiden Messungen allein. Zwei Informationen werden für die Berechnung der Gesamtexposition gebraucht: erstens das Verhältnis von direkter und indirekter Beleuchtung, welches durch die Quantifizierung der auf das Objekt fallenden Lichtmenge relativ zu der auf die Umgebung fallenden erreicht wird; und zweitens die täglichen und jahreszeitlichen Schwankungen der Beleuchtung durch indirektes Licht, insbesondere diffuses Tageslicht. Zur Verfeinerung und Erprobung der Methode wurden zwei Gemälde verwendet, die in verschiedenen Ausstellungsräumen, verschiedenen Verhältnissen von diffusem Sonnenlicht und direktem Kunstlicht ausgesetzt wurden – das eine einem niedrige, das andere einer hohen Lichteinstrahlung..*

Resumen — *Las estimaciones precisas de la exposición acumulativa de luz es un pre-requisito importante para el establecimiento del control del daño fotomecánico a objetos de museo en exposición. Este asunto es complicado ya que los puntos de luz utilizados para resaltar ciertas características iluminan la superficie de los objetos desigualmente; además, las fuentes de luz indirecta, por ejemplo la luz solar difusa en los espacios de exposición, aportan variaciones totales de los niveles de iluminación dependiendo de la hora del día y de la estación. Este artículo presenta una metodología para determinar la exposición anual para objetos de dos dimensiones, combinando los resultados de lecturas continuas de iluminación adyacentes al objeto y de mediciones puntuales sobre la superficie iluminada. Es un método que permite una estimación más precisa de la exposición total que usando uno de los dos métodos independientemente. Se requieren dos grupos de información para calcular la exposición acumulativa: primero, la proporción de la iluminación directa con la indirecta, a la cual se llega al cuantificar la cantidad de luz visible a la que está expuesto el objeto en relación a la recibida por el entorno; y segundo, la variación diaria y estacional en iluminación de fuentes de luz directas, particularmente luz-día difusa. Para refinar y comprobar el método se escogieron dos cuadros en diferentes galerías expuestos a diferentes proporciones de luz solar difusa y de luz artificial directa, una en bajos valores y la otra en elevados.*