New developments in understanding daylight exposure in heritage interiors

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Abstract

This paper reports on an investigation into daylight exposure in National Trust (England, Wales and Northern Ireland) interiors. Developing a study of a top lit staircase at Mount Stewart, the focus of this research is the daylight performance of side lit rooms. The multistrand methodology involved: conventional use of light data loggers with a novel camera system based on high dynamic range (HDR) imaging; simulation using climate based daylight modelling (CBDM); and detailed recording of room use by staff. Although integrating this data has proved challenging, early results from both the simulation and the HDR system already provide insights into collections management practises for Trust staff.

Introduction

The introduction of recommendations for lighting control first widely published in 1960s led to substantial changes in practice in museums and heritage buildings (Thomson 1961). Previously, day lit interiors were either 'blacked out' or subject to varying levels of control to

reduce light levels or cumulative exposure within these recommendations. This proved particularly challenging for heritage buildings where limited or no electric lighting means daylight is relied upon as the main source of illumination for visitors and staff. In the UK, the National Trust has drawn upon traditional household management practice to generate room by room strategies for utilising daylight during opening hours. The core principles are to exclude daylight when not required, to avoid direct sunlight where light responsive materials are present, and to manage light exposure according to annual light budgets reflecting accepted museum practice (National Trust 2011). This requires knowledge of the daylight present throughout the year, acquired through monitoring, and also risk management analysis of each interior and its contents.

To support and check light management performance, dosimeters employing UK standard Blue Wool No. 1 and occasionally lux data loggers, are placed where light exposure is considered typical in a room according to light plans based on assessing light levels on all walls at different blind positions at different times of the day and year. Particularly important and/or vulnerable objects are also assessed. Monitoring is deployed in light sensitive interiors by trained staff under the guidance of professional conservators, balancing risk and typicality (of exposure) with the visibility of dosimeters which may detract from visitor experience, to give a broad sense of the distribution of light exposure within an interior at annual intervals.

Light levels can vary substantially across short distances and in the case of daylight within brief time periods – for example as clouds pass in front the sun. Such great variability makes determining the distribution of daylight in interiors extremely challenging. This has become increasingly obvious since the introduction of Climate Based Daylight Modelling (CBDM) which can predict cumulative exposure levels across room surfaces in simulated buildings. A recent study carried out by Historic Royal Palaces in the Great Hall of Hampton Court represents one of the most detailed evaluations of daylight across large surfaces using illuminance data loggers, but has also demonstrated the scale of resources required to directly monitor light in detail over large areas[1]. Cognisant of this and using experience gained during an earlier study of the daylighting in a staircase at Mount Stewart, Northern Ireland (Blades et al 2016), a novel camera based monitoring technique was developed to analyse the fall of daylight at Ickworth House, Suffolk.

The aims of this research were to:

- Model actual daylight performance in side lit interiors typical of National Trust properties.
- Evaluate daylight simulation by measurements of actual daylight illumination in real interiors
- Provide guidance to refine daylight management in historic interiors containing light responsive collections and decoration in response to increasing opening hours.

Methodology

The introduction of high dynamic range (HDR) imaging has enabled the use of cameras to measure brightness (luminance in cd/m^2) across a wide field of view. A suitably calibrated camera and lens can generate false-colour images showing patterns of absolute levels of luminance (which corresponds to perceived brightness). Whilst measures of luminance help lighting design, false-colour images do not directly relate to illuminance (i.e. the light falling *onto* surfaces), whose cumulative measurement determines light exposure. However, for surfaces which are predominantly Lambertian (i.e. diffuse reflectors of light), illuminance (E_r) can be derived from luminance (L_r) using the equation $E_r = \pi L_r / \rho_r$, where ρ_r is the reflectance of the surface. HDR has the, as yet, under exploited potential to enable measurement of illuminance levels across large surface areas.

A multi stranded approach was adopted to determine the viability of this technique as well as the accuracy of simulations. Previous validation of the leading daylight simulation tool 'Radiance' had been carried out for an empty and simple room. This project analysed real interiors with contents and decoration requiring conservation in order to inform the Trust's approach to light management. The Smoking Room at Ickworth (Figure 1) was selected to simplify monitoring and simulation, since there are few external obstructions influencing how daylight reaches the three windows. The room is rectangular with a slightly curved window wall; it is sparsely furnished with important historic paintings, a modern carpet and wallpaper; and its windows are equipped with shutter and blinds that are typical of National Trust house interiors.

In the initial phase of the research project, reported here, the following steps were undertaken:

- Surveying room geometry and dimensions
- Constructing a three dimensional computer model of the room
- Monitoring light levels using digital data loggers
- Installing a camera employing HDR to capture luminance values
- Simulating the room and generating daylight dosage values
- Logging the use and control of light

The first phase of monitoring tests was undertaken in 2014 and the second in 2015: the third is still underway in 2016 and will be reported on at the conference.

The survey of the room influenced both monitoring and simulation. 'Representational' accuracy is critical in simulating lighting performance (Cannon-Brookes, 1997). The elements most influential for the daylighting of the room were given the greatest attention: the precise dimensions of the windows and reveals; glazing transmission; reflectance values of finishes; and the transmission properties of blinds to be used in later assessment. Reflectance was measured with two techniques. The first was the CIBSE reflectance guide

(LG11) colour cards. These allow comparison of surfaces to colour swatches of known reflectance and an estimate of diffuser reflectance with an error margin in the order of +/- 2%. The second was paired measurements of luminance and illuminance using calibrated meters with similar error margins. Special attention was given to glazing area, as dimensional inaccuracy of +/- 2mm in a small pane of a sash window can cause an error of 1-2%.

A three dimensional representation of the room was made using 'Sketch Up' (Figure 2). Different finishes were represented separately using layers, with particular care taken to represent sash windows correctly. These had a variety of details, ranging from different joinery mouldings to overpaint on the glass, all of which were reproduced. Furniture and paintings were represented by generic shapes to which measured reflectance values were applied. Blinds and shutters were modelled on separate layers to allow later manipulation during evaluation.

The number of lux data loggers deployed was constrained by budget and presentation requirements. Four loggers were placed in the Smoking Room. Lux data were logged at 15 minute intervals using Ickworth's radiotelemetric monitoring system. The four Smoking Room locations were: on top of the door cases; on the walls flanking the window wall; and on the wall facing the windows, one centrally and the other on top of a commode.

 HDR images were captured by a digital SLR camera (Canon 550D with 10-18mm Canon lens) positioned on a tripod in one corner for the room and tethered to a Mac Mini. The camera could see the walls facing north east and south east (the latter opposite the window wall), and was levelled to avoid the need for perspectival correction. After it was found that the tripod was frequently disturbed, requiring reregistration of the images to permit comparison, the camera was moved in the second season of monitoring to a bespoke bracket mounted on a window surround. Every ten minutes a sequence of 9 exposures was taken at 2 f-stop intervals. These were compiled to form a single HDR image of the scene's luminance 'visible' to the camera. Images with no light present were deleted to economise on data storage. Due to the wide angle employed to capture two walls of the room a vignetting correction was applied, the frame extremities having been found to suffer a reduction of approx. 50% in light capture.

During the initial phase, the luminance images were calibrated by reference to pieces of plain card of known (diffuse) reflectance hung from picture chains. Selected pixel points on these cards were converted to illuminance using the reflectance equation above. Sufficient points were converted to permit interpolation and comparison with near simultaneously collected light levels recorded by the data loggers. Before final calibration of the HDR process the pairs of values were within 20%. The contribution of new picture lighting installed between the first and second phases was taken account of by deleting data based on images taken without daylight illumination. The card reference points were replaced by areas of the patterned wallpaper. In order to determine the smallest usable 'patch' of wallpaper which could be guaranteed to have the same average reflectance as a large, representative sample of the wallpaper, a sample of the wallpaper was used for photometric characterisation by

measuring precisely the patterns of reflectance for the two principal shades and the various intermediate tones. Patches of wallpaper with similar average pixel values were identified in the HDR image, using the patch centre as a reference point to derive the illuminance field from luminance by interpolation. As these patches were more numerous and widely scattered across the wall visible in the reference image they were more effective than the cards in converting wall surfaces in the HDR images to illuminance 'surfaces'(Figure 3). The technique is also less visually intrusive than hanging standard reflectance cards off the picture chains. The reproduction of small-scale illumination effects, such as shading due to the chimney breast, was unnecessary as the research was focussed on the distribution of daylight incident on the room. Thus the derived illumination field across the two walls is presented as two planar surfaces (Figure 4).

It was found early on that the opening and closing of shutters and blinds did not coincide with opening hours, affecting interpretation of monitored light levels as well as parameters for (realistic) simulation. Therefore use of the room was manually logged during the second and third phases, including switching of lights and manipulation of blinds and shutters (Table 1).

Findings from data collection and simulation

As expected, the simulation provided the easiest means of generating results. Using climate files for Norwich, the model was imported into customised 'Radiance'-based software and annual dosage predictions made for various lighting scenarios over a year, based latterly on current increased opening hours, including: no light control; the use of shutters to exclude daylight out of hours; and the use of shutters and blinds to exclude direct sunlight. This was useful immediately in demonstrating the magnitude of the effect of different window treatments in a south facing room. For example, assuming opening from 11.00 to 17.00 throughout the year without daylight control, the average annual cumulative exposure of the painting over the fireplace was predicted as 2,500 klxhrs, compared to a recommended 600 klxhrs for moderately light sensitive materials (Figure 5). The simulation for 2015 opening hours (11.00 to 17.00) and the current use of blinds led to a dosage calculation of 141 klxhrs (Figure 6). From the images as well as the numerical predictions it was clear that low angle sunlight in early morning in south facing rooms can have a major effect if not excluded. Consequently, House staff were advised to raise blinds in south facing rooms last in their opening sequence. Comparing the output of three of the data loggers with the simulation of current opening conditions showed the simulation slightly over estimated the measured exposure (Table 2). This disparity seems largely accounted for by slightly shorter actual opening hours, revealed in the manual logs, and may also be due to simplifications in the model leading to overestimation.

As standardised climate files contain patterns of averaged measurements (e.g. direct normal illuminance) compiled from several years of monitored data that will never repeat in precisely the same way, it is pointless to compare measurements taken in a short period of real time with illuminance values (derived from standardised climate data using CBDM) predicted for a corresponding period. Even over a full calendar year, prevailing patterns of

measured conditions could differ from those in the standardised climate file due to inter-annual variability [2]. Although the effects of unique patterns in the data become much less significant when a full year is considered, the manual control of daylight in a side-lit building through shutters and blinds adds a further variable to the comparison of lux values based on standardised climate data with measured lux values.

In the first two phases there was frequent divergence between the manual logs, measured light levels and HDR images. The data loggers were recalibrated to increase sensitivity and the frequency of measurements (from 15 to every 5 minutes), and the manual logs were refined. Processing this level of detail was onerous, but enabled time spent on cleaning and other operational activities to be identified in addition to the actual number of hours of lighting use for visitor access.

The calibration system for the wallpaper enables direct comparison between the data from the loggers and the HDR captures (Table 3). Bulk processing for the HDR images and conversion to illuminance will provide a substantial set of simulated data to compare with data measured by the data loggers and will be presented at the conference. Nevertheless, the simulated data has already demonstrated the importance of controlling out of hours daylight and direct sunlight, particularly in the summer months. In the winter light exposure rarely exceeds 'safe' limits and indeed requires supplementary lighting to enable visitors to see the room comfortably, based on a minimum illuminance of 50 lux (Table 4).

Lessons learned

Understanding the location of data loggers and how the room is being used is essential to the interpretation of variable light levels identified by measurements over short (5 minute) intervals. Simple comparison of the data loggers confirmed expectations that the wall facing the windows would receive more daylight than the side walls. This relationship remained relatively stable largely due to the deployment of blinds. Simulation output show far greater variation when blinds are not used.

The recording characteristics of data loggers also need to be fully understood before deployment, although actual use may be the only means of revealing inconsistencies, such as some loggers recording illuminance when others did not. A regression analysis of a comparative test of the four loggers found reasonable consistency with R^2 scores averaging 0.92 between pairs of loggers. However, for levels below 50 lux the R^2 reduced to an average of 0.74. Discussion with the manufacturers revealed that the sensors were set up to discard any readings below 10 lux. The loggers were recalibrated by the manufacturer to measure accurately at the lower lux range and to record values below 10 lux.

Comparison with HDR images found that the loggers often missed brief lighting events recorded in the manual logs, for instance when staff switched on lights or opened shutters to clean for only a few minutes, so the logging interval was reduced to five minutes in the third phase of monitoring. In addition, trial presentation of the house at night time has meant that

lighting has been left switched on whilst shutters are closed. Reconciling such detailed events with measured and simulated data is onerous, but essential in enabling the removal of electric light from the digitised data so that only daylight performance is simulated.

HDR was complicated by the absence of WiFi in the Smoking Room, requiring a standalone system; nor had the viability been established of long term remote operation of a digital SLR from a computer. Thus interruptions in recording in the first and second phases, caused by power failures and camera failure, and probably software, have been addressed in the third phase by programming a daily hard reboot into the system and mounting on a fixed bracket to prevent accidental movement.

Translation of the luminance data generated by HDR imaging into illuminance is still under development, one area of challenge being the reflection characteristics of saturated colours. The technique suits large surface areas with a consistent finish and the scale of simplification reported here is analogous to that undertaken in simulation models. Given this, it is encouraging to see that a degree of convergence between the two in the images generated of illuminance distribution. In practice, every HDR capture needed to be reviewed to eliminate the occasions when people masked sections of the walls, which upset the inference of illuminance from the preselected reference 'patches'. Parallel data from the loggers had to be removed to enable comparison between measured and simulated data: this may be automated in the future, but does reduce the data available for comparison.

For the latest phase, a sunshine sensor was mounted near the house to replace averaged sky data from Norwich Airport. This measures global and diffuse radiation, and can be directly correlated with internal measurements of illuminance, and enhance validation of its simulation.

Conclusions

This research project has enabled current data logging of light to be better understood in conjunction with simulations based on CBDM and a novel system of illuminance measurement employing HDR cameras. Field conditions raise constant challenges yet ground the approach in practical reality. A multi-strand approach combining measurements of internal and external illumination with simulation has improved our understanding of the implications of room orientation and the actual daylight performance of historic interiors, which enables day to day management of light sensitive collections through the operation of shutters (for blackout) and blinds (for solar and daylight control) to be refined according to the risk of illumination at different orientation and different times of year. This is producing simple guidance which will be disseminated in future publications.

Word count: title, keywords, abstract (excluding author details) 3,056

Notes

1   Reported at the ICON 2016 conference by Vlachou-Mogire, C., Gibb, I. and Frame, K. and due to be published.

2   The same is of course true for the much more established practice of dynamic thermal modelling.

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Captions:

Figure 1. The Smoking Room at Ickworth, near Bury St Edmunds 2014

Figure 2. 3D model of the Smoking Room built in Sketch Up

Figure 3. The distribution of reference patches on the wallpaper selected to permit interpolation of illuminance values derived from luminance values generated by HDR

Figure 4. Illuminance values across the wall surfaces generated from a single HDR image, represented using false colours

Figure 5. Simulation of annual dosage with the blinds and shutters fully open between 11.00 and 17.00 throughout the year

Figure 6. Simulation of annual dosage with the blinds and shutters as currently operated during 2105 opening hours

Table 1. Example of the activity log used to record lighting and room use

Table 2. Comparison of measured and simulated annual dosages for three reference points

Table 3. Comparison of illuminance levels measured by data loggers and derived from HDR images at three reference points

Table 4. . Simulated annual daylight exposure of a chairback (figure 1) facing the Smoking Room windows, at four room orientations with different light control regimes

Word count: 390

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Author details

Stephen Cannon-Brookes (PhD, FSLL) is a Part-time lecturer at UCL in the Institute of Environmental Design and Engineering, where he his principal work is in daylighting buildings, lighting for presentation of cultural heritage and lighting for health and wellbeing. He has taught for seven years on the Exhibition Design MSc at the Technical University in Graz, Austria and given workshop courses on museum lighting mostly recently in St Petersburg, Russia. He is principal of CBL, a specialist lighting consultancy, whose work is focused on lighting for museums and historic buildings as well as privately owned collections. He has been President of the International Council of Museums' Architecture

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John Mardaljevic (PhD, FSLL) is Professor of Building Daylight Modelling at the School of Civil & Building Engineering, Loughborough University. Mardaljevic pioneered what is now known as Climate-Based Daylight Modelling. Mardaljevic's practice-based research and consultancy includes major projects such as the New York Times Building and The Hermitage (St. Petersburg). He currently serves as the 'UK Principal Expert on Daylight' for the European Committee for Standardisation CEN / TC 169 WG11 and is CIE-UK Representative for Division 3 (Interior Environment). In 2012 Mardaljevic was presented the annual UK lighting award by the Society for Light and Lighting (SLL).

Katy Lithgow is Head Conservator at the National Trust, responsible for professional standards in collections conservation and leading the Trust's conservator community. She has an MA in Archaeology, Anthropology and History of Art from Cambridge, and the Postgraduate Diploma in Wall Paintings Conservation from the Courtauld Institute of Art, London, where she taught following an internship at the Victoria and Albert Museum, London. She joined the National Trust in 1991 as a preventive conservator, specializing in storage and protecting collections during building works. In 1995 she became the Trust's Wall Painting Conservation Adviser and in 2002 Conservation Advisers Manager, before being appointed Head Conservator in 2005. She has published and lectured on wall painting conservation, preventive conservation, conservation management, interpretation in conservation, heritage science and sustainability. Katy is an Accredited Conservator-Restorer (ACR), a Fellow of the International Institute of Conservation (FIIC), Chair of the PACR scheme's Accreditation Committee, and a Trustee of the National Heritage Science Forum.

Nigel Blades is Preventive Conservation Adviser (Environment) for the National Trust. His main role is to advise on environmental control solutions and preventive conservation for the care of collections; and oversee environmental data collection and interpretation for the Trust's historic properties. Dr Blades provides training and technical support in preventive conservation for house staff through property advisory visits and training courses and is closely involved with the Trust's conservation science research. Before joining the National Trust in 2008 Dr Blades was Lecturer at the UCL Centre for Sustainable Heritage, where he was joint course director for the MSc Sustainable Heritage and undertook research into preventive conservation.

Figures

Figure 1. The Smoking Room at Ickworth, near Bury St Edmunds 2014
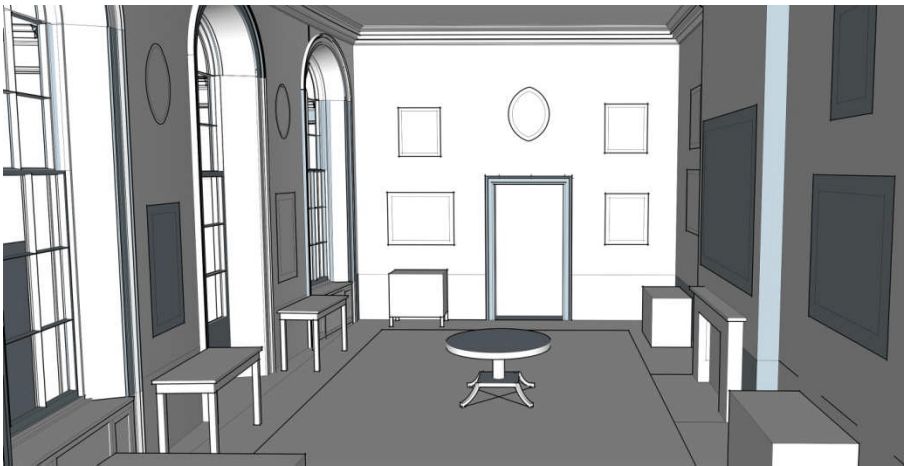

Figure 2. 3D model of the Smoking Room built in Sketch Up

Figure 3. The distribution of reference patches on the wallpaper selected to permit interpolation of illuminance values derived from luminance values generated by HDR
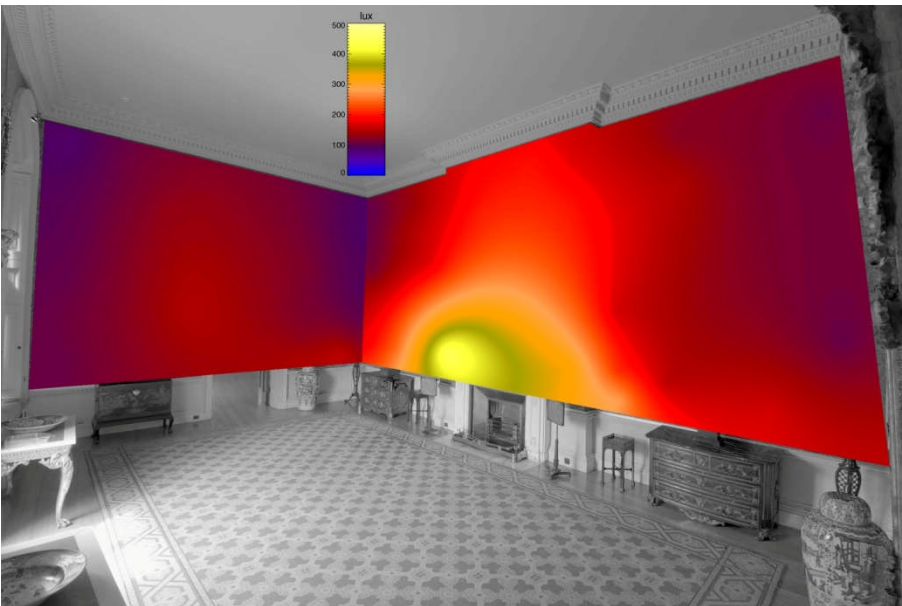

Figure 4. Illuminance values across the wall surfaces generated from a single HDR image, represented using false colours.
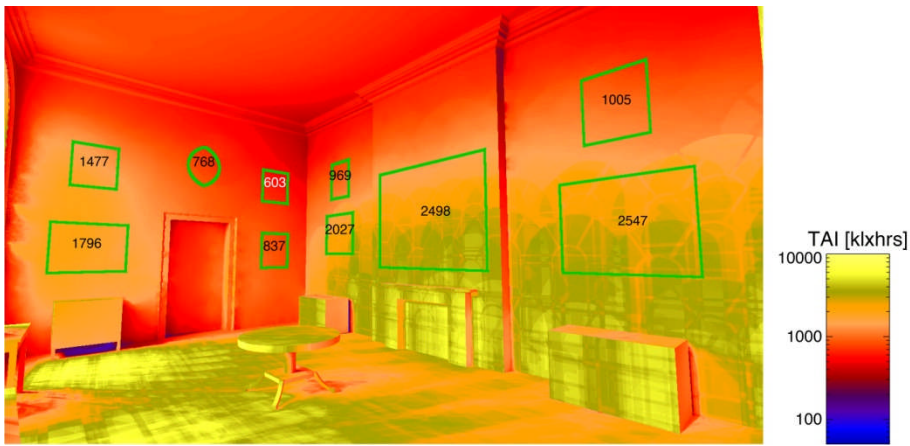
Figure 5. Simulation of annual dosage with the blinds and shutters fully open between 11.00 and 17.00 throughout the year

Figure 6. Simulation of annual dosage with the blinds and shutters as currently operated during 2105 opening hours

Tables.

Room: ***Smoking Room***
Month: ***May***

ICKWORTH Room Activity Log

(please add a tick or '1' in the appropriate column)

Date	Day	Start	Close	Shutters Open	Lights On	House Open	(function) Cleaning	Special	(please record any events or activities not part of normal room use)
01 May	Sun	09.26	09.28		½				Removing shutter bars
		11.02	11.05		1		1		
		11.47	17.27	1	1	1			
02 May	Mon	09.22	09.23	1	½	1			Removing shutter bars
		09.45	09.55	1	½		1		Hoovering
		10.35	10.37		½		1		S..king (?)
		11.46	11.55	1	1	1			
03 May	Tue	09.22	09.23		½		1		Unlocking
		11.00	11.04	1	½		1		Dusting
		11.50	17.20	1	1				
05 May	Thu	09.45	10.00	1	½		1		
		10.47	10.50		½		1		Dusting
		11.49	15.45	1	1	1			

Table 1. Example of the activity log used to record lighting and room use

	Logger location		
	On western door surround	On commode west of fireplace	Mantelpiece on southeast facing wall
Measured exposure 2015 (normalised from Jul-Dec)	55klxhrs	118klxhrs	178klxhrs
Simulated exposure, published 2015 opening hours (11.00-17.00)	~70klxhrs	~150klxhrs	~220klxhrs

Table 2. Comparison of measured and simulated annual dosages for three reference points

	Logger location		
	On western door surround	On commode west of fireplace	Mantelpiece on southeast facing wall
Illuminance level logged at 12.00 on 15/05/16	152lx	301lx	383lx
Illuminance calculated from an HDR capture at 12.00 15/05/16	150+/-10lx	310+/- 10lx	360+/- 15lx

Table 3. Comparison of illuminance levels measured by data loggers and derived from HDR images at three reference points

	North facing	East facing	South facing	West facing
No blinds or shutters – daylight admitted at all times of day	3,563 klxhrs	9,014 klxhrs	9,823 klxhrs	7,727 klxhrs
Daylight admitted during open times only (shutters open 11.00-17.00, otherwise closed)	1,767 klxhrs	2,088 klxhrs	8,861 klxhrs	2,970 klxhrs
Shutters open 11.00-17.00 and direct sun excluded	1,755 klxhrs	2,053 klxhrs	5,062 klxhrs	2,377 klxhr

Table 4. Simulated annual daylight exposure of a chairback (figure 1) facing the Smoking Room windows, at four room orientations with different light control regimes.