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How is museum lighting selected? An insight into current practice in UK museums

Daniel Garside, Katherine Curran, Capucine Korenberg, Lindsay MacDonald, Kees Teunissen & Stuart Robson

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Keywords
museum lighting; lighting specification; colour rendering; colour temperature; light-emitting diode (LED); energy reduction

1. Introduction

Museum lighting must satisfy a broad range of criteria but, most critically, needs to make museum objects visible (with an appearance matching specific constraints), whilst preserving them as much as possible. Considering that light is a well-known cause of damage to museum objects, and that museum lighting can drastically contribute or detract from a visitor's experience, lighting is a very important aspect of museum management. Further to these requirements, museum professionals who are responsible for the selection of lighting must also consider a range of other factors, such as cost (including maintenance), aesthetics, energy efficiency, longevity, colour temperature, flicker, etc.

The way in which museum professionals select lighting is not well documented, though the work of Perrin et al.[1] provides a valuable insight. It is presumed that in the absence of a shared best practice a great variability exists in the selection process from institution to institution, even though there are numerous publications which offer guidance on museum lighting specification.[2]

The results of several semi-structured interviews with museum professionals, principally from within conservation science and research departments from different heritage organisations in the UK, are reported here. The aim of this research was to investigate:

1. The way in which decisions about museum lighting are made;
2. The importance placed on industry parameters such as correlated colour temperature (CCT—which can be thought of as the 'blue-ness' or 'yellow-ness' of a light source), the general colour-rendering index (CIE-R_a, which describes the ability of a light source to produce colours similarly to how they would appear under a reference light source of the same CCT),[3] and efficacy of light sources, in decision-making;
3. The level of ubiquity, and rationale for such, of LED light sources.

A set of seven questions (provided in the appendix) concerning these topics was created by the authors to guide the interviews. It is hoped that this work, whilst providing a record of current practice, will also act as a resource for those looking to develop future technological and procedural tools for museum environments, and will assist by giving an insight into the working environment in which lighting decisions are made.

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1 Tess Perrin, Jim Druzik and Naomi Miller, *SSL Adoption by Museums: Survey Results, Analysis, and Recommendations* (Richland, Washington: US Department of Energy, 2014) https://energy.gov/sites/prod/files/2015/02/f19/gateway_museums-report_0.pdf.

2 See, for example: *Lighting Guide 8: Lighting for Museums and Art Galleries* (London: Society of Light and Lighting, CIBSE, 2015); Garry Thomson, *The Museum Environment*, 2nd ed. (London: Butterworth-Heinemann, 1986); *CIE 157:2004 Control of Damage to Museum Objects by Optical Radiation* (Vienna: Commission Internationale de l'Eclairage, 2004), 157; *IES RP-30-96 Museum and Art Gallery Lighting: A Recommended Practice* (New York: Illuminating Engineering Society of North America, 1996); James Druzik and Stefan Michalski, *Guidelines for Selecting Solid-State Lighting for Museums* (Los Angeles: Canadian Conservation Institute/Getty Conservation Institute, 2012) http://www.connectingtocollections.org/wp-content/uploads/2011/08/SSL-Guidelines-Ver.-10.0.pdf (accessed 9 November 2016).

3 *CIE 13.3:1995 Method of Measuring and Specifying Colour Rendering Properties of Light Sources* (Vienna: Commission Internationale de l'Eclairage, 1995).

2. Method

2.1. Interviewees

Interviews were conducted during spring 2016 with 12 museum professionals representing 10 UK-based museums, galleries or historic property management groups. A small number of these professionals represented UK-wide groups, but the majority represented large London-based institutions. There was an unavoidable, though relatively minor, variability in the range of job roles, as the institutions are structured distinctly, resulting in different and thus not entirely comparable job titles such as principal scientist, conservation scientist and preventive conservator. Even where job titles are mirrored, the specific role might have different responsibilities and scope, depending on the size of the institution. The interviewees were recruited through introductions from project partners, personal connections of authors, or cold-call emails.

One caveat is that the nature of those participants involved has proved to be a limitation that has led to the exclusion of certain relevant perspectives from being included in the work. Thus, future work that considers the perspective of others involved in museum lighting, such as exhibition teams or representatives from external lighting design companies, is recommended. It should also be noted that the conclusions here principally apply to larger national museums, and might not be entirely applicable to smaller regional or local museums.

2.2. Interview procedure

The interviews were semi-structured around a set of questions composed by the authors. The choice to conduct these interviews in a more informal format rather than a fully-structured one was based on the desire to allow unanticipated topics to enter into the conversation in order to limit the potential for important subjects to be neglected due to any naivety in preplanning. This conversational format meant that the resulting data was qualitative rather than quantitative, which to an extent hinders meaningful comparisons, but the variety of job roles, institutional sizes, and the small sample size, already made quantitative comparison of limited use. It should be noted that interviewees were not aware of any recent surveys similar to the present one.

3. Lighting specification

3.1. Roles and responsibilities

All interviewees noted that their principal responsibility with regards to lighting was in controlling the impact of lighting on material damage. This generally involved the monitoring and analysis of existing lighting systems and natural illumination, creating general guidance documents for the specification of lighting in their specific institutions and for loan items, and providing guidance and recommendations for the fitting out of new galleries or gallery refits. Few saw themselves directly responsible for the appearance of museum objects, considering this to be a creative decision outside of their remit.

All interviewees had multiple responsibilities other than input into the lighting specification process, although several were particularly interested in the subject and devoted time and resources to performing empirical research. Many considered communication and dissemination a key part of their role, noting that they often found themselves in the position of needing to educate other teams within their institution on subjects including lighting. One respondent commented 'This is not my science, my job is pulling it out and presenting it to others'.

Furthermore, the range of roles played in the procurement of lighting varied amongst those interviewed. Whilst some created guidance documents which would then be passed on to estates teams and exhibition designers or lighting designers specifically, others had a much more hands-on role, testing specific lighting before installation or making recommendations on a case-by-case basis.

3.2. General considerations

Asked what each considered to be 'good lighting', responses were split between 'safe', 'invisible' (it is not noticed), and 'lighting which is appropriate for your objects and your exhibition' (noting the variability of requirements dependent on the particular object[s] being presented). Asked to present a list or range of priorities, many focused on prioritising the safety requirements of lighting. The principal safety concern for lighting was that it fell below specific illuminance criteria, dependent on the assumed sensitivity category of the object in question. The specific target values were generally those provided by Thomson of 50 lux for sensitive items and 200 lux for less sensitive items,[4] which are based not on conservation orientated work, but on the visual preference work of Loe et al.[5]

4 Thomson, *The Museum Environment*.

5 D.L. Loe, E. Rowlands and N.F. Watson, 'Preferred Lighting Conditions for the Display of Oil and Watercolour Paintings,' *Lighting Research and Technology* 14, no. 4 (1982): 173–92.

On a scale of other priorities, following the requirement for appropriate lux levels, considerations included: limiting or excluding ultraviolet (UV) radiation, generally defined by those interviewed as radiation below 400 nm, obtaining an acceptable general colour-rendering index (CIE-R_a) value, and time and capital costs associated with fitting and maintenance. Luminous efficacy was also a driver; it was noted that many institutions are switching to LED due to its higher efficacy compared to other lighting technologies. However, the difference in efficacy between one LED type and another was considered to be marginal compared to the differences between LEDs and other lighting technologies. Therefore, this factor was not generally considered at the final stage of selection, rather only at preliminary stages.

It was noted that whilst re-lamping and retrofitting was generally handled by 'in house' teams, where new galleries or large temporary exhibitions were created it was common for an external lighting design company to be contracted to perform the work. This process was less common in smaller institutions, where generally it would not be so practical.

When asked whether recommendations were normally followed, the broad response by the interviewees was that recommendations for lux exposure and UV content were almost always followed, but other recommendations (such as for CIE-R_a or CCT) were more loosely interpreted. In a small number of cases recommendations for CCT were not made. It is understood that this distinction is due to lux exposure and UV content having clearly demonstrable damage related impacts, whereas the effect of CIE-R_a or CCT was less clear to those involved. In one case, lamping for an entire gallery was replaced after installation (at great expense), following an original choice to use a cheaper lamp with a lower CIE-R_a value which had resulted in unacceptable lighting quality.

The interviewees generally did not consider spatial characteristics of lighting such as the angle or spread of illumination, broadly responding that this would be the remit of a lighting designer or exhibition designer rather than a conservator.

3.3. Tools used to guide lighting specification

When asked about the tools used to make such recommendations and choices, responses included references to guidelines and reference sources, most often those by Jim Druzik and Stefan Michalski,[6] along with Gary Thomson's work.[7] References to specific units such as 'lux' were used in tandem with indices such as CIE-R_a (referred to more colloquially as 'CRI'). There was a general feeling that the current climate is one of swift technological change in lighting, which has created an increased difficulty in keeping up with developments. It was noted that conferences and industry workshops were very beneficial in assisting professionals to stay up to date.

One respondent commented:

> Things are moving so quickly that to rely on books which have taken two years to produce [does not suffice, because] things have moved on. Books (plus journals) used to be the main reference. Now things are moving at such a rapid pace.

6 Druzik and Michalski, 'Guidelines for Selecting Solid-State Lighting for Museums.'

7 Thomson, *The Museum Environment.*

4. Lighting safety

A range of techniques were used to qualify whether specific lighting was 'safe' or not. The most common practical technique was the spot metering of lux values incident on specific objects, and selective dimming to drop incident lighting to the desired lux level in response to this. Some larger institutions with access to microfading equipment were able to use this in the determination of sensitivity of specific objects. One interviewee provided details of a spectral power distribution (SPD) based method for considering the safety specifically of phosphor based LED illumination, whereby the height of the blue peak was compared to the height of the broader peak above 500 nm, and if the former was more than three times the height of the latter ('rule of thirds') such lighting was singled out as potentially unsafe. Other interviewees had heard of this criterion, and some used it as a rough guide, but one noted that in practicality the wavelength of the blue peak generally gave a better indication of the potential of the lamp to cause damage. Another interviewee referred to Joseph Padfield's work on a 'RE%' protocol ('relative spectral sensitivity normalised exposure values'),[8] using the damage functions described in Aydinli et al.,[9] and later in CIE 157:2004[10]

8 Joseph Padfield, 'Relative Spectral Sensitivity,' http://research.ng-london.org.uk/scientific/spd/?page=info#Relative_Spectral_Sensitivity (accessed 19 May 2016).

9 Sirri Aydinli et al., 'On the Deterioration of Exhibited Museum Objects by Optical Radiation,' *CIE Technical Collection* (Bern: Commission Internationale de l'Eclairage 1990).

10 C*IE 157:2004 Control of Damage to Museum Objects by Optical Radiation* (Bern: Commission Internationale de l'Eclairage 2004 http://www.cie.co.at/index.php?i_ca_id=433).

5. Visual testing vs quantitative descriptors

One of the most interesting and perhaps surprising findings was the ubiquity of visual testing of lighting, mentioned by all and employed by most, and generally performed prior to any large new installation. In contrast, for re-lamping existing display spaces manufacturer-supplied attribute values (CIE-R_a and CCT), were generally relied upon as this required less time and effort and was cheaper than visual testing.

A common approach for selecting lighting for new spaces, or where a space was being comprehensively re-lit, is to use objective parameters (principally CIE-R_a) to set a bar for the minimum requirements for lighting, and then to conduct an additional informal visual test before a final decision was made. For example, a single bulb of a handful of different types might be purchased, and the appearance of a test object compared under each lamp in turn. In a single case, visual testing was actively avoided on the basis that visual testing could not deliver meaningful insights where the aim was high colour fidelity rendering as opposed to visually pleasing rendering. In another case, extensive visual testing was performed using many different types/brands of lamp, a whole real gallery, and a large number of museum staff, with a final decision resulting almost entirely from the results of such testing.

6. Objective industry parameters

6.1. Colour rendering

The interviewees were very interested in the subject of accurate representation, and almost all seemed to regard accurate object representation as a key priority. This is to be expected considering that authenticity in museums is a subject that is key to the very concept of a museum, and has been the focus of a great deal of time, attention and energy for many decades.[11]

The figures for CIE-R_a quoted in internal documents at each institution were either 80, 85 or 90 as a minimum figure (the maximum possible value of CIE-R_a is 100), with Thomson generally referenced as the inspiration for the practice of setting such a minimum figure.[12] In one institution, an R_w value, where '$_w$' denotes 'worst', was calculated for each proposed light source and a lower cut-off of 80 imposed.[13] However, most interviewees seemed unsure of the practical relevance of CIE-R_a, with many considering it a rough guideline which would be considered secondarily to a visual inspection of lighting.

Those who were particularly interested in colour rendering were able to discuss its nuances in depth. However, whilst the subject was considered philosophically in great detail by some interviewees, the metric which was actually used to analyse the colour rendering of a light source remained the relatively blunt tool of CIE-R_a. A few interviewees were aware of the Illuminating Engineering Society of North America's (IES) Color Metric Task Groups work on a new method for evaluating light source color rendition, and whilst it was respected, it was questioned whether it represented a meaningful improvement over CIE-R_a.[14]

On the subject of lighting philosophy, there was strong support for use of an index with the conceptual priority of colour fidelity such as CIE-R_a. That is to say; given a choice between illuminating an object such that it was rendered aesthetically pleasing, visually restored to a previous condition (such as was explored by Viénot et al.[15]) or simply presented as it would appear under daylight/tungsten illumination, as is the comparison implicit in the calculation of CIE-R_a, most opted for the latter. Whilst there was clear interest in the other options, and other creative ways in which to consider colour rendering, it was generally believed that the role of the museum should be to represent objects in an unbiased manner, and thus a colour fidelity index was considered an appropriate tool for discussing a light source's colour rendering properties. In the case where lighting was used to create special effects, the opinion was noted that 'you have to be very clear about what you are doing and why' in order to maintain the reputation of the museum as an arena for honest and unbiased representation.

6.2. Correlated colour temperature

All interviewees had at least a basic understanding of colour temperature if a limited understanding of chromatic adaptation. Colour temperature was generally not seen as a conservation issue (though there were exceptions to this), but rather as a creative consideration. One interviewee noted that it was manipulated to great effect by external lighting designers in order to create specific effects or atmosphere.

The justification for CCT specification values generally appears to stem from two sources. Firstly, from guidance documents such as Druzik and Michalski's, and secondly from a desire to match existing lighting. As such, specifications tended to opt for a 3000 K CCT, though in a number of cases no specification for CCT was set.

CCT was rarely considered as a means to control damage, as considered in CIE 157:2004, nor as a way to enhance visual appearance such as in the

11 For example see Herb Stovel, 'Origins and Influence of the Nara Document on Authenticity,' *Association for Preservation Technology (APT) Bulletin* 39, no. 2/3 (2008): 9–17 http://is.muni.cz/el/1423/podzim2013/SOC310/crd/jar/aut/Stovel-Nara-Document-on-Authenticity-APT-2008.pdf (accessed November 9 2016).

12 Thomson, *The Museum Environment.*

13 R_w is the special colour-rendering index (R_i) value of the test-colour sample with the colour shift of greatest magnitude.

14 *IES Method for Evaluating Light Source Color Rendition – TM-30,* Color Metric Task Group of the Illuminating Engineering Society of North America (IES), 2015 https://www.ies.org/store/product/ies-method-for-evaluating-light-source-color-rendition-3368.cfm.

15 Françoise Viénot, Guillaume Coron and Bertrand Lavédrine. 'LEDs as a Tool to Enhance Faded Colours of Museums Artefacts', *Journal of Cultural Heritage* 12, no. 4 (2011): 431–40.

work of Nascimento and Masuda.[16] One interviewee referred to the seminal work of Kruithof which suggested that there was an area of the space representing lux vs CCT which was 'comfortable' and another which was not.[17] This work, along with Scuello et al. was given as justification for choosing low CCT illumination values similar to tungsten.[18] No specific issues relating to color temperature were raised by interviewees.

7. Visitor requirements

Generally, the interviewees believed that visitor requirements were mostly being met, although there is often difficulty in defining exactly what such requirements actually are. Previous research on the subject has suggested that the most important visitor needs are 'clarity of object form and accuracy of object color'.[19] There was broad agreement that the most common complaint from visitors related to spaces which appeared too dark to enjoy or utilise functionally, and that these complaints came disproportionately from older visitors.

Unsurprisingly, considering the conservation-based job roles of the interviewees, the option of remedy through increase of light levels was seen as unacceptable in most cases. The field of scientific study concerned with brightness perception is complex and ongoing, and it has been posited that brightness might be better predicted by a function other than the luminosity function which is used for the derivation of lux values.[20] One possibility would be the tuning of a spectral output more closely to known peak human sensitivities, such as in Thornton's use of prime colour lamps.[21] From a museum perspective, this offers the possibility that objects and spaces might be made to appear brighter without increasing the level of induced damage.

Whilst all interviewees were interested in this possibility, the point was made that whilst spectral tuning might benefit a prototypical object, it will not necessarily benefit real objects in real environments nor, importantly, *groups* of real objects. It was also noted that issues could arise where an SPD was optimised for brightness, but its damage potential was considered using a luminosity function based measure such as lux, as varying the location of a blue peak could easily increase the damage potential but negligibly effect the lux value.

8. LED lighting

8.1. Extent of LED use

LEDs are used, to some extent, in all the institutions involved in this survey. In several they are the primary lighting technology while in a small number they are used sparingly, such as, for example, only in the lighting of text information panels. There was no one specific brand or type ubiquitously used across institutions, rather each institution appeared to have relationships with different manufacturers and suppliers.

The key driver behind the adoption of LEDs appears to be luminous efficacy increases and the resultant energy use reductions, as required by institution-wide directives, or as part of applications for planning permission. Secondary to this consideration, benefits noted included decreased maintenance costs from an LED's extended lifetime and their common availability especially when set against a lack of availability of traditional bulbs, often due to specific legislation which has in effect phased out some older technologies.[22] The question of whether or not LED lighting was a suitable replacement for older technologies in terms of visual appearance generally came down to consideration of the CIE-R_a value, the requirement that the specific lamp under consideration was not composed of multiple coloured LEDs which might have resulted in coloured shadows, and a subjective visual assessment comparing the new against the incumbent lighting.

16 See *CIE 157:2004 Control of Damage to Museum Objects by Optical Radiation*; Sérgio Nascimento and Osamu Masuda, 'Best Lighting for Visual Appreciation of Artistic Paintings—Experiments with Real Paintings and Real Illumination', *Journal of the Optical Society of America* A31, no. 4 (2014): 214–19.

17 Arie Andries Kruithof, 'Tubular Luminescence Lamps for General Illumination', *Philips Technical Review* 6 (1941): 65–96.

18 See Michael Scuello et al., 'Museum Lighting: Optimizing the Illuminant', *Color Research & Application* 29, no. 2 (2004): 121–27 http://onlinelibrary.wiley.com/doi/10.1002/col.10231/abstract; Michael Scuello et al., 'Museum Lighting: Why Are Some Illuminants Preferred?,' *Journal of the Optical Society of America* A21, no. 2 (2004): 306.

19 Christine Wilson Kesner, 'Museum Exhibition Lighting: Visitor Needs and Perceptions of Quality,' *Journal of the Illuminating Engineering Society* 22, no. 1 (1993): 45–54.

20 Michael P. Royer, 'Tuning Optical Radiation for Visual and Nonvisual Impact' (PhD, The Pennsylvania State University, 2011), http://search.proquest.com/docview/888520435/ (accessed 9 November 2016).

21 William A. Thornton, 'The High Visual Efficiency of Prime Color Lamps', *Light Design Applications* 5 (1975): 35–41.

22 cf. Louise Smith, 'The Phasing out of Incandescent Light Bulbs, advice for UK Government Members of Parliament, Standard Note: SN/SC/4958, 2010, http://metatrontechnologies.com/wp-content/uploads/2015/07/Phasing-out-of-Incandescent.pdf (accessed 9 November 2016).

One element holding back some interviewees from further investment was an opinion that LED technology was not yet 'fully proven'. Many pointed out that the claims made regarding the lifetimes of LEDs were yet to be confirmed in real world environments due to the relatively new nature of the technology. Some also noted the high costs associated with having to change the underlying lighting infrastructure, where retrofitting wasn't possible or appropriate. Some interviewees were unsure about the ability of LEDs to remain colour stable over the expected lifetime of the products, and noted preliminary results from a report prepared for the US Department of Energy on retrofit lighting at the Smithsonian American Art Museum in the US.[23]

8.2. Safety of LED lighting

Most interviewees were aware of warnings which had been issued and well publicised in the mainstream press regards the potential of LED sources to be especially degrading for specific objects.[24] Interviewees saw these warnings as controversial and likely to be unwarranted. Respondents were confident that research had been conducted which cleared LEDs of causing an unacceptable level of damage in comparison with other lighting technologies.[25] When asked how they might assess a light source for safety, most replied that safety was assessed solely through use of an illuminance meter and lux targets ('we never normally adjust the lighting type for a given artwork, we adjust the intensity'), and not through analysis of the SPD or any other lighting attribute. Those who did critically assess the SPD generally used no specific tools to do so (other than the 'rule of thirds'), focusing attention on the wavelength of the spectral emission peak ('all lighting we measure the SPD, and check it is reasonable').

8.3. Reception of LED lighting

Interviewees reported that visitors had not generally responded to any changes in lighting technology, and this was taken to mean that any switch to LED had at least not provoked any negative reaction. However, the survey was inconclusive as to whether or not the technology was well received. This could be a meaningful avenue for future work, perhaps building on the work of Perrin et al.[26] In terms of the professionals' own opinions of the use of LED lighting, all seemed favourable, though it was unclear how much this was due to extraneous or related phenomena such as a placebo effect caused by the excitement of the new technology, or simply the different chromaticities or luminous intensities of replacement technologies:

> I like what I've seen. The galleries where we have just LED spots, I feel happier. I went to [another institution, with abundant LED lighting], I really like the galleries where they had LED lighting, and it was more of a gut feeling rather than something which I could put my finger on, but actually, it felt cleaner to me.

9. Summary of the survey results

1. Object safety is considered in terms of limiting lux.
2. The spectral characteristics of lighting, as they relate to damage, are not routinely considered.
3. UV is blocked or light sources which produce minimal UV output are used as standard.
4. LEDs are being used, principally due to their decreased power requirements, as part of institution wide efforts to use less energy.
5. The efficacy of specific LED products is not yet commonly considered, as LEDs as a group offer such a vast improvement over incumbent technologies.

23 N. Miller and S. Rosenfeld, *Demonstration of LED Retrofit Lamps at the Smithsonian American Art Museum, Washington, DC,* 2012, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21476.pdf (accessed 9 November 2016).

24 Lewis Smith, 'Will We Have to Look at Sunflowers in the Dark? Scientists Discover Museum Lights Are Damaging Valuable Masterpieces by Van Gogh and Cézanne, *Mail Online*, January 7, 2013, http://www.dailymail.co.uk/sciencetech/article-2258344/Scientists-discover-LED-lights-damaging-valuable-masterpieces-artists-including-Van-Gogh-C-zanne.html (accessed 9 November 2016).

25 cf. Letizia Monico et al., 'Degradation Process of Lead Chromate in Paintings by Vincent van Gogh Studied by Means of Synchrotron X-Ray Spectromicroscopy and Related Methods. 1. Artificially Aged Model Samples', *Analytical Chemistry* 83, no. 4 (February 15, 2011): 1214–23 and Manuela Lunz et al., 'Can LEDs Help with Art Conservation? – Impact of Different Light Spectra on Paint Pigment Degradation', *Studies in Conservation*, http://www.tandfonline.com/doi/full/10.1080/00393630.2016.1189997.

26 Perrin, Druzik, and Miller, *SSL Adoption by Museums: Survey Results, Analysis, and Recommendations.*

6. Fidelity seems to represent a meaningful philosophical concept for colour rendering considerations in museums.
7. However, the mechanics of existing metrics are 'taken with a pinch of salt', and not well understood.
8. Visual inspection is used as a secondary method for selection, after minimum objective factors are passed.
9. Colour temperature is not considered from a conservation perspective.

10. Discussion

There is ubiquitous use of lux as a tool for considering potential for object damage. There is widespread acknowledgement of the limitations of this method, namely that lux values are *photopic* units, meaning that the figure is weighted according to the spectral sensitivity of the human eye as defined by the 'luminosity function'.[27] It is therefore incorrect to assume that the damage function, the spectral function which represents the ability of different wavelengths of light to cause damage to any object (or group of objects) matches this sensitivity in any way. One reason why this approximation has sufficed up until now is that where only a small number of different lighting technologies with different SPD types exist, simple relationships between lux and damage index (DI) also exist.[28] These will be rough, and potentially different for each technological SPD type, but would suffice to an extent that the benefit of being able to use lux as a tool for specification outweighs the negative implications of only being able to roughly predict the damage likely to occur as the result of using a specific lamp. Imagine the case where only tungsten-based illumination technologies exist, with identical relative SPDs. In such a scenario, an increase in lux will be purely multiplicative across the entire spectrum, and in perfect linear correlation with an increase in DI. With the introduction of additional technologies with different SPD types, and specifically with the introduction of LEDs, where there is greater within-group SPD variability than has previously been seen with other technologies, such correlations are weakened.

27 cf. https://en.wikipedia.org/w/index.php?title=Luminosity_function&oldid=740914386 (accessed 9 November 2016).

28 Joseph Padfield, 'Relative Spectral Sensitivity'.

A further note, mentioned by several interviewees, is that whilst the luminosity function is unlikely to match the damage function of any particular object, such variability exists in damage functions between different object types that no one damage function would ever be able to suffice in accurately representing all objects.

There are many benefits of being able to use lux as a measurement tool. Firstly, it provides a 'common language' between many different parties, specifically, lighting designers who are used to using lux as representative proxy of brightness and curators who are familiar with guidelines using lux as a proxy for DI, the rational for which was described above. Secondly, it is readily available as while not all suppliers will list the SPD of a light source, all will list its lux value.

A welcome development would be for suppliers to provide SPD information as standard, so that industry-customers are better able to assess the suitability of a product for their specific needs. This relies on the customer having a certain level of expertise, and time/commitment to making such an assessment.

In an age where manufacturers are not limited to the paper space in a catalogue or on the side of a box and the computational power required to calculate a huge number of different indices from spectral data is readily available, manufacturers should be able to provide information designed to better service the needs of specific user groups. One such index could be the DI as defined by CIE 157:2004 document.[29]

29 *CIE 157:2004 Control of Damage to Museum Objects by Optical Radiation.*

There is still a great deal of work to do for those who specify lighting in museums. Firstly, the decision of how much damage is *reasonable* to allow is always going to have to be made on a case by case basis. Secondly, predictions of damage by light are greatly aided by knowledge of the specific spectral sensitivity of materials, and that of those materials placed in a variety of environmental situations and material combinations. The prototypical DI utilises a generic damage function, which whilst working well as a multipurpose function, is greatly improved by entering in a material specific damage function. In specific cases the damage functions of a particularly problematic material might easily be considered by replacing the generic damage function with a material specific damage function, and lighting specified in such a way as to limit change in that material.

A surprising result in this research was the ubiquity of visual testing. Visual testing can be seen from two different angles. The first states that it contradicts and violates the idea of authenticity which is relatively well served by fidelity indices such as CIE-R_a by introducing subjective preferences into the decision-making process, which may well result in decisions being taken by individuals that do not align with an institution's philosophical values. The second position states that visual testing complements fidelity index-based selection, that is, where a fidelity index provides an initial benchmark which candidate products must pass, then visual inspection can be beneficially used to consider subtle and environment specific attributes that are not well served by such existing metrics. As the development of indices continues, and we continue to learn more about the links between objective parameters and subjective responses, then potentially this benefit will be diminished until it becomes negligible.

A final thought: the critical attributes for future lighting specification guidelines should be simplicity, clarity and accessibility. This is because while there exists an active and energetic community of researchers engaged in museum lighting driven to understand and implement the most complex of original research in order to inform their own lighting specifications, such levels of expertise and devotion will only ever be available within the largest of institutions. When considering advice and tools for the wider museum and gallery community, it must be remembered that lighting specification is generally the responsibility of those who have many other responsibilities to fulfil.

Interview Questions

(1) What is your role in your organisation and what type of input do you have into lighting decisions?
(2) What is 'good' lighting to you?
    (a) Broadly, what are your priorities for lighting for museum use?
    (b) Who specifies the lamps to be used in your institution? (e.g. designer/conservator/scientist/curator)
        (i) Are these specifications always followed? If not, what considerations take precedence?
    (c) What tools (data/indexes/standards) are used to select lighting?
    (d) Do you/colleagues assess that lighting is 'safe' to objects? If so, how?
    (e) How important is the geometry of illumination, e.g. directional or diffused? How much does it depend on the material surface of the objects, e.g. matte, glossy, patinated, etc.
    (f) Is selection of the light sources purely based on specification items or (also) based on visual inspection? Is the visual inspection done in a specific environment?
(3) Does your institution use LEDs to illuminate objects in galleries? (Type/brand?)

(a) How do you assess if LEDs are suitable for use to illuminate museum objects?
(b) What has prompted your institution to use LEDs?
  (i) What factors are preventing your institution from using LEDs more widely?
(c) Where/how are LEDs used in your institution?
  (i) Are LEDs used inside or outside showcases or both?
  (ii) How widespread is the use of LEDs in your galleries?
(d) Have you noticed anything special about the appearance of objects/spaces when illuminated by LED illumination? (brightness/naturalness/saturation)
  (i) Would you want to make objects appear brighter, if this could be done without causing more damage to objects?
(e) Do you have specific concerns/problems regarding LEDs (versus conventional lamps)?
  (i) Have you observed damage on objects caused by LEDs?
(f) If your institution has recently switched from conventional lamps to LEDs in some galleries/showcases, has this change been noticed by visitors?
  (i) If so, positive or negative feedback?
  (ii) How satisfied is your institution with LEDs in general?

(4) How much thought is given to the choice of the colour temperature of lighting?
  (a) Do you know what is meant by 'chromatic adaptation'? (Chromatic adaptation is the human visual system's ability to adjust to changes in illumination in order to preserve the appearance of object colours.)
  (b) Is chromatic adaptation considered when designing lighting?
  (c) Have you/your colleagues/visitors noticed issues with colour temperature/ chromatic adaptation specifically in galleries/ showcases where LEDs are used?
  (d) Would it matter if the colour temperature of illumination changed from one room to another?
  (e) Is the colour temperature used to create a specific atmosphere in the environment?
(5) How is the subject of 'accuracy' approached when considering lighting?
  (a) How would you feel about a lighting setup which prioritised:
    (i) Emulating the original appearance of an object (is this ever known?)
    (ii) Discerning spatial detail, graphics and text
    (iii) Recreating the appearance of an object under natural illumination (how accurate should this be, and what is considered as natural illumination?)
    (iv) Correcting for dark conditions by making things appear more saturated
(6) What are your current concerns regards museum lighting?
  (a) What type of tool would you benefit from?
  (b) What type of technology would you / your objects / your visitors benefit from?
  (c) Are visitor requirements met? (When are visitors' requirements met?)
(7) *Do you know of any surveys on the topic of museum lighting which have been conducted previously?*

ORCID

Daniel Garside http://orcid.org/0000-0002-4579-003X

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Abstract
The results of a series of interviews with museum professionals on the subject of museum lighting specification and selection are reported, with the aim that this report should provide an insight into current practice. Specific attention is given to the usage of industry parameters (lux, CIE-R_a, CCT), and to investigating the level of ubiquity of light-emitting diode (LED) technology. It is found that the damage potential of lighting is considered most commonly in terms of lux dosage, that a minimum cut off in terms of CIE-R_a is used to specify lighting 'quality', and that LED usage is growing, primarily as a result of institution-wide energy use reduction drives.

Résumé
«Comment choisir l'éclairage dans un musée? Un aperçu de la pratique actuelle dans les musées britanniques»

Les résultats d'une série d'entretiens avec des professionnels de musées sur le thème des spécificités et du choix de l'éclairage dans les musées sont présentés dans le but de donner un aperçu de la pratique actuelle. Une attention particulière est accordée à l'utilisation des paramètres de l'industrie (lux, CIE-R_a, CCT) et à l'étude du degré d'omniprésence de la technologie LED. On constate que le dommage potentiel de l'éclairage est considéré le plus souvent en termes de mesure en lux, qu'une partie minimale en termes de CIE-R_a est utilisée pour préciser la «qualité» d'éclairage et que l'utilisation de la LED augmente principalement à la suite d'une demande de réduction de la consommation d'énergie à l'échelle de l'institution.

Zusammenfassung
"Wie wird die Beleuchtung in Museen ausgewählt? Ein Einblick in die gängige Praxis in britischen Museen"

Die Ergebnisse einer Serie von Interviews mit Museumsmitarbeitern zur Spezifikation und Auswahl von Museumsbeleuchtung werden hier vorgestellt, mit dem Ziel so die gängige Praxis zu erfassen. Besondere Aufmerksamkeit wurden dem Gebrauch der Industrieparameter (lux, CIE- R_a, CCT) sowie der Untersuchung der Verbreitung von LED Technologie zuteil. Die Ergebnisse zusammenfassend kann man sagen, dass das Beschädigungspotential der Beleuchtung am häufigsten in der Luxdosierung ausgedrückt wird, dass ein Minimum Cut-Off im Sinne von CIE- R_a eingesetzt wird, um Lichtqualität auszudrücken, und dass der Gebrauch von LEDs aufgrund von institutionsweiten Energiesparprogrammen steigt.

Resumen
"¿Cómo se selecciona la iluminación en los museos? Una visión de la práctica actual en los museos del Reino Unido"

En este artículo, con el propósito de proporcionar una visión de la práctica actual, se presentan los resultados de una serie de entrevistas con profesionales del museo sobre el tema de las especificaciones y la selección de iluminación en museos. Se presta especial atención al uso de los parámetros de la industria (lux, CIE- R_a, CCT) y se investigan los niveles de ubicuidad de la tecnología LED. Los resultados muestran que normalmente se considera el potencial de daño de la iluminación en términos de dosis de lux; que para especificar la 'calidad' de iluminación se utiliza un límite mínimo en términos de CIE- R_a,, y que el uso de LED está creciendo como resultado, principalmente, de la reducción del uso energético impulsada por las distintas instituciones.

摘要
如何选择博物馆的照明设备？英国博物馆现况解读
本文作者通过系列采访博物馆业内专家，梳理出关于"博物馆照明规格和设备选择"这一议题的访谈结果，并旨在深入了解现行状况。文中尤为关注工业参数（lux, CIE- R_a, CCT）的用法，并研究了无处不在的 LED 科技的水平。经调查，大家普遍认为照明的破坏潜力与lux（勒克斯）量有关；与照明停止运转最低限度相关的 CIE - R_a（显色指数）可以反映出灯的"质量"； 博物馆正在大规模削减能源消耗，此举是导致 LED 灯使用量增长的主要因素。

Biographies

Daniel Garside is a PhD researcher within the 3DIMPact group, working since May 2015 on a project, 'Appearance of Objects in Museums under LED Illumination', funded by an EPSRC iCASE award supported by Philips and The British Museum, and affiliated to SEAHA. He has a background in photographic and visual sciences, with a specialisation in colour science. Previously he was a visiting lecturer in Photographic Science at the University of Westminster.

Katherine Curran is a lecturer in Sustainable Heritage and Assistant Course Director on the MSc in Sustainable Heritage. Her research interests include the conservation of modern and contemporary materials such as plastics, polymer chemistry and degradation, and the analysis of volatile organic compound (VOC) emissions from historic objects.

Capucine Korenberg is a senior conservation scientist at the British Museum. Her research concentrates on assessing the suitability of conservation treatments for museum objects, understanding the deterioration processes in museum objects and finding ways to preserve museum collections. More specifically, she has recently worked on laser cleaning and microfading. She has worked at the British Museum for more than 13 years.

Lindsay MacDonald is a research associate at UCL whose particular interest is colour, including the human visual system, colorimetry of imaging devices, spectral characterisation of illumination and materials, and colour image processing. He has published over 120 papers in journals and the proceedings of peer-reviewed conferences. He has edited eight books on image science and its application to cultural heritage, the most recent being *Digital Heritage*, published by Elsevier in 2006.

Kees Teunissen is a senior research scientist at Philips Lighting Research, Eindhoven, Netherlands, and a visiting professor at Southeast University, Nanjing, China. He holds a BSc degree in electrical engineering and a doctoral degree in psychophysics from the Delft University of Technology, the Netherlands. At Philips he is responsible for researching quality of light aspects in products and systems, in particular related to colour vision and colour science and for safeguarding and optimising user experience in integral lighting solutions. He is a member of the Illumination Engineering Society (IES) of America and of the International Commission on Illumination (CIE).

Stuart Robson is head of the UCL Department of Civil, Environmental & Geomatic Engineering. He is known for his research in the field of dynamic 3D co-ordination and monitoring of engineering, medical and heritage structures using traceable optical metrology techniques. His reputation is built around low cost photogrammetric imaging networks and sequences in which he has a key international profile. He leads the 3D Impact Research Group at UCL which comprises two academics, two teaching fellows, a senior research fellow, three Research Associates and 14 PhD and EngD students.

Contact address

Daniel Garside, Lindsay MacDonald, Stuart Robson
Department of Civil, Environmental & Geomatic Engineering
University College London
Chadwick Building, Gower Street
London WC1E 6BT
UK
Email: daniel.garside.14@ucl.ac.uk (lead author)
Email: ucfslwm@ucl.ac.uk
Email: s.robson@ucl.ac.uk

Katherine Curran
UCL Institute for Sustainable Heritage
Central House, 14 Upper Woburn Place
London WC1H 0NN
UK
Email: k.curran@ucl.ac.uk

Capucine Korenberg
Department of Conservation and Scientific Research
British Museum
Great Russell Street
London WC1B 3DG
UK
Email: ckorenberg@britishmuseum.org

Kees Teunissen
Philips Research Eindhoven
High Tech Campus 34
Eindhoven 5656 AE
The Netherlands
Email: kees.teunissen@philips.com