Measuring the Illumination Exposure of LED Illuminants in a Multispectral Imaging System

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When imaging cultural heritage objects, conservators and others express concerns about the illumination levels used; the question can be put simply: “What are the light levels (of the imaging modality to be used) and how do they compare to museum lighting standards?” We will provide a response using data from the Leon Levy Digital Dead Sea Scrolls Library (http://www.deadseascrolls.org.il/?locale=en_US). The Leon Levy imaging system uses 12 LEDs at wavelengths spanning the visible and near infrared with a monochrome camera for image acquisition. The LED panels typically illuminate at 30-60o and the camera is normal to the object. Diffusers between the LED panels and the object even out the illumination pool and also make it typically much larger than either the object or the field of view.

We employ two ways to measure and calculate the light to which the scrolls are exposed during the imaging. The first measures the equivalent typical room light exposure (conservation lab/imaging room/exhibition) of the LEDs. The second calculates the incident power in mW/M^2 on the scrolls from the LEDs and relates that to current museum lighting standards. Additionally, and perhaps more importantly, we have measured several scroll fragments exposed to exceedingly high lights levels with a device known as a microfader (Whitmore, 1999; Whitmore & Smith, 2001)The microfader exposes a 200 micron size spot to the visible spectrum from a tungsten lamp and continually measures the reflectance spectra. The spectra are then converted into the CIE L*a*b* colorspace, which provides orthogonal distances and minimum detectable color changes. This data, presented below, shows that the scroll substrate is quite robust with respect to photolytic changes.

It is important to differentiate between lux and W/M^2 as units of light. Lux relates to human vision and is the illuminant spectra convolved with the photopic eye response, as shown in Figure 1. W/M^2 is a physical unit, irradiance, and is more basic in that it is easy to measure with spectrometers and power meters. It is not easy to convert between units since one needs to know the wavelength involved; i.e. one cannot simply say that Y lux is Z W/M^2 (see Figure 1). The figure also shows that the human eye perceives the same amount of irradiance as being dimmer or brighter at different wavelength. For example, 1 W/M^2 at the peak of the curve is ~ 683 lumens, while the same irradiance at ~470 nm would be perceived as much dimmer, ~60 lumens.

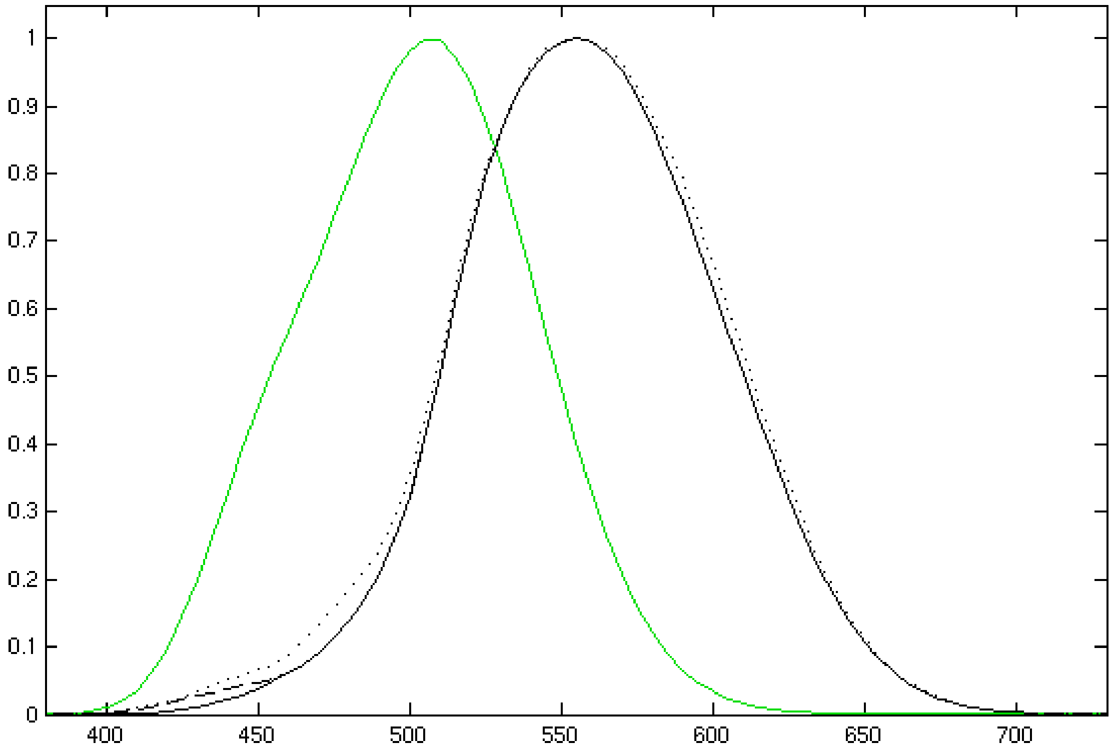

Figure 1. The black curve shows the luminosity function that relates irradiance to lumens and lux.

A key feature of analysis of photon damage to cultural heritage objects is the Bunsen-Roscoe Law of reciprocity. According to this principle, the total exposure is the product of the irradiance and the exposure time. As long as the product is the same, the effect produced by the exposure is the same. A short exposure at high intensity has the same effect as a long exposure at low intensity. For example, 20 W-Hours/M^2 is equivalent to 5 W/M^2 for 4 hours or 2 W/M^2 for 10 hours. This is how we can compare lighting exposures with different intensities.

Our first method uses a lux meter and a duplicate of the IAA camera to measure the equivalent exposures. Using a Sekonic L-358 incident light meter we measured illumination from our standard room light fluorescent lights to be about 240 lux at the scene. Note that this is about half the 500-lux that is prescribed for normal office illumination and for many laboratory and conservation tasks.
Fine detail work is often prescribed at double or quadruple this light level (see Table 1).

Activity	Illumination *(lux, lumen/m^2)*
Public areas with dark surroundings	20 - 50
Simple orientation for short visits	50 - 100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, Homes, Theaters, Archives	150
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Operation Theatres	1,000
Detailed Drawing Work, Very Detailed Mechanical Works	1500 - 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 - 5000
Performance of very prolonged and exacting visual tasks	5000 - 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 - 20000

Table I. Common and Recommended Indoor Light Levels

Indoor light levels are commonly in the range *500 -1000-lux* - depending on activity. For precision and detailed work, the light level may even approach *1500 - 2000 lux*. The table provides guidance for recommended light levels in different workspaces:

A few details about the imaging are required here. One is that the exposure times are set to fill the camera pixel wells to ~ ¾ of their full capacity. This is in order to retain dynamic range at the bottom end and avoid saturation at the top. In practice, it means adjusting the exposure times until the histogram mean is ~ 48000. At the Megavision offices in California, we set up a spectralon target and camera with a set of parameters similar to the IAA lab, 39 MP sensor, 120 mm lens at f/11 and 1200 dpi spatial resolution. Under these conditions, an exposure of 0.51 seconds at a measured broadband room illumination of 240 lux reached about ¾ of saturation.

Next the incident light meter measurements of scene illumination produced by each of the visible bands were used to set the light power of each of the visible bands, so that the light meter measured 240 lux at the scene. The duration for each band's exposure was set so the histogram average of the white Spectralon image was again ¾ of saturation (the same as room light exposure and the IAA standard exposure).

Exposure durations to fill the pixel well to ¾ of saturation varied from.15 to .84 seconds, as seen below:

Wavelength	Exposure in seconds
Room (fluorescent)	0.51
Royal Blue (447 nm)	0.51
Blue (470 nm)	0.79
Cyan (505 nm)	0.84
Green (480 nm)	0.84
Amber (460 nm)	0.41
Red	0.23
Deep Red	0.15

As expected, the average exposure roughly matches the exposure to room lighting.

Multiplying the average exposure duration by the total number of exposures gives an approximate equivalence to exposure to normal room light. Thus the total exposure of a 30-image capture sequence would be equivalent to about 16 seconds of exposure to normal room light. Since the "normal room light" of this test is about half of that prescribed for conservation work, the total 30 exposure sequence is equal to about 8 seconds of exposure to normal conservation work area room light.

This works out to about 1 lux-hour of integrated exposure for the imaging sequence. How does this compare with the IAA standards and the CIE standards? According to the project director, the IAA maximum integrated illumination of *any* sort over a year is 15,000 lux-hours. This exposure maximum is the recommendation of the CIE report of museum object lighting see table 3.4 of (Allen, 2001) The analysis shows that we are 4 orders of magnitude below the standard.

Note that this analysis does not specifically include the 4 IR LEDs. Lux measurements are designed to relate to human vision and so do not include any wavelength above ~ 700 nm, as Figure 1 shows. While lux meter measurements do not extend into the IR, it is not far-fetched to include the IR exposures in this approximation, though it is likely that the IR exposures will have less affect on the material than the visible light exposures, even though sensor sensitivity falls off as the illuminant goes deeper into the IR and thus exposures grow longer. However, as wavelengths get longer, photons are proportionally less energetic so increasingly less able to cause a change to a material with which it interacts. The ability of light to create photo effects drops by ~ 1/10 for every 200 nm towards the red. This is why most exhibitions prohibit flash photography, since it produces the most energetic photons, UV and deep blue.

Let's run a quick analysis for a single green wavelength. As Figure 1 shows, the peak is in the green, around 555 nm. At that wavelength, the conversion factor is one lux=1.4mW/M$^{2.}$ For that LED, we can calculate that integrated exposure in irradiance units and convert the lighting standard into the same units. Assume that the entire output of the LED falls only in the field of view of the camera (not true by quite a bit, so this provides an upper limit to the exposure by over-counting the light on the object). For a 3 W optical power LED and 1 second exposure, we get 1.36E5 mW-s/M^2 while the 15000 lux-hours exposure translates to 5.9E8mW-s/M^2, for a ratio of ~4000. While this is for only one wavelength, note that the lux to mW conversions dies off significantly on both sides for the other wavelengths, reducing their contribution quite a bit; by the time we get into the blue and red we are down by ~ 0.1. Since we over counted the illumination anyway, this method gives a result on the same scale as using the illumination meter.

The microfader data was acquired on two fragments of the scrolls, both without text. One was quite light and other darkened quite a bit, similar to the background we see on illegible fragments. For the light scroll fragment, ΔE76, the standard color space measurement changed as shown in Figure 2: after an exposure of 4,000,000 lux-hours, the total change of ΔE76 was 2.1. For this parameter, a change of ΔE76=1 is the minimum detectable by the human eye. If we take this to correlate to the maximum change allowed, we can relate this back to light exposures. According to Figure 2, ΔE76 reaches 1 at ~600,000 lux-hours, making the *yearly maximum* light exposure the equivalent of about 40 years exposure and the 1 lux-hour from the imaging itself is 68 years of 24/7 exposure. The dark fragment was exposed for 2,000,000 lux-hours and the final change in ΔE76=0.8, which is not detectable by the eye.

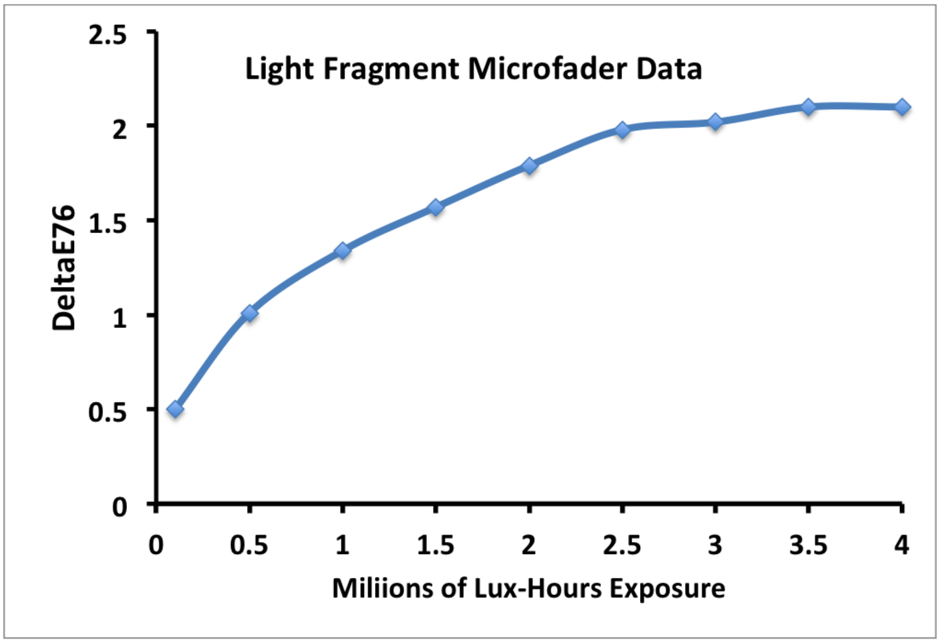

Figure 2. ΔE76 as a function of visible spectrum light exposure for a light colored Dead Sea Scroll Fragment.

In conclusion, the total exposure of the multi-spectral image capture is less than the normal room light exposure required to prepare the object for capture and less than the yearly exposure maximum allowed by the IAA by a factor of ~1/10000

For the microfader data, we are indebted to Jim Druzik of the Getty Conservation Institute in Los Angeles, CA.

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