Collection Forum

MICROFADING: THE STATE OF THE ART FOR NATURAL HISTORY COLLECTIONS

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Society for the Preservation of Natural History Collections

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Abstract.—Microfading is a powerful tool for assessing the risk of light damage in collections. It is an accelerated light exposure method for rapidly and nondestructively estimating the fading rates of colorants on real objects that relies on measuring the early response of a submillimetre spot of colorant exposed to megalux levels of light.

While the main benefit is better identification and protection for the most light-sensitive elements of a collection, it has also been shown to have very significant access, financial, and operational benefits. The basic equipment is suitable for routine screening by a trained conservator in a museum. Alternatively many institutions' needs may be met using a contract service. This paper provides an up-to-date review of the technique's development, and how it is used as a tool for collection management and research.

Introduction

The essential dilemma faced by museums in exhibiting potentially light-sensitive materials is neatly summarised as "seeing versus saving" (Michalski 2011). Striking a balance between display and the inevitable and irreversible damage caused to light-sensitive objects is very difficult without specific fading rate data. The problem with published information, where it exists, is that for reasons discussed below it may not accurately or in some cases even approximately reflect the behaviour of the particular objects in question. Importantly, this is true even if the identity of the pigment or dye is known. Restricting display according to the most conservative interpretation of published data or past experience—the usual fall-back position—has serious access and financial implications that create their own organisational and logistical problems. This is the problem that the accelerated light exposure technique known as microfading was developed to address.

As discussed in this paper microfading was developed by Whitmore et al. (1999) at Carnegie Mellon University, and a similar *in situ* microspot fading test was independently developed by Pretzel (2000, 2008). Whitmore's instrument focuses a submillimetre spot of very intense visible light on an object and tracks the resultant (visually undetectable) colour change in real time using reflectance visible spectroscopy (Fig. 1). It is rapid, virtually nondestructive, and specific to the object tested.

It has three unique advantages over other forms of accelerated light ageing. Firstly, because it is essentially nondestructive, colorants on real museum objects can be tested. Secondly, it is not necessary to have identified or know anything about a colorant, and finally the method is rapid, with typical fading runs of less than half an hour. Using the technique it is possible to evaluate the fading behaviour of two or three moderately complex coloured artefacts or works of art, including data interpretation, in a day.

The essential components consist of a UV and IR filtered xenon arc light source, optical fibres, and a series of lenses for delivering and focusing the light on to a small area (less than 0.5 mm diameter) of the object being tested. The light reflected from the object is directed to a reflectance spectrometer, through a second set of optical fibres and lenses. The spectrometer tracks reflectance change in real time as the colorant responds to the test illumination.

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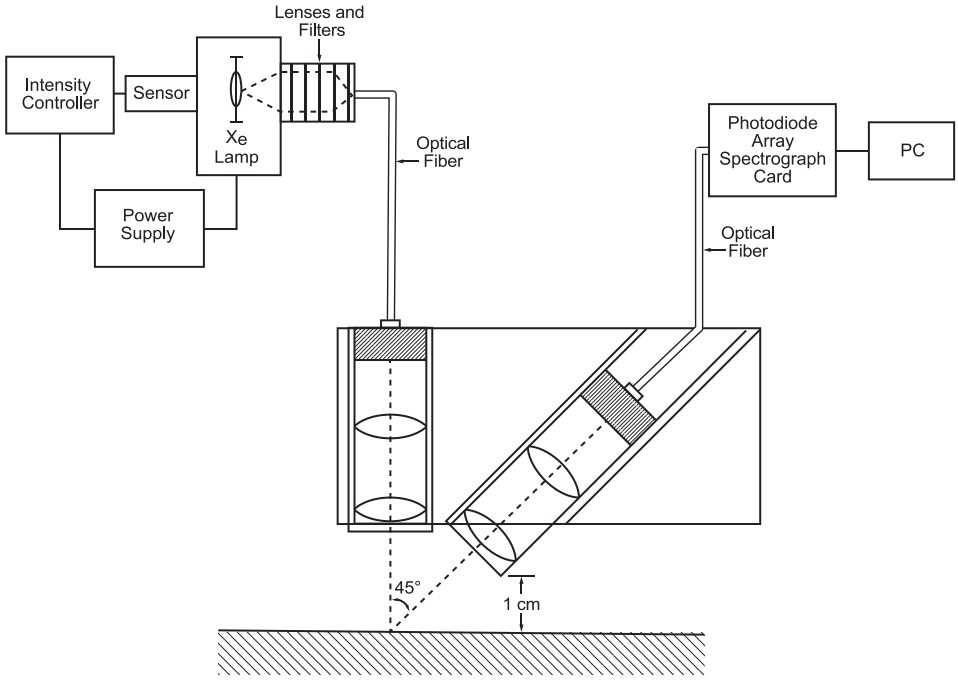

Figure 1. Schematic diagram of a microfader (redrawn). Reprinted from the *Journal of the American Institute for Conservation,* vol. 38, no. 3, with the permission of the American Institute for Conservation of Historic and Artistic Works, 1156 15th Street, NW, Suite 320, Washington, DC 20005, info@conservation-us.org, www.conservation-us.org.

Conservators are usually interested in the degree of perceptible color change resulting from a given cumulative light exposure. This value is calculated from spectral change using standard color difference formulae from which a single aggregated figure ΔE, or total color change, is derived. This is often compared to the response of ISO Blue Wool standard fabrics (BWS) used as internal standards exposed under the same conditions (Fig. 2) and/or as a function of cumulative exposure, usually expressed as megalux hours (Mlx-hr). The BWS range from the most light-sensitive at Blue Wool 1 (BW1) to the least at BW8, with each successive step approximately three times as lightfast as the one preceding it. Approximate dose-response data for the BWS aggregated from published sources by Michalski (1987) can be found in the International Commission on Illumination's "CIE157:2004 Control of Damage to Museum Objects by Optical Radiation" (CIE 2004, table 3.3). They are given as Mlx-h required to produce a "just noticeable difference" (JND, sometimes known as a just noticeable fade, JNF) or Mlx-hr/JND. Microfading is best suited to measuring color change equivalent to, or more rapid than, BW1 down to the method's effective detection limit of about BW3 or BW4. This encompasses the range described in CIE157 as having "high responsivity" to light for museum purposes. Colorants more lightfast than this are not at serious risk of light-fading under normal low-UV museum lighting conditions.

In addition to its use as a routine screening tool for exhibitions, microfading has important applications in research, in the testing and selection of materials for conservation, and the in the identification of colorants. While the main focus of this paper is collections management, some of these other applications as well as the strengths

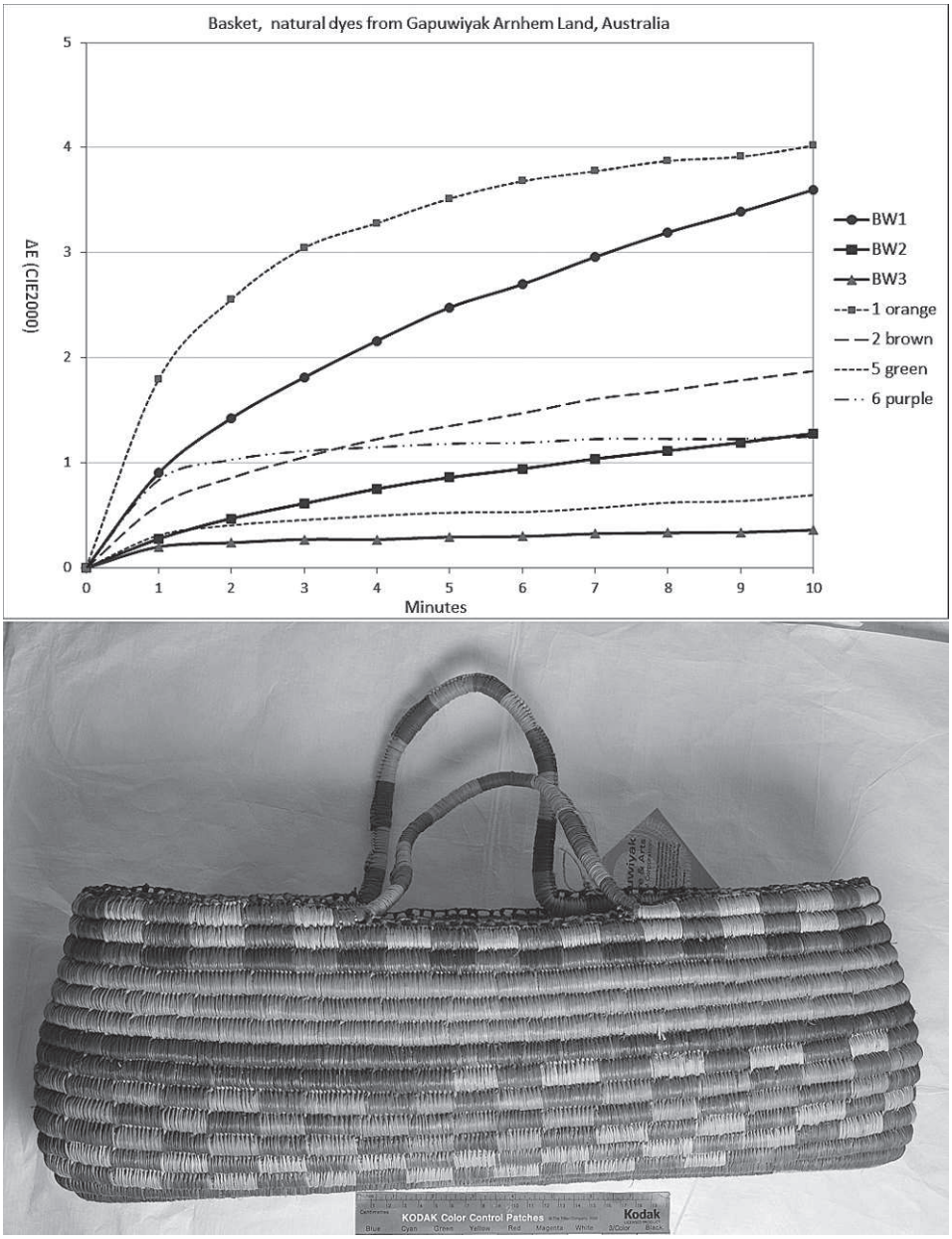

Figure 2. The (micro-) fading curves of natural dyes on an Australian Indigenous basket. Note the large spread of fading rates. The vertical axis is color change, the horizontal axis is minutes of microfading at approximately 6 Mlx.

and limitations of the method and practical hardware and data analysis issues are discussed.

''Fade'' and ''fading'' are used throughout as a shorthand; however, not all light-induced color changes involve a loss of chroma, darkening, or lightening—the usual understanding of the terms.

Why Microfading?

Why fade-test individual objects instead of using published fading rate data for typical colorants? Before considering this question it is worth stating that because it is unlikely that most museums will acquire a microfader, improving the range and quality of fading rate data in the literature through publication will be an important role for those who do. Initiatives like the Canadian Conservation Institute's Light Damage Calculator (Canadian Conservation Institute 2012) will become even more useful as a wider range of data from both microfading and traditional accelerated ageing is entered into it.

The first problem with published information is that dyes and pigments' identities are usually unknown, particularly outside the niche areas of well understood—mainly European—historical graphic, fine art, and textile traditions. This is certainly the case for the mid-19th century on, a period when color technology exploded. As already stated identification is unnecessary for microfading although, conversely, the spectral and fading rate information from microfading may assist with identification. This is dealt with in more detail below. Specimens in natural history collections in particular contain biopigments for which we have little or no reliable data but that contain important scientific information about animal and plant nutrition, communication, camouflage, thermal regulation, and sexual selection as well as being a source of pleasure to museum visitors and researchers alike.

Even where pigment identification is possible, real colorant systems' responses to light depend crucially on specific physical, chemical, technological, and ageing properties that cannot be easily or economically inferred even using sophisticated analytical methods. A related problem is that published data are usually based on the results of accelerated ageing of freshly prepared surrogate or made-up samples that cannot in principle replicate real objects with their complex histories and compositions.

In addition to the obvious dependence of fading on the chemical identity of a particular dye or pigment, the physical disposition of colorants within the substrate—for example, whether they are molecularly dispersed, clumped together, or (in the case of textiles) reactive dyes—is thought to play a primary role in their fading (Baxter et al. 1957, Gupta 1999).

Prior fading and tint strength also lead to variations in the fading rate of a given colorant of as much as one to two blue wool steps (Michalski 1997, CIE 2004).

Fading is almost never unimolecular, and the chemical environment (substrates, mordants, photochemical catalysts, antioxidants) can play a significant role. Indigo, for example, is much more lightfast on wool than cotton (Padfield and Landi 1966). A similar effect is apparent in the very different stabilities of iron gall inks on parchment and paper in the example in Figure 3. This may be because although photoxidation is the most common fading mechanism, photoreduction also occurs in air, usually where the substrate is more easily oxidised than the colorant as is sometimes the case for proteinaceous substrates (Giles et al. 1972).

In an example of unexpected catalysis, Doll et al. (1998) found that the photo-fading of certain ink jet dyes could be significantly accelerated by contact with other colors in areas where they were printed together, an effect that would not be predictable even if their individual identities and fading rates were known.

Manufacturing idiosyncrasies including particle size, washing, paper finishing methods, the number of dye bath applications, and the botanical or biological origin of dyes further undermine predictions based on surrogate studies.

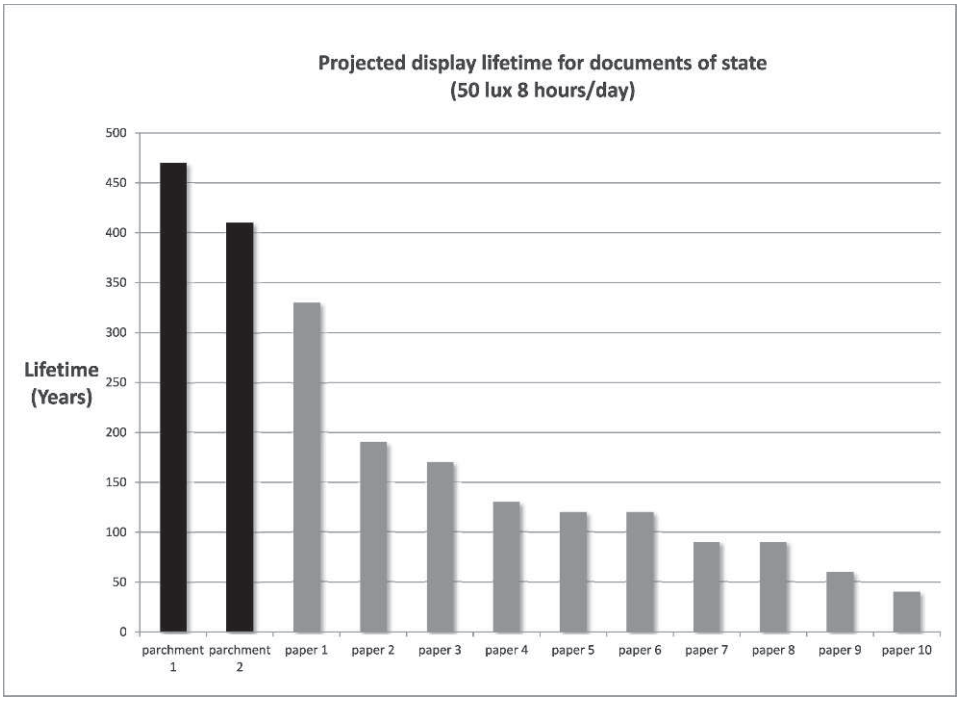

Figure 3. Years exposure to one just noticeable difference (JND = 1.6 ΔE_{00}) for a set of important mid-19th-century state documents intended for display. Ten JNFs are considered to effectively end a document's display lifetime.

Finally, fading rates are influenced by environmental factors such as relative humidity and components that act as humectants, as well as the availability of molecular oxygen where fading is due to photo-oxidation, an effect that low oxygen display mechanisms attempt to exploit (Beltran et al. 2012b).

Limitations of Microfading

The usefulness of accurate fading information is obvious to anyone who has had to make exposure decisions, particularly for rare or high-value material. Microfading has significant advantages over generalised fading rate data for the reasons given above, but what are the uncertainties associated with it and what limitations do they place on the interpretation and use of microfading data?

Before examining this in more detail, it is important to realise that nearly all of the uncertainties that affect the predictive value of microfading are common to conventional accelerated light-ageing methods as well. The differences, where they exist, are those of magnitude rather than kind.

Whitmore et al. (2000) originally developed microfading as a method of rapidly locating dyes and pigments likely to fade rapidly under gallery lighting conditions, rather than predicting what something might look like after 20 or 200 yr on display. However, he found that conservators and conservation scientists were seeking more predictive information, probably responding to the increasing use of lighting guidelines based on cumulative exposure and maximum fading targets (Colby 1992, Ashley-Smith et al. 2002, CIE 2004). In considering this question, having identified a range of factors that

potentially limit the accuracy of microfading as an absolute predictive method, he concluded that "[t]he accurate prediction of the fading of different colorant systems is an elusive, perhaps unachievable goal."

The factors Whitmore identified include the effect of the geometry of the test area on color measurement at such a small scale, the spectral distribution of the light source, and situations where microfading—which measures only photochemical change while the object is under illumination—cannot replicate other factors that affect color especially in the long term. Nonphotochemical changes to optical properties may be particularly important in natural colorant systems where appearance is almost invariably related to structures vulnerable to natural polymer degradation and biological attack. Alterations to texture, gloss, and transparency—including the deterioration of structures responsible for interference colors—may be as important or more important agents of color change than the light fading they are often mistaken for. These may usually be distinguished from fading by examining the spectral changes recorded at intervals during test fading.

Simulated before and after digitally altered photographs (Morris and Whitmore 2007), or the estimated color changes provided by the Canadian Conservation Institute's (CCI) light damage calculator (Canadian Conservation Institute 2012) based on fading data are excellent demonstration and decision-assisting tools, but probably not to be taken too literally when applying them to individual objects. Michalski (2010) has commented that the dose response data for the BWS referred to above—which underpin both the CCI's light damage calculator and absolute lightfastness calculations based on their use as internal standards for microfading—have a potential uncertainty as large as ± 1 BWS step. At the time of writing, both the CCI and the Getty Conservation (GCI) are conducting research to correlate microfading and conventional accelerated light-ageing dose responses for the BWS and to reduce this uncertainty.

Two areas that appear to be of particular concern in relation to the predictive value of microfading and the interpretation of results are reciprocity "failure" and the measurement of color change itself.

Reciprocity

Reciprocity is the assumption that fading depends only on total exposure; that is, 100 lx exposure for 5 yr in a museum case is equivalent to 1,000 lux for 6 mo or 15 min microfading at 6 Mlx. This is also the basis of lighting guidelines that allow for cumulative exposure budgets to be "spent" in any way so long as they are not exceeded within the budget period (e.g., Ashley-Smith et al. 2002). "Reciprocity failure" is a term derived from photography but now commonly used in accelerated light-ageing studies where this quantitative relationship does not—or appears not to—hold at much higher intensities than museum lighting. Theoretically this might be where a bottleneck in the progression of reactions leading to the destruction of a chromophore sometime after the absorption of a photon becomes rate determining—for example, the diffusion of reactants (oxygen) or intermediates to a reaction site. In practice this would be difficult to distinguish from an apparent nonlinearity, which has nothing to do with light intensity per se, but local temperature rise and dehydration perhaps (Feller 1994). Feller gives a few examples of situations where he would expect reciprocity failure to be significant for accelerated light ageing in general, and Michalski (1987) cites studies in which reciprocity holds for textile dyes, food dyes, and the yellowing of epoxy. The most expansive literature review on the reciprocity law is that of Martin et al. (2003), who included within

his study experiments in photography, photoconductivity, photo-medicine, photobiology, and polymer photodegradation. The last category is the one most germane to microfading, and here slightly more than 60% behaved fully in accord with reciprocity, while another 23% slowed with higher exposure intensities. This left 17% reported as ''reciprocity failures.'' Martin et al. proposed his own model to account, among other things, for this apparent bottleneck in the reaction rates with higher intensity, but his solid-state model remains somewhat controversial.

Underlying much of the speculation and some of the very limited research into the ubiquity and extent of deviations from reciprocity at microfading intensities is the expectation that the phenomenon will cease to be a problem at some yet to be determined but still accelerated light intensity. This may be the case; however, as Whitmore points out, the causes and magnitudes of reciprocity failures (where they occur) are likely to depend on factors particular to the physical and chemical properties of the colorant system under test rather than as a simple function of light intensity or the identity of the colorant.

In principle it is relatively easy to test for reciprocity effects using microfading by attenuating the illumination beam with a neutral density filter and extending the exposure duration. In practice the drop in intensity is typically limited to about an order of magnitude by a combination of the fading rate of the colorant and instrument drift. However, Liang et al. (2011) were able to lower the effective detection limit to 1% of full power in some cases using an innovative automated recalibration process. Del Hoyo-Mendelez and Mecklenburg (2011) determined that for some very fugitive natural dyes demonstrating reciprocity over the first order of magnitude does not necessarily mean reciprocity holds at lower levels.

Some microfading reciprocity results have been published, and many more unpublished tests have been conducted; however, as yet there has been no published large scale systematic microfading investigation of the phenomenon or an agreed upon test protocol that would ensure comparable results. This is important because observed reciprocity effects depend not only on the variables mentioned above, but also on procedural issues like the cumulative light dose used. This can affect results because rapid early fading tends to magnify differences that are not as apparent in the longer term. Whitmore et al. (1999) has published data for a few colorants that illustrate equivalence between microfading and conventional light box ageing as well as demonstrating reciprocity over the test intensities he used, and Liang et al. (2011) from Nottingham Trent University have found reciprocity held for a majority of painted-out samples on paper of fine art pigments tested, including some over two orders of magnitude, but the same team also reported reciprocity breakdown for the pigments Prussian blue and orpiment (Lange and Liang 2011). Del Hoyo-Mendelez and Mecklenburg (2011) found that the most stable colorants they tested obeyed reciprocity, but that materials of lower light-fastness exhibited greater apparent deviations.

Colorimetry

Color measurement itself is a source of uncertainty. The relationship between color change, which is an estimate based on models of how the ''average observer'' perceives reflectance differences and pigment concentration changes (the physical reality), is complex and nonlinear. Liang et al. (2011) argue partly for this reason that spectral change in the absorption region (ΔR) is a better measure of sensitivity; however, the relationship between reflectance change and colorant concentration, described by the

Kubelka Munk equations, is itself far from straightforward in real situations (Johnston-Feller 2001). Bacci et al. (2004) have shown that ΔE does not reflect photochemical damage as accurately as ΔR within the dominant absorption region, and it is possible to speculate that some apparent reciprocity deviations might even disappear if the latter were used. On the other hand, it may be argued that precisely because the relationship between pigment concentration and perceived color change *is* nonlinear—and changes in appearance really are the issue—ΔE is the most relevant metric. ΔE is also prevalent in the conservation literature and advice on fading (for example, CIE157), it has the advantage of being widely understood by conservators, and it is easily calculated from colorimetric data produced by spectrometer software. In reality, for practical exhibition risk management purposes, the choice is probably inconsequential.

Several different perceptual models are used to calculate color difference (ΔE) from spectral change, and they do not necessarily agree (Kuenhi 2008). Two iterations of the CIE equations widely used in industry and almost exclusively in conservation—the first produced in 1976 (CIELAB) and the latest in 2000 (CIE2000)—differ by as much as a factor of two in their respective estimations of ΔE for blues (including the ISO Blue Wool Standards) for the same exposure, and even more for some high chroma yellows. The CIE2000 color space is the most perceptually uniform of the two; however, CIE76 is widely encountered in the conservation literature. For comparative purposes it is probably better to report both.

Scaling up the measured color change of a single pigment or dye to its appearance in the context of a whole object presents another set of challenges. Estimates of how much fading (ΔE) is required to produce a JND vary over nearly an order of magnitude according to the observer and the effects of lighting, contrast, adjacent colors and other aspects of the complex visual context (Richardson and Saunders 2007, Brokerhof et al. 2008). A figure somewhere between a ΔE_{00} of 1 and 2 (where the subscript designates the color space) seems to be the generally accepted compromise (e.g., Pretzel 2008).

Risk Assessment Using Microfading

Given these uncertainties, how is one to use microfading data? It is useful to distinguish between absolute and comparative fading rates. Microfading's ability to predict exactly what a real object's color will look like in 50 yr is unproven (but not necessarily inaccurate) and is likely to remain so for some or all of the reasons outlined above. This is true for any accelerated method. In a general sense the limits to its predictive accuracy will naturally become better understood as fading in real time under known conditions (e.g., Ford 1992) is compared to accelerated results, particularly in well-defined technological or natural fields. At the J. Paul Getty Museum in Malibu, California, the microfading results for particularly vulnerable tinted albumen photographs were followed up with direct colour monitoring. At the end of 26 wk of direct monitoring it was estimated that the first detectable visual change would occur in 110 wk of continuous exhibition, and while other objects might not respond so predictably, this was generally what microfading had predicted when considering the uncertainty ranges that Brokerof et al. (2008) and Richardson and Saunders (2007) had estimated for establishing a JND on a work of art (Miller and Druzik 2012) as well as the BWS dose-response uncertainties referred to above.

When microfading is used to directly compare fading rates, as opposed to estimating long-term behaviour under museum lighting conditions, higher precision may be assumed. This is where the method is used to select the most lightfast objects from a

range of alternatives for exhibition or loan. Information of this kind is particularly useful at the exhibition design stage. It may also be used to probe the effect of environmental conditions, for example, testing the fading rate of pigments in a painting under different oxygen concentrations to assess the value of low oxygen encapsulation.

Microfading data are most useful when it is used in conjunction with the kind of risk management framework (lighting guideline) that sets limits on the amount of color change the museum can tolerate over a given period. This approach has been described by Colby (1992) at the Montreal Museum of Fine Arts and Ashley-Smith et al. (2002) at the Victoria and Albert Museum and Michalski (2011) on the Canadian Conservation Institute Caring for Collections website. These lighting guidelines really only reach their potential with the kind of specific data microfading provides, and Ford and Smith (2009) have described the use and benefits of microfading data in this context (see below).

Most collection risks cannot be precisely quantified with the available data; however, something like order-of-magnitude estimates are still considered useful. In this context the predictive uncertainties in relation to microfading data and their interpretation are not unusual. Although fading rates within the ''high responsivity'' category in CIE (2004) span more than an order of magnitude, the recommended exposure, based on an average lightfastness for the range, is only 15,000 lx-h/yr (typically a few weeks). The range is so broad precisely because of the lack specific fading data to locate colorants within it, and it is a serious problem for many museums because a large proportion of their collections fall within that range. The value of microfading lies in being able to clearly distinguish between the top, middle, and bottom of this range (3–4 Blue Wool steps) and set relative exposure limits accordingly.

In considering whether to adopt microfading at this stage of its development and given the uncertainties, it is interesting to examine the hypothetical consequences of using microfading data that proves to be wrong or a lighting guideline that turns out to be insufficiently conservative. Consider the case where a museum's tolerance for fading is predicated on a 500-yr displayable lifetime—the ''survival'' target chosen by the Victoria and Albert Museum. If in 20 yr it were determined (by the next generation of conservators) that today's data, or interpretation thereof, had overestimated the lightfastness of a colorant by a factor of two, it will to a first approximation have faded an unintended extra 10 yr of its target lifetime over that 20 yr. This would still leave a remaining service lifetime of 480 instead of 490 yr. Actually, for relatively pristine and rapidly fading colors—for which initial fading is often much more rapid than the rate averaged over the entire period—the early damage may be much more consequential. This is, in fact, an argument in favour of microfading in order to identify such colorants (Whitmore's original aim) since a completely uninformed decision is likely result in even worse overexposure.

Collections Management

Conservators are usually in the uncomfortable position of recommending restrictions on display duration and light levels without really knowing if they are proportionate to the risk of light damage in any particular case, and sometimes in the face of serious pressure to relax them, a role Michalski (1990) referred to as the ''lighting police.'' With microfading this particular dynamic can be avoided, and on the much rarer occasions when disruptive restrictions really are found to be necessary, the data tend to be the focus rather than the roles and authority of curators and administrators and conservators.

Figure 3 gives the individual display periods to 1 JND ($\Delta E_{00} = 1.6$) of a set of mid-19th-century state documents held by a national archive, as assessed by microfade testing.

The first two—the documents most visitors come to see—are written in iron gall ink on parchment, and the rest are iron gall ink on paper. They all date from 1840. The entire set of documents has been the centrepiece of a permanent exhibition for just over 20 yr; however, the display conditions are currently under review as part of a plan to rehouse them in a new and more publically accessible location. The archives recently received advice from an expert in conservation lighting to restrict all of the documents to 6 wk/yr (15,000 lx-h) as a precaution based on their being of potentially ''high responsivity'' to light. As it happens, this advice was almost exactly what the microfading results for the least lightfast documents (9 and 10) would indicate; however, applying that restriction across the board would have made it extremely difficult to design a satisfactory exhibition. The two most important outcomes of microfade testing for the archive were to confirm that an acceptable exhibition strategy could be built around the two most important documents (from the public's perspective) because they are suitable for something like permanent display, but that to continue to display all of the documents together, even at very low light levels, would shorten the legible lifetime of the most fugitive, which fade 10 times faster, to an unacceptable degree for such important state documents.

In a similar example, microfading was carried out by the Canadian Conservation Institute for the Canadian Museum of Nature to select pages from a collection of pristine scrapbooks by Catharine Parr Traill so they could be safely displayed. Because of the value of the collection and light-sensitive elements in the scrapbooks, such as natural dyes and pigments in pressed plants and insects, there was a temptation to keep the whole collection from being displayed. Microfade test results allowed conservators to knowledgeably choose pages that were less sensitive, instead of limiting access to the whole scrapbook out of fear. In addition, the fading data for different plant species helped conservation staff when choosing similar plants for other long-term exhibitions (Tse et al. 2011).

The flip side to identifying and better protecting the most vulnerable artefacts is having the confidence to relax restrictions on less fugitive objects. This not only allows for increased access and more flexible lighting options but also can result in significant financial savings, particularly for collecting organisations with long-term or permanent exhibitions whose preventive conservation programme includes periodically rotating light sensitive material off display to limit cumulative exposures. The National Museum of Australia had for some years used a lighting guideline that restricted items in the ''high responsivity'' range to 2 yr per decade (Ford and Smith 2009); however, the estimated cost of each replacement—on the order of $1,000/object taking into account curatorial time finding and interpreting replacements, registration and conservation activities, and installation—had become unaffordable. This is not an isolated example; for example, the Netherlands National Museum of Ethnography has reported the same problem (Reuss et al. 2005). The use of microfading to make distinctions within the high responsivity range on an object-by-object basis, together with a lighting guideline that additionally prioritised object replacements on other grounds, led to an estimated 70–80% reduction in light-driven replacement costs (Ford and Smith 2010). Conservation benefits included increased protection for objects with colorants assessed as more fugitive than average for the range; fewer objects unnecessarily exposed to the hazards of preparation, transport, and exhibition involved in routine proactive object replacement; and freeing up time from routine object substitutions for other conservation activities.

Research

Microfading is continuing to play a role in research as well as collection management. One of the earliest studies using microfading was carried out *in situ* on known

biocolorants in lepidoptera by one of the authors (Druzik) almost 10 yr ago at the GCI. The work, unpublished, showed that phorcabilin, sarpedobilin, papiliochrome II, papiliochrome M, papiliochrome R, and ommatin D were all highly light sensitive. The GCI and the University of California (UCLA) have collaborated on research into the fading of feathers using microfading (Pearlstein and Keene 2010, Pearlstein et al. 2011). They reported that the "benefit of microfading [lies] in the ability to perform accelerated aging and color measurements on the same location, avoiding the variability introduced by the feather's movement and repositioning" (Pearlstein et al. 2011, p5). Ford and Smith (2011) have published a survey of the fading rates of materials used in Australian Indigenous objects including feathers, natural fibres, and natural dyes and resins. The Tate Gallery (Lerwill 2011), the GCI (Beltran 2012a, 2012b), and the Smithsonian (del Hoyo-Meléndez and Mecklenburg 2010) have all investigated aspects of anoxic storage and display, where in addition to its speed, specificity, and the small sample area of the technique, the ability to test materials (including real works of art) through glass is a major advantage. Lavédrine (2011) has measured the relative fading rates of colored starch grains in the Lumière Brothers' autochrome transparency process using a microfader modified to operate in transmission mode through a microscope objective. Tse et al. (2010) at the Canadian Conservation Institute have investigated the effect of aqueous treatments and calcium phytate on the light sensitivity of iron gall inks, Stenger et al. (2010) used microfading to assess the fading rate of lithol red as part of a larger project to characterise the pigment and its deterioration, and Connors et al. (2005) have studied the light sensitivity of Japanese wood block prints.

The ability to swap illuminants or otherwise shape the spectral power distribution of the source (see below) will allow the rapid evaluation of the damage associated with new exhibition light sources such as LEDs or potentially less damaging triband sources (Cuttle 2000). The use of tuneable filters for the source allows the microfader to be used to determine the wavelength bands most responsible for the fading of specific pigments (Lerwill et al. 2008), which may lead to the development of selective filters for exhibition lighting designed to remove them (Getty Conservation Institute 2010).

Some of the ongoing research into the technique itself (for example reciprocity) has already been mentioned, and the continuing development of instrumentation by various groups is covered in a following section.

Pigment Identification

A good deal of pigment identification, which is an expensive and time-consuming operation that often involves physical sampling, is carried out with the aim of determining the fading risk; however, there are other reasons to identify pigments. A microfader may also be used as a fibre optic reflectance spectrometer (FORS), a method that has been used to help identify pigments, dyes, and inks (Leona and Winter 2001, Bartol 2008, Biscula et al. 2008, Neevel and van Bommel 2008). With appropriate filters and a xenon source, reflectance spectra from just below 400 nm to about 1,000 nm are possible using the Newport microfader where the choice of spectrometer options allows measurement of that range. The fading pattern itself may also assist with identification, for example, the characteristic darkening of vermilion. Visible spectra themselves are not necessarily diagnostic; however, in combination with handheld XRF, for example, the method is very useful, particularly where the range of possibilities is constrained by technological or historical happenstance.

Hardware, Software, and Training

The choice of intensity, spot size, and various elements of the hardware are a compromise between often opposing requirements; for example, for the method to be suitable for routine lightfastness screening it needs to be rapid; however, the megalux levels required to shorten test times may increase the probability and extent of reciprocity failure. Likewise tiny test spot sizes are necessary to achieve high fluxes, minimise the test-faded area, and allow fine features like ink strokes to be measured, but they also result in increased measurement variation due to inhomogeneity at the scale of the test area. There will never be a ''perfect'' microfader, only instruments with different strengths and weaknesses according to their cost and the purpose for which they are designed.

There are many conceivable variations on the hardware theme, several of which have been realised in practice (Lerwill et al. 2008, Druzik 2010, Liang et al. 2011, Łojewski et al. 2011), and some of them have been evaluated side-by-side (Druzik and Pesme 2010). They all share similar fundamental characteristics: that is, a maximum IR and UV filtered visible light output of between about 3 and 16 Mlx (or approximately 2–10 mW in radiometric terms) within a test spot size of less than about 0.5 mm. IR filtering minimises heating of the test area; however, there are differences in reported temperatures with Lerwill et al. (2008) and Ford (2009a) measuring rises of about 5°C and Whitmore et al. (1999) more like 25°C for similar light intensities. UV filtering can (in principle) be tailored to approximate gallery lighting conditions; however, it requires modifications to the equipment (below). As mentioned, Lavédrine adapted the instrument to work in transmission rather than reflectance mode to probe the relative lightfastness of early transparencies.

The most popular form of Whitmore's basic design, available as a complete unit from Newport Corporation (Stratford Connecticut), currently consists of an Apex xenon fibre illuminator that incorporates the lamp power supply, xenon bulb, and focusing optics in single relatively compact unit (Fig. 4). This is coupled with a Control Development (South Bend, Indiana) PDA-512 spectrometer with a measurement range of 200–1,100 nm depending on choice of slit width and resolution, and the optic fibres, filters, and lens assemblies. An alternative lens assembly holder that incorporates a camera mount (Fig. 5) is available from another supplier (Four Hour Day, Towson, Maryland). The whole setup costs less than $15,000 at today's prices. The argument in favour of the ''standard'' Newport equipment is that its performance is reasonably well characterised, and interlaboratory results are relatively consistent (Ford 2009b, Druzik and Pesme 2010); however, this is not an argument against the development and use of different instruments that may be cheaper, more compact, or better approximate real lighting conditions (below) or have some other advantage. The aim is to deliver a uniform spot of high-intensity light to the surface of an object and record the changing reflectance spectra, and it does not much matter how this is achieved, so long as it works.

The spectral power distribution (SPD) of the source depends on the nature of the illuminant and additional filtering; for example, Whitmore used a colored filter to reduce the correlated color temperature of the xenon source from 5,500 K, which is a reasonably good simulation of sunlight through UV-filtered window glass, to 2,850 K approximating incandescent lighting (Whitmore et al. 2000). Although the lower color temperature results in significantly slower fading rates for some colorants at the same intensity, most users employ the higher color temperature because it provides a built-in safety factor by generally overestimating responses expected of artificial lighting. As already mentioned Lerwill et al. (2008) have fitted a tuneable bandpass filter to the source. White LED and

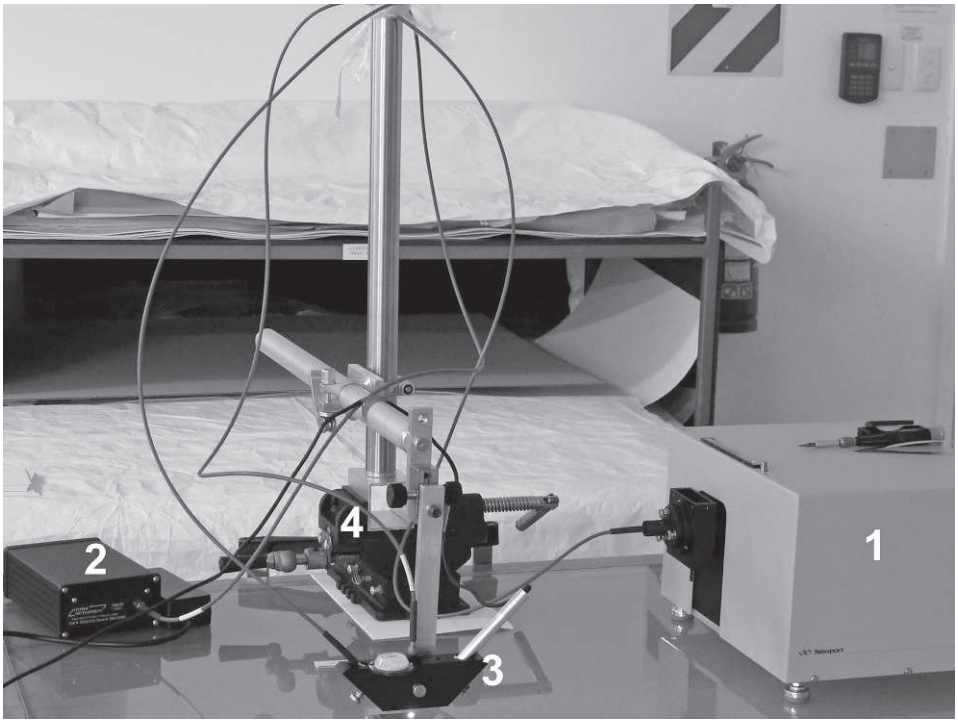

Figure 4. Portable Newport Oriel Microfade Tester. (1) Apex xenon fibre illumination lamp; (2) Control Development PDA 512 USB UV-Vis spectrometer; (3) measuring head; (4) X-Y translation stage and support armatures.

halogen sources have been substituted for xenon (Łojewski et al. 2011, Druzik 2012), and while at present they deliver lower fluxes, the situation will undoubtedly change (Fig. 6). Whitmore and Tao (2010, Tao and Whitmore 2010) have recently replaced the glass condenser and collimating lenses in a Newport Apex xenon lamp with parabolic mirrors overcoming spectral power distribution (SPD) reproducibility problems associated with chromatic aberration of the condenser and allowing measurement into the near-UV, thereby replicating daylight through unfiltered window glass.

Other modifications such as autofocus (Liang et al. 2011) are optional rather than essential or have drawbacks. For example, a version in which the light is delivered to and received from the test area directly through a bifurcated optical fibre (Fig. 6) without lenses (McGlinchey 2008, Druzik 2010) delivers minor gains in portability and ease of setup; however, the modification sacrifices key advantages of Whitmore's design, most notably the focal length (about 12 mm), which allows the measuring head to stand off the surface being measured, thereby avoiding physical contact with the object, the ability to use a camera to easily locate and record the exact area under test, and testing through glazing.

Microscope boom stands can be easily adapted to provide a support for the measuring head and controlled movement across artworks and other large objects. Mounting the measuring head support on an X-Y or X-Y-Z translation stage with motorised (Lerwill et al. 2008) or manual control (Ford 2009a) (Fig. 4) significantly improves the instrument's useability and avoids the need to move the object under test. Like

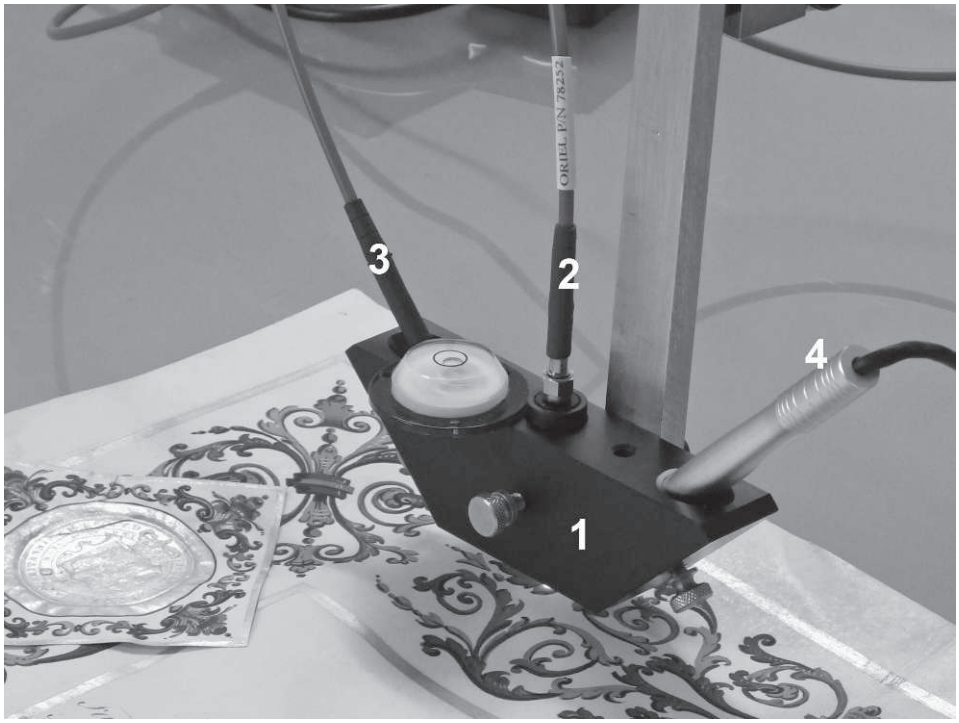

Figure 5. Probe detail. (1) 4 Hour Day probe block; (2) illumination fibre and lens assembly; (3) spectrometer fibre and lens assembly; (4) USB microscope camera.

micrography, with which it shares optical stability and focus requirements, good stability of the supporting structure for the measuring head is critical, a requirement that tends to work against portability, however small the light source or spectrometer.

In principle any fibre optic visible spectrometer is suitable; however, in practice the option to continuously monitor live ΔE using supplied software is not common. This capacity, which is a minimum requirement for microfading, is important for monitoring the progress of a test so that in (the rare) cases where there is a risk of perceptible damage, it can be terminated. Live ΔE can be added to most spectrometers via third party data acquisition and instrument control software such as National Instrument's Labview; however, the programming required is a specialised skill.

Data acquisition, analysis, and reporting are probably the biggest impediments to the efficient use of microfading as a rapid screening tool for most users. GCI Spectral Viewer™, a free program written specifically for the Control Development spectrometer data files for microfadometry by Lionel Keene (Getty Conservation Institute), is very useful; however, it stores data in a proprietary format that is unlikely to be readable into the future and has limited data analysis and presentation options, and extracting data for further analysis requires cutting and pasting by hand. The use of macros in spreadsheets like Microsoft Excel allow the automation of data acquisition from any spectrometer data file and subsequent data post-processing and visualisation in a form that can be easily exported to report templates in Microsoft Word or PowerPoint with live update between them.

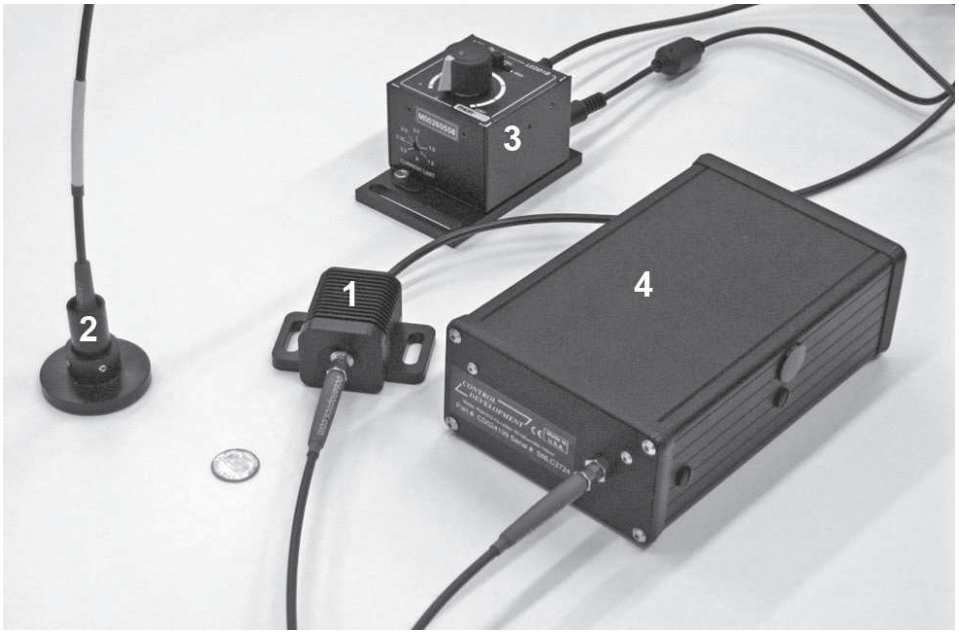

Figure 6. Prototype mini- microfade tester, GCI. (1) LED illuminator; (2) bifurcated lensless probe; (3) variable LED power supply; (4) spectrometer.

A question for institutions with a need for more accurate fading rate data is whether to purchase the equipment and develop the necessary skills and knowledge in-house or to contract in microfading services. At the time of writing, there is at least one contract microfading service available. Most organisations have a short list of important collection items that are always in demand for exhibition or loan and/or are thought to be particularly vulnerable to fading, and for many of these it might be enough to have these assessed. This is likely to be true for archives and libraries with limited exhibition programs. Large museums with diverse collections in which light-driven object replacement programmes are an integral part of their preventive conservation strategy will find it cost effective to acquire their own microfade testing capacity, and it is likely that it will be a standard option for central service laboratories like the Canadian Conservation Institute (who already have it).

As a routine screening tool, the equipment and data interpretation are sufficiently straightforward for a conservator trained in its use to obtain much better and more specific fading data than is available from the literature. There are some manual skills involved in using the equipment, and the flexibility to develop (and validate) measurement methods for different types of objects and surfaces is important, particularly for diverse collections. Acquiring, analysing, and interpreting the data involves using spectrometer software and programs like XL or GCI Spectral Viewer, and the operator needs sufficient background or training to interpret visible spectra and the characteristic patterns of spectral change that accompany changes in the absorption bands of colorants and substrates during fading. Like other scientific analytical techniques such as XRF and infrared spectroscopy that were once purely the domain of specialist scientists, the level of expertise and theoretical understanding required depends on the questions being asked—which at their most basic in the case of

lightfastness testing is which objects are at most risk of fading? At times this might be simplistic; for example, unravelling the role of the different contributions of structural colors and biopigments in animal coloration is difficult even for highly specialised scientists in the area, let alone interpreting changes to those colors. In cases like this the contribution of microfading may be limited to establishing an upper limit to light fading; however, mitigating the risk of unacceptable fading is truly a case of not letting the perfect become the enemy of the good.

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