MICRO-FADING TESTS TO PREDICT THE RESULT OF EXHIBITION: PROGRESS AND PROSPECTS

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ABSTRACT

In our laboratory we have developed a micro-fading tester, a device capable of performing non-destructive accelerated fading tests on sub-millimetre areas of coloured materials. The original purpose of these micro-fading tests was to provide rapid 'screening' of the colourants present on artifacts and to identify those having extreme sensitivity to visible region light exposure. Recent field tests have made it clear that another important application of these test results is the prediction of colour changes that would result from light exposure in particular exhibition conditions and schedules. In this paper we explore the accuracy of the micro-fading tests, and the factors that affect that accuracy. An overall judgment of the use of micro-fading test results and the prospects for future refinement of the tests are discussed.

INTRODUCTION

In a recent publication [1] we reported the development and testing of a new device (shown schematically in Fig. 1) capable of detecting fugitive colourants through non-destructive light-fastness measurements made directly on artifacts. In principle, the device works as a reflectance spectrophotometer, with the critical features of a very intense probe beam and a diode-array detector. Through the use of very small test areas (c. 0.4mm diameter) and continuous real-time colour measurements to monitor the course of fading, the tests can be performed successfully without perceptible colour changes occurring in the object. High intensities of visible light (c. 7 million lux at the test area) produce rapid fading of fugitive colourants (a $\Delta E = 5$ colour change is produced in about five minutes for materials having lightfastness equivalent to Blue Wool no. 1), and the fading that results was found to be very similar to that in more conventional xenon-light accelerated aging tests. The absorption of light by the sample was found to raise the surface temperature to a maximum of about 45-50°C in the test area. Since the initial construction and testing of this device, we have used it successfully to test art objects in a number of museum conservation studios. In these field trials the instrument has proved capable of performing accelerated fading tests rapidly and with no perceptible alterations in the objects tested. By comparing the fading rates of materials on artifacts to the measured fading of reference standards (Blue Wool cloths), fugitive colourants were identified on a number of objects, thus providing essential information for their future care.

The field tests in museums demonstrated the capabilities of the instrument for its intended use as a detector of fugitive colours. However, many of the conservators who participated in the tests envisaged a related, yet different, use for the test results: they judged the fading produced in the accelerated tests as a prediction of the course of fading of the objects in their galleries. To use the terminology of Wilhelm and Brower [2, p. 64], the micro-fading tests, which were designed to be *comparative* tests (relating the
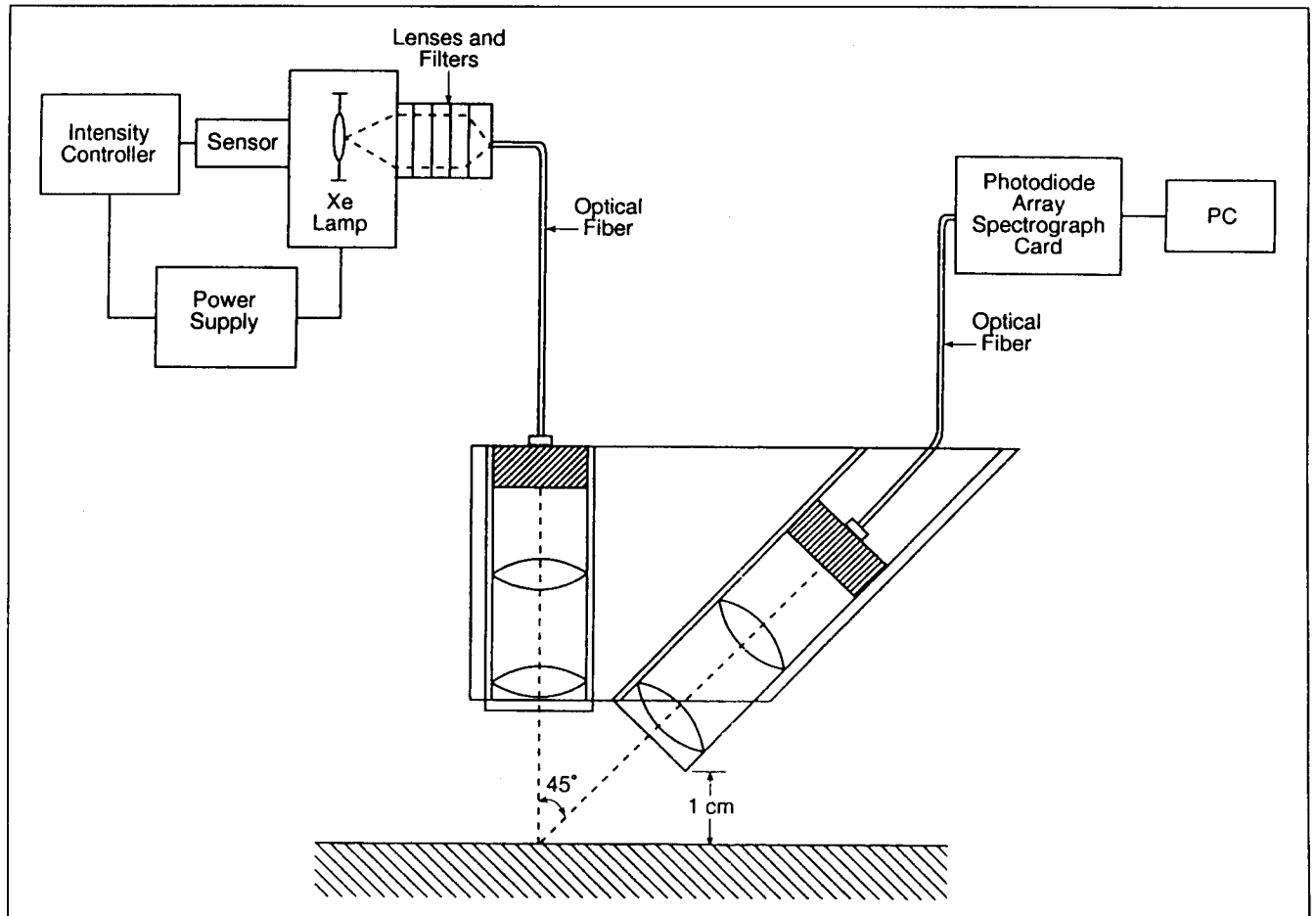

Fig. 1   Schematic of micro-fading tester (after [1]). Reprinted from the *Journal of the American Institute for Conservation*, Vol. 38, No. 3 with the permission of the American Institute for Conservation of Historic and Artistic Works, 1717 K Street NW, Suite 200, Washington, DC 20006, USA.

lightfastness of an artifact material to a fading reference material such as a Blue Wool), were being interpreted as *predictive* tests. Just as accelerated light tests of materials tend to be translated into 'museum years' of equivalent exposure dose, conservators seemed strongly inclined to view the micro-fading test results in terms of the fading that would result from equivalent lux-hours of exposure in the galleries of their institutions. Particularly for objects where exhibition policy is a negotiated compromise of lighting type, level, and accumulated dose, information about the degree of fading expected from a particular dose was considered absolutely vital information for that decision.

It has long been recognized that accelerated light-fading tests are convenient, but only approximate, indicators of overall light stability. For example, in the American Society for Testing and Materials (ASTM) standard test method for the lightfastness of pigments used in artists' paints [3], it is stated that 'these test methods are used to approximate the colour change that can be expected over time in pigments used in artists' paints in normal indoor exposure'. Yet a cautionary note follows immediately: 'The colour changes that result from accelerated exposure may not duplicate the results of normal indoor exposure in a home or gallery. The relative resistance to change, however, can be established so pigments can be assigned to categories of relative lightfastness'. A number of research efforts have been devoted to comparison of the course of accelerated and natural fading (for a critical review, see [4]), with correlations that are good overall, though occasionally poor [2, pp. 73-75; 5]. These poor correlations are thought to arise from test conditions that fail to replicate a critical feature of natural fading, or that cause changes in the physical or chemical nature of the colourants so that reactions in accelerated tests take a fundamentally different course to those in natural exposure.

In developing accelerated testing protocols for predicting the performance of materials, recognized difficulties and inherent uncertainties of the test procedures, analytical methods and sample variations are usually dealt with by scaling-up the tests to include many numbers of sample types, exposed in a variety of test conditions and monitored with an array of measurements. Through statistical analysis and comparison of accelerated test results to natural aging test results, an accelerated test protocol evolves that is assumed to be a reasonable estimation of future performance. For predicting the future aging of art objects

housed in galleries, the good news is that the controlled conditions found in museums are likely to have much less variation than, for example, outdoor weathering. The bad news is that, by its nature, each artifact is essentially unique in terms of its materials, construction and history, and the study of many surrogate samples may not improve the prediction for a particular artifact. The recognition of the unique nature of every artifact motivated the development of the micro-fading tester, which is capable of extracting information about material stability from the object itself.

The micro-fading tester can indeed provide some information about a particular artifact: that is, the response of the colourant systems to the accelerated test conditions. The question that follows is, how close are these results to predictions of natural fading in gallery conditions? In this paper we examine various factors that affect the accuracy of micro-fading tests and the degree of confidence one can reasonably have in assessing the test results as forecasts of future performance of the materials of an artifact. We suggest criteria that might be used to judge the accuracy of the forecast, and we highlight a number of variations on the test protocol that may help to improve that accuracy. Finally, we offer some judgments about the use of micro-fading test results for predicting future performance and suggestions for further research.

FACTORS AFFECTING THE ACCURACY OF THE MICRO-FADING TEST

Colour measurements

The spectrophotometric colour measurements that are made with this instrument generally conform to the criteria defined in the standard protocols for so-called bidirectional geometry measurements (in this case, for normally incident illumination and detection of reflected light at 45° to the normal) [5, 6]. For sample types that are conducive to this type of measurement (planar, opaque materials), the measurements of colour and colour differences correlate very well with a commercial spectrophotometer. Figure 2a shows the comparison of colour differences between Munsell paint chips calculated from spectral measurements made with the micro-fading tester and a commercial reflectance spectrophotometer.

Samples that do not conform to this ideal smooth, opaque and uniform colour area are less well described by the measurements made with the micro-fading tester. In particular, the discrepancy
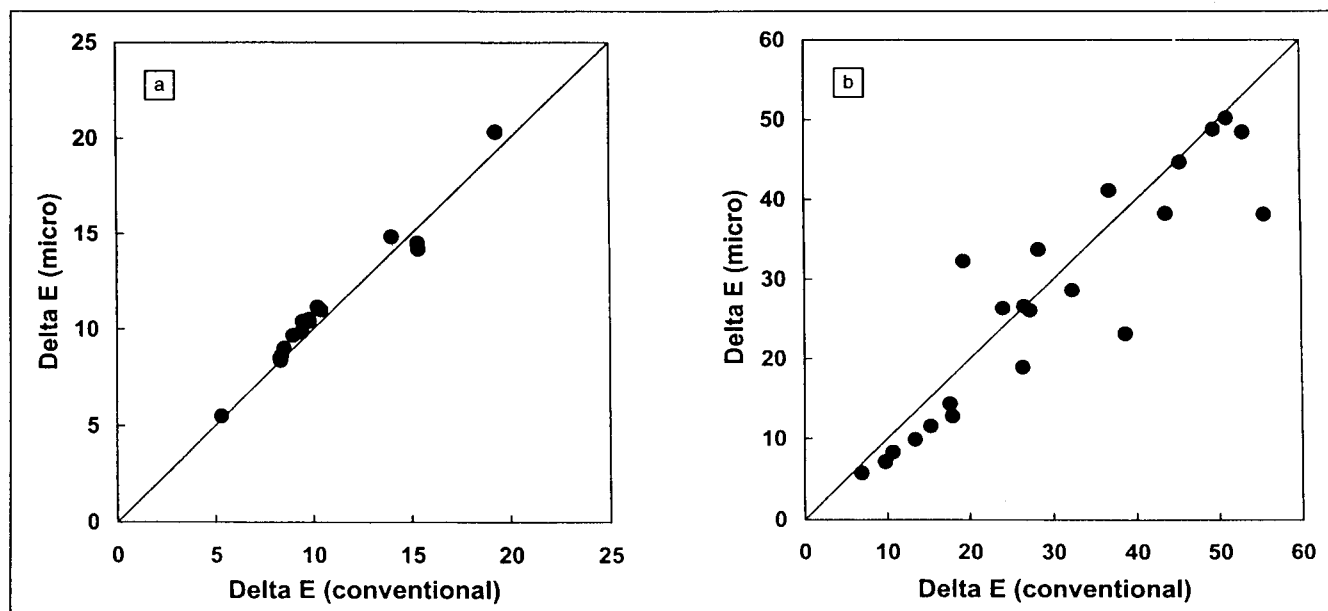

Fig. 2   (a) Colour differences of Munsell chips measured with micro-fading tester and conventional reflectance spectrophotometer. (b) Colour differences of textile swatches measured with micro-fading tester and conventional reflectance spectrophotometer.
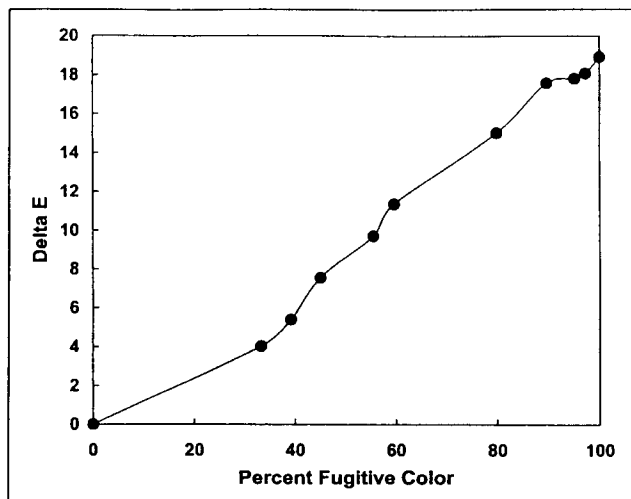
Fig. 3   Colour differences (measured on a conventional reflectance spectrophotometer) of additive mixtures of black ink dots on yellow paper after fading of the paper to $\Delta E = 19$.
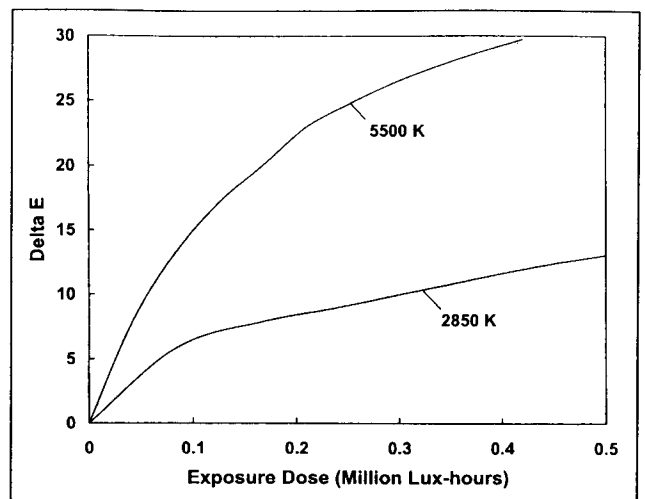

Fig. 4   Micro-fading test results for a yellow marker pen on paper, exposed to a xenon source filtered to produce a high (5500K) and low (2850K) correlated colour temperature.

with conventional colour measurements increases for samples that are not well represented by the tiny test areas probed in the micro-fading tester. Thus, materials which have textured and/or translucent surfaces, such as textiles, produce colour changes in the micro-measurements that are somewhat smaller than those recorded with a conventional instrument that views a larger (c. 3mm diameter) area (see Fig. 2b). Since it is impossible to define an absolute reference measurement to which the micro-fading measurements may be compared, the accuracy of the measurements for these irregularly coloured materials cannot be quantified. Nevertheless, in our experience the comparison shown in Figure 2b is fairly typical of the discrepancies to be expected in these measurements: colour differences measured in the micro-fading tester for materials having irregular or textured surfaces will tend to be lower (by as much as 25% for very uneven surfaces) than similar measurements made by a conventional reflectance spectrophotometer.

Colour changes measured on tiny areas of colour will also not translate accurately to the changes in appearance of the material if the colour is not uniform: that is, if the colour area is perceived as an additive mixture of small coloured areas. Scumbled passages of paint, dot-matrix paintings or prints, or even obliquely illuminated roughly textured surfaces displaying patterns of light and shadow [7, Figure 14], will be read by a viewer at a distance as the sum of the colour contributions from the smaller areas. The micro-fading tests provide information only on the colour change of an individual 0.4mm-diameter area, and the appearance change of the additive colour mixture will be different, depending on the relative proportions and fading tendencies of the components. Figure 3 shows an example of an additive mixture of black dots on a faded yellow paper, in which the measured ΔE of the additive mixture is reduced as the proportion of stable black in the mixture increases. Thus, the micro-fading test of the fugitive yellow paper would greatly overestimate the overall appearance change of the larger colour area.

There is no general method for translating the results of fading of small areas of additive mixtures into the overall colour change of an additive colour mixture. The only realistic estimation may be to assume the colour change of the mixture will be roughly proportional to the fraction of fugitive colour in the mixture.

Spectral distribution of light source
The light-induced fading reactions of colourants are generally wavelength-dependent, and the sensitivity of a colourant system

to the different wavelengths of light is known as its action spectrum [4, p. 63]. While a comprehensive determination of the action spectra of colourant systems has yet to be done, it is common to find that particular colourant systems tend to have greater sensitivity to certain wavelengths of light, and consequently the overall fading rates will depend on the spectral distribution of the light source [8]. The micro-fading tester uses a xenon arc lamp as the light source for the fading test. The spectrum of the filtered output of the lamp is continuous and of relatively constant intensity across the visible wavelength region [1, Fig. 2]. This source thus has a high correlated colour temperature (around 5500K) and has been found to be a reasonably good simulation of the visible spectrum of daylight. As a result, the fading rates measured with the micro-fading tester are believed to be most relevant to light stability in galleries illuminated with daylight, or with other high colour temperature broadband sources.

For gallery settings in which this is not the case, the straightforward micro-fading test results may not be accurate predictors of light fading. However, modifications can be made both to the device and to the test protocol for a better approximation of fading under other light sources. With the use of coloured glass filters, the output of the xenon lamp can be modified to simulate a lower colour temperature source. As expected, differences in fading rate can be observed for those colourant systems that are sensitive to the blue end of the visible spectrum (the wavelengths whose intensities are reduced when the colour temperature is decreased). Figure 4 shows fading results of a yellow colourant that fades much more slowly (by a factor of about 5) when illuminated with a lower colour temperature source (a xenon lamp with a suitable filter) of identical photometric intensity.

The adaptation of the micro-fading tester for accelerating exposure to a light source whose spectrum is not continuous, but is composed rather of a series of discrete lines, is not as straightforward. In principle, the micro-fading tester output could be split into a number of optical fibres, each filtered to pass a narrow band of wavelengths corresponding to one of the bands of the gallery light source, then recombined to create a spectrum of the desired discrete wavelengths. (This same strategy could also be used to construct a spectral output to simulate lighting environments having mixed sources, such as daylight and artificial sources.) We have not performed this modification, and it is unknown how the results of the modified test will relate to the test with a continuous spectrum of similar colour temperature.

Angular distribution of light source

In the micro-fading tester, focused light impinges on a sample at angles within 15° of the surface normal. Clearly this illumination geometry does not resemble gallery settings, where typically a combination of diffuse and obliquely directed light is used. The angle at which objects are illuminated has been found to have a small effect on the photochemical damage that results, and is related to the penetration of the light through the surface and the path length of the light within the material [9-13]. The general trend found in these studies is that the effect of different angles of illumination is relatively small except for raking light that cannot enter the surface of the object; near-normal incidence produces the maximum degradation because of the efficient penetration of the light into the material; and diffuse or oblique lighting can produce somewhat more damage in a transparent material due to the greater path length of light through it. Overall, the micro-fading test results are believed to differ from gallery performance by no more than a factor of 2 as a result of the angular distribution of the illumination.

Reciprocity failure

Probably the most difficult problem to recognize and remedy in accelerated light-aging tests is the failure of the so-called reciprocity principle: that is, when the fading under high light intensities does not resemble the outcome of exposure to the same dose of lower intensity illumination. This condition is only discovered when tests are carried out at a wide range of light intensities and the dose-response of the fading is found to be different (either greater or lesser fading at equal dose) at higher intensities [2, 4, 14]. In cases where this has been observed, the reciprocity failure has been attributed to some condition that occurs under exposure to high light intensities and not under low intensities: greater sample temperatures that can alter reaction rates, perhaps by desiccating the sample; oxygen starvation in the sample, caused by the photo-oxidation reactions outpacing the diffusion of oxygen into the sample and thus suppressing the degradation by depriving it of a critical reactant; or rapid reaction to create high concentrations of intermediate compounds that can react together in ways not attainable at the lower concentrations produced at low light intensities [2, 4, 15].

While many workers have attempted to define the tolerable limits of light intensity so that reciprocity failure is avoided, such prescriptions are in fact unrealistic: reciprocity is not an intrinsic attribute of an aging test, rather it describes the response of a particular sample in that test. Whether a sample shows unnatural fading under high light intensities will depend on the nature of the individual sample: the rate of fading reactions depends not on the total light intensity but on the intensity of the photo-chemically active wavelengths of light, which are different for different colourant systems; the importance of moisture and oxygen to fading reactions is peculiar to each colourant system; and the possible significance of ancillary reactions, such as oxygen diffusion or intermediate side-reactions, is also difficult to generalize. Furthermore, for accelerated tests on artifacts, it is extremely unlikely that such key information will be known when making judgments regarding possible reciprocity failure. For all these reasons, reciprocity is generally assumed to hold unless there is clear evidence that certain materials, or a large number of samples, have shown discrepancies between tests done at high and low light intensities.

Despite the risk of encountering reciprocity failures when testing at the high light intensities used in the micro-fading tester, there are some key features of this device that may work to reduce that risk, or at least make it more predictable. By filtering out infrared wavelengths of the light source, the heating effect on the sample is limited (temperatures reach 50°C maximum), and the risk of desiccating the sample during the brief testing period is small. Similarly, the rapidity of the test and the sensitivity of the device make it possible to probe the sample while avoiding the long irradiation periods or the large degree of reaction that might desiccate the medium or consume the available oxygen in the sample. Finally, the continuous real-time colour measurements allow fading results to be obtained at very small doses before oxygen or water depletion is likely to occur, and make it possible to recognize the changes in fading kinetics that might result if oxygen or water depletion should eventually occur.

In cases where accurate predictions of fading behaviour are desired, reciprocity should be checked in the usual way, by comparing dose-responses at varying incident light intensities. Figure 5 shows an example of a comparison in which the micro-fading tester has been modified using a number of screens to reduce the intensity of the illumination. The colour changes are produced at successively slower rates with reduction of the light intensity (Fig. 5a), but when adjusted for dose the fading is seen to occur at nearly identical rates for the different test conditions (Fig. 5b). The lowest feasible light intensity depends on the rate of fading and on the length of exposure that is practical. While this lowest light intensity is still likely to be many times the ambient light intensity encountered in gallery settings, the constancy of the dose-response over a wide range may be taken as evidence that ancillary processes such as oxygen diffusion are unlikely to be important factors in the test.
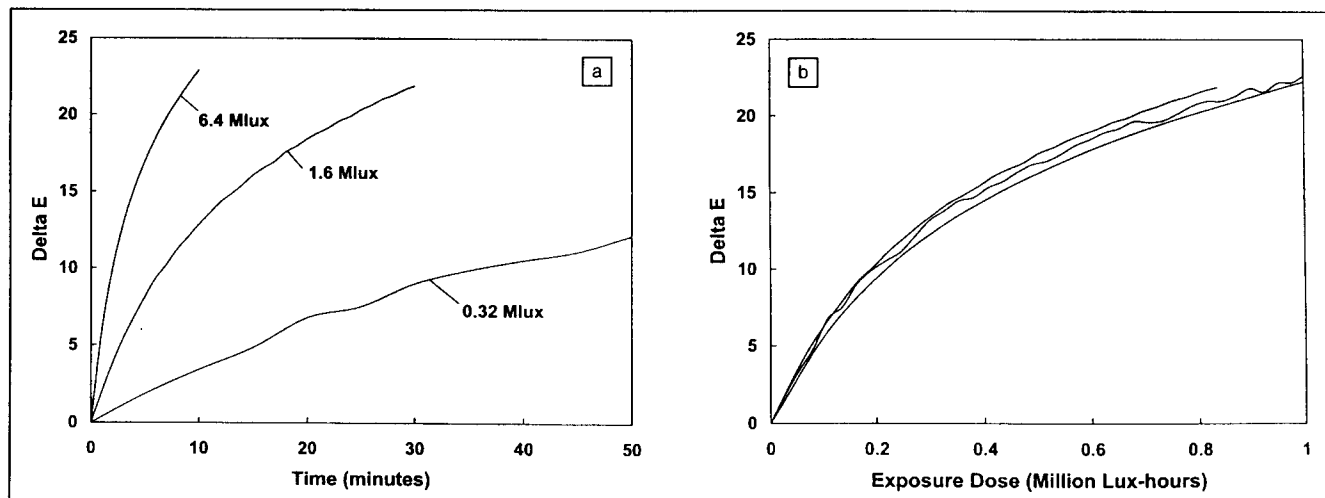

Fig. 5 Micro-fading test results at various light intensities for gouache applied to paper: (a) colour changes as a function of time during the tests; and (b) colour changes as a function of dose for the same tests.
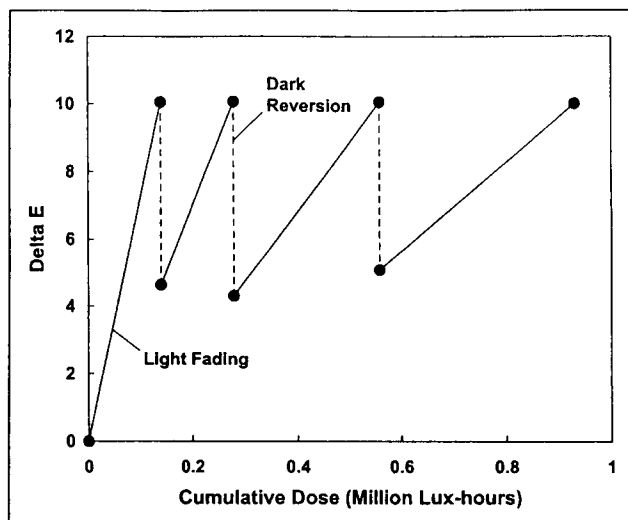
Fig. 6   Results of an interrupted micro-fading test of the blue colourant on a cyanotype.

Another test protocol that might in theory be helpful in diagnosing reciprocity failure is interrupted exposure. In this procedure, a micro-fading test is performed to produce a fading change with a well-defined rate. The light exposure is then terminated by closing a shutter at the lamp, while all else remains in place. After a period of time the shutter is re-opened and another fading test is done. The initial rate of fading for this second test is compared to the final fading rate of the first test. If there is a significant difference after the dark period, it is possible that water or oxygen was depleted during the first test, and the critical reactant was replenished in the sample while the light was off. If this is observed, the initial fading rate, when water and oxygen are present at their normal levels, may be a better estimate for the fading rate at ambient light levels. While we have attempted to observe this behaviour in interrupted exposure tests of samples known to be relatively impermeable to oxygen or moisture-sensitive, we have not been successful in observing any change in fading rate between the end of one test and the beginning of a subsequent test. Consequently, we cannot offer guidelines at this stage for the length of recovery period that might be needed in order to detect evidence for reciprocity failure by this method.

Complex or unusual consequences of light exposure

Some light reactions are known to be processes that do not lead to immediate irreversible colourant loss. Some dyes and photographic materials are known to fade by being chemically reduced during light exposure, only to resume their original appearance as the colourant is regenerated in subsequent oxidation reactions after the light exposure has ended [16]. Alternatively, it has been reported that colour can deepen from decreased dye aggregation in the heat of an exposure test, and subsequent cooling can restore the original colour [17]. An interrupted micro-fading test can be used to detect such rapid colour reversion. Figure 6 shows the interrupted exposure test of a cyanotype, the colour of which fades during the light exposure but recovers during a dark rest period.

There are other chemical reactions that occur separately from photochemical processes and these can be important in determining the overall appearance changes resulting from light exposure. Perhaps the most familiar is the colour reversion of paper that has been exposed to light [18-20]. Since the micro-fading tester only provides information about the colour changes that occur concurrently with the light exposure, the possibility of post-irradiation changes occurring long after the test cannot be

investigated with this device alone. The only reasonable method is to re-examine tested areas visually at a later time. While such post-irradiation effects that either restore colour or create new colour are known, they have not been found to occur to any great degree with conventional colourant systems.

CONCLUSIONS

The accurate prediction of the fading of different colourant systems is an elusive, and perhaps unachievable, goal. So many aging processes may contribute to change over time that one must hesitate to accept at face value the apparent forecast of light aging, or any accelerated aging, tests. Nevertheless, it is difficult to argue with the notion that exhibition policy guided by some information, however approximate, is preferable to decisions made in the absence of any information at all.

In this context, the potential of the micro-fading tester, which provides object-specific information about light sensitivity, has yet to be explored fully. For objects where the accuracy of the prediction is important to guide exhibition policy, we have suggested modifications of the simple test protocols that could prove useful in assessing or improving the validity of the test. Recognizing those materials that are not evaluated well by the tester in its current design (such as textured or transparent materials, or additive colour mixtures) will avoid spurious test results that yield misleading predictions of the course of fading, although it is still possible to use the test to detect light sensitivity qualitatively. Clearly, the modification of the tester by adjusting the light source so as to provide a good simulation of the gallery lighting environment is a prudent step. It is possible that other modified test procedures, such as the tests at various lower light intensities and the interrupted exposure tests, might also alert the operator to spurious results that may arise from reciprocity failures or post-irradiation colour changes, but it remains to be seen whether the prediction of behaviour can be improved with further modifications of the tests in these circumstances.

As with any accelerated aging test, it is likely that confidence in interpreting the test results as predictive will rest ultimately on the nature of the specific artifact. Certain types of object, such as paints, may have a history of performing relatively straightforwardly in accelerated light-aging tests, and confidence in the accuracy of the test results may be reasonably high. Other objects, such as photographic prints, that frequently show reciprocity failures in high-intensity light exposure tests or are known to have poor dark stability, may only rarely be predicted reliably in accelerated aging tests. Even in these cases, however, test results may still prove useful as a general guide. Experiments to compare predicted colour changes with actual fading behaviour for specific objects in well-characterized ambient lighting environments would be a useful subject of future research.

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