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FULL PAPER

A PORTABLE MICRO-FADING SPECTROMETER FOR VERSATILE LIGHTFASTNESS TESTING

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The design and experimental method for the use of a novel instrument for lightfastness measurements on an artwork is presented. The new micro-fading spectrometer design offers increased structural stability (which enables portability) and increased versatility over the previous, published design, broadening the scope of locations at which data can be acquired. This reduces the need for art handling or transportation in order to gain evidence-based risk assessments for the display of light-sensitive artworks. The instrument focuses a stabilized high powered xenon lamp to a spot 0.25 mm diameter (FWHM) while simultaneously monitoring colour and spectral change. This makes it possible to identify pigments and determine the lightfastness of materials effectively and non-destructively. With 2.59 mW or 0.82 lumen ($1.7 \cdot 10^7$ lux for a 0.25 mm focused spot) the instrument is capable of fading Blue Wool 1 to a measured 11 ΔE_{ab} value (using CIE standard illuminant D65) in 15 min. The temperature increase created by focused radiation was measured to be 3 to 4 °C above room temperature. The system was stable within 0.12 ΔE_{ab} over 1 h and 0.31 ΔE_{ab} over 7 h. A safety evaluation of the technique is discussed which concludes that some caution should be employed when fading smooth, uniform areas of artworks. The instrument can also incorporate a linear variable filter. This enables the researcher to identify the active wavebands that cause certain degradation reactions and determine the degree of wavelength dependence of fading. Some preliminary results of fading experiments on Prussian blue samples from the studio materials of J. M. W Turner (1755-1851) are presented.

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1 Introduction

Those responsible for the world's cultural treasures within museums have a duty to preserve these works whilst allowing public access. Often these two requirements result in museum policy being driven in opposing directions. The necessity of illumination for the display of

photo-sensitive works of art is an example of this impasse. Therefore, the application of technology to solve issues in the conservation and display of works of art warrants further investigation.

To determine the safety of display and effectiveness of display policy, a novel micro-fading spectrometer has been designed and constructed taking inspiration from the Whitmore design[1,2] and its application[3,4,5]. An instrument was constructed that was capable of identifying materials more light sensitive than Blue Wool #2 through direct fading in artworks on a sub-millimetre diameter spot such that the faded spot is not discernable by the viewer. Fading and colour change are carried out simultaneously.

It is intended that some improvements on this design will increase the portability and ease with which a researcher can conduct micro-fading, so the need for object transportation is reduced, and therefore the rate and also scope of locations at which data can be acquired increased.

To increase the accuracy of colour measurements and improve the ease of application, some changes to the previous design were implemented. An improvement of the precision of probe positioning relative to the sample, a good homogeneity of illumination across the faded area, a controlled intensity at the illuminated surface from the lamp, and an improved ease of confocal probe alignment were amongst the changes. A reduction in the heating of the sample area by the illuminating spot was also achieved and a method of documenting the exact location of fading on an artwork is being developed.

The instrument also differs from a previous design by Paul Whitmore *et al* in that a linear variable filter system was added, which enables assessment of the wavelength dependence of fading and broadens the scope of information that can be acquired regarding fading of artist's materials.

Tests are carried out on sub-millimetre diameter spot size while at the same time monitoring change in the reflectance factor of the sampled region. To do this the monitored spectrum is converted using the Commission International de l'Eclairage (CIE) 1976 L*a*b* equation for the 2° standard observer under the standard illuminant D65. Via this method an automated calculation of colour difference of the fading spot is monitored in real time in ΔE_{ab} units.

2 Instrument Design and Performance

2.1 Instrument Design

The instrument developed is approximately half the cost of the previous published design. It is a flexible, compact, lightweight and mobile instrument which removes the need for transportation of art work and unnecessary art handling (Figures 1 and 2). It can function in two modes of operation: firstly, as a transportable compact microfading spectrometer capable of identifying the sensitivity of artifacts to visible light exposure, and secondly, with a linear variable filter to increase the scope of investigation beyond that of the broad spectrum. The latter application is discussed further in section 3.

For use as a microfadometer, a high-powered continuous-wave xenon light source (Ocean Optics HPX2000) is connected directly to a solarization resistant optical fibre with a 600 micron fibre core. The end of this fibre is connected to a confocal probe designed for this task, containing two matched achromatic pairs. Light passes through an extended hot mirror utilized to remove the infrared in order to reduce temperature and the ultraviolet to better simulate the museum environment (Figure 3). The filtered light is focused to a 0.25 mm spot by the matched achromatic doublet pair on the sample surface.

It is possible to move the location of the lenses in the probe as they are contained within lens tubes on adjustable mounts. Adjusting the position of the first lens (from the light source) alters the working distance and the size of the focused spot size. To a certain extent it is possible to do this without significantly altering the fading rate. This is because moving the first lens closer to the fibre output couples more light to the spot which compensates for the increase in fading area. This possible alteration of the instrument can lead to increased sampling area, and therefore data that is more representative of varied and highly-textured surfaces. This would be useful for example when fading reconstructed paint samples rather than actual art work where a small faded area is not an important safety measure to prevent visible damage.

In order to monitor colour change, scattered light from the small sample area is then coupled back into the optical system via another optical probe of the same design at 45 degrees to the normal. Sampled radiation then passes through a neutral density filter to avoid saturation of the fibre optic spectrometer. The spectrometer (Avantes Avaspec 2048) receives this signal via an optical fibre, and

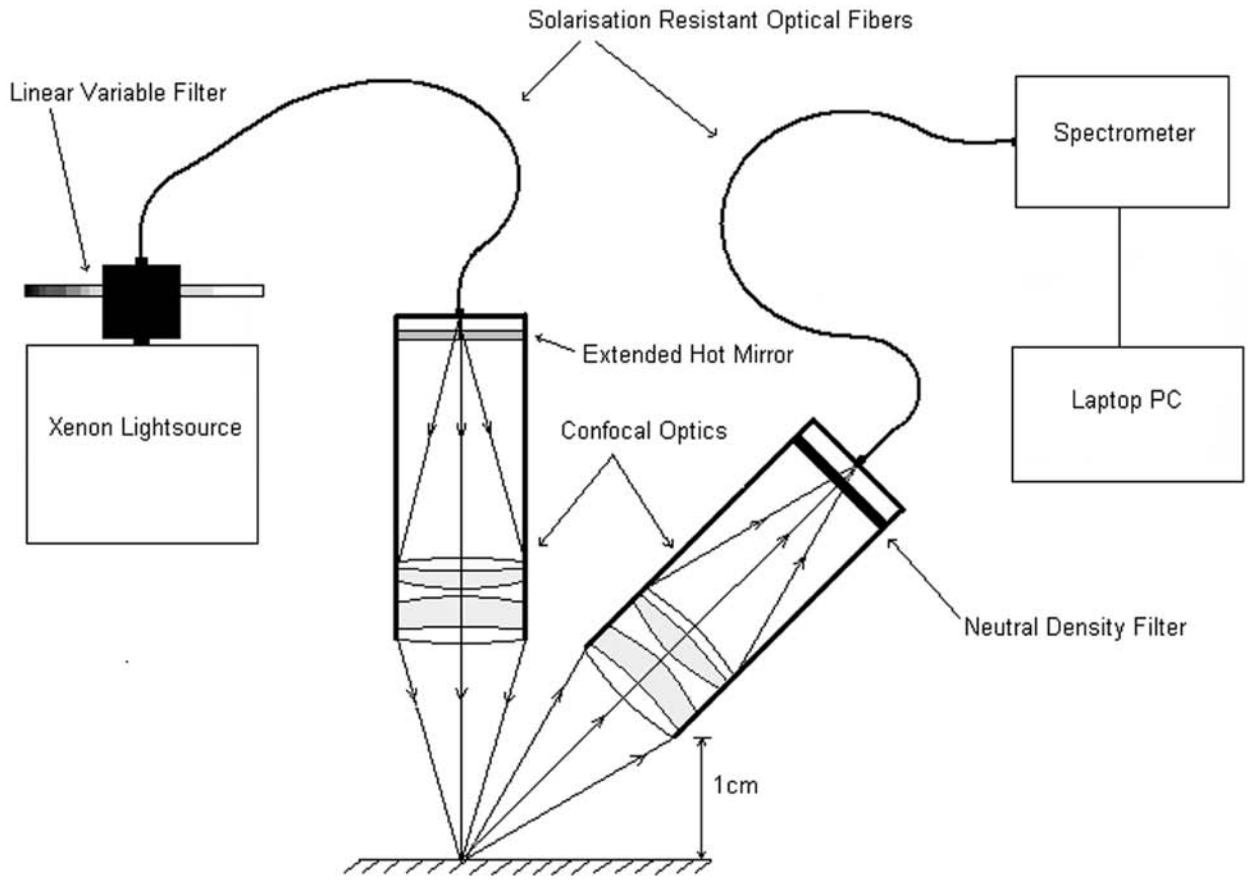

Figure 1: A schematic representation of the Microfadometer, including linear variable filter.

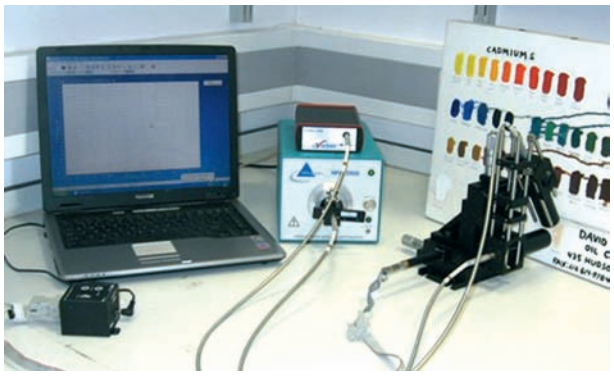

Figure 2: The instrument fading a sample.

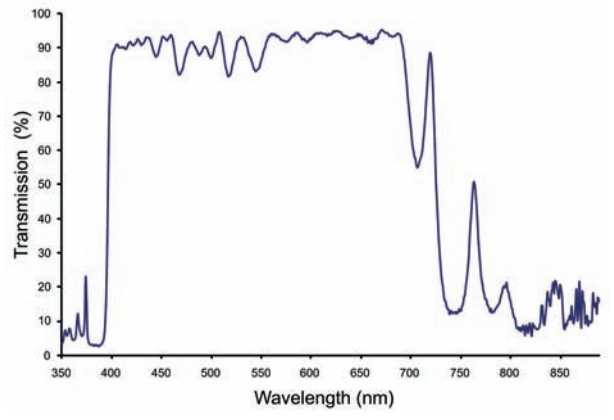

Figure 3: The measured transmission of the extended hot mirror used to filter the incident radiation of the instrument.

the software (AvaSoft 7.0) analyzes change in the spectrum and the rate of fading occurring in real time.

The probe is mounted on an XYZ stage capable of sub-micron scale movements. The Z axis stage is motorized. It is therefore possible to achieve fine alignment of the probe with the surface remotely rather than leaning over the artwork. This in turn enables adjustment when the probe is beyond arms-reach, e.g. over an art work when the probe is mounted on a gantry to enable movement over the surface of an artwork that is laid flat. This is also an important aspect of the design, as it becomes possible to achieve best focus remotely.

To achieve best focus, the software gives the integrated counts from the reflected spectrum over the full spectral range (400 to 700nm), which enables fine adjustments undetectable when aligning by eye. By making small incremental adjustments in position that would not be possible using a manual micrometer screw, it is possible to define best focus to a greater accuracy.

Future efforts to develop the instrument will include attaching a webcam to the probe which will enable a record of the location of fading on an artwork to be recorded. As well as this, an automated

fadometer system is in development which will be used to produce large amounts of data for a variety of samples and enable greater throughput to more accurately categorize the behaviour of a larger number of samples.

2.2 Probe Alignment

To ensure confocality, both probes were illuminated with low intensity radiation and focused onto a CCD chip (Figure 4). For easier analysis, in Figure 4c the red area indicates the sampling area of the receiving probe and green the illuminating area (this creates a yellow overlap). The yellow region indicates where both fading and colour monitoring takes place.

When correctly aligned, it was shown that best focus of the probe provides the maximum signal to the spectrometer, and ensures reproducible spot size. Failure to align correctly leads to the probe focusing incorrectly, which can lead to a large variation in the calculated fading rate.

To fade a sample, the instrument operates as a reflectance spectrometer with a high powered light source. In order to make reflection measurements, a dark spectrum and reference spectrum are acquired. The reference spectrum is recorded on a polished barium sulphate sample.

A neutral density filter is used to reduce the beam to a level where best focus can be obtained without a significant level of radiation being incident on

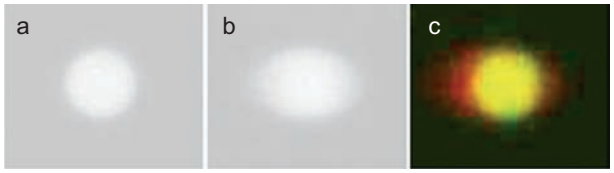

Figure 4: Images produced in focusing the instrument probes onto a CCD chip (a) illuminating probe, (b) sampling probe, (c) illuminating and sampling probe (a and b) combined in alignment.

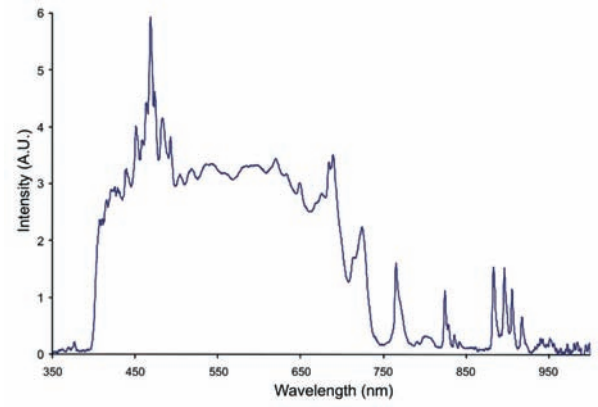

Figure 5: The relative power spectrum of incident radiation used in broad spectrum fading tests.

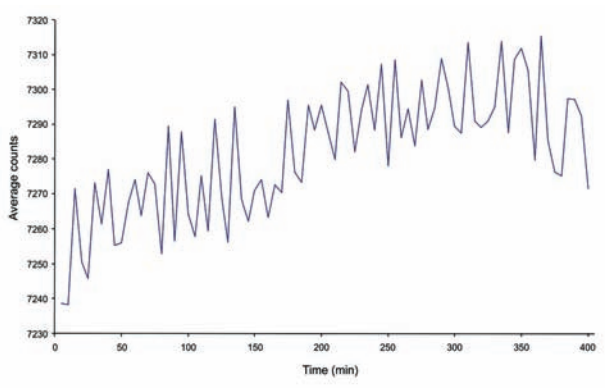

Figure 6: The total counts of the spectrometer from 400 nm to 700 nm over 400 min.

the sample. The probe is adjusted on the sample in order to come to best focus and acquire maximum reflected intensity on the object in the desired location. The shutter of the lamp is then used to stop illumination as the neutral density filter is being taken out in preparation for fading. Colour differences are monitored in real time using the spectrometer software in order to prevent fading beyond acceptable levels which have been independently determined in the development process.

2.3 Light Source Behaviour

The instrument produces 2.59 mW or 0.82 lumen ($1.7 \cdot 10^7$ lux for a 0.25 mm focused spot). The relative power spectrum of light incident on the sample measured using a calibrated spectrometer is shown in Figure 5. The xenon bulb output will alter as it ages and this makes it necessary to monitor probe output regularly.

If it is desired to compare the time a sample undergoes fading using the fadometer to years in a gallery setting, we need to assume the sample would fade to the same degree independent of the rate in which it is faded (or that reciprocity holds[6]). At 50 lux for 8 h per day 7 days per week, the fading rate of the instrument can be considered as 1 min approximately being equivalent to 2 years in a gallery setting assuming reciprocity holds over 5 orders of magnitude. We will examine the issue of reciprocity for a range of fugitive pigments in a separate study. Unlike conventional fading, the microfadometer is capable of testing reciprocity over at least 4 orders of magnitude. Other limitations of the technique which prevent more certain statements in this vein being made, such as difference in the spectral power distribution between gallery lighting and the xenon lamp of the instrument and sample colour reversion are discussed by Whitmore et al [2].

Analysis of the stability of the system took place over 400 min using illumination of barium sulphate as a non fugitive reference over this period. Variation at any wavelength from 410 to 720 nm was within 1.5% with the majority within 1% variation.

Total counts of the spectrometer at all wavelengths increased 1.1% over the period (Figure 6). The dark current over 7 h was constantly monitored and subtracted by the spectrometer software.

The stability of the system was shown to produce an error no greater than ΔE_{ab} of 0.31 at any reading over the 7 h period. The initial hour produced no more than a ΔE_{ab} of 0.12 at any reading.

2.4 Probe Position Sensitivity

In order to determine empirically the diameter of the area that would be faded by the incident light, the focused spot of the probe was analyzed by observing its alteration through focus using a CCD. FWHM values were taken when varying the working distance of the probe to the CCD (Figure 7) which gave a spot size on the CCD chip of 33 pixels or 0.25 mm. It was verified that 1 pixel width was 7.5 µm as per manufacturer specifications. From this technique it was possible to determine the spot size diameter to 1 pixel or 6% of the fading area. Figure 7 illustrates that the diameter of the spot did not alter for 50 µm through focus.

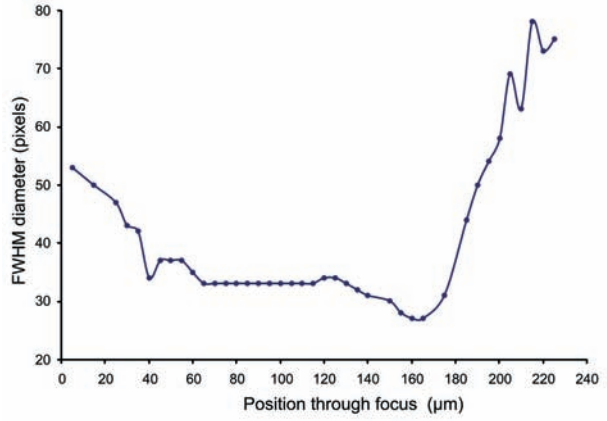

Figure 7: The FWHM of the focused spot profile through focus in 5 µm increments.

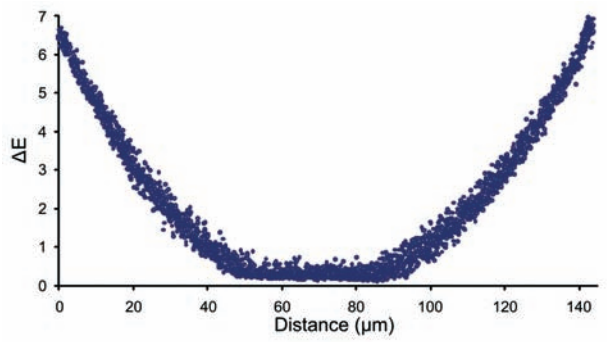

Figure 8: Alteration of colour measurements from microfadometer probe movements in 50 nm increments through focus represented in relative ΔE_{ab} values when measuring a white tile and comparing the colour measured with L=100 a=0 b=0.

The effect that small errors in focusing have on received signal and colour measurements was investigated. The sensitivity in positioning of the probe relative to the surface being sampled was determined by calculating relative ΔE_{ab} at various locations through focus, compared to values L=100 a=0 b=0. This provided an illustration of how a small change in probe position, (for example relaxation of the probe holder, or altering of the sample/probe geometry in repositioning the probe from the white target to sample) can create error in measured colour.

The relative colour difference was measured moving the probe in 50 nm increments through focus along the optical axis when illuminating a polished barium sulphate white tile. Colour data readings are shown in Figure 8, demonstrating that the colour measurements did not alter for 40 µm through focus. From this analysis, colour measurement is shown to be more sensitive than the variation in size of the illuminated spot with probe position, as it is required not only that the spot be focused but also the two probes be aligned.

In order to investigate the accuracy of colour measurement using the instrument, reflectance standards were used to investigate the accuracy of the instrument in comparison to results from other colour measurement techniques. This indicated that some standards, although accurate and reliable for use with colour measurement instrumentation that use relatively large sampling areas, these standards are less accurate on the scale of measurement of the instrument under discussion (0.25 mm). It was found a significant variation in reflectance over the surface can be observed over the sub-millimetre scale for all reflectance standards.

2.5 Sample Visibilty and Size

A series of faded spots were produced ranging from ΔE_{ab} 1 to ΔE_{ab} 8 on both Lightcheck ULTRA and Lightcheck Sensitive (Figure 9). Lightcheck is made of a light sensitive coating printed onto a paper substrate. The colour changes of Lightcheck indicate the degree of exposure. These samples were chosen as they provide an approximation to a worst case scenario in that they both provided very smooth highly fugitive surfaces. With both types of sample, it was possible to observe many

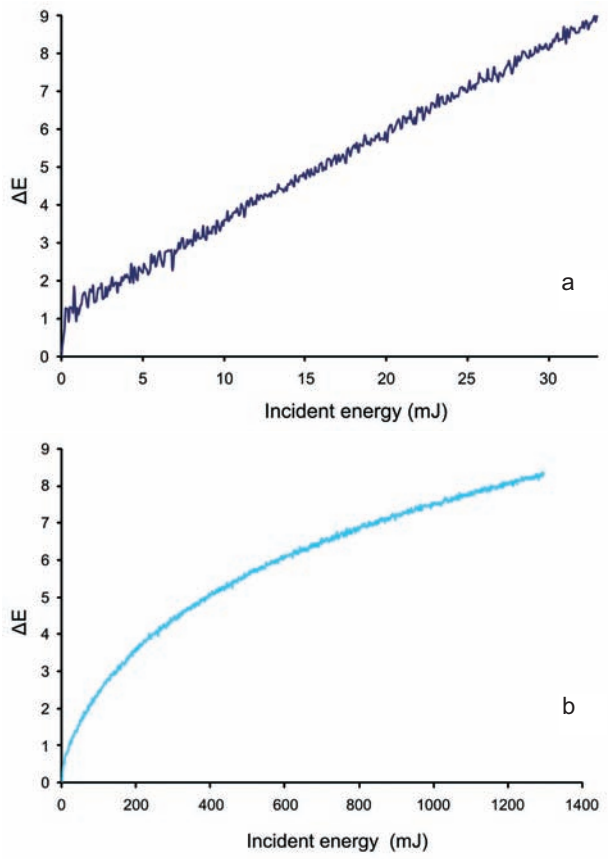

Figure 9: Colour change produced using the Microfadometer on Lightcheck ULTRA (A) and Lightcheck Sensitive (B).

spots in the series. It was found that 5 different observers if shown the location could see spots down to a colour difference of 2 or 3 ΔE_{ab} units on a pristine Lightcheck surface under good lighting. Importantly it was found that in situations where the Lightcheck surface was altered to reduce uniformity, for example by folding to vary the surface texture, it was impossible to see to such low levels of damage.

Practically speaking, when fading rougher, more textured, varied surfaces, for example when fading samples of oil paint on canvas it is possible at times to fade to ΔE_{ab} of 15 and more and not observe any alteration as has been previously considered the case.[1] This indicates that the damage is hidden by the texture in which it exists and can be visible even at such low levels of fading.

These findings are further verified when fading watercolours. It is possible at times to fade to ΔE_{ab} 15 and beyond and observe no change visually. However this depends on the uniformity of the surface. Importantly, on many samples which were very uniform, such as various Prussian blue samples a fade of 5 to 6 ΔE_{ab} was visible on close inspection and often also at reading distance (25 cm).

After fading the series it was possible to image the damage profile of each spot. An image of a spot faded to a colour difference of 5 ΔE_{ab} on Lightcheck Sensitive was captured using a calibrated microscope. Analysis showed good uniformity of illumination and fading across the focal region. As well as this, a typical example of the measured normalized profile of a 5 ΔE_{ab} faded spot, and a measured normalized profile of the incident illumination at best focus was also compared and shown to match well (Figure 10). The microscope camera was calibrated to 800 pixels per mm and this showed a variation in the FWHM spot size dependent on the degree to which we faded. This ranged from 0.22 for ΔE_{ab} of 2 to 0.25 for ΔE_{ab} of 8. A separate investigation of spot size up to 16 ΔE_{ab} showed that continued fading led to continued increase of FWHM spot size.

3 Wavelength Tunable System

3.1 Technique Introduction

Colourants that are regarded as fugitive are faded predominantly by the visible region,[7] therefore the effect of visible radiation of different wavelengths on deterioration of fugitive pigments warrants further investigation via a wavelength tunable system.

It is possible to filter the xenon lamp of the instrument using linear variable filters (Ocean Optics LVF-UV-HL and LVF-HL) to move through the desired wavelength range, and shape the fading spectrum. The filter bandwidth of this technique is 20 to 30 nm FWHM and it is possible to vary the central wavelength of the filter in the visible range (Figure 11)

In previous efforts to investigate the wavelength dependence of fading, Aydinli, Krochmann et al.[8] and McKlaren[7] divided the visible spectrum into 3 wavelength sections to observe the relative degree of damage. In later work by Kenjo,[9,10] the number of divisions increased to seven wavebands (located from 390 nm to 700 nm) on six different colorants. Similarly, Saunders and Kirby[11] used broad band interference filters with bandwidths of 70 nm, peak transmittances at 50 nm intervals in the visible range from 400 nm to 700 nm.

Building on this work and utilizing new apparatus, the wavelength dependence of fading of many pigments and samples can be investigated further and at a greater resolution than previously attempted. This will be done to highlight active wavebands and determining the wavelength speci-

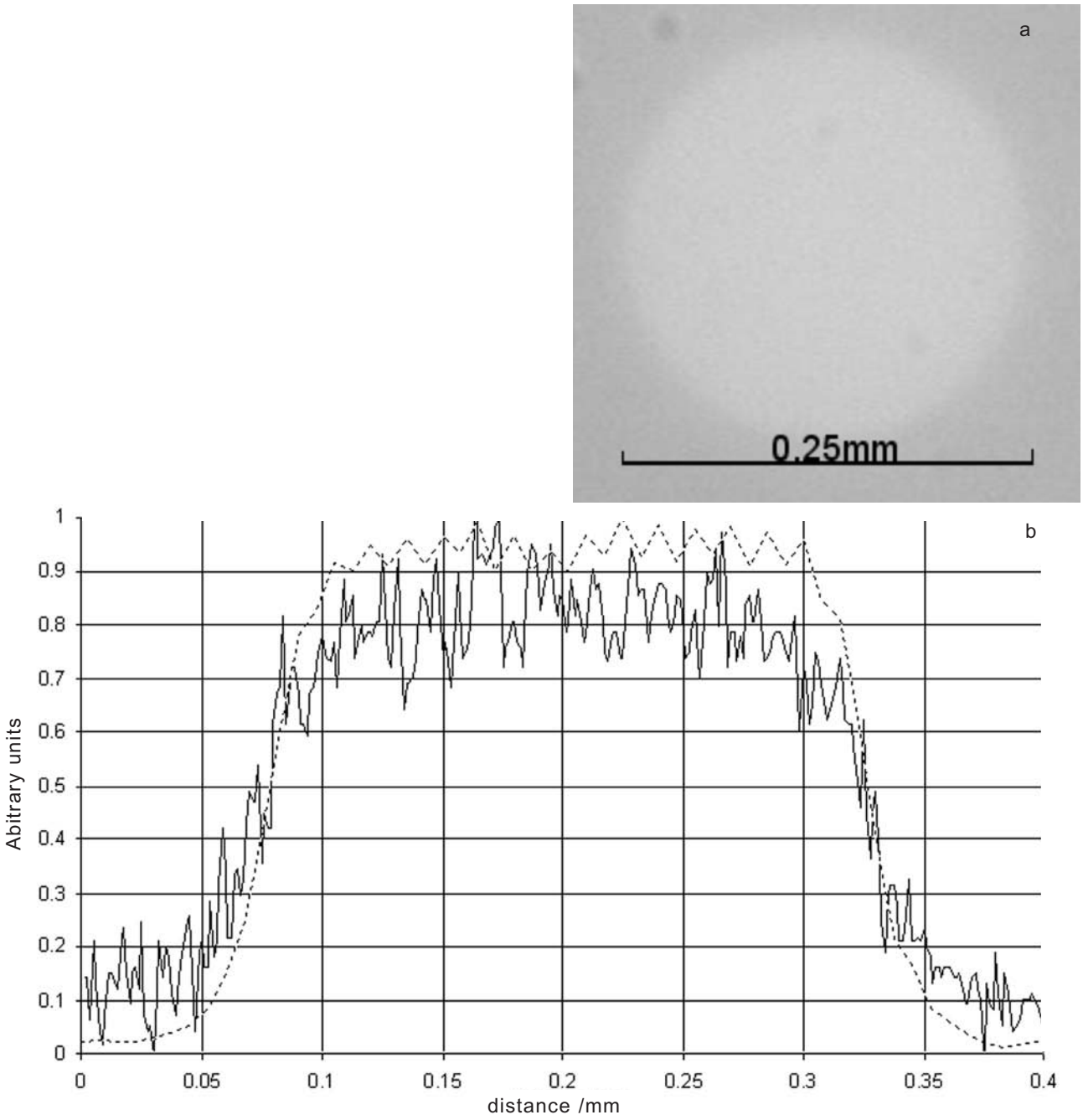

Figure 10. (a) An image of a spot faded to a colour difference of 5 ΔE_{ab} on Lightcheck ULTRA captured using a calibrated microscope. (b). A typical example of the measured normalized profile of a 5 ΔE_{ab} faded spot (indicated by the continuous line) and a measured normalized profile of the incident illumination at best focus (dashed line).

ficity of degradation caused by the specific visible regions for light sensitive materials.

3.2 Experimental Method

The tunable instrument operates in a similar way to that described previously. The spectra must be recorded before and after fading in order to obtain a colour difference value.

After an initial reading has been taken, the variable filter is adjusted to the chosen wavelength prior to fading the sample. The filter is then removed after fading to take a spectral measurement. Due to the presence of the filter, colour measurements are not possible during fading unless the shutter is opened, the filter removed, and a measurement rapidly taken in order not to alter the degree of fading.

In order to gain information on the wavelength dependence of fading, the variation in power with wavelength of the instrument must be compensated for. This is because neither the transmission of the filter system (Figure 11), nor the power of the

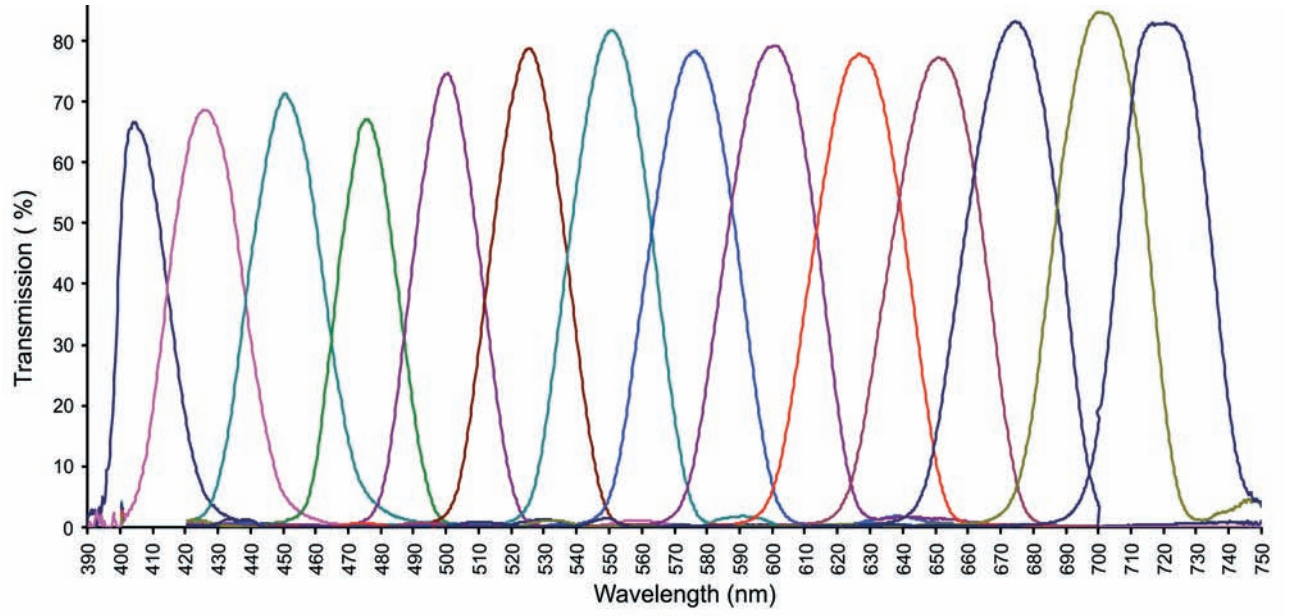

Figure 11: Tunable filter transmission at various wavelengths typically employed by the tunable instrument.

xenon source at various wavelengths is constant (Figure 5).

The addition of the variable filter holder increased the distance between the light source and the fiber, thus reducing the incident power to 1.46 mW or 0.46 lumen at focus (without the variable filter). This reduction in incident power leads to a reduction in fade rate.

It was found that fading spot size remains at 0.25mm when sampled using a CCD at intervals from 400 nm to 700 nm using the same technique as discussed in section 2.4.

The technique of initially monitoring the sample lightfastness using a broad spectral fade enables the user to determine a suitable length of time to fade the sample. A half hour period has typically been used to fade samples as fugitive as Blue Wool 1 to 2. Results from this technique are presented in section 4.3.4.

4 Results and Discussion

4.1 Rate of Fading

ISO Blue Wool Standards are an internationally accepted method of measuring fading within the conservation community. Eight different degrees of lightfast dyes can be used (with 1 being the least lightfast to 8 the most). The effect of fading Blue Wool samples 1, 2, and 3 by focusing 2.59 mW to a 0.25 mm diameter area can be seen in Figure 12. This illustrates that the instrument is capable of fading Blue Wool 1 to a ΔE_{ab} value of 7 in just over 5 min and Blue Wool 2 to the same level in twice that time period as expected.

4.2 Temperature Increase

In order to evaluate the safety of the instrument for use on artworks and to know to what degree temperature may play a part in any observed results, it was necessary to quantify the temperature increase caused by the focused radiation. Two techniques were employed. On separate occasions two different thermocouples were coated

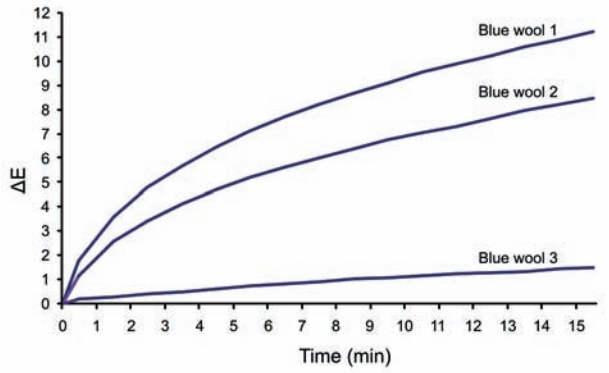

Figure 12: The fading rates of Blue Wool 1, 2 and 3 for the instrument when fading using the broad spectrum.

Figure 13: A photograph of a liquid crystal thermometer immediately after being irradiated with the microfadometer. Note 22 is clearly visible at 22 °C room temperature and the bottom right hand corner of the 26 showing a small circular area which has been increased in temperature to approximately 26 °C by the focused probe.

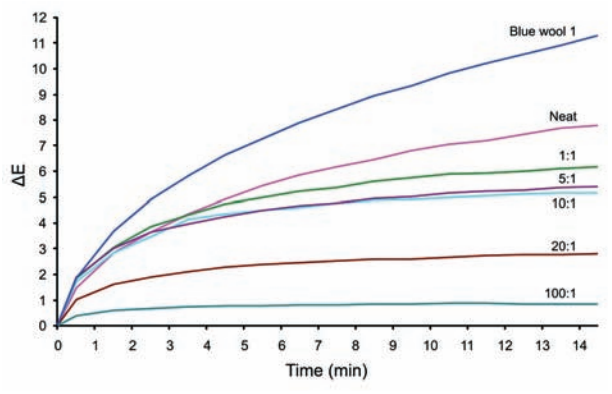

Figure 14: Some initial results of fading experiments on Prussian blue pigment samples from the studio materials of J. M. W Turner. A note for clarity is these results were created using the instrument without the use of a variable filter as defined in section 3.

with various light and dark paint samples on paper and illuminated by the focused spot. A thermocouple was also lightly coated with a variety of paints as well as exposing the bare sensing junction.

The same temperature increase of 3 °C to 4 °C above room temperature was observed in all cases.

As a second method, a thermometer that contains heat-sensitive (thermochromic) liquid crystals that change colour to indicate different temperatures was used. A number in a series corresponding to the environmental temperature becomes translucent when it is reached. By focusing the probe onto the various temperature-sensitive numbers, 26 °C clearly altered whereas all others from 12 to 34 (increments of 2 °C) did not. The area heated by the radiation remained briefly unaltered after the light was removed by a shutter, before cooling. A photograph of this can be seen in Figure 13.

4.3 Application to Prussian Blue Pigment

One pigment has consistently been reported to be phototropic (that is, to lose colour due to light exposure, and to regain it in the dark): Prussian blue, ferric ferrocyanide, iron(III)hexacyanoferrate(II), conventionally represented as $Fe_4[Fe(CN)_6]_3 \cdot xH_2O$. The formula quoted by Berrie[12] is more correct: $M^{I}Fe^{III}Fe^{II}(CN)_6 \cdot nH_2O$, where M^{I} is a potassium (K^+), ammonium (NH^{4+}) or sodium (Na^+) ion, and n=14-16. Reports of fading in light in the presence of normal air and/or nitrogen have been summarised by Kirby[13,14] and Rowe.[15] Complete colour loss under hydrogen was noted by Russell and Abney.[16,17] Reduction of Fe(III) to Fe(II), a reversible reaction, is the cause.

Samples of Prussian blue pigment (Tate Gallery Archive 7315.7#6) from the studio materials of J. M. W Turner (1775-1851, the materials dating from the end of his life) underwent analysis using the instrument in both modes of operation previously discussed.

4.3.1 The Effect of Water Dilution

The effect of water dilution of the Prussian blue sample in gum Arabic medium was investigated. Painted samples on filter paper were prepared from an undiluted stock suspension of Prussian blue in gum Arabic (Neat), 1 part Prussian blue sample with gum Arabic to 1 part water (1 to 1) and 1 part Prussian blue sample with gum Arabic to 5 parts water (5 to 1) in various dilutions through to 1 part Prussian blue sample with gum Arabic to 100 parts water (1 to 100). The results of the rate of fading can be seen in figure 14. Fading rate is dependent on the intensity of the colour wash: a very dilute wash does not cover all of the paper substrate with pigment particles, and as the pigment is the most light sensitive component, increasingly pigment-rich samples fade more rapidly.

4.3.2 The Reversion of Colour

Colour reversion of Prussian blue samples in the dark was also investigated over a period of 2 days with 2 colour reversion periods. The sample was fixed in position and then faded. During the 2 reversion periods (14 and later 10 h) the sample was kept in darkness by housing it to remove incident light. The probe was not moved during the experiment. Colour measurements during the fading process along with changes due to reversion are represented in Figure 15.

The pigment became less sensitive to the exposure of light after the initial cycle of fading. Further investigation is necessary to establish how long (or if at all) it takes for the reversion in the dark to bring back to its original value. As previously stated a reversible reaction between Fe(III) to Fe(II) is the cause of this reversion.

4.3.4 The Wavelength Dependence of Fading

The degree of fading by filtered radiation from 400 nm to 700 nm (bandwidth 20-30 nm FWHM) was investigated in increments of 25 nm through the visible region for a neat Prussian blue sample. The length of time with which we faded was altered at

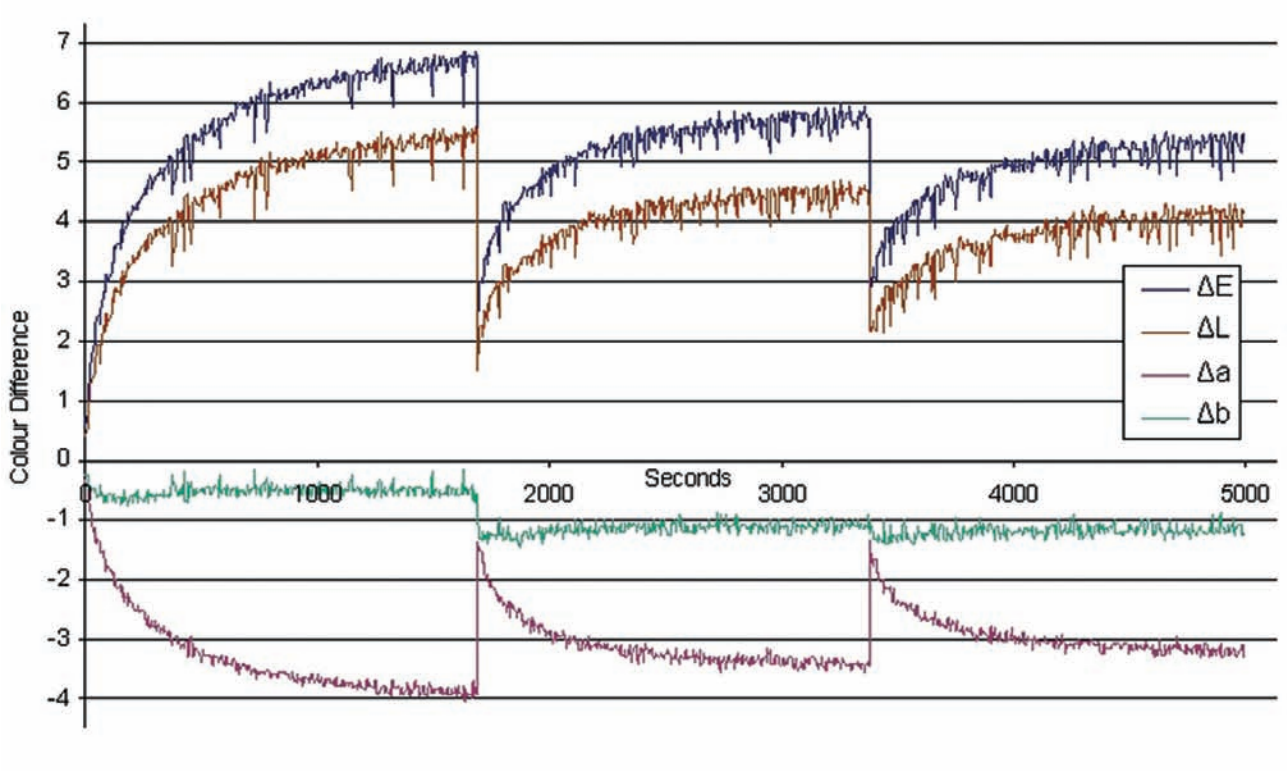

Figure 15: The reversion of Prussian blue pigment over a 2 day period, with 2 pauses of 14 and later 10 h during which colour reversion of the pigment took place in the dark.

each wavelength. This was done in order to compensate for the variation in incident power with wavelength caused by the spectral power distribution of the lamp (Figure 5) and varying transmission of the filter at each wavelength (Figure 11). This resulted in a power distribution at focus as illustrated below in Figure 16.

With the linear variable filter in place, the temperature was measured by the thermocouple, and was found to increase by approximately 1 °C independent of wavelength.

Figure 17 shows a preliminary result of the action spectrum of the Prussian blue tested, that is colour change as a function of wavelength for the same amount of incident energy at each wavelength. The action spectrum shows that the blue end of the spectrum causes more damage than the red part of the spectrum. Further results of this type applied to other samples will be presented and discussed in a future publication.

5 Conclusions

A novel instrument and a new experimental method have been presented and employed that enables the investigation of photosensitive samples and works of art. The instrument demon-

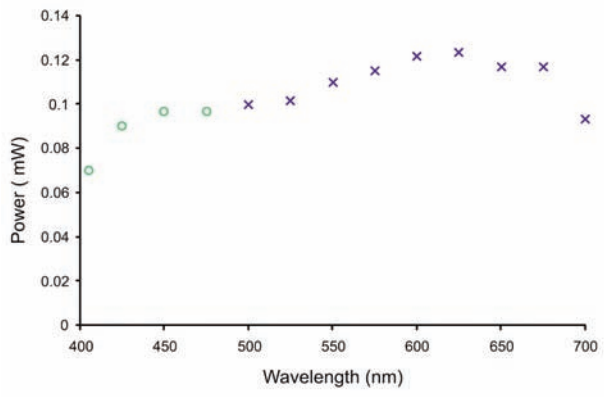

Figure 16: The power variation at focus of the wavelength of tunable microfadometer. An Ocean Optics LVF-UV-HL is used from 405 nm to 475 nm and an LVF-HL filter from 500 nm to 700 nm.

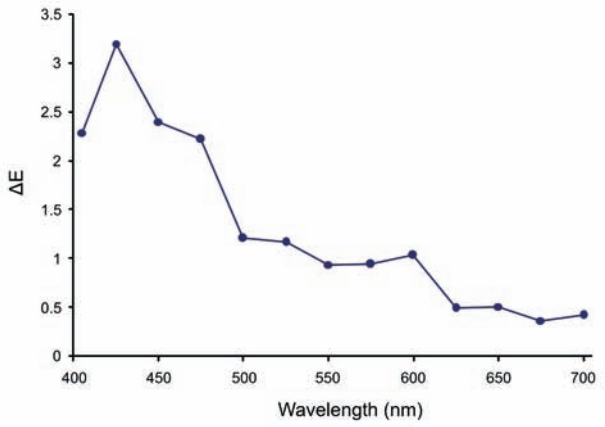

Figure 17: The action spectrum from 405 nm to 700 nm of the neat Prussian blue sample.

strates increased structural stability increasing the portability over an earlier design, broadening the scope of locations at which data can be acquired.

Increased precision of probe positioning relative to the sample, homogeneity of illumination across the faded area, controlled intensity at the illuminated surface from the lamp, and an ease of confocal probe alignment are present in the new design.

Two different measurement methods indicate a temperature increase of 3 to 4 degrees during fading experiments.

The instrument is capable of fading Blue Wool 1 to a ΔE_{ab} value of 7 in just over 5 min and Blue Wool 2 to the same level in just over 10 min.

Incorporating a linear variable filter enables the investigation of the wavelength dependence of fading of many samples to a greater resolution than previously attempted.

It was also found that colour change is not the only factor that increases the visibility of faded spots. The smoothness and uniformity of a surface also plays a role, leading to the conclusion that damage is hidden by the texture of its surroundings. When fading very smooth and uniform surfaces colour change was observable in the case of very small differences. Therefore under certain circumstances, greater caution should be employed when the prevention of visible bleaching is a consideration of the fading process.

Investigation of the error in colour measurement, and colour difference calculations produced by small differences in position, indicated that alignment by eye may be a significant cause of error in measurements. A motorized micrometer stage used for fine adjustment of the focus can reduce the errors.

Suitable future efforts will be in creating an automated focusing method which would be more suitable for increased accuracy and repeatability of measurements. Following this, improvements to create full automation of the instrument will take place in order to characterize a large number of samples many times without human intervention. In doing so, it will be possible to gain large amounts of data for single samples, and therefore errors due to such small sampling area can be reduced by averaging over a very large number of fades when investigating samples rather than real art works. Larger sample sets and increased spot size are also desirable in order to increase the reliability of future wavelength dependent investigations.

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7 References

1. P.M.Whitmore, X. Pan, C. Baillie, *Predicting the fading of objects: Identification of fugitive colourants through direct nondestructive lightfastness measurements*, J. Am. Inst. Cons., 1999, **38**, 395-409.

2. P.M. Whitmore, C. Baillie, S.A. Connors, *Micro-fading tests to predict the result of exhibition: progress and prospects*, in: A. Roy, P. Smith, Eds., *Tradition and Innovation: Advances in Conservation*, International Institute for Conservation, London, 2001, 200-205.

3. P.M. Whitmore, *Pursuing the Fugitive: Direct Measurement of Light Sensitivity with Micro-fading Tests*, in: H. K. Stratis and B. Salvesen, Eds., *The Broad Spectrum: The Art and Science of Conserving Coloured Media on Paper*, Archetype Publications, London, 2002, 241-243.

4. C. Bowen, B. J Mangum, M. Montague, *Pursuing the Fugitive: The User's Point of View: Micro-Fading Test Results and the Shaping of Exhibition Policy,* in: *Studies in The Materials Techniques and Conservation of Colour on Paper*. Archetype Publications, London, 2002, 245-251.

5. S. Connors, A. Sandra, M. Whitmore, R. Keyes, E. I Coombs, *The Identification and light sensitivity of Japanese woodblock print colorants: impact on art history and preservation* in: P. Jett, J. Winter, B. McCarthy, Eds., *Scientific research on the pictorial arts of Asia: proceedings of the second Forbes Symposium at the Freer Gallery of Art*, Archetype Publications, London, 2005, 35-47.

6. D. Saunders, J. Kirby, *Light-induced damage: investigating the reciprocity principle*, Archaeological Conservation and its Consequences, Preprints of the ICOM-CC 11th Triennial Meeting, Edinburgh, ICOM-CC, Paris, 1996, 87-90.

7. K. McLaren, *The spectral regions of daylight which cause fading*, J. Soc. Dyers Colour., 1956, **72**, 86-99.

8. S. Aydinli, E. Krochmann, G.S. Hilbert, and J. Krochmann. *On the deterioration of exhibited museum objects by optical radiation*, CIE Publication 89/3, CIE Technical Collection, 1990.

9. T. Kenjo, *Certain deterioration factors for works of art and simple devices to monitor them*, Int. J. Mus. Manag. Curator., 1986, **5**, 295-300.

10. T. Kenjo, *Discolouration of some red colours irradiated with some monochromatic lights*, Sci. Conserv., 31-34, **26,** 1987.

11. D. Saunders, J. Kirby, *Wavelength-dependent fading of artists' pigments*, in: A. Roy and P. Smith, Eds., *Preventive Conservation: Practice, Theory, and Research*, International Institute for Conservation, London. 1994, 190-194.

12. B. Berrie, *Prussian Blue*, in: E.W. Fitzhugh, Ed., *Artists' Pigments: a Handbook of their History and Characteristics*, National Gallery of Art, Washington, 1997, 191-217.

13. J. Kirby, *Fading and colour change of Prussian blue: occurrences and early reports*, National Gallery Technical Bulletin, 1993, **14**, 63-71.

14. J. Kirby, D. Saunders, *Fading and colour change of Prussian blue*, National Gallery Technical Bulletin, 2004, **25**, 73-99.

15. S. Rowe, *The effect of insect fumigation by anoxia on textiles dyed with Prussian blue*, Stud. Conserv., 2004, **49**, 259-270.

16. N.S. Brommelle, *The Russell and Abney report on the action of light on water colours*, Stud. Conserv., 1964, **9**, 140-152.

17. W.J. Russell, W. Abney, *Action of light on watercolours*, Report to the Science and Art Department of the Committee of Council on Education, HMSO, London, 1888.