A Versatile Microfadometer for Lightfastness Testing and Pigment Identification

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ABSTRACT

The design and experimental method for the use of a novel instrument for lightfastness measurements on artwork is presented. The new microfadometer design offers increased durability and portability 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 millimeters (FWHM) while simultaneously monitoring color change. This makes it possible to identify pigments and determine the lightfastness of materials effectively and non-destructively. With 2.59mW or 0.82 lumens (1.7×10^7 lux for a 0.25mm 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 minutes. 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 hour and 0.31 ΔE_{ab} over 7 hours. 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 paint box of J. M. W Turner (1755-1851) are presented.

Keywords: Micro-fading, Lightfastness, Fadometer, Watercolor materials, Spectroscopy

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 at Tate, a microfadometer has been designed and constructed taking inspiration from the Whitmore design[1, 2, 3] and application[4]. It is intended that some improvements on this design will increase the portability and ease with which a researcher can conduct micro-fading. From this design the need for object transportation is reduced and therefore the rate and also scope of locations at which data can be acquired increased.

The instrument differs from a previous design by Paul Whitmore *et al* due to the application of a linear variable filter system, 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.

O3A: Optics for Arts, Architecture, and Archaeology
edited by Costas Fotakis, Luca Pezzati, Renzo Salimbeni
Proc. of SPIE Vol. 6618, 66181G, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.726029

2. INSTRUMENT DESIGN AND PERFORMANCE

2.1 Design

The instrument developed is a compact, lightweight, more economical, mobile instrument which removes the need for transportation of art work and unnecessary art handling (see figures 1 and 2). It can function in two modes of operation: firstly, as a transportable compact microfadometer 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 2.3.

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

It is possible to move the location of the lenses in the probe. This enables alteration of the working distance and focused spot size without significantly altering the fading rate (as not all of the fiber output is focused to the spot). This possible alteration of the instrument can lead to increased sampling area, and therefore data that is more representative of more varied and textured surfaces. This would be useful for example when fading reconstructed paint samples rather than art work where a small faded area is not an important safety measure to prevent visible damage.

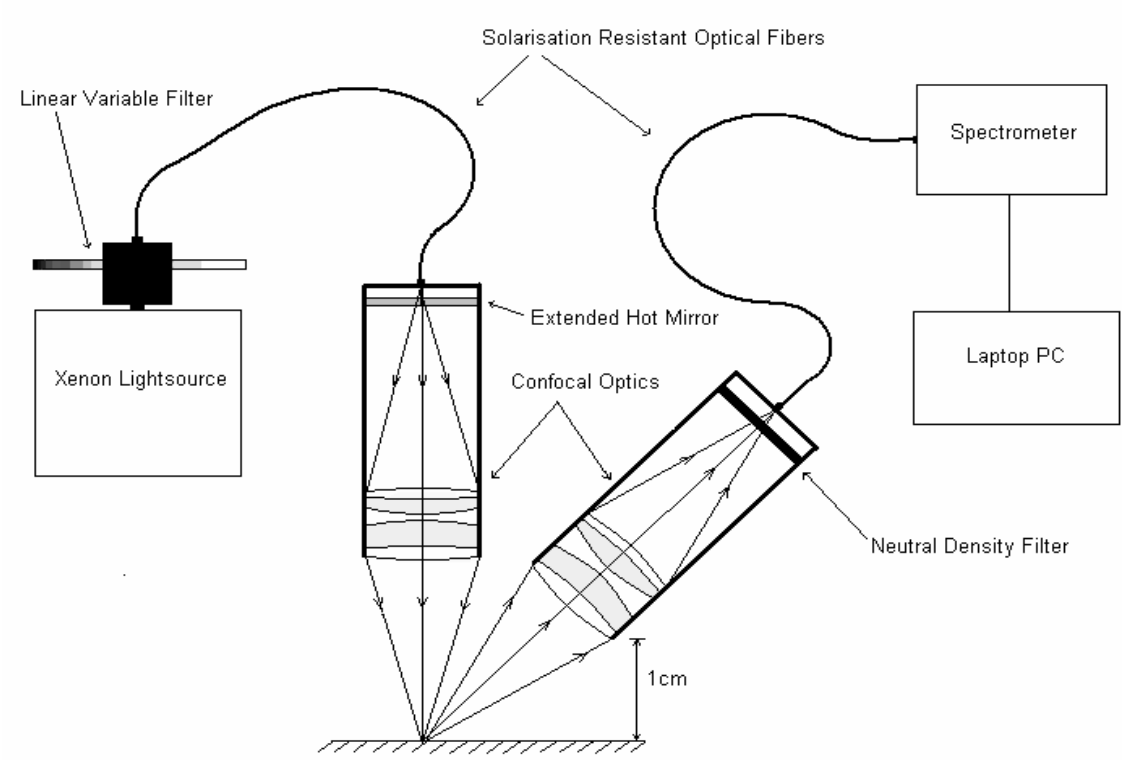

Figure 1. A schematic representation of the Microfadometer including linear variable filter.

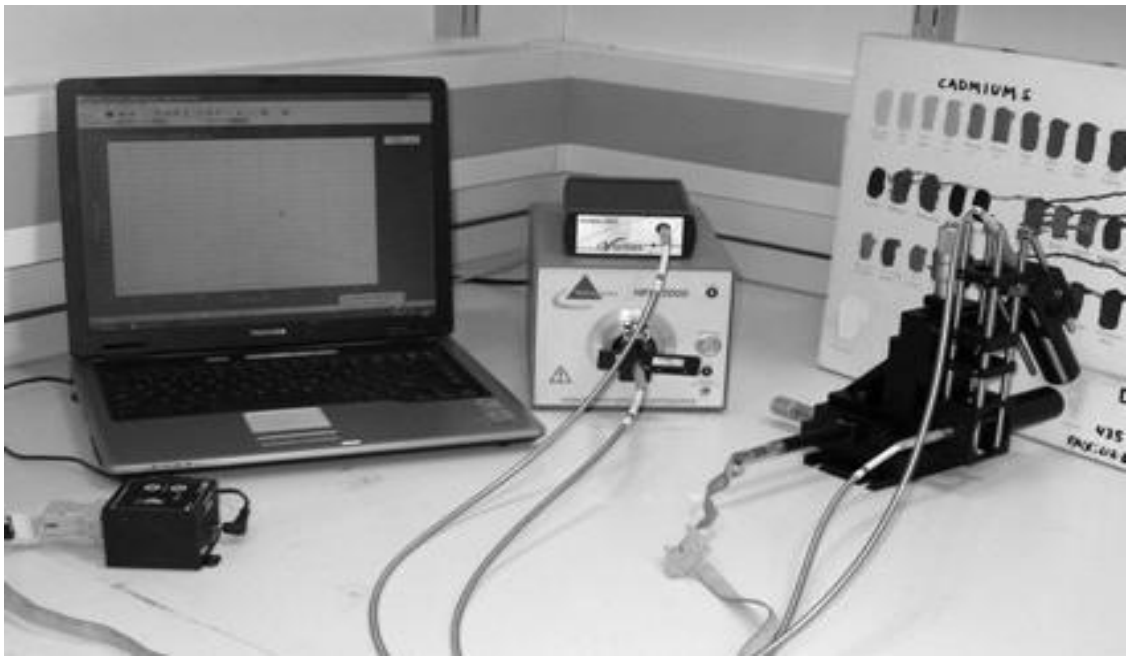

Figure 2. The instrument fading a sample.

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 fiber optic spectrometer. The spectrometer (Avantes Avaspec 2048) receives this signal via an optical fiber, and 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 micron scale movements. The Z axis stage is motorized. It is therefore possible to achieve fine alignment of the probe with the surface remotely. This is an important aspect of the design, as it becomes possible to achieve best focus remotely away from the artwork. This in turn enables any necessary 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.

2.1.1 Experimental method

To ensure confocality of both probes, they were illuminated with a low level of radiation, and both focused onto a CCD chip. Best focus gives the maximum signal, and ensures reproducible spot size, failure to do this means that the faded spot varies in size, 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 barium sulphate sample,

A neutral density filter is used to reduce the beam to a level where best focus can be obtained without such significant levels of radiation being incident on 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. Following this the probe is moved more than 0.5mm using the micrometer mount (in order not to sample the area previously illuminated during alignment). With the shutter still closed, the software is then instructed to sample spectra periodically, and to take the initial spectrum of the pigment during the fade as the reference from which color difference calculations take place. The shutter is opened and fading begins.

Color differences are monitored (using CIE standard illuminant D65) in real time using the spectrometer software in order to prevent fading beyond acceptable levels which have been independently determined in the development process.

2.2 Performance Characterisitics

The instrument produces 2.59mW or 0.82 lumens (1.7 x10^7 lux for a 0.25mm focused spot). The relative spectrum of light incident on the sample is shown in figure 3. The varying sensitivity of the spectrometer with wavelength and fiber attenuation to the spectrometer used for sampling has been compensated for. The xenon bulb output will alter as it ages and this makes it necessary to monitor probe output regularly.

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

Total counts of the spectrometer at all wavelengths increased 1.1% over the period (see figure 4). The dark current over 7 hours was constantly monitored and subtracted by the spectrometer and software.

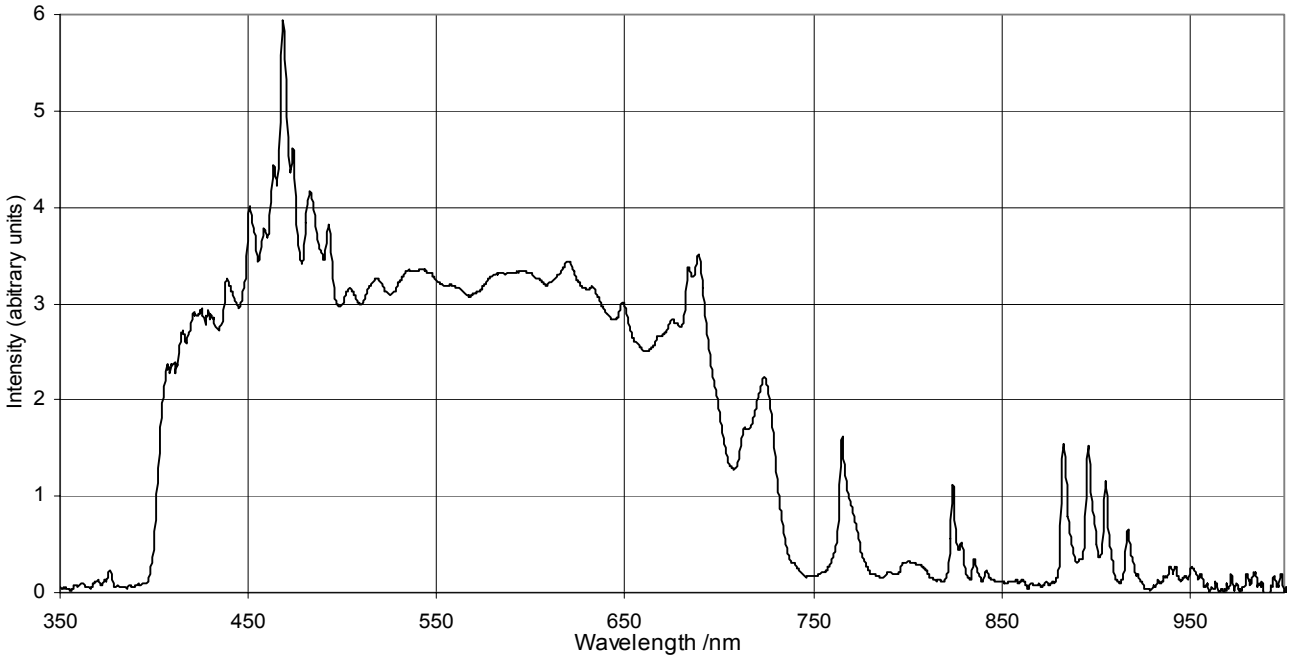

Figure 3. The relative spectra of incident radiation used in broad spectrum fading tests.

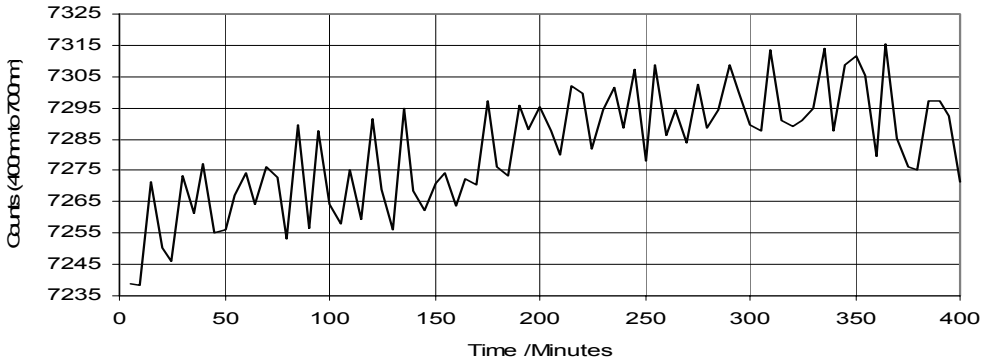

Figure 4. The total counts of the spectrometer from 400nm to 700nm over 400 minutes.

Via simulation, the measured systematic error at each wavelength was used to determine its relevance in terms of color measurement. The instability of the system was applied to typical samples and shown to produce an error no greater than ΔE_{ab} of 0.31 at any reading over the 7 hour period. However, the initial hour produced no more than a ΔE_{ab} of 0.12 at any reading. The results of the simulation is consistent with the directly monitored ΔE_{ab} when illuminating barium sulphate as a non fugitive sample.

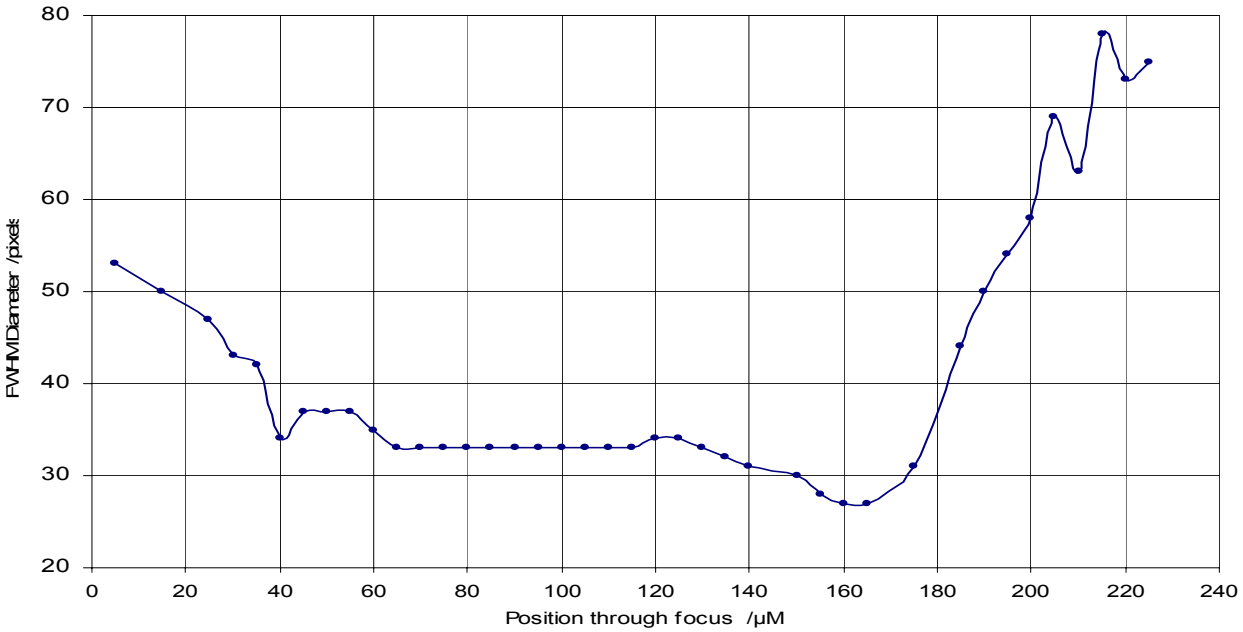

Figure 5. The FWHM of the focused spot profile through focus in 5 micron increments.

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 at 5 micrometer intervals by varying the working distance of the probe to the CCD (see figure 5). This led to the realization that the FWHM of the recorded spot size on the CCD chip is 33 pixels or 0.25 mm. It was independently verified that 1 pixel width was 7.5 microns 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. This illustrated that the diameter of the spot did not alter for 50 micrometers through focus.

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).

Focusing 2.59mW to 0.25mm spot causes fading of Blue Wool samples 1, 2, and 3 as seen in figure 6. This illustrates that the instrument is capable of fading Blue Wool 1 to a ΔE_{ab} value of 7 in just over 5 minutes and Blue Wool 2 to the same level in just over 10 minutes.

In order to evaluate the safety of the instrument for use on artworks and to know what degree temperature may play in any observed results, it was necessary to quantify the temperature increase caused by the focused radiation. Two techniques were employed. On separate occasions 2 different thermocouples were coated 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 was observed in all cases. Increases of 3° to 4°C were observed independent of room temperature

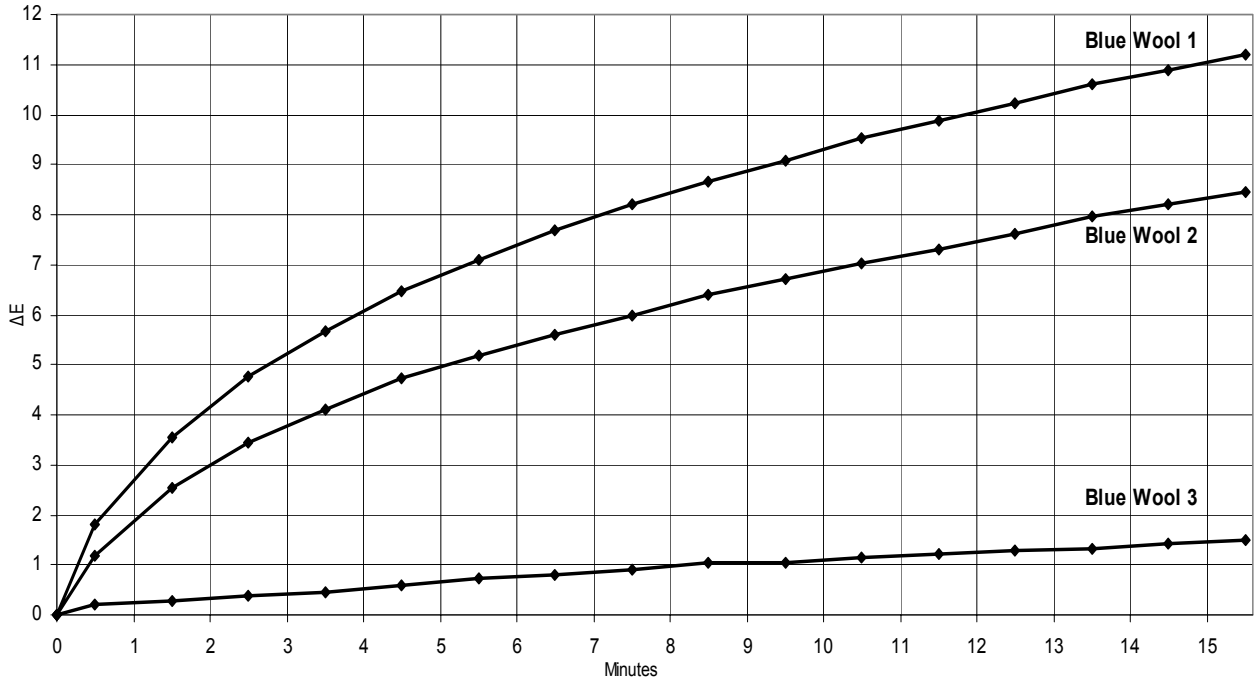

Figure 6. The fading rates of Blue wool 1, 2 and 3 for the instrument when fading using the broad spectrum.

Figure 7. 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.

As a second method, a thermometer that contains heat-sensitive (thermochromic) liquid crystals that change color 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 degrees) did not. The area heated by the radiation remained altered after the light was removed by a shutter, before cooling. A photograph of this can be seen in figure 7.

A series of faded spots were produced ranging from ΔE_{ab} 1 to ΔE_{ab} 8 on both Lightcheck ULTRA and Lightcheck Sensitive. Lightcheck is made of a light sensitive coating printed onto a paper substrate. The color 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 with 5 different observers it was possible (if shown the location) to observe many spots in the series. With close inspection under good lighting it was typically possible to see a spot of color difference of ΔE_{ab} 2 or 3. In situations where the Lightcheck sample was altered in some way 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 oils on canvas such as ultramarine or ivory black it is possible at times to fade to ΔE_{ab} of 15 and more and not observe any alteration. This indicates that the damage is hidden by the environment in which it exists although in the right conditions visible even at such low levels of fading.

These findings are further verified when fading watercolors. 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 blues a fade of 5 to 6 ΔE_{ab} was visible on close inspection and often also at reading distance, secondly if a small lighter part of a sample was faded, and this lighter area faded was similar in size to that of the instrument spot size, the faded area would be more evident. This indicated that some caution should be employed.

After fading the series it was possible to image the damage profile of each spot (see figure 8). The microscope camera and image processing software were 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.

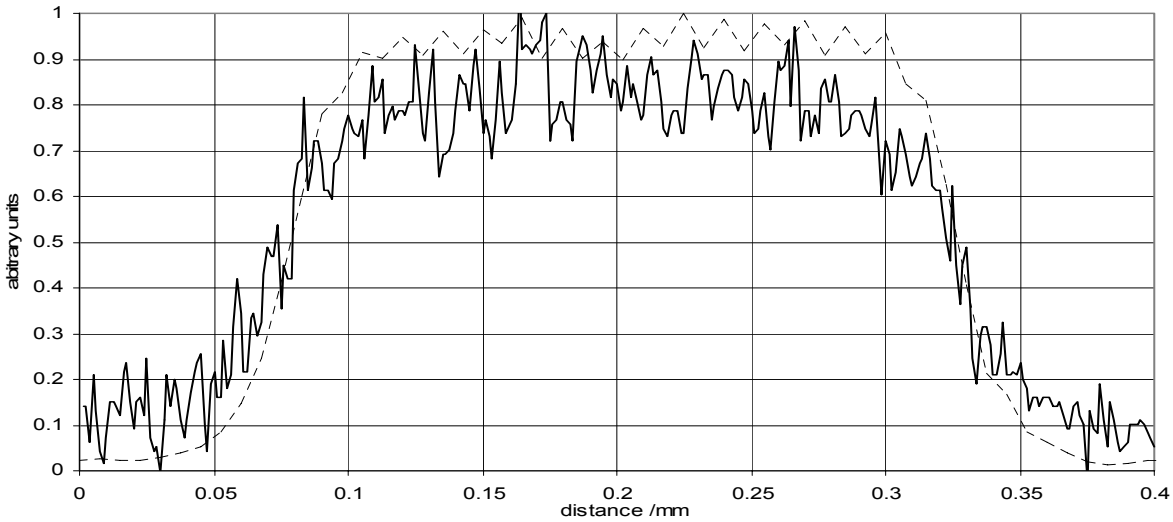

Figure 8. A typical example of the measured normalized profile of a $5\Delta E_{ab}$ faded spot (continuous line) and a measured normalized profile of the instruments radiation at best focus (dashed line).

2.3 Wavelength Tunable System

Fugitive colorants are faded predominantly by the visible region[5], 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 a linear variable filter to move through the desired wavelength range, and shape the fading spectrum. The filtered peaks created via this technique in the visible region are approximately 23nm FWHM and it is possible to vary the central wavelength of the filter in the visible range.

In previous efforts to investigate the wavelength dependence of fading, Aydinli, Krochmann *et al*[6]. and McKaren[5] divided the visible spectrum into 3 wavelength sections to observe the relative degree of damage. In later work Kenjo[7, 8], and also Saunders and Kirby[9] the number of divisions was increased and wavelength dependence was investigated in the visible region by division into 7 separate wavebands.

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 action and activation spectra and wavelength specificity of degradation caused by the visible region for light sensitive materials.

2.3.1 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 color difference value.

After a color reference has been taken, the variable filter must firstly be placed in the filter holder and adjusted to the desired wavelength prior to fading the sample, and removed after fading to take a spectral measurement. Due to the presence of the filter, color 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. Importantly time spent with this task must be compensated in the length of the fade. In order to gain information on the action spectrum the variation in power with wavelength of the instrument must be compensated for (see figure 9).

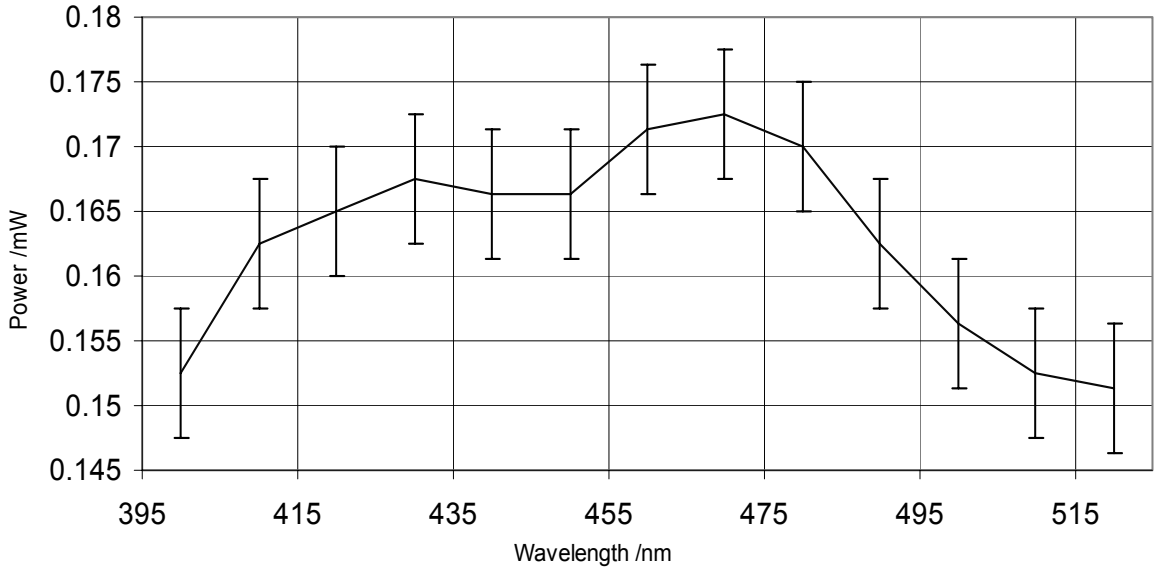

Figure 9. The instrument power variation with wavelength from 400nm to 520nm.

The addition of another optical element reduces the incident power to 1.46mW of power or 0.46 lumens at focus (when the filter is removed from the variable filter holder). This reduction in incident power leads to the data not being altered to the same degree by periods of illumination outside of that desired to fade. For example: periods of adjustment or alignment, or time taken to obtain the desired wavelength. This is made evident when considering the small amount of power transmitted with the filter in place.

When using the linear variable filter, the temperature was measured, using the thermocouple, as increasing by approximately 1°C independent of wavelength.

It was found that fading spot size remains at 0.25mm when sampled using a CCD at 10nm intervals from 400nm to 530nm.

The technique of initially monitoring the sample lightfastness using a broad spectral fade enable 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.

2. PRELIMINARY RESULTS

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. 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 10.

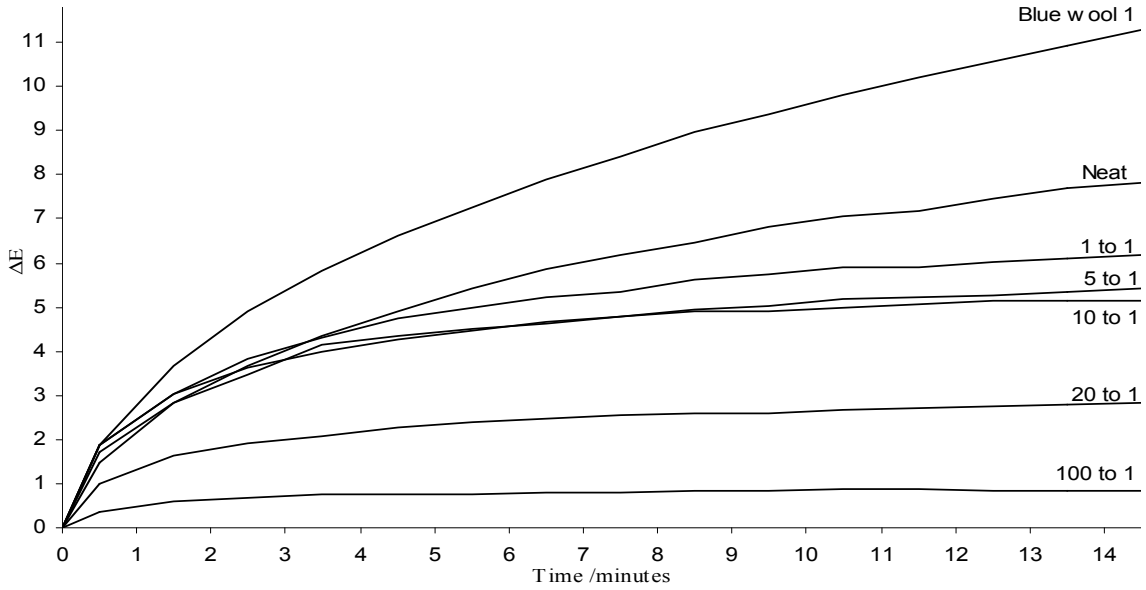

Figure 10. Some initial results of fading experiments on Prussian blue pigment samples from the studio materials of J. M. W Turner. Note these results were created using the instrument without variable filter as defined in section 2.1

The degree of fading by filtered radiation from 410nm to 510nm (peaks 25nm FWHM) was investigated in 20nm increments for a neat Prussian blue sample. The length of time of the fade at each wavelength was altered in order to compensate for the variation in power with wavelength. Figure 11 shows a preliminary result of the action spectrum of the Prussian blue tested.

These results and further results of this type applied to other samples will be presented and discussed in a future publication.

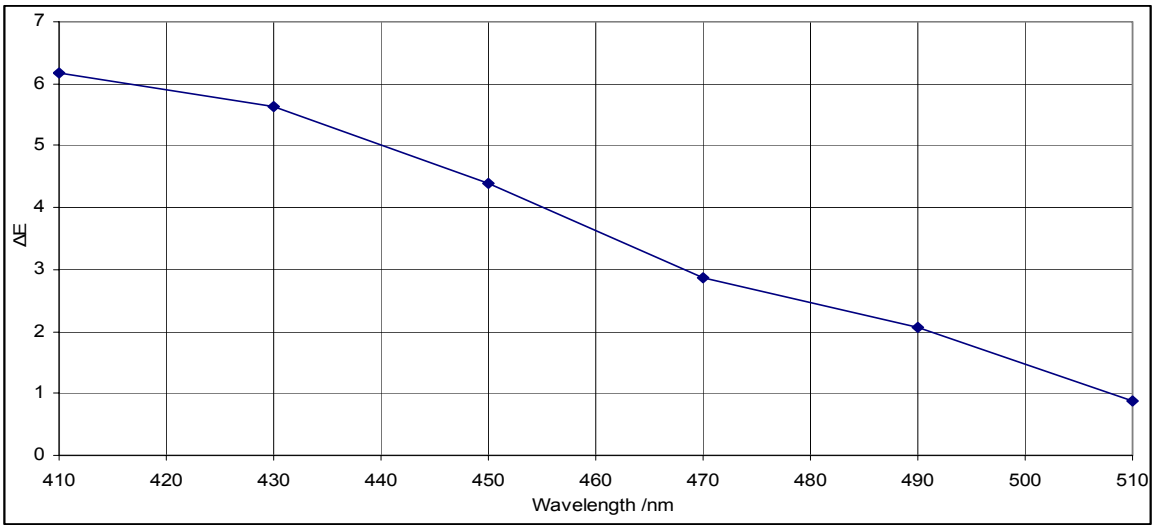

Figure 11. The action spectrum from 410nm to 510nm sampled in 20nm increments of a neat Prussian blue sample from the studio materials of J. M. W Turner (TGA 7315.7#6).

3. CONCLUSIONS

A novel instrument and experimental method has been presented and employed that enables the investigation of photosensitive works of art. The instrument demonstrates increased durability and portability over an earlier design, broadening the scope of locations at which data can be acquired.

The instrument is capable of fading Blue Wool 1 to a ΔE_{ab} value of 7 in just over 5 minutes and Blue Wool 2 to the same level in just over 10 minutes. The fading process creates a measured temperature increase of 3 to 4 ^{o}C at the focus.

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 the degree of fading 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 environment it is within. Therefore under certain circumstances, greater caution should be employed when the prevention of visible bleaching is a consideration of the fading process.

ACKNOWLEDGMENTS

This research is funded by the Public Sector Research Exploitation Fund (PSRE) which sponsors the project at Tate.

Andrew Lerwill's thanks and appreciation go to the Tate Conservation Department for support of the project.

Many thanks also to Dr Gareth Cave of Nottingham Trent University for his ideas and constructive criticism, and Gary Wells also of Nottingham Trent University for his assistance with microscope measurements.

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