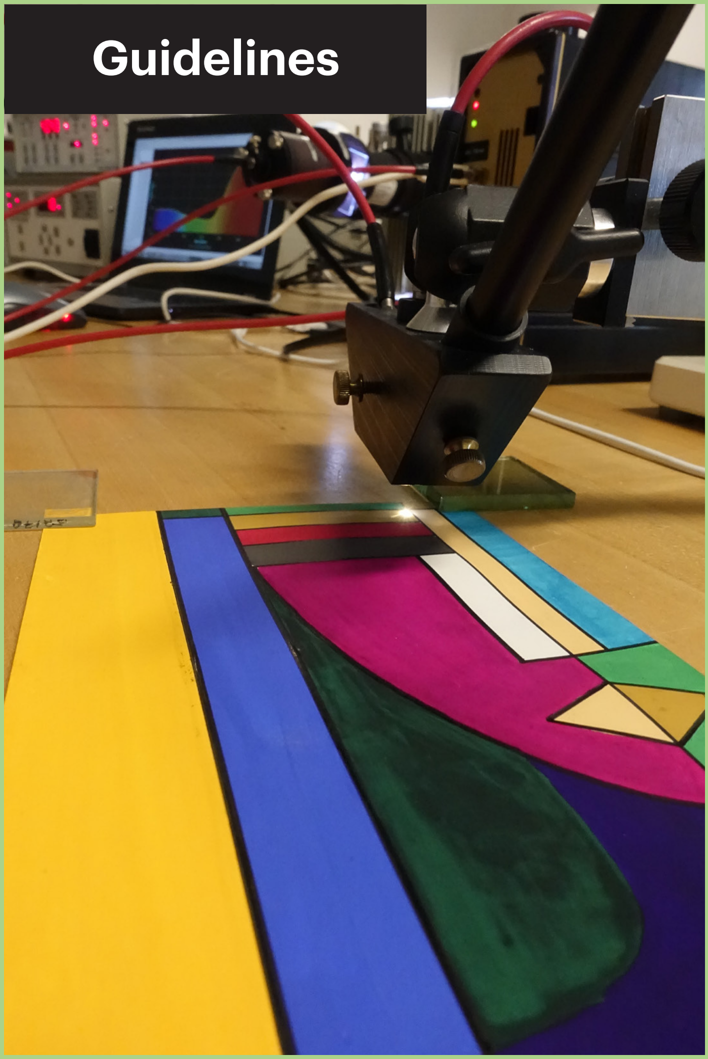
Microfading Tester

Light Sensitivity Assessment and Role in Lighting Policy



Vincent Laudato Beltran
Christel Pesme
Sarah K. Freeman
Mark Benson

Getty
Conservation
Institute

Microfading Tester:

Light Sensitivity Assessment and Role in Lighting Policy

Guidelines

Vincent Laudato Beltran
Christel Pesme
Sarah K. Freeman
Mark Benson

Getty Conservation Institute
Los Angeles

1200 Getty Center Drive, Suite 700
Los Angeles, CA 90049-1684
United States
Telephone 310 440-7325
Fax 310 440-7702
E-mail gciweb@getty.edu
www.getty.edu/conservation

ISBN: 978-1-937433-95-6 (online resource)

The Getty Conservation Institute (GCI) works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The Institute serves the conservation community through scientific research, education and training, field projects, and the dissemination of information. In all its endeavors, the GCI creates and delivers knowledge that contributes to the conservation of the world's cultural heritage.

Front cover: Microfading tester in use on a bespoke workshop painting by Gina Eichmüller.
Photo: Vincent Laudato Beltran.

Conservation
Research
Foundation
Museum

Contents

Acknowledgments

This publication represents the culmination of a highly collaborative effort, and the authors gratefully acknowledge the following contributors. The guidance and insight provided by our reviewers was an invaluable part of the writing process; our deepest thanks to Agnes Brokerhof, Andrew Davis, Michał Łukomski, Sara Reiter, Cindy Connelly Ryan, Katherine Schilling, and Joelle Wickens. Numerous colleagues at the Getty and in the broader cultural heritage field offered an abundance of support and encouragement during the development of this document, including Chelsea Bingham, JP Brown, Maristella Casciato, Kirsten Dunne, Gina Eichmüller, Cynthia Godlewski, Marc W. Harnly, Eléonore Kissel, Tom Learner, Joohee Lee, Ayanna Lynch, Laura Maccarelli, Gary Mattison, Savannah Novencido, Ellen Pearlstein, Marcia Reed, Renée Riedler, Rachel Rivenc, Jacob Thomas, Season Tse, and Paul Whitmore. We'd also like to extend our sincere gratitude to Bruce Ford, whose wisdom and candor about microfading testers acted as a beacon for this manuscript.

Finally, this document was the direct beneficiary of the generous sharing of MFT protocols, experience, and tips by many colleagues at the following institutions, and the authors are immensely thankful:

AGH University of Science and Technology

British Museum

Canadian Conservation Institute

Centre de Recherche sur la Conservation /
CNRS — Muséum national d'Histoire naturelle —
Ministère de la Culture

Conservation Center Vejle / Odense City Museums

Getty Conservation Institute

Getty Research Institute

Harvard Art Museums / Straus Center for
Conservation and Technical Studies

Heritage Conservation Centre,
an institution of the National Heritage Board

Imperial War Museum

Institute for the Preservation of Cultural Heritage
at Yale University

J. Paul Getty Museum

Library of Congress Preservation Research and
Testing Division

Menil Collection / Museum of Fine Arts, Houston

The Museum of Modern Art

National Archives UK

National Galleries Scotland

National Gallery of Art /
Museum Conservation Institute

National Library of the Czech Republic

National Museum of Australia

Nottingham Trent University

Science Museum UK

University of Fine Arts, Dresden

Whitney Museum of American Art

Winterthur / University of Delaware Program
in Art Conservation

1. INTRODUCTION

The microfading tester (MFT; also refers to microfade testing) is an analytical technique developed by Paul Whitmore (then at Carnegie Mellon University) to determine the in situ light sensitivity of an artwork (Whitmore, Xun Pan, and Bailie 1999). The MFT was designed to rapidly induce and monitor color change in fugitive materials. This is achieved by exposing the sample surface to a high-intensity, stable, and focused (typically 0.5 mm or less in diameter) light spot and simultaneously examining the affected area using a spectrophotometer. While the resulting color change may be perceived as damage, this is mitigated by the small area of exposure and the termination of the test once a minimum color change threshold is reached, rendering the change visually imperceptible. The MFT allowed for the direct identification of the most fugitive colorants in an artwork and comparison to the color change behavior of light-sensitive standard material. Access to this predictive information for a specific object provides valuable context when deciding on a preservation lighting policy.

MFT represented an advance over previous lightfastness assessments, which relied on the evaluation of representative mock-up samples or direct monitoring of object color change during display. The use of mock-up samples to inform the light sensitivity of an object is hindered by time-consuming chemical analysis of the colorant system and mock-up preparation that may not wholly reflect the chemical and physical nature of the object. While color monitoring of objects during exhibition provides a direct assessment, this too is a laborious process, requiring the object to first undergo an overall color change, possible unmounting of the object from its display (and subsequent remounting), and careful repositioning of the spectrophotometer on the same areas.

Interdepartmental collaborations involving MFT can reshape the dialogue about lighting policy and management. Provided with information on object vulnerability to light, discussions among collection staff—conservators, collection managers, curators, registrars—regarding selection of objects for exhibition may shift from an "us versus them" relationship to one focused on risk management and facilitating greater access where possible. If color change is thought to negatively affect the object, the use of the MFT allows one to protect artwork that is susceptible to light-induced color change (or inform of possible consequences if display is necessary). Conversely, display restrictions can be relaxed for objects shown to be more lightfast by MFT. The latter is particularly significant with respect to access and time (i.e., it reduces the need to change out objects mid-exhibition) when the object was previously thought to be highly sensitive to light.

Though MFT has been accepted as an important preventive conservation tool and is employed at over seventy institutions worldwide (see appendix 1), there remain obstacles to its more widespread use. While the original MFT setup described by Whitmore, Xun Pan, and Bailie (1999) is most common, subsequent designs have explored various light sources, measurement geometries, and means of automation. This has led to ambiguity as to which iteration is most appropriate for a specific context. MFT is also a rare example of an analytical technique that has emerged from within the conservation field rather than having been transferred from a larger external field. As a consequence, instrumental support and training that might be provided by a commercial company is limited, and a self-supporting MFT user community remains underdeveloped. Access to didactic information about MFT is particularly important for sustaining institutional knowledge about an instrument that may be operated and maintained intermittently.

The Getty Conservation Institute (GCI) and partner institutions have sought to examine these issues related to advancing MFT practice. Following several MFT-focused meetings convened in 2016 by the Rathgen Laboratory, the New York Conservation Foundation, and the Gothenberg Museum of Art, the GCI hosted a public seminar and experts meeting in March 2018 with conservation scientists and conservators experienced with MFT. Outcomes from this meeting included a published report summarizing the current state of MFT practice and defining paths forward (Beltran 2019), as well as the development of two collaborative MFT training workshops for the 2019 annual meetings of the American Institute of Conservation and the Western Association of Art Conservation.

This document, *Microfading Tester: Light Sensitivity Assessment and Role in Lighting Policy*, begins to address the field's need for additional didactic material related to MFT and is part of the GCI's Guidelines series presenting practical tools for advancing heritage conservation. The aims of this document are as follows:

- Establish a baseline of knowledge for prospective and current MFT users, as well as stakeholders involved in lighting policy;
- Discuss the aforementioned obstacles to more widespread use of MFT in the heritage field;
- Reflect the range of current MFT practice with respect to operation, data collection, and interpretation; and
- Promote regional and global dialogue about MFT practice to foster a self-supporting user community.

Each of the chapters that follows emphasizes specific topics related to MFT. Chapter 2 is focused on the fundamental color science underpinning the analytical technique. Essential color and perception concepts are discussed, along with descriptions of lighting and color space standards established by the International Commission on Illumination (Commission International de l'Eclairage [CIE]) and lightfastness standards developed by the International Standards Organization (ISO). This provides the necessary context for understanding the spectral reflectance and colorimetry data collected by MFT.

Succeeding chapters explore the MFT technique in depth. The components of an MFT setup—light source, fiber optics, lenses, measurement geometry, and spectrophotometer—and variations in design are discussed. Also examined are uncertainties and misperceptions associated with MFT, some of which are common to all accelerated aging techniques. This is essential for the effective communication of MFT results with stakeholders involved in collection care and exhibition. This is followed by consideration of the practicalities of conducting MFT, including sample and instrument setup, the collection of spectral data, and data analysis and visualization; this discussion was informed by the generous sharing of current MFT operating protocols by numerous institutions. It should be noted that the goal is not to define "best practice" but to provide context for how MFT has been employed in the field.

The final chapter presents a decision-making framework for lighting policy and the role of MFT in this process. It begins with a description of general principles for sustainable collection care and preventive conservation—including a value-based approach, museum or collection lifetime, and preservation target—and how these can broadly inform lighting guidelines. Several examples of MFT analyses of artists' materials and objects are presented, along with a discussion of how this information can be used to more objectively manage the risk of light-induced color change of artwork.

The appendices at the end of the document are as follows: a directory of institutions utilizing MFT, current as of publication (appendix 1), a glossary of terms (appendix 2), colorimetry calculations (appendix 3), a practical case study describing MFT use for exhibition screening (appendix 4), and a sample MFT analysis report (appendix 5).

References

Beltran, Vincent Laudato. 2019. *Advancing Microfading Tester Practice: A Report from an Experts Meeting Organized by the Getty Conservation Institute, March 13–15, 2018.* Los Angeles: Getty Conservation Institute. https://hdl.handle.net/10020/gci_pubs/advancing_mft_practice.

Whitmore, Paul M., Xun Pan, and Catherine Bailie. 1999. "Predicting the Fading of Objects: Identification of Fugitive Colorants through Direct Nondestructive Lightfastness Measurements." *Journal of the American Institute for Conservation* 38 (3): 395–409.

2. COLOR SCIENCE IN THE CONTEXT OF MFT

Sarah K. Freeman

Color science is a broad topic that can be explored through the lenses of biology, chemistry, mathematics, physics, physiology, and psychology. It encompasses the study of color stimuli, illumination, and human color perception. This chapter aims to briefly summarize prevailing definitions of color and color perception and provides an overview of how color and light measurements can be interpreted with standards created by the International Commission on Illumination (CIE) and the International Organization for Standardization (ISO).

The CIE is a technical, scientific, and cultural nonprofit organization whose objective is to provide an international forum for the discussion of all matters relating to the science, technology, and art of color and light. The organization provides recommendations and standards for colorimetry, illumination, and photometry and has created widely used standards available as published technical reports (e.g., CIE 2004a, 2004b, 2018), which can also be accessed in ISO standards. Similarly, the ISO is an independent, nongovernmental organization that develops international standards, technical reports, and specifications to support quality and safety assurance in world trade. While its purview is broad, the ISO often collaborates with the CIE on the development of lighting standards.

The CIE and ISO standards are among the tools that have shaped how many professionals tasked with the preservation of cultural heritage develop guidelines for the preventive care and handling of objects. The microfading tester relies on the color management framework developed by the CIE and the ISO. This includes reference data for standard illuminants and standard observer color matching functions, three-dimensional color spaces, and color difference equations that are fundamental to the interpretation of MFT data.

The ability of MFT to directly assess the light sensitivity of objects before display has made it an important tool for leveraging stakeholders in the constant negotiation between access for engagement in the present and preservation of material cultural heritage for future generations. How we define color and describe color change is critically important for establishing an effective lighting policy.

Electromagnetic Spectrum

An understanding of color begins with light. The human eye detects electromagnetic radiation in a small portion of the electromagnetic spectrum from 380 to 700 nanometers (nm) called the visible light region (fig. 2.1). This region corresponds to wavelength and frequency ranges for seven principal colors, which together create white light. The electromagnetic spectrum encompasses the entire distribution of electromagnetic radiation or energy and is measured by wavelength (described in meters, though nm is more convenient for the visible region) and frequency (units of Hertz or cycles per second). Light can be characterized as a waveform of energy, a combination of propagating electric and magnetic waves. Light also

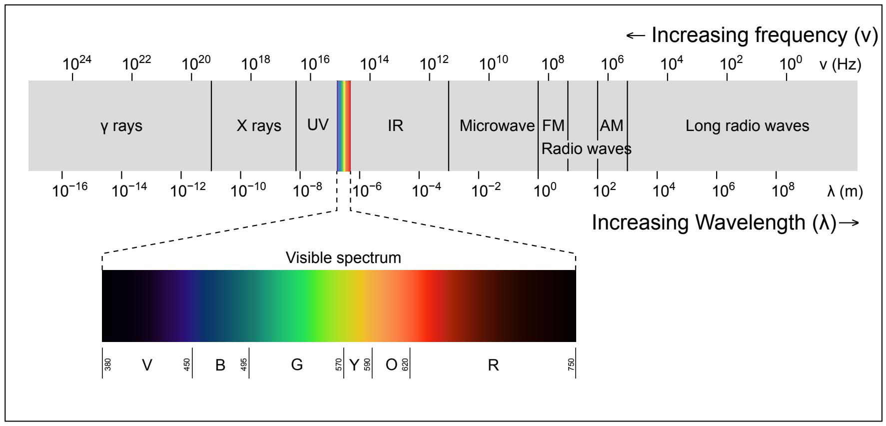


FIGURE 2.1 Electromagnetic spectrum. Image: Philip Ronan, 2007. Licensed under Creative Commons Attribution-Share Alike 2.5 Generic, 2.0 Generic, and 1.0 Generic license.

moves at a characteristic speed, defined by the variable c, well known by Einstein's equation of special relativity, $E = mc^2$, where E is energy, m is mass, and c is the speed of light.

In addition to its wave properties, energy in the electromagnetic spectrum can be described in terms of photons. Photon energy is dependent on wavelength and frequency; as photon energy increases with decreasing wavelength and increasing frequency, there is greater potential to initiate photochemical reactions within the absorbing material, which may result in color change (Michalski 2018).

Ultraviolet (UV) and infrared (IR) radiation exist beyond the visible spectrum, ranging from 100 to 380 nm and 700 to 1,000 nm, respectively. Possessing a higher photon energy, UV is known to cause damage when absorbed by cultural heritage material by inducing photochemical reactions that can result in the weakening of the support. UV is often filtered from a xenon-arc MFT light source so that it more closely resembles gallery lighting conditions, which typically reduce most UV radiation with coatings or filters on light fixtures and/or windows, as well as glazing on framed materials. Note that UV from the MFT light source can be included if the expected display conditions contain a significant UV component. Though possessing a reduced photon energy, IR is also excluded from a xenon-arc MFT light source so that the sample surface is not subject to excessive heating. Removing damage risk factors associated with UV and IR ensures that the MFT provides an assessment of color change from visible light exposure. For more detailed information on the damage caused by UV and IR, consult CIE Technical Report 157, *Control of Damage to Museum Objects by Optical Radiation* (CIE 2004b), which is frequently cited in the conservation literature.

Visible light can also be characterized by its color temperature. This refers to the behavior of an idealized thermal black-body radiator that absorbs radiation of all frequencies and emits black-body radiation that is dependent on that object's temperature. In practice, color temperature is defined for light sources that approximate black bodies and can appear red, orange, yellow, white, and blueish-white. Color temperature is expressed in units of kelvin (K), with values above 5,000 K considered "cool" (blueish) and those below 3,000 K considered "warm" (yellowish). While the typical color temperature for museum gallery lighting is 3,000 K, recent studies have shown that viewer preference may extend to higher color temperatures (e.g., Scuello et al. 2004; Pinto, Linhares, and Nascimento 2008; Nascimento and Masuda 2014). Daylight color temperatures are dependent on time of day and cloud cover, varying from 3,500 K immediately after sunrise or before sunset (the "golden hour") to 5,500 K during midday and 6,500 K when overcast. (Note that the CIE standard illuminants D50 and D65 correspond to color temperatures of 5,000 K and 6,500 K, respectively.) UV- and IR-filtered xenon-arc light sources used in MFT range in color temperature from 5,500 to 5,700 K (Pesme et al. 2016).

Color Theory

The modern study of the visible spectrum began with Sir Isaac Newton's treatises on light, which he presented to the English scientific community in the seventeenth century (Williamson and Cummins 1983). Newton demonstrated how white light splits into seven principal colors (red, orange, yellow, green, cyan, indigo, and violet) when passed through a glass prism. These seven colors, also referred to as the visible spectrum, were illustrated in a color circle in Newton's seminal text *Opticks* in 1704 (fig. 2.2). Although earlier attempts to explain color with wheels and spheres had been presented (Whitmore 2002), Newton was the first to describe the visible spectrum as a series of colors with different wave energies.

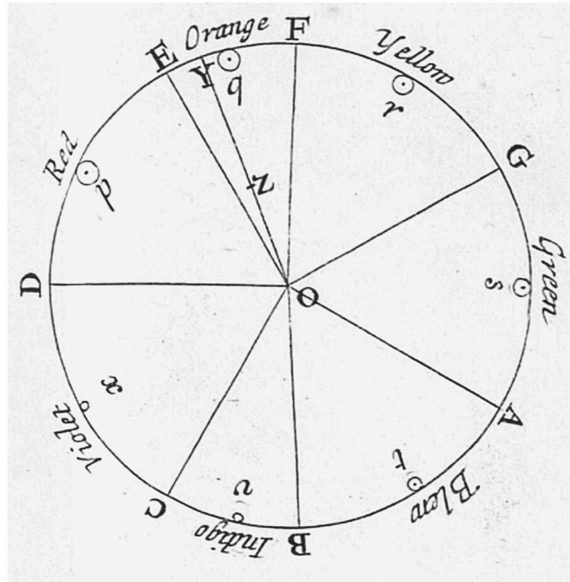


FIGURE 2.2 Color circle rendering describing 7 principal colors: Rubeus (red), Aureus (auburn/orange), Flavus (yellow), Viridis (green), Caeruleus (blue/cyan), Indicus (indigo) and Violaceus (violet). From Sir Isaac Newton, *Opticks*, 1704.

Newton also demonstrated that the color of light is additive, with different wavelengths of light overlapping to create a new color. He described primary additive colors as red, green, and blue because they can be combined to form white light, a principle that is later correlated to the anatomy of the human eye. (Primary colors can also be mixed to form secondary colors—green, orange, and violet—and merging of primary and secondary colors can form tertiary colors.) Additive color principles were applied to early models of color space, which still apply today to RGB (red, green, and blue) digital color systems for colorimetric and electronic visualization with televisions, computer monitors, and smart phones.

In contrast, subtractive color is based on mixtures of primary colorants that absorb incident light and reflect back to the viewer the subtractive colorant rather than the additive color. When colorants such as paint or dye are mixed, the wavelength of the primary color is absorbed and the secondary color is observed. CMYK (cyan, magenta, yellow, and black) is a subtractive color system used in the printing industry. For more about color mixing and light, see Roy S. Berns, ed., *Billmeyer and Saltzman's Principles of Color Technology* (2000).

Many scientists challenged Newton's mathematical theories about color and light, which shifted the focus to the human perception of color as reflected light rather than the physical properties of light rays. An early proponent of color perception originating from human physiology and psychology, rather than the physical sciences, was Johann Wolfgang von Goethe. Goethe's philosophy of color was published in 1810 in the *Theory of Colours* and was a direct challenge to Newton. Goethe suggested in a series of observations that the perception of color came from an emotional response to light. He illustrated his theory of color and its relationship to mood in an 1809 color wheel entitled *Cercul culorilor pentru symbolizarea spirit* şi *sufletului omului* (*Color circle symbolizing the spirit and soul of man*) (fig. 2.3). This visual depicts six principal colors: red = "beautiful" (*schön*); orange = "noble" (*edel*); yellow = "good" (*gut*); green = "useful" (*nützlich*); blue = "common" (*gemein*); and violet = "unnecessary" (*unnöthig*). These descriptors are assigned to four categories of mood: "reason" (*vernunft*) for beautiful and noble (red and orange); "understanding" (*verstand*) for good and useful (yellow and green); "sensuality" (*sinnlichkeit*) for useful and common (green and blue); and "imagination" (*Phantasie*) for unnecessary and beautiful (purple and red). Although many of Goethe's ideas were controversial, the relationship of color to psychology is inherent in modern color theory.

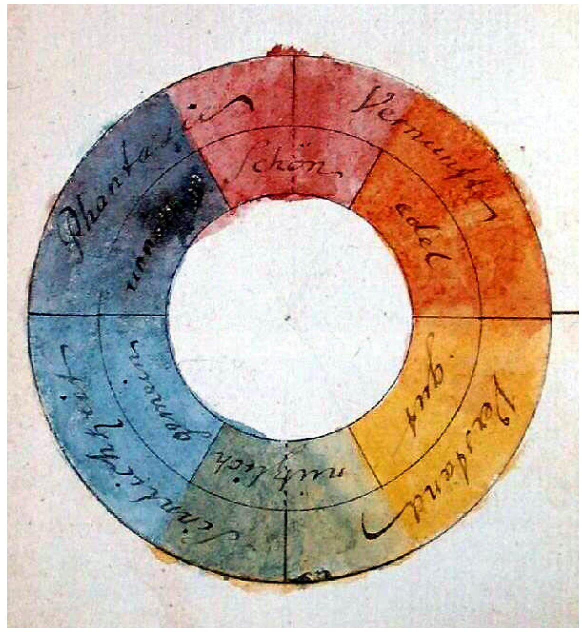


FIGURE 2.3 Color wheel. From Johann Wolfgang von Goethe, *Zur Farbenlehre* (*Theory of Colours*), 1810.

Color Perception

In an effort to quantify color perception, the concept of a just noticeable difference (JND) emerged from the nineteenth-century field of psychophysics, the study of sensation and perception. Ernst Heinrich Weber and Gustav Theodor Fechner figure prominently in this early development in experimental psychology. Through studies of touch senses, Weber was the first to describe the smallest perceivable difference between two stimuli as a JND. Weber realized that the threshold for the detection of a change in a stimulus was often a fixed percentage of the stimulus strength. He studied the perception of weight and noticed that as weights increased, so did the increments for which we could detect changes. This became known as Weber's fraction, which is written $\Delta \phi / \phi = c$, where c is a constant, $\Delta \phi$ is the difference threshold, and ϕ is the original stimulus magnitude (Gescheider 1997).

Fechner expanded on Weber's fraction, theorizing that there were two scales: a psychological scale of sensation and a physical scale of energy. Fechner showed that the JND had a nonlinear relationship with sensation and intensity, with the magnitude of a sensation proportional to the logarithm of the intensity of the stimulus causing it. This became known as the Weber-Fechner law, which is as follows: $\Psi = k \log \phi$, where Ψ is the magnitude of the sensation, ϕ is the physical intensity of the stimulus, and k is a scaling factor that varies from one sensation to another (Gescheider 1997).

The JND is used widely in experimental psychology as a statistical measure rather than as an exact quantity, because the difference noticed by a person will vary somewhat during the trial. It is therefore necessary to conduct many trials to determine the JND threshold, which may be defined by the difference observed in 50% of trials, though other ratios (e.g., 75:25) of stimulus recognition are also used (Gescheider 1997; Ashley-Smith, Derbyshire, and Pretzel 2002; Richardson and Saunders 2007; Fenech et al. 2013).

JND in the Conservation Field

The term "just perceptible difference" and its first application in the field of cultural heritage conservation appeared in a 1973 article by B. H. Crawford, "Just Perceptible Colour Differences in Relation to Level of Illumination." The term "just noticeable fade" (JNF) as a measure of fading became more prevalent in the conservation literature after the Canadian Conservation Institute created the Light Damage Calculator in 1987, which was based on a number of studies that used the ISO Grey Scale to characterize the onset of a perceptible effect (Michalski 1987). The Grey Scale consists of nine pairs of nonglossy neutral grey-colored chips. In early lightfast studies, the Grey Scale chips were used alongside Blue Wool samples to determine the corresponding fastness rating (as described in ISO 105-A02) (Whitmore 2002; Ford and Druzik 2013).

Based on earlier standards in the textile industry, the Blue Wool Fade Card (also described as the Blue Wool Scale or Blue Wool Standard) was developed by the ISO in 1954 (ISO 105-B01:2014 and ISO B02:2104) as a standard for lightfastness in both sunlight and artificial illumination (Whitmore 2002) This standard consists of eight dyed wools of increasing lightfastness, with Blue Wool (BW) 1 being the most fugitive and BW 8 the most stable. Each wool sample requires twice as much light exposure to fade to the same degree as the previous sample (Whitmore 2002). The three most sensitive swatches—BW1, 2, and 3—encompass high light sensitivity colorants (Michalski 2018) and can be used as an internal standard for comparison to samples analyzed in any accelerated light aging test, including MFT.

The lack of available instrumentation to measure color change at that time led the textile and dye industries to develop visual comparator tools like the ISO Grey Scale and Blue Wools to aid in characterizing color change (Whitmore 2002; Michalski 2018). As handheld color measurement instruments became accessible in the 1980s, conservators confirmed that persons varied greatly in what they could detect and how they would define what was just noticeable (Ford and Druzik 2013).

While some sources refer to a just noticeable fade (JNF) rather than a just noticeable difference (JND), these terms are often used interchangeably in conservation. However, it should be noted that they are derived from different sources. As previously described, the JND originated in the field of psychophysics and applies to any change in stimuli from the environment. The JNF comes from the conservation literature and refers specifically to color fading. More recently, Ashley-Smith, Derbyshire, and Pretzel (2002) have suggested using perceptible change (PC) rather than JNF to describe color change rates. In this text, we use the broader term JND.

Munsell Color System

As color theory evolved, diagrams explaining color relationships became more elaborate, incorporating mathematics and the human vision system. An essential classification system for color is the empirically based Munsell System of Color Notification. A precursor to CIE color space, the Munsell system represents the color properties of hue, chroma, and value in a three-dimensional model (fig. 2.4, https://munsell.com/about-munsell-color/how- color-notation-works).

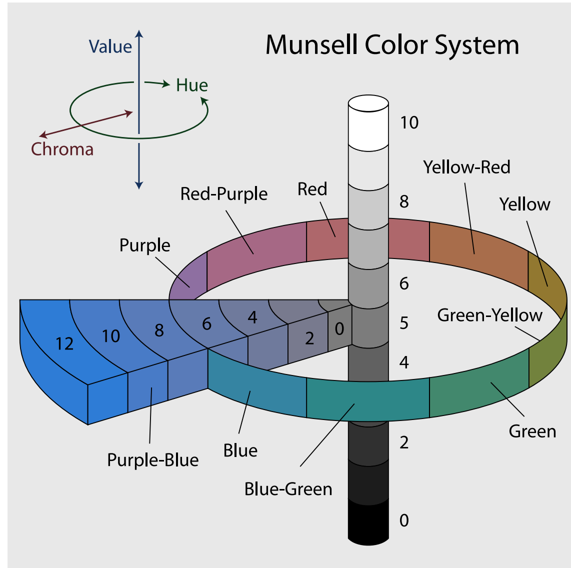


FIGURE 2.4 Munsell System of Color Notification. Image: © 2007 Jacob Rus, licensed under Creative Commons Attribution-Share Alike 3.0 Unported license.

"Chroma" is the degree of saturation or intensity of a color, "hue" refers to the color family (e.g., blue, red, or yellow), and "value" is a function of brightness (e.g., light to dark, white to black). Color tiles are arranged in a three-dimensional model based on measurements of human color perception, and a numerical value is assigned to each color. Extending vertically at the center of the model is the value scale from 0 to 10, with 0 for black and 10 for white. The horizontal scale depicts hue, with each wedge representing a color family. Chroma is arranged with increasing intensity (up to 12) toward the perimeter of the wheel. The relationship of hue, chroma, and value illustrated in the Munsell system remains the core of color space interpretation now represented in other color spaces, including those from the CIE.

Color Measurement

The importance of color in the interpretation of objects and the increased availability and ease of use of color measurement instrumentation, including MFT, has facilitated the application of this technology by the conservation field.

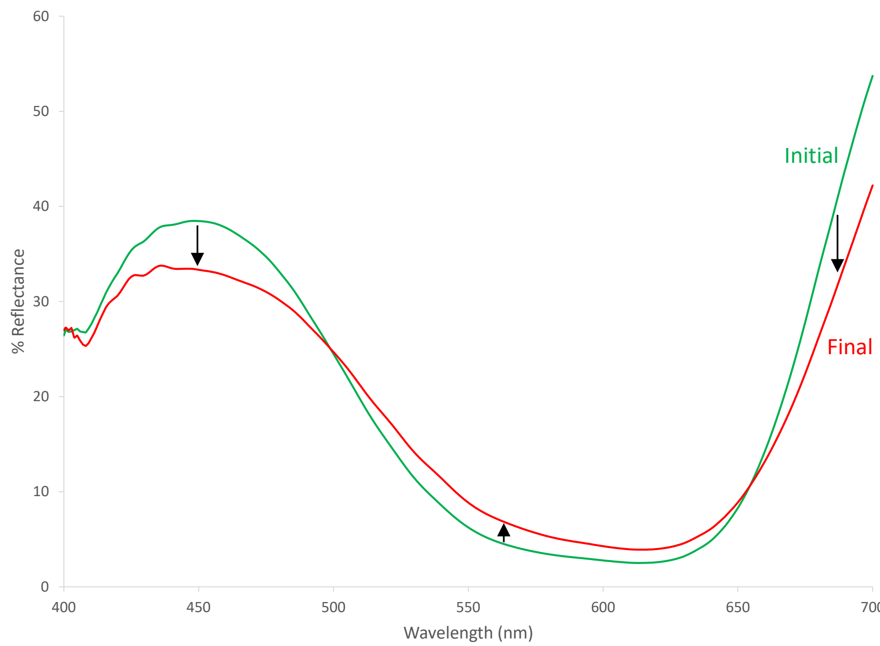
Instrumentation

Three instruments have been in use in conservation as tabletop or handheld devices: colorimeters, densitometers, and spectrophotometers. A colorimeter measures reflected light from a sample that passes through three color filters: red, green, and blue; the instrument interprets the color as a tristimulus value (RGB) that aligns with human color vision. However, colorimeters lack the ability to collect spectral reflectance data appropriate for more complex color analysis. While it does not assess color or collect spectral data, a densitometer measures reflected light that has interacted with a surface to determine the density or degree of darkness of a material. More recently, handheld spectrophotometers have become important tools for conservators. A spectrophotometer provides added information by examining a material's reflection or transmission behavior by measuring spectra, which shows light intensity as a function of wavelength. MFT incorporates a spectrophotometer to continuously collect spectral data while the object is exposed to a focused and high-intensity light spot; colorimetric values are then calculated from the spectral data. The collection and interpretation of MFT data are described in more detail in subsequent chapters.

Spectral Reflectance

The spectral reflectance of a material is expressed as the percentage of light reflected back from a test site, the difference having been absorbed by or transmitted through the surface. Spectral reflectance can also be visualized as a curve with percent reflectance shown as a function of wavelength. This measurement provides a useful illustration of color change for a test site during MFT; the first and last spectra can be plotted together to show the resulting shift in the amount of light reflected and absorbed during the test period (fig. 2.5).

FIGURE 2.5 Initial and final MFT spectral reflectance curves for Blue Wool 1. The final spectra displays decreasing reflectance/increased absorbance in the blue (~400-500 nm) and red (~650–700 nm) regions and increasing reflectance/decreased absorbance in the green-yellow region (~500–650 nm).



Spectral Power Distribution

Similar to the relationship between a spectral reflectance curve and color, a spectral power distribution (SPD) curve is unique to a light source and is referred to as its fingerprint. Measured by a spectrophotometer, the SPD plots the light source's power output at each wavelength across the visible region and into the ultraviolet and infrared regions. (Note that this differs from spectral reflectance, which examines reflected energy from a surface.) The strength and distribution of the emitted energy varies for each light source, which is important when evaluating lighting for display purposes. With respect to MFT, xenon-arc light sources provide a fairly continuous SPD, while SPDs for light-emitting diode (LED) sources can exhibit more peaks and troughs (fig. 2.6). Color rendering indices, which measure the ability of a light source to realistically show color in comparison to a reference source, can also be theoretically determined from the spectral power distribution curve.

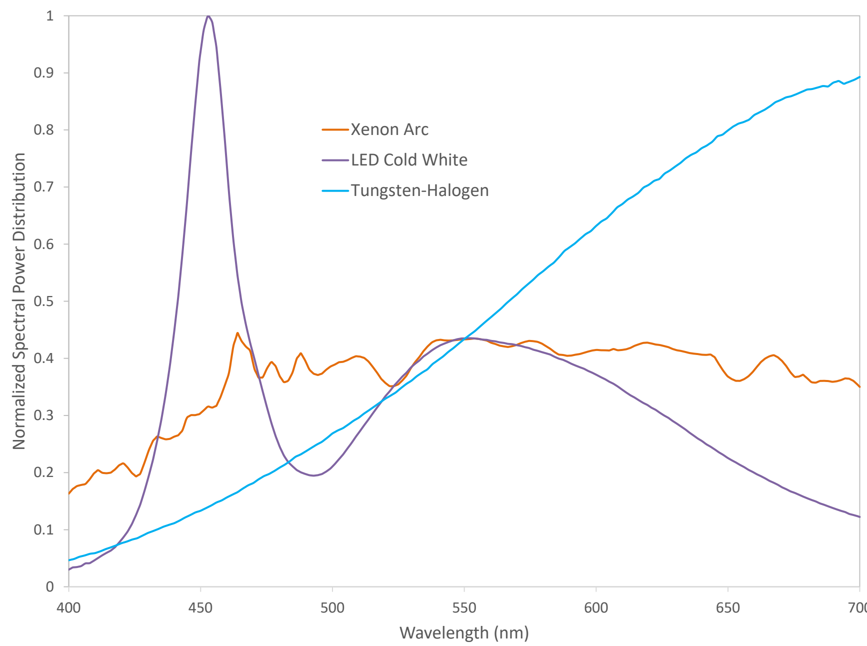


FIGURE 2.6 Spectral power distribution for a xenon-arc lamp, cold white LED, and tungsten-halogen lamp. Xenon-arc lamps and LED are commonly employed as MFT light sources.

CIE Standard Illuminants

To address the growing field of color science and color applications in the graphic and textile industries, the CIE created theoretical standard illuminants to allow for the comparison of colors measured with different light sources. Defined by tables of average spectrophotometric data (relative energy vs. wavelength), these illuminants are used in colorimetric calculations to compute the tristimulus values of reflected or transmitted object colors under specified conditions of illumination. In 1931, the CIE introduced standard illuminant A for tungsten incandescent bulbs at 2,900 K; B for direct daylight at 4,900 K; and C for average daylight at 6,800 K. The standard illuminant D series was introduced in 1963 and supplanted illuminants B and C as more realistic representations of natural daylight (CIE 2004a; Saunders 2020). Standard illuminants for LEDs have also been recently introduced (CIE 2018).

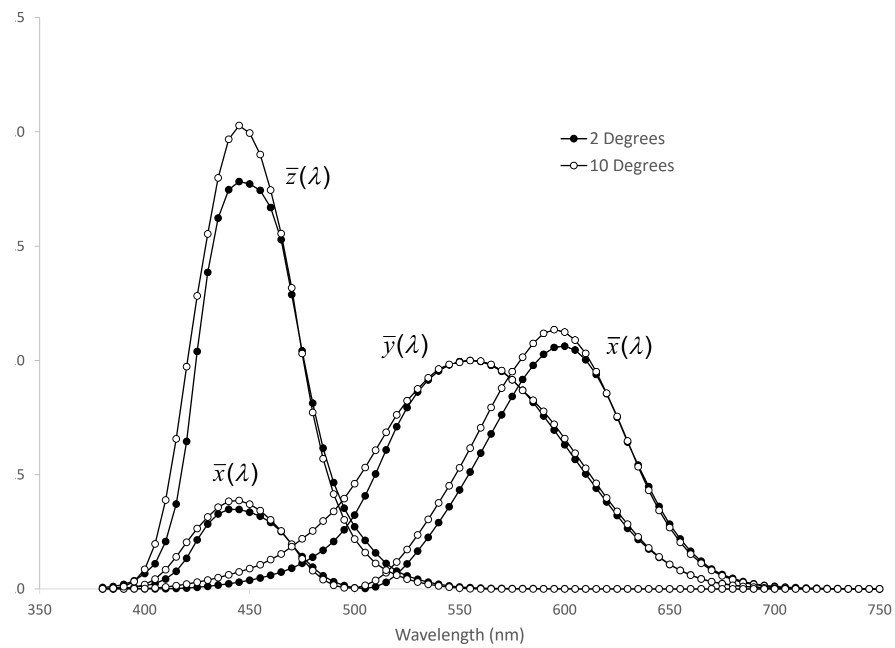
D65 is a common standard daylight illuminant for color and lighting studies, including MFT (Johnston-Feller 2001; Saunders 2020). It corresponds to a color temperature of 6,500 K and represents the average midday light comprising both direct sunlight and the light diffused by a clear sky. Colorimetric calculations for MFT data typically employ D65 as the standard illuminant. Light sources that are statistically similar to the D65 relative spectral power distribution can be considered D65 light sources.

CIE Standard Observers and XYZ Color Space

When light energy interacts with the surface of an object, a portion of the light is reflected back to an observer who perceives the color through stimuli in the eye that is interpreted in the brain. Scientists have determined that the human eye contains three types of cone photoreceptors—long, medium, and short—that contribute to color perception in mid- to high-brightness conditions, with each cone sensitive to different, yet overlapping, wavelengths of visible light. The cones are commonly associated with the color to which they are most sensitive: long cones are centered near 700 nm in the red region of the visible spectrum, medium cones are most sensitive at 546 nm in the green region, and short cones are focused at 435 nm in the blue region. The individual spectral sensitivities of these cone types form the basis of color matching functions or tristimulus values. It should be noted that tristimulus values do not account for metamerism, in which two colors appear similar under one lighting condition but different under disparate lighting conditions; in this case, a spectral measurement is needed to differentiate the two colors.

To quantify the ability of the human eye to perceive color, a series of color matching experiments were conducted by W. David Wright and John Guild in the 1920s that formed the basis of the CIE 1931 Standard 2° Observer. In these small-scale studies, human observers looked at a white screen through an aperture having a 2° field of view; this specific angle was chosen as color sensitivity was believed to be focused on a 2° arc of the fovea, which is a pit centered on the retina where visual acuity is greatest. With half of the screen illuminated by a test light, the observer adjusted the amount of three colored lights (red, green, and blue) until the other half of the screen matched the test light color. The results of the observers were combined and averaged to create the tristimulus values, which are also referred to as the $\bar{x}$, $\bar{y}$, and $\bar{z}$ color matching functions (Billmeyer and Saltzman 1981) (fig. 2.7). Based on these results, the CIE mathematically determined an additive color space called CIE 1931 XYZ. The CIEXYZ color space transformed visible light to an approximation of what the human eye perceives using three values to characterize color.

FIGURE 2.7 $\bar{x}$, $\bar{y}$, and $\bar{z}$ color matching functions for CIE 2° and 10° Standard Observers.



In 1964, the CIE supplemented the Standard 2° Observer with a Standard 10° Observer to account for a wider field of view and provide a more accurate representation of human color vision. While the Standard 10° Observer is often recommended for colorimetry applications with a field of view beyond 4° (Johnston-Feller 2001), the Standard 2° Observer remains in common use, as studies have suggested that the difference in perception with a larger field of view may not be great enough to warrant use of the Standard 10° Observer (Crawford 1973; Berns 2000). In addition to standard illuminant D65, the Standard 2° Observer is also typically employed in MFT colorimetry calculations, following the initial protocol described by Whitmore, Xun Pan, and Bailie (1999).

CIELAB Color Space and Color Difference

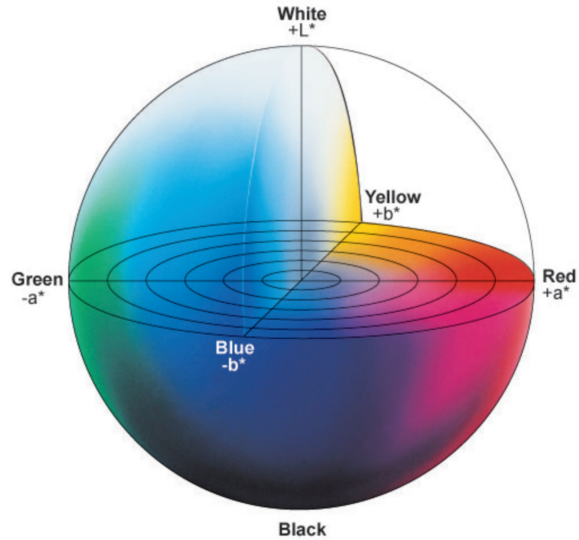


FIGURE 2.8 CIELAB color space. Image: courtesy of Konica Minolta Sensing.

In 1976, the CIE defined a new color space called CIEL*a*b*, or CIELAB. Derived from CIEXYZ, CIELAB was intended to be more perceptually uniform with respect to human color vision, such that the similar numerical difference in these values corresponded to the same perception of visual change. As discussed later, inconsistencies were found that resulted in further refinements. CIELAB color space became the recommended and internationally sanctioned method for reporting colorimetric values (Berns 2016) (fig. 2.8). Note that the use of asterisks (L*a*b*) identifies its association with CIELAB color space rather than Hunter Lab color space, which was a precursor to CIELAB.

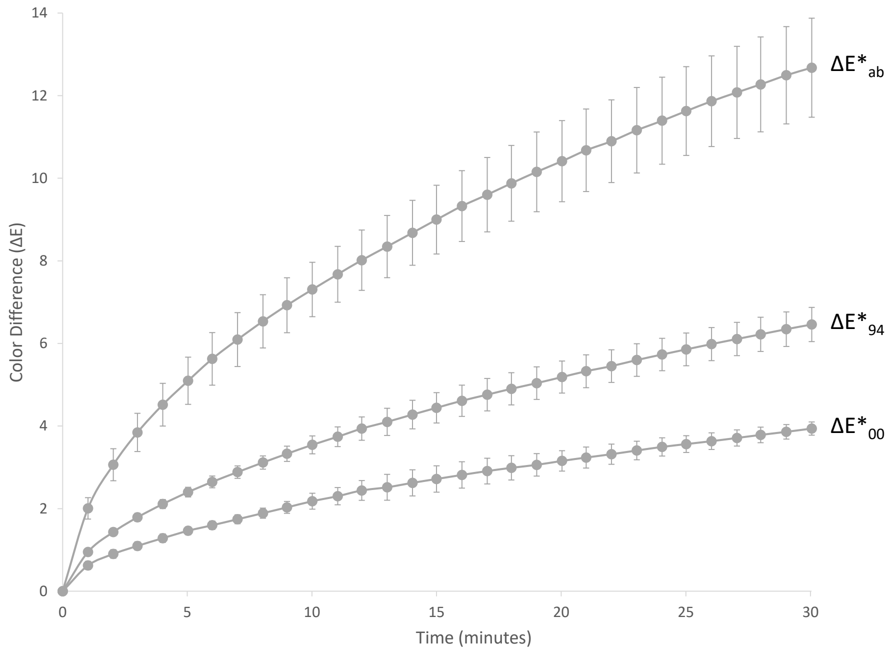
The CIELAB color space expresses color as three numerical values: L* for lightness, a* for green-red components, and b* for blue-yellow components. The lightness value, L*, represents the darkest black at L* = 0 and the brightest white at L* = 100. The a* axis represents green in the negative direction and red in the positive direction, and the b* axis represents blue in the negative direction and yellow in the positive direction. a* and b* values of 0 represent true neutral grey.

When using a spectrophotometer, its software calculates the CIE tristimulus values (X, Y, and Z) from the spectrum of a sample, from which the L*, a*, and b* values can then be derived. This calculation is done by multiplying the spectral reflectance of the sample at wavelength spacings from 1 nm to 20 nm by (a) the spectral power distribution of a reference illuminant (such as D65) and (b) the standard observer color matching functions (2° or 10°); each product is then summed over the visible region and normalized to produce X, Y, and Z values for the sample (CIE 2018). To convert from X, Y, and Z to L*, a*, and b*, the tristimulus values are first divided by those of a 100% reflecting white standard; subsequent calculations are shown in appendix 3 (Billmeyer and Saltzman 1981).

L*a*b* values for two given colors can be used to measure the color difference, or ΔE. The initial color difference calculation introduced in 1976, denoted as ΔE^*_{ab}, was defined as the Euclidian or straight-line distance between two points in CIELAB color space and is as follows: $\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$. Despite its initial motivation, CIELAB continued to present issues of perceptual nonuniformity, as the human eye exhibits higher sensitivity to certain colors. This prompted further refinements of the 1976 ΔE^*_{ab} calculation, which were introduced by CIE in 1994 (ΔE^*_{94}) and 2000 (ΔE^*_{00}).

The equations for ΔE^*_{94} and ΔE^*_{00} are considerably more complex than the Euclidian distance determined by ΔE^*_{ab}. (Appendix 3 provides color difference calculations for each.) The ΔE^*_{94} calculation incorporated differences in lightness, chroma, and hue values and added weighting factors specific to graphic art and textile applications (though these are typically set to one in the ΔE^*_{00} calculation) (CIE 2004a, 2018). The ΔE^*_{00} calculation added important corrections that accounted for differences in chroma and hue values in the blue region of CIELAB color space, further corrected inaccuracies in L* (lightness), and modified scaling along the a* (red-green) axis to correct for the nonuniformity of grey and neutral colors (CIE 2018). The correction in the blue region is especially relevant for MFT because of the reliance on Blue Wools as a standard reference (Ford and Druzik 2013). Though ΔE^*_{ab} remains in common use due to its ease of calculation, the ΔE^*_{00} equation is considered the most accurate color difference calculation with respect to perceptual uniformity in CIELAB color space. (Note that comparisons of color change must use the same color difference equation.) Figure 2.9 compares the color difference equations as applied to MFT data collected for a Blue Wool 1 Standard.

FIGURE 2.9 Comparison of color difference equations applied to MFT data on a Blue Wool 1 Standard.



The relationship between instrumental color difference (ΔE) and how it is perceived (expressed in JNDs) is subject to variability (Ford and Druzik 2013; Pretzel 2008). While due in part to the choice of color difference equation and the color of the samples, this variability is also related to ancillary factors on which JND is dependent, including differences in individual sensitivities of human vision, which impacts the perception of color; object size and orientation; the transparency, texture, and gloss of the sample surface; the illuminating light source; and the light level used during assessment (Richardson and Saunders 2007; Ford and Druzik 2013). Calculated JND values are primarily based on psychophysics research using standard experimental conditions: a neutral grey background for side-by-side comparisons of color samples illuminated by a daylight balanced (CIE D standard illuminant) light source (Ashley-Smith, Derbyshire, and Pretzel 2002; Richardson and Saunders 2007). Michalski equates 1 JND with a ΔE^*_{ab} value of 1.6 based on measurements using ISO Grey Scale 4 (GS4, from ISO 105-A02) (Michalski 1987; CIE 2004a). Similarly, Pretzel (2008) suggests that a ΔE^*_{00} of 1.5 represents a suitable compromise for 1 JND when using GS4 to evaluate color change in textiles; this is corroborated by Ashley-Smith and colleagues (2002) for use with light-sensitive objects in the Victoria and Albert collection. Richardson and Saunders (2007) also noted that the average viewer can distinguish a perceptible color change in adjacent color samples at a ΔE^*_{00} of approximately 2 under standard lighting conditions and readily recognizes change for a ΔE^*_{00} of 4. Presumably, the JND threshold would be larger if a viewer is confronted with a visually complex artwork that is subject to the varied factors described earlier. Thus, MFT assessments of an object surface that induce a ΔE^*_{00} value of ~1.5 (or 1 JND) indicate very subtle changes in color.

Conclusion

The goal of this chapter is to provide an introduction to the interdisciplinary field of color science that has led to CIE and ISO standards for color and light evaluation, which are useful in conservation practice. As a prequel to a discussion on color, the reader is reminded of the electromagnetic spectrum and the visible light range within the energy continuum. Early discoveries of light, color, and color perception provide the basis for psychophysics and the concept of a just noticeable difference. This was followed by the development of CIEXYZ and CIELAB, three-dimensional color spaces based on a series of experiments describing how humans see color. MFT analysis uses CIELAB color space to define differences in color. The relationship between the induced change in color, its instrumental measurement, and its perception is key to evaluating the light sensitivity of material cultural heritage.

While the visual perception of the object by the observer (e.g., visitor, conservator, curator, or lighting designer) remains a primary factor in guiding the management of color, light sensitivity assessments of objects is increasingly becoming a priority for conservators and allied professionals as instrumentation and published research are more accessible. Using devices such as a spectrophotometer, color change measurements before, during, and after gallery display can help conservators evaluate the light stability of the material in real time. Color change can also be evaluated prior to exhibition using accelerated aging tests, such as MFT or lightbox exposures. While lightbox studies typically examine representative mock-up samples, MFT data can be obtained directly from the object surface. The in situ color change incurred by MFT may be considered damage, but this is mitigated by the small size of the exposure area (less than 0.5 mm in diameter) and real-time monitoring of color change such that the test can be halted before becoming visible to the viewer. In all cases, color monitoring requires a significant time commitment of staff to be trained on the instrumentation, organize and document the setup (including the location of test sites, instrument orientation, and spot size), obtain precise measurements, and process and interpret the collected data (Ford 1992).

References

Albers, Josef. 2013. *Interaction of Color: 50th Anniversary Edition.* New Haven, CT: Yale University Press.

Ashley-Smith, Jonathan, Alan Derbyshire, and Boris Pretzel. 2002. "The Continuing Development of a Practical Lighting Policy for Works of Art on Paper and other Object Types at the Victoria and Albert Museum." In *ICOM-CC 13th Triennial Meeting, Preprints, Rio de Janeiro, 22–27 September 2002*, ed. R. Vontobel, 3–8. London: James & James.

Berns, Roy S., ed. 2000. *Billmeyer and Saltzman's Principles of Color Technology*. 4th ed. New York: Wiley.

———. 2016. *Color Science and the Visual Arts: A Guide for Conservators, Curators, and the Curious.* Los Angeles: Getty Conservation Institute.

Billmeyer, Fred, and Max Saltzman. 1981. *Principles of Color Technology*. 2nd ed. New York: Wiley.

CIE. 2004a. *Colorimetry*. 3rd ed. Technical Report 15. Vienna: Commission Internationale de l'Eclairage.

———. 2004b. *Control of Damage to Museum Objects by Optical Radiation.* Technical Report 157. Vienna: Commission Internationale de l'Eclairage.

———. 2018. *Colorimetry*. 4th ed. Technical Report 15. Vienna: Commission Internationale de l'Eclairage.

Crawford, B. H. 1973. "Just Perceptible Colour Differences in Relation to Level of Illumination." *Studies in Conservation* 18 (4): 159–66.

Eng, Charlotte W., Frank D. Preusser, and Terry T. Schaeffer. 2016. "Reflections on Light Monitoring: Evaluating Museum Lighting Options for Modern and Contemporary Art." *Studies in Conservation* 61: 2–44.

Fenech, Ann, Catherine Dillon, Konstantinos Ntanos, Nancy Bell, Mark Barrett, and Matija Strlič. 2013. "Modelling the Lifetime of Colour Photographs in Archival Collections." *Studies in Conservation* 58 (2): 107–16.

Ford, Bruce L. 1992. "Monitoring Colour Change in Textiles on Display." *Studies in Conservation* 37 (1): 1–11.

Ford, Bruce, and J. Druzik. 2013. "Microfading: The State of the Art for Natural History Collections." *Collection Forum* 27 (1–2): 54–71.

Gescheider, George A. 1997. *Psychophysics: The Tundamentals*. 3rd ed. London: Psychology Press.

Goethe, Johann Wolfgang von. [1810] 1970. *Theory of Colours*. Translated from German by Charles John Eastlake. Cambridge, MA: MIT Press.

Johnston-Feller, Ruth. 2001. *Color Science in the Examination of Museum Objects: Nondestructive Procedures*. Los Angeles: Getty Conservation Institute.

Koenderink, Jan J. 2010. *Color for the Sciences*. Cambridge, MA: MIT Press.

Michalski, Stefan. 1987. "Damage to Museum Objects by Visible Radiation (Light) and Ultraviolet Radiation (UV)." In *Lighting in Museums, Galleries and Historic Houses: Conference Postprints, Bristol, 9–10 April 1987*, 3–16. London: Museums Association.

———. 2018. "Agent of Deterioration: Light, Ultraviolet and Infrared." Government of Canada. www.canada.ca/en/conservation-institute/services/agents-deterioration/light.html.

Nascimento, Sérgio Miguel Cardoso, and Osamu Masuda. 2014. "Best Lighting for Visual Appreciation of Artistic Paintings: Experiments with Real Paintings and Real Illumination." *Journal of the Optical Society of America A*. 31 (4): A214–A219.

Newton, Isaac. [1704] 1952. *Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*. New York: Dover.

Pesme, Christel, Andrew Lerwill, Vincent Beltran, and James Druzik. 2016. "Development of a Contact Portable Microfade Tester to Assess Light Sensitivity of Collection Items." *Journal of the American Institute for Conservation* 55 (2): 117–37.

Pinto, Paulo Daniel, João Manuel Maciel Linhares, and Sérgio Miguel Cardoso Nascimento. 2008. "Correlated Color Temperature Preferred by Observers for Illumination of Artistic Paintings." *Journal of the Optical Society of America A*. 25 (3): 623–30.

Pretzel, Boris. 2008. "Now You See It, Now You Don't: Lighting Decisions for the Ardabil Carpet Based on the Probability of Visual Perception." In *Preprints of ICOM-CC 15th Triennial Conference, New Delhi,* vol. 2, ed. Janet Bridgland, 759–65. New Delhi: ICOM-CC.

Sands, Sarah. 2016. *Delta E: A Key to Understanding Lightfastness*. Readings in JUST PAINT. Golden Artist Colors, Inc.

Saunders, David. 2020. *Museum Lighting: A Guide for Conservators and Curators*. Los Angeles: J. Paul Getty Trust.

Scuello, Michael, Israel Abramov, James Gordon, and Steven Weintraub. 2004. "Museum Lighting: Optimizing the Illuminant." *Color Research and Application* 29 (2): 87, 121–27.

Shevell, Steven K., ed. 2003. *Science of Color*. 2nd ed. Oxford: Elsevier Science.

Whitmore, Paul M., ed. 2002. *Contributions to Conservation Science: A Collection of Robert Feller's Published Studies on Artist's Paints, Paper, and Varnishes*. Pittsburgh: Carnegie Mellon University Press.

Whitmore, Paul M., Xun Pan, and Catherine Bailie. 1999. "Predicting the Fading of Objects: Identification of Fugitive Colorants through Direct Nondestructive Lightfastness Measurements." *Journal of the American Institute for Conservation* 38 (3): 395–409.

Williamson, Samuel J., and Herman Z. Cummins. 1983. *Light and Color in Nature and Art.* New York: Wiley.

X-rite Color Services. 2008. "Fundamentals of Color Appearance: A Practical Approach to Understanding and Managing Color Quality." Course materials. X-rite Color Services, Grand Rapids, MI.

3. MFT FUNDAMENTALS: COMPONENTS, OPERATION, AND UNCERTAINTY

Vincent Laudato Beltran

In 1999, Whitmore, Xun Pan, and Bailie published a seminal paper introducing the microfading tester to the cultural heritage field. This accelerated aging technique had the unique capability to identify the in situ light sensitivity of an artwork by exposing an extremely small surface area to an intensely bright light while monitoring the resulting light-induced color change. Comparisons of these object-specific data to MFT analysis of Blue Wool Standards allowed for an assessment of the rate of color change. The general approach of direct light sensitivity assessments of objects was independently described by Costain et al. (1995), Michalski (1997), and Pretzel (2008).

Whitmore, Xun Pan, and Bailie (1999) also defined the necessary operational requirements for the MFT, which can be summarized as follows:

- Continuous spectrum of wavelengths in the visible region (400–700 nm)
- High color temperature light source with filters used to exclude ultraviolet and infrared light
- Stable light intensity to increase ability to detect slight color change
- Light delivery system using fiber optic cables and lenses in a 0/45 geometry, resulting in a highly focused and intense spot of light
- Rapid and simultaneous spectral analysis

Since the concept for MFT was developed within the cultural heritage field and no off-the-shelf unit existed, their paper detailed the various components, largely from Newport Oriel (now owned by MKS Instruments), used to create such an instrument. (Newport Oriel subsequently developed an MFT kit that included part numbers.) The majority of MFTs employed around the world are based on this initial blueprint and are colloquially known as Whitmore MFTs (fig. 3.1).

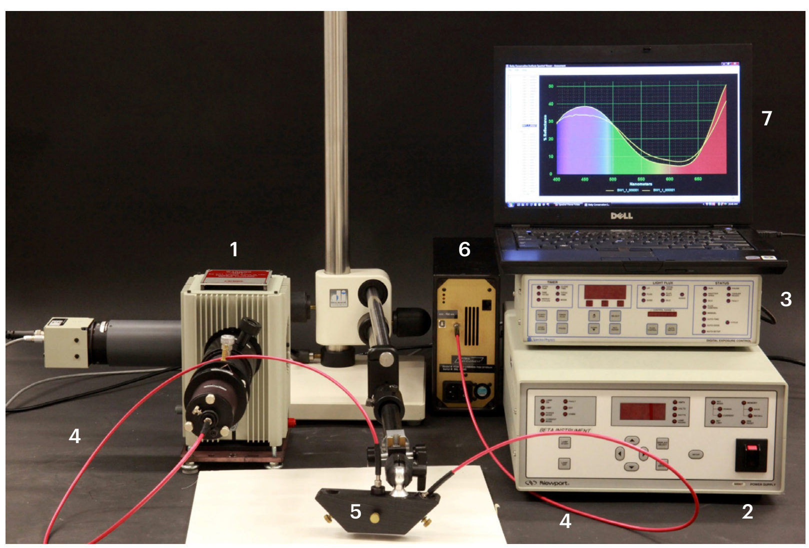


FIGURE 3.1 Whitmore MFT components. Shown are the (1) xenon-arc light source, (2) power supply, (3) digital exposure controller, (4) fiber optic cables, (5) 0/45 measurement head, (6) spectrophotometer, and (7) laptop.

As stated in the introduction, MFT users began to investigate alternative light sources and geometries, as well as possibilities for automation. While iterative changes are expected with the maturation of an analytical technique, these adaptations were largely developed and implemented by individuals; the absence of an organized community of MFT users limited communication about the various MFT designs and their appropriateness for specific contexts. For organizations interested in MFT, the multiple iterations created confusion as to which route to pursue and likely delayed acquisition in some cases. Moreover, MFTs based on the Whitmore design required assembly of discrete parts, which can be daunting to new users.

When introduced to the cultural heritage field, MFT remained largely in the domain of conservation science. However, the circle of MFT users soon widened to include conservators and other collection care staff, revealing areas of growth and uncertainty. Potential concerns include the applicability of MFT results subject to high-intensity light to the low light levels present in museum galleries, use of Blue Wool Standards, differences in spectral power distribution (SPD) of light during testing and display, and atypical sample behavior. Though operation of the MFT is relatively straightforward following a period of training and use, it is crucial that MFT data and interpretations of these results are presented clearly, transparently, and in proper context, particularly for colleagues with varying expertise in color science and lighting.

This chapter introduces the fundamentals of the MFT, including its various components and basic principles of operation. The discussion is based largely on the original Whitmore design due to its prevalence and the transparency of its various parts, but extends to subsequent designs that have sought to revisit the operational requirements of MFT. (Chapter 4 delves into practical considerations for conducting an MFT analysis.) The chapter closes with an examination of some of the uncertainties inherent to the MFT process to clarify its boundaries of application.

MFT Components and Operational Principles

An MFT is used to assess the extent of light-induced color change occurring on an object. As such, an MFT system can be separated into three broad segments:

- Light source to provide stable high-intensity light
- Focused light delivery system from lamp to sample and from sample to spectrophotometer
- Spectrophotometer to assess the reflected light and the light sensitivity of the sample

Light Source

Xenon-Arc Lamp

Given the requirements of a continuous wavelength spectrum in the visible region and a high color temperature light, a 75-watt (W) xenon-arc lamp was selected as the light source for the original Whitmore MFT design. Xenon-arc lamps generate an intense white light and are commonly used in daylight simulation studies. The color temperature of a filtered xenon-arc lamp is approximately 5,500 to 5,700 K (Pesme et al. 2016).

The requirement of stable light intensity is also compatible with the use of xenon-arc lamps. The luminous output of a xenon-arc lamp can be monitored and automatically adjusted by a digital exposure control, which ensures that the lamp intensity remains constant during each run and throughout the day. This signal stability allows MFT to measure small color differences of the sample and eases calculation of the light dose during a run, assuming the spot size is accurately defined.

Further, using both a digital exposure controller and a radiometer/photometer (to measure the resulting intensity) allows one to set the lamp intensity to the same level each day. This consistency facilitates comparison of MFT results obtained on different days, which is particularly useful when assessing common reference material such as Blue Wools. (As lamp performance deteriorates, a higher wattage may be needed to achieve this threshold intensity.) Alternatively, one could choose to maximize light intensity beyond this target to increase the color change observed for slower fading material, such as BW3. While Whitmore, Xun Pan, and Bailie (1999) reported xenon-arc light intensities as high as 950 millilumens (mlm) for a 0.4-mm-diameter spot, resulting in an illuminance of 7.6 million lux (direct sunlight ranges from 30,000 to 100,000 lux), a number of MFT users choose to operate at lower light intensities (e.g., ~600 mlm).

The xenon-arc lamp employed by many legacy Whitmore MFTs is situated in an adjustable mirrored housing to focus the beam and is attached to a power supply and a digital exposure controller unit. Subsequent iterations looked for more compact xenon-arc lamps that facilitated transport (fig. 3.2); these alternate xenon-arc lamps had a self-contained power supply and largely omitted the digital exposure controller, as experience suggested that their stability was satisfactory. The cost of replacing xenon-arc bulbs for these compact units can be significantly higher than that of bulbs for the original xenon-arc lamp, though they are expected to last longer.

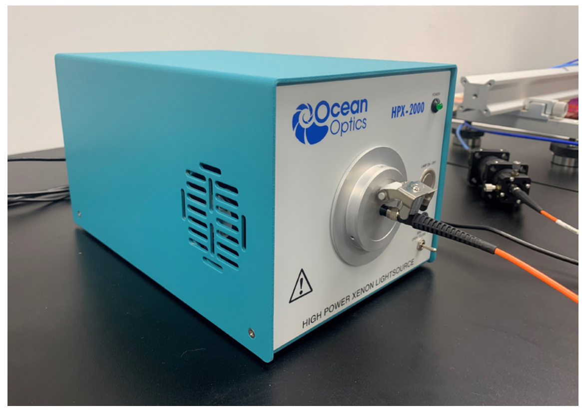


FIGURE 3.2 Compact xenon-arc lamp with a self-contained power supply. Image by Katherine Schilling.

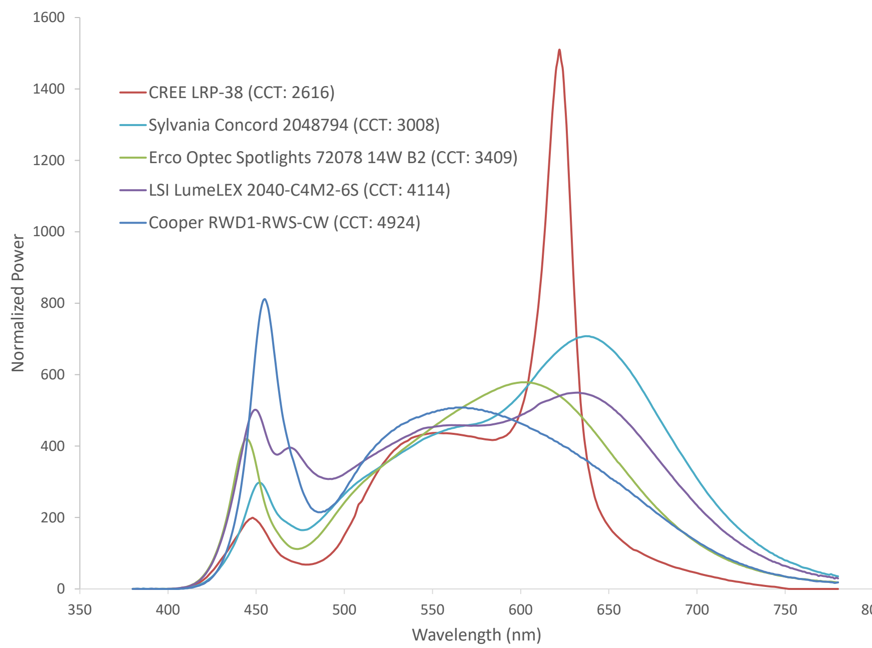
The use of xenon-arc lamps is typically accompanied by filters to block the UV and IR components of the light, allowing only light in the visible region (400–700 nm) to reach the sample surface. This is consistent with the removal of nonvisible wavelengths in museum gallery lighting to reduce the risk of damage to light-sensitive artwork. While glass filters are typically employed, the original Whitmore system provided the option of a water filter to mitigate IR. Neutral density filters are also used to reduce the intensity of the light equally across the wavelength spectrum; this aids with the alignment of the lamp and spectrophotometer spots on the sample and allows for careful MFT analysis of objects with unknown color change behaviors. Filters can also be used to isolate specific wavelength bands or potentially reshape a xenon-arc SPD to more closely resemble that of an LED lamp.

LED Lamps

LEDs are a semiconductor light source that have largely superseded incandescent lights in many galleries due to their energy efficiency and extended lifetime. Because of increased LED usage in museums and interest in assessing the color change of objects when exposed to LED-specific SPDs, MFT users have explored LEDs as an alternative to xenon-arc lamps. LEDs can also be more cost-effective and require less setup (e.g., focusing mirrors are not used) than xenon-arc light sources. For MFTs that are to be employed at different locations, the smaller size of LEDs may be more conducive to transport (though several users travel with compact footprint xenon-arc lamps).

A primary difference between LEDs and xenon-arc lamps is their SPD. Whitmore, Xun Pan, and Bailie (1999) called for a continuous spectrum of wavelengths in the visible region for MFT, which is provided by a xenon-arc lamp; this allows for exposure of the sample to the worst-case scenario. In contrast, LEDs are not broad-band light sources, as its SPD contains characteristic peaks and troughs (fig. 3.3). Further, some LEDs have reduced output intensity below ~450 nm and above ~700 nm, which can contribute to measurement noise and unreliability in these regions. A potential concern of using LEDs as an MFT light source is that troughs in its SPD might coincide with regions of sample absorbance responsible for color change. Thus, a sample could theoretically be deemed light sensitive when exposed to a broadband xenon-arc lamp and characterized as stable for a specific LED light source. For example, Hattori, Yoshizumi, and Crews (2012) noted that AATTC Blue Wool Standard L2 was responsive in the UV region, which would be affected by exposure to an unfiltered xenon-arc lamp (which is atypical for MFT) and less so by exposure to an LED source.

FIGURE 3.3 Comparison of spectral power distributions for different LED lamps. Created via the Spectral Power Distribution Curves website by Joseph Padfield at the National Gallery, London.



Discussion of MFT light sources at the GCI's 2018 MFT Experts Meeting (Beltran 2019) focused on the purpose of testing. If used as a screening tool to identify light-sensitive artwork (such a case study is presented in appendix 4), either xenon-arc or LED was considered a suitable light source. If an MFT is to be employed as a research tool, the broadband nature of a xenon-arc lamp may be preferred over the notched spectra of an LED source; damage function studies might employ filters to focus on the effect of narrow wavelength ranges. It should be noted that MFT results using a specific LED profile may be less relevant should the object be exposed to significantly different lighting conditions in the future. This may be an especially important factor when screening objects that will travel to multiple venues, as only light dose (and not SPD) is typically specified in loan agreements. While additional studies are needed and forthcoming, initial MFT experiments examining the exposure of select samples to xenon-arc and LED light sources suggested that their respective Blue Wool rankings (i.e., comparison of color difference curves to that of BW1, 2, or 3) were similar (Pesme et al. 2016).

Additional light-related MFT requirements put forth by Whitmore, Xun Pan, and Bailie (1999) called for a high color temperature light source, the exclusion of UV and IR radiation, and a stable light intensity. High color temperature LEDs are widely available, as are LEDs at cooler color temperatures. This range of color temperature options available to museum lighting designers poses interesting MFT research possibilities. The blending of multiple LED lamps has been explored via a controllable 4 LED source, and development of an LED carousel for the automated MFT by Instytut Fotonowy allows for testing with different LED light sources. The lack of a significant UV or IR component in LED light makes these filters unnecessary.

With respect to stability, LEDs are not typically paired with an exposure controller to actively monitor and regulate its output. The output of LEDs generally responds linearly to the applied current (e.g., half current results in half the output intensity), which simplifies the determination of light levels. While there is some concern about long-term stability, given sufficient warm-up time, it is expected that the short-term stability of LEDs should be satisfactory, though this should be checked periodically for typical MFT durations. Long-term changes can be monitored by a daily record of operating conditions.

Light Delivery System

Fiber Optic Cables and Lenses

Light is transferred from the light source to the sample and from the sample to the spectrophotometer via a series of fiber optic cables and focusing lenses. Both xenon-arc and LED lamps use a small filament that can direct much of its output onto a fiber optic cable. The original Whitmore design used an illumination fiber optic cable (from the light source to the sample) that had a smaller diameter (200 μm) than that of the collecting fiber optic cable (600 μm, from the sample to the spectrophotometer), providing tolerance when aligning the illumination and collection spots. Note that care should be taken when handling fiber optic cables; excessive bending or flexing of the cables can cause refraction of the optical signal or permanent damage by creating micro cracks on the glass fibers, compromising the integrity of the data.

The MFT spot size on the sample is typically less than 0.5 mm in diameter and is a function of the diameter of the illumination fiber optic cable and the conjugate ratio of the focusing lens. Use of a smaller spot size may increase the light intensity and decrease testing time to achieve a given light dose (reported in lux-hours). However, results for a reduced spot could be less representative of the sample surface and potentially increase surface heating; this latter point is particularly important to verify before testing artwork to ensure its safety. Larger spot sizes may be more appropriate for materials with higher surface roughness but can extend testing duration to reach a given light dose.

For the original Whitmore MFT design, two pairs of convex or converging lenses are situated in cylindrical housings attached to the illumination and collection fiber optic cables. These lens assemblies are then mounted in a test head with a 0/45 geometry; this indicates light arriving perpendicular or normal (0°) to the sample surface, while diffuse reflected light from the surface is collected at 45° from normal. The lens pairs in the illumination and collection assemblies act to converge the light rays onto the sample and the collecting fiber, respectively; the point of convergence is known as the focal point (fig. 3.4). Between the lenses, the light is collimated or parallel. Consideration should also be given to the numerical aperture, which

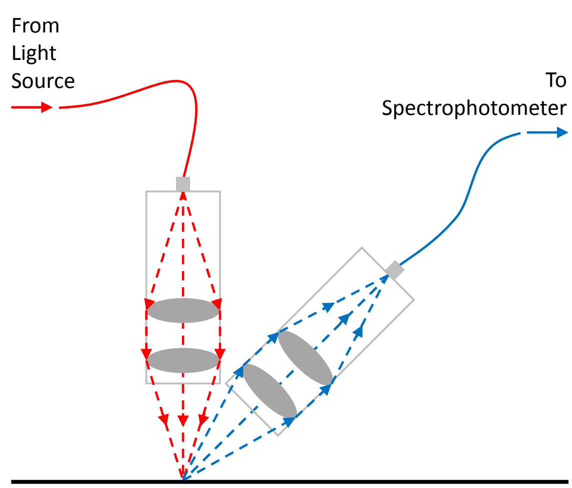


FIGURE 3.4 Light rays traveling through the illumination and collection lens assemblies. Adapted from Jacob Thomas.

describes the range of angles within which light that is incident on the fiber will be transmitted along it; the numerical aperture of the lens should match that of the fiber optic cable to ensure that it collects all of the light (Thomas, pers. comm. 2021).

The choice of lens informs the working distance between the sample and the light probe. The original Whitmore MFT employed lenses for both the illumination and collection assemblies with a focal length of 25 mm and a magnification of 1.3x. This allowed for noncontact operation (analysis without touching the sample surface) at a working distance of approximately 1 cm, due to the protrusion of the collection lens assembly (fig. 3.5). This setup provides an opportunity to test objects through glazing so long as the testing surface remains within the 1 cm working distance. Alignment of the focal points on the sample, such that the collection area overlaps the illumination spot, is attained by adjustment of the vertical position of the test head (containing both the illumination and collection assemblies).

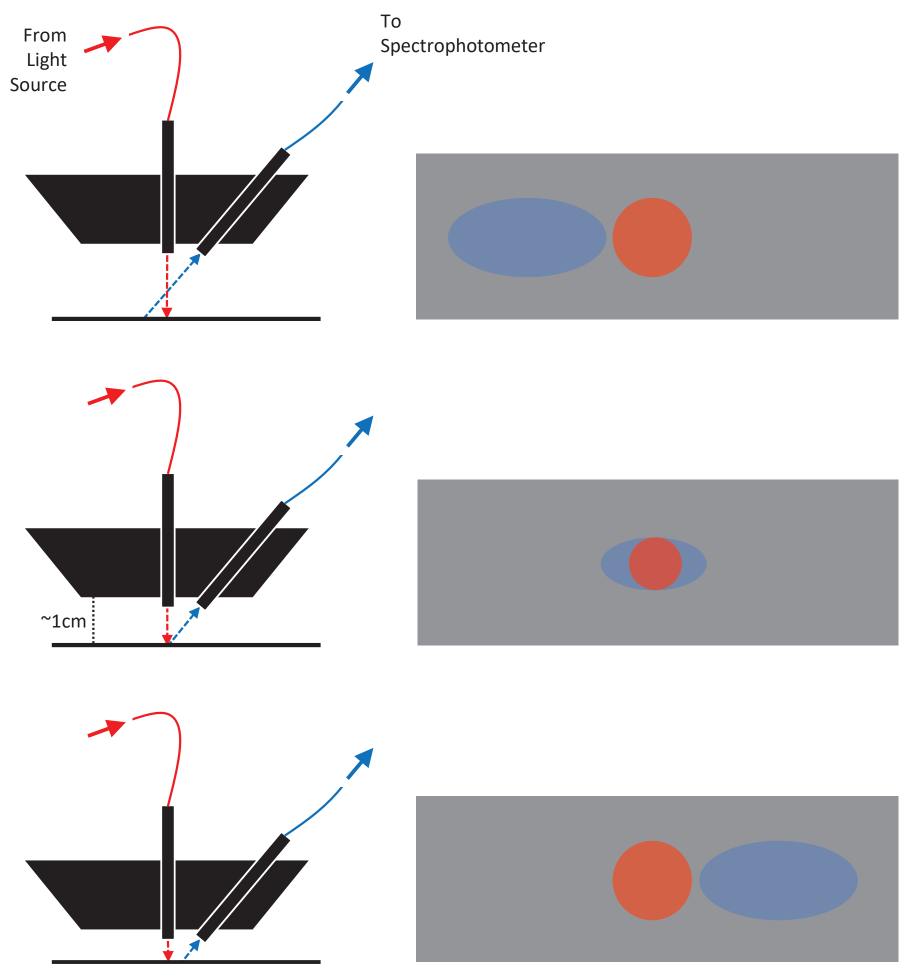


FIGURE 3.5 Profile (left) and plan (right) views of alignment of illumination (red) and collection (blue) spots. Adapted from Paul Whitmore and Jacob Thomas.

Chromatic and spatial aberrations present in standard lenses have led some users to employ higher-cost achromat lenses to minimize these irregularities and produce a more uniform fading spot. However, the performance of standard lenses likely remains satisfactory for MFT. Though light intensity across the test area may have small nonuniformities, the validity of the test should not be affected as the objective is to determine a relative rate of color change of an unknown material compared to a standard material (Whitmore, Xun Pan, and Bailie 1999).

In addition to the lens assemblies, many MFT users employ a USB pen camera or digital microscope in the test head. The camera is commonly positioned at a 45° angle from the sample surface, similar to the collection lens assembly. While it is possible to conduct MFT without a camera, its ability to visually define the precise position of the MFT spot on the sample surface is invaluable when selecting a test location and documenting the analysis for a report. The camera is also useful when verifying the alignment of the illumination and collection spots and sharpening the focus of the illumination spot itself (achieved by adjusting the vertical position of the illumination assembly within the test head).

Alternate Geometries

MFT users have explored the use of alternate measurement geometries beyond 0/45, including noncontact retroreflection probes and contact heads. Retroreflective probes return the reflected light along the same path as the illumination beam, providing a wider depth of focus and eliminating the need to align separate illumination and collection spots (fig. 3.6). While users can maintain the 45° angle between the surface and the probe to mimic a 0/45 geometry, the retroreflective probe allows for use of different measurement angles; shifts away from 45° will affect the resulting light intensity and dosage on the sample surface and require angle-specific calibration.

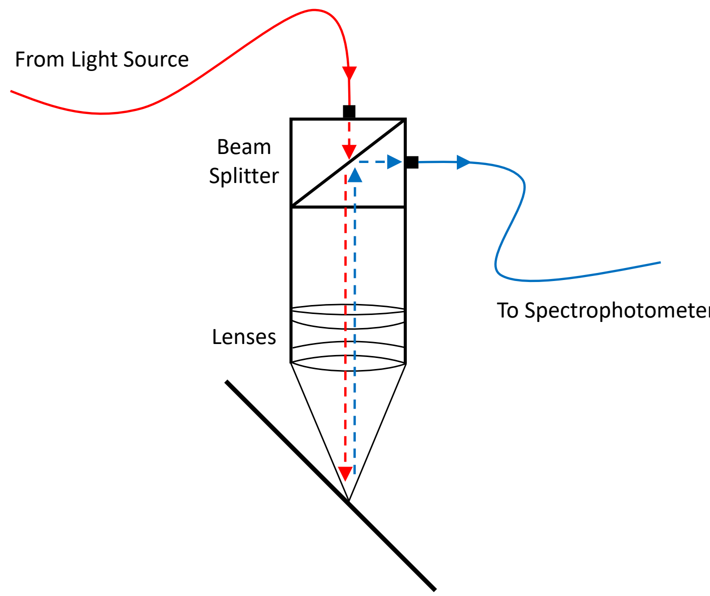


FIGURE 3.6 A schematic for a retroreflective probe. Adapted from Haida Liang.

Contact MFT probes gently touch a Mylar template resting on the sample surface. These probes do not require alignment of the illumination and collection spots (though the probe must be aligned with the test site) and may be beneficial when testing surfaces with significant microroughness. Beyond contact itself, the possible drawbacks of a contact MFT probe are its inability to test through glazing, the need for a flat surface, and the fact that the area is not visible during testing. Several types of contact probes have been developed, including the following:

- A "6 around 1" probe, with the central circle delivering light to the surface and the perimeter circles returning light to the spectrophotometer (previously employed at the Museum of Modern Art, New York) (fig. 3.7)
- A probe containing a 3 mm ball lens (previously employed at the GRI; Pesme et al. 2016)
- An angled fiber holder with predrilled holes that positions separate illumination and collection fibers terminated with a 1.5 mm ferrule (Pesme et al. 2016)

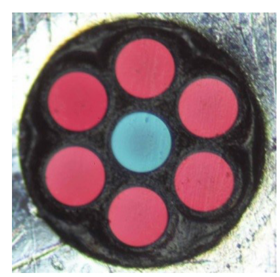


FIGURE 3.7 A 6/1 bifurcated fiber optic tip (blue circle: light introduced to sample; red circles: light directed to spectrometer) employed as a contact MFT head. Photo: Christopher McGlinchey, MoMA.

The “6 around 1” probe, ball lens probe, and retroreflective probe are each attached to a bifurcated fiber optic cable, which houses both the illumination and collection fiber optic cables and has attachments to the light source, spectrophotometer, and probe.

Mounting

Positioning of a noncontact MFT probe—0/45 test head and retroreflective probe—over the sample surface can be achieved in a variety of ways. Attachment of the MFT probe to a gantry or rail system can allow for manipulation in the x-, y-, and z-directions, though coarse vertical adjustment is typically limited (fig. 3.8). Mounting of the MFT probe on a copy stand or microscope stand with a boom arm also allows for three-dimensional positioning with increased vertical flexibility (see fig. 3.1). Tripods are used as an alternate mounting technique, particularly when doing in situ measurements of vertical objects. Note that in most cases the test head can be rotated to accommodate measurement on nonhorizontal surfaces.

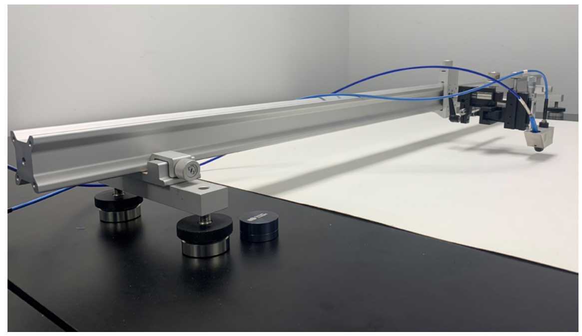


FIGURE 3.8 MFT measurement head attached to a rail system. Image by Katherine Schilling.

Spectrophotometer

The MFT incorporates a spectrophotometer to monitor and record spectral data on the light-induced color change of the material. The spectrophotometer is attached to the collection lens assembly via a fiber optic cable. Key operational attributes for MFT spectrophotometers are rapid and near-simultaneous spectral analysis and a wavelength range encompassing at least the visible region. Many MFTs based on the initial blueprint defined by Whitmore, Xun Pan, and Bailie (1999, 397) employ a spectrophotometer with a photodiode array (PDA) detector because of its “stability and ability to monitor relatively high light intensities.” As technology advanced, subsequent iterations of MFT began to use spectrophotometers with charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS) detectors; these were available at relatively low cost, and their performance met the needs of MFT (Thomas, pers. comm. 2021). The spectrophotometer’s native software should facilitate monitoring of color change during the test via its user interface; if absent, third party software may be used to provide this capability (Thomas, pers. comm. 2021). This allows one to assess the real-time color change of a collection item and stop the test once a predetermined threshold color difference or ΔE is reached, ensuring that this change remains imperceptible to the viewer.

Automation

The operation of a Whitmore MFT typically involves several manual steps, including:

- Alignment of the illumination and collection spots
- Opening and closing of the shutter and/or removal and reinsertion of the neutral density filter
- Initiation of spectral data collection and resetting the ΔE value in the spectrophotometer software

While routine for experienced MFT users, these actions can be an obstacle for new and intermittent operators who must recollect their specific order and cadence. The Instytut Fotonowy has created an automated MFT that addresses the manual steps listed above. The automated MFT seeks to simplify operation for the user and may improve the robustness and accuracy of color change rates determined from MFT data. Automated repositioning of the MFT probe to a new test location has also been explored, but this should be limited to testing of mock sample sets rather than artwork, which requires careful supervision. A residual benefit of the manual operation required of a Whitmore MFT is the acquired understanding of the motivations for each step and the ease of component access in case of repair or replacement; it is hoped that this knowledge is maintained and shared and that the evolution of MFT follows a "white box" (transparent inner logic) rather than a "black box" (limited to inputs and outputs) trajectory.

Uncertainty in MFT

MFT is the primary means by which the in situ color stability of an artwork can be determined. However, as with any analytical technique, MFT data and its interpretation is associated with uncertainty, and there can be misperceptions about the technique. In both cases, effective communication is essential to ensure that expectations of MFT are aligned.

Reciprocity

The wide disparity between the high light intensities of MFT (~5 Mlux [million lux]) and the much lower levels present in galleries (less than ~200 lux) poses a common concern regarding the relevance of its results. Like all accelerated aging techniques, MFT is confronted with the concept of reciprocity; this refers to a material response that is a function of exposure (or dosage), which can be defined as the product of intensity and time. If reciprocity holds, a similar response should be observed for the same exposure, whether the intensity is low and the duration is extended or the intensity is high and the duration is brief. Note that reciprocity is not an intrinsic material property but a response of a material to a test condition.

While several MFT studies have examined reciprocity for various materials and presented examples of both reciprocity upheld and breaking down (e.g., Whitmore, Xun Pan, and Bailie 1999; del Hoyo-Meléndez and Mecklenburg 2011; Beltran et al. 2014; Lerwill et al. 2015), this question remains open due to the wide range of materials and MFT test conditions. A major concern with reciprocity breakdown is that the dose response may be so distorted as to mistake stability for instability; that is, an artwork is estimated as stable with MFT but proves unstable in typical light conditions. Though thought to be unlikely for the vast majority of materials, such behavior has been observed in select grasses and leaves (Beltran et al. 2014) and arsenic sulfide–based realgar and orpiment (proposed at the 2018 GCI MFT Experts Meeting; see Beltran 2019). The community of MFT users should continue to publicly flag similar outlier behavior. Reciprocity testing involving the use of a range of light intensities and durations may also be particularly important for extremely sensitive colorants.

Blue Wools

Despite this uncertainty with reciprocity, what is promising is the fact that Blue Wool 1, 2, and 3—encompassing the range of high light sensitivity material (Michalski 2018)—generally maintain their lightfastness rankings when examined by MFT. This allows one to use BWs as an internal standard to bridge between the results produced during high-intensity MFT light exposure and the expected behavior of the material while on gallery display. Once an object is classified by a BW equivalence, one can budget its light exposure based on the average light dose needed to achieve a JND for the BW. (This process is discussed further in chapter 5.) While Michalski (1987, 2018) reports average JND light doses for BW1, 2, and 3, some MFT users report that these may underestimate the sensitivity of the BWs; this reflects the uncertainty in the average

JND light doses, which range “approximately to the estimates of the adjacent Blue Wool” (Michalski 2018). Thus, considering the increasing complexity of each assessment, MFT can be used to:

- Confidently identify whether an object colorant is fugitive;
- Cautiously differentiate the degree of light sensitivity relative to that of BW Standards; and
- Cautiously predict quantitative color change when exposed to visible light in the gallery by comparison to the color change behavior of BW Standards in similar conditions (Lerwill et al. 2015).

The physical nature of Blue Wool Standards themselves poses uncertainty. Their presentation as textiles make it important to identify and repeat testing at the top of threads, with users looking for a characteristic “twinkle” when locating the MFT spot. Though a shift toward a nontextured BW Standard would be preferable, the cultural heritage field’s position as a minor BW user relative to industrial application makes it difficult to advocate for change. There have been ongoing research efforts in the conservation field to independently develop an alternative standard with lightfastness rankings similar to BW1, 2, and 3. There also exist several versions of BW Standards—loose weaves and card-mounted weaves—and MFT users have observed some inconsistency in the responses of BW1, 2, and 3; further, some users have observed varying BW behavior between batches. (See Sidebar: ISO and AATCC BWs.) Given that MFT results are calibrated against the BWs, this irregularity in response could lead to differing assignments of BW equivalence depending on the specific BWs tested. The occasional addition of BW4 in MFT analysis highlights the need to include UV to effect change in more lightfast standards. The potential inclusion of UV in MFT analysis may be relevant for gallery and historic house displays that contain a sizable UV component.

ISO and AATCC Blue Wools

As described in ISO 105-B02:2014, Blue Wool fabrics can refer to separate standards specified by the ISO and AATCC (American Association of Textile Chemists and Colorists). Both are used for lightfastness testing, though in practice most MFT users employ ISO BWs. As discussed in chapter 2, the ISO BW Standard has eight grades, with 1 and 8 representing the most fugitive and the most lightfast material, respectively. Similarly, the AATCC BW Standard is ranked from L2 to L9, with L2 being the most light sensitive and L9 the most stable. While the ISO BW standards use eight individual dyes, the AATCC BW Standards use a blend of two dyes in varying proportions. Both the ISO and AATCC BWs are created such that the higher number reference is approximately twice as resistant to light-induced color change as the preceding reference; however, results for the two BW Standards are not interchangeable.

Spectral Power Distribution

As previously mentioned, the shift from the use of xenon-arc to LED lamps as the MFT light source was motivated by the desire to more closely match the SPD of gallery LED lighting. This would theoretically allow for characterization of light-induced change of an object for a specific lighting condition (e.g., LED type, color temperature). However, given the uncertainty in MFT results due to concerns about reciprocity and BW consistency, there is debate as to the efficacy of aligning the SPDs for MFT and gallery lighting. Further, as shown in figure 3.3 above, different white LEDs can have SPDs that are markedly distinct. Following the work of Druzik and Pesme (2010), Pesme et al. (2016), and a round-robin test conducted by Bruce

Ford (an independent MFT consultant from the National Museum of Australia, discussed in part in Pesme et al. 2016), the comparison of MFT data on a range of samples using various light sources and instrument setups should continue to be an area of active research.

Color Change Behavior

While MFT can be conducted on many different objects to obtain information on light-induced color change, the ideal sample is opaque, nonfluorescent, and not highly reflective or direction-dependent. Further, the color change behavior of the sample itself can present complicating factors. For example, some users have reported that MFT analysis of some historical papers is unable to replicate the yellowing behavior commonly observed for such materials. While light plays a role in this process, it is hypothesized that the limited temperature increase at the MFT test spot may constrain a yellowing process that is in part thermally driven. Further, ancillary factors associated with accelerated aging (e.g., reduced availability of reactants such as oxygen to the test site) might also restrict the expected color change behavior of historical paper. On the other hand, MFT may play a role in assessing the extent to which yellowed papers can be bleached by exposure to light.

Samples with unusual color change behaviors can complicate the interpretation of MFT results. During an MFT test, both Prussian blue and iron gall ink typically exhibit significant light-induced color change and can be characterized as highly light-sensitive. (Note that these samples also change when exposed to light sources other than MFT.) However, once placed in the dark, these colorants will begin to regain color, rendering the MFT interpretation incomplete (Ford 2014). Repeated MFT runs of Prussian blue and iron gall ink samples interspersed with dark periods may be used to investigate whether the extent of recovery is consistent or regained to a lesser degree over time. Similarly, fluorescent colors can undergo changes that can be challenging to evaluate with MFT.

Verifying Predictions

As described in the introduction, a primary use of MFT is to predict the color change behavior of an object before it is placed on exhibition, providing a unique opportunity to inform decisions about object selection and appropriate light intensity and duration. These MFT predictions based on accelerated aging data should ideally be paired with the collection of real-time monitoring data of object color change during exhibition. However, acquisition of this in situ color data with a handheld spectrophotometer may prove impractical for many objects due to restrictions on staff time and object access, as well as the difficulties associated with taking repeated color measurements on the same locations over a duration of time. A compilation of comparative color change studies examining MFT and real-time data would speak to the uncertainties associated with MFT and foster increased confidence in the technique. Though published comparative studies are scarce, two notable examples were presented by Freeman et al. (2014) and Ford and Smith (2017).

Conclusion

The various iterations of MFT presented in this chapter both align with the basic operation principles of the technique and seek to push its boundaries. By increasing transparency in the available options and motivations for their selection, prospective, new, and experienced users can make more informed decisions on the design of an MFT apparatus. As always, communication with the MFT user community is encouraged to gain more practical insight on the technique (see appendix 1).

Also with regard to transparency, it is important to understand the uncertainties associated with MFT and effectively communicate these aspects with relevant stakeholders. It should be noted, however, that MFT is not unique in this respect, as all accelerated aging techniques are subject to similar issues. MFT remains an important and unique preventive conservation and risk management tool that can benefit the object (protect the most fugitive artwork and increase access to more lightfast objects), the collection (refine lighting policy), and the institution (support efficient use of resources).

References

Beltran, Vincent Laudato. 2019. "Advancing Microfading Tester Practice: A Report from an Experts Meeting Organized by the Getty Conservation Institute, March 13–15, 2018." Getty Conservation Institute, Los Angeles. https://hdl.handle.net/10020/gci_pubs/advancing_mft_practice.

Beltran, Vincent, Jim Druzik, Andrew Lerwill, and Christel Pesme. 2014. "An Examination of Light-Induced Color Change in Anoxia and Hypoxia Using the Microfading Tester." In *Research and Technical Studies Group Postprints, AIC Annual Meeting, San Francisco, 27 May–1 June 2014,* vol. 5. Washington, DC: AIC.

Costain, Charles, Stefan Michalski, Nancy E. Binnie, and Isabel Garcia. 1995. "Evaluating the Light Sensitivity of Coloured Materials In Museum Collections." *International Institute for Conservation—Canadian Group Conference '95 Abstracts*, 16. Calgary: IIC-CG.

del Hoyo-Meléndez, Julio M., and Marian F. Mecklenburg. 2011. "An Investigation of the Reciprocity Principle of Light Exposures Using Microfading Spectrometry." *Spectroscopy Letters* 44 (1): 52–62.

Druzik, Jim, and Christel Pesme. 2010. "Comparison of Five Microfading Tester (MFT) Designs." In *Textile Specialty Group Postprints, AIC Annual Meeting, Milwaukee, WI, 11–14 May 2010,* vol. 20. Washington, DC: AIC.

Ford, Bruce. 2014. "The Accelerated Light-Fading of Iron Gall Inks in Air, Hypoxia and Near-Anoxia." In *ICOM Committee for Conservation 17th Triennial Meeting, Melbourne, Australia, 19–23 September 2014*, ed. Janet Bridgland. Paris: International Council of Museums.

Ford, Bruce, and Nicola Smith. 2017. "A Reality Check for Microfade Testing: Five Examples." In *ICOM-CC 18th Triennial Conference Preprints, Copenhagen, 4–8 September 2017*, ed. Janet Bridgland, art. 1508. Paris: International Council of Museums.

Freeman, Sarah, James R. Druzik, M. Harnly, and Christel Pesme. 2014. "Monitoring Photographic Materials with a Microfade Tester." In *ICOM-CC 17th Triennial Conference Preprints, Melbourne, 15–19 September 2014*, ed. Janet Bridgland, art. 1402. Paris: International Council of Museums.

Hattori, Hika, Kunio Yoshizumi, and Patricia Crews. 2012. "Wavelength Sensitivity of AATCC Blue Wool Lightfastness Standards under Light Radiation." *Dyes and Pigments* 92 (3): 936–41.

ISO 2014. "Textiles—Tests for Colour Fastness—Part B02: Colour Fastness to Artificial Light: Xenon Arc Fading Lamp Test." International Organization for Standardization, Geneva, Switzerland.

Lerwill, Andrew, Christel Pesme, Vincent Beltran, and James R. Druzik. 2015. "Investigating the Validity of Microfading Spectroscopy to Predict Photochemically Induced Color Change at Lower Light Levels." NIP & Digital Fabrication Conference, 123–28. Portland: Society for Imaging Science and Technology.

Michalski, Stefan. 1987. "Damage to Museum Objects by Visible Radiation (Light) and Ultraviolet Radiation (UV)." In *Lighting in Museums, Galleries and Historic Houses*, 3–16. London: Museums Association, UKIC, and Group of Designers and Interpreters for Museums.

———. 1997. “The Lighting Decision.” In *Fabric of an Exhibition, Preprints of Textile Symposium 97*, 97–104. Ottawa: Canadian Conservation Institute.

———. 2018. “Agent of Deterioration: Light, Ultraviolet and Infrared.” Government of Canada. www.canada.ca/en/conservation-institute/services/agents-deterioration/light.html; accessed 17 February 2021.

Pesme, Christel, Andrew Lerwill, Vincent Beltran, and James R. Druzik. 2016. “Development of Contact Portable Microfade Tester to Assess Light Sensitivity of Collection Items.” *Journal of the American Institute for Conservation* 55 (2): 117–37.

Pretzel, Boris. 2008. “Now You See It, Now You Don’t: Lighting Decisions for the Ardabil Carpet Based on the Probability of Visual Perception and Rates of Fading.” In *Preprints of ICOM-CC 15th Triennial Conference, New Delhi,* vol. 2, ed. Janet Bridgland, 759–65. New Delhi: ICOM-CC.

Whitmore, Paul M., Xun Pan, and Catherine Bailie. 1999. “Predicting the Fading of Objects: Identification of Fugitive Colorants through Direct Nondestructive Lightfastness Measurements.” *Journal of the American Institute for Conservation* 38 (3): 395–409.

4. MFT PRACTICE: SETUP, DATA COLLECTION, AND ANALYSIS

Vincent Laudato Beltran

The previous chapter described the basic components of a microfading tester and introduced several iterations: Whitmore, retroreflective, contact, and automated. The use of these MFT types follows a consistent outline that involves sample selection and preparation, instrument setup, data collection, and data analysis and reporting. Each of these segments is discussed in depth in this chapter, with practical details informed by numerous standard operating procedures and experiences generously shared by the MFT user community, as well as key MFT papers in the conservation literature, including Whitmore, Xun Pan, and Bailie (1999), Ford and Druzik (2013), and Tse (2019). While a general discussion is the overall aim, emphasis is placed on the Whitmore MFT due to its prevalence and the fact that its individual components are visible to the viewer.

This chapter is not intended to delineate a "single, ideal" practice but rather to reflect the breadth of practice and the rationale for variations in protocol. It seeks to support the typically intermittent use of MFT by informing new users, refreshing the memories of existing users, and offering a means of continuity should key staff depart. The MFT Institution Directory in appendix 1, which lists cultural heritage institutions employing the instrument, provides another avenue of consultation. Of course, this text ultimately plays a supplemental role to the hands-on use of MFT and the procedures developed by each institution.

Sample Setup

Before conducting MFT to assess the light sensitivity of an object, the user must first determine why and how the sample is to be tested. While this process is elaborated in chapter 5, this section explores the prioritization of object selection, when to conduct MFT, how to choose testing locations, and object handling considerations.

Prioritization

Conducting MFT on all objects requested for display is ideal but may be impractical. When considering what to test, it is important to prioritize objects based on several factors:

- Likely to be highly sensitive to light
    - Presence of suspected fugitive colorants
    - Pristine condition
- Likely to experience high cumulative light exposure or exposure to daylight
- High significance and/or will be impacted significantly by color change
- Composed of materials for which knowledge of color change behavior when exposed to light is limited or unknown

Published guidelines can be used to roughly estimate the expected light sensitivity of various materials. However, in practice, the color change behavior of a media type can be quite variable, with specific examples exhibiting a range of light stability (Ford and Smith 2017). In the absence of MFT, adherence to conservative guidance is recommended, especially if color preservation is a priority of the institution. If MFT analysis is possible, decisions on object-specific lighting and access can be informed by direct assessment of the light sensitivity of that object.

Scheduling

If MFT is supporting exhibition development, testing should be carried out during the early stages of decision making. This will allow ample time to craft alternate plans should MFT identify light-sensitive material. For the MFT user, it is suggested that objects be accumulated for batch testing (as done for the MFT case study and report in appendices 4 and 5, respectively), as this will minimize time spent on instrument setup, calibration, and Blue Wool testing for internal calibration. Since MFT may be employed intermittently, the user should also allow sufficient time to become reacquainted with the operational protocol and/or train new users. If transport of the instrument is possible, consider conducting MFT where the objects are located, as this can widen windows of accessibility to the object.

In addition to exhibition-driven use, MFT can be used in a regular testing program. Some users have allotted recurring periods for MFT testing, which has the benefits of technical skill development and consistent assessment of MFT performance, as well as:

- Investigations of the permanent collection to inform the necessary frequency of object rotation;
- Examinations of newly acquired objects or recently conserved material;
- Pursuit of research questions; and
- Potential for providing service to external clients.

It would be particularly beneficial to the field if institutions, conservation centers, or private entities were to offer MFT access to external clients, as many small to mid-size museums or individual collectors may not possess the budget or staff to acquire an instrument. Such an effort was described by Tse (2018), a former Canadian Conservation Institute scientist; in addition to conducting her own MFT analyses, she was responsible for organizing MFT use (selection, logistics, and training) by heritage organizations throughout Canada.

Site Selection

When an object is selected for examination by MFT, a testing protocol should be developed using any relevant historical or technical information and in conjunction with collections staff, including conservators and curators. The initial step is to identify all distinct colors on the object, recognizing that this identification may be subjective if chemical analysis is lacking. Consideration of the technique used to apply color may be useful to select test sites; for example, when color results from additive mixing mechanisms using a few primary hues, it may be sufficient to limit testing to the primary colors. For colors varying in shade, medium color densities are preferred, as these areas will produce higher reflectance values that, if light sensitive, will result in more color change. While detection of color change will be more difficult due to lower reflectance values, testing of darker shades is suggested if lighter regions are not present. In addition to areas of color, consideration should be given to examination of the substrate. Regarding locations of potential test areas on the object, proximity to recognizable features is beneficial in terms of report documentation. In the worst-case and highly unlikely scenario that visible change is caused by MFT, testing in visually complex areas of the object will mitigate the impact to the viewer.

Selection of the number of test sites for each color may be influenced by the purpose of testing, available testing time, and how cautious the curator or conservator feels about exposure of the object to MFT.

With typical MFT durations ranging from 5 to 30 minutes, time can be a major factor, particularly if many objects are to be tested within a limited period. Some users choose to examine only one location per color when screening objects prior to exhibition or if the object is known to be light-sensitive. The rationale for a single test is based on the idea that an artist's color palette is limited and that similar colors will exhibit comparable change.

Examination of multiple sites allows for data averaging and assessment of statistical error, which may be deemed essential for research or publication purposes and increasing confidence in the data that will inform display recommendations. Some users choose to do two tests per color and if presented with a disparity, conduct a third test. While same-color locations can be in close proximity, testing in different areas of the object can inform its overall color change behavior (Pesme et al. 2016). To allow for spatial and temporal separation during analysis, it is preferable to test all colors on the object once, then conduct subsequent tests of each color at different locations. The second round of testing can be further streamlined by prioritizing the most light-sensitive colors. As previously stated, additional tests of a specific color may focus on variations in color density (mid-tones first, followed by light and/or dark).

Additional testing is necessary for colorants identified as highly fugitive (i.e., color change behavior less than BW2), as the implications of such a finding can have a broad impact on exhibition development. And, as Ford (pers. comm. 2020) points out, "Wrongly identifying a colorant as fugitive is an expensive error." Subsequent tests of very light-sensitive material will often permit early termination of the MFT run once it is determined that the color change behavior tracks with the initial result.

Test locations selected on an object should be noted on a printed or digital image and cross-referenced with the object accession number and MFT data filenames. This overall location map can be supplemented by localized images of each test location taken with a pen camera or digital microscope, all of which may be archived with the MFT report (fig. 4.1 and appendix 5). Careful MFT operation will not leave a visible trace on the object, and this can be verified by examination of localized images before and after testing.

FIGURE 4.1 Closeup of MFT spot taken with pen-cam; spot diameter is ~0.3 mm. Image by Kirsten Dunne, National Gallery of Scotland.

Handling

In consultation with conservators about access and handling requirements, the object must be secured so that movement does not occur during the MFT run. This can be done with weights, pillows, cradles, magnet/steel plates, and so on. Once the object position is fixed, test locations can be reached by moving the test head of the MFT by way of its mounting system. For a smaller object, it may be more convenient to move the object to the next test location while keeping the test head fixed, though object safety is of paramount concern. If repositioning art beneath the test head, be sure to raise the test head to a safe height, ensuring that its components (e.g., test head, fiber optic cables, USB cables) do not touch the sample surface. Additional handling guidelines include the following:

- Block footings of the rail system to prevent sliding along the table surface when moving the test head into position; one may also increase the height of the rail system by lifting it onto blocks.
- Employ a locking mechanism to ensure that the test head remains a safe minimum height above the sample surface.

- Rotate the test head when examining objects on a nonhorizontal surface (e.g., angled, vertical) so that it is perpendicular to the plane of the test site.
- Consider unframing and removal of glazing for objects where the distance from the testing surface to the test head is greater than ~1 cm (for noncontact MFT test heads).
- Possible extension of the test head beyond the counter edge and above the test site to accommodate analysis of larger objects brought near the MFT.

MFT Setup

Prior to data collection, the MFT must be carefully placed with respect to its environment to ensure stable test conditions. Initiation of the MFT will follow a start-up protocol to warm up the lamp, record operating conditions, and conduct calibrations. Aspects of this protocol may be instrument-dependent, but its general arc is consistent for all MFT types.

Environment

The major environmental variable that negatively affects MFT operation is vibration. The consequence of excessive vibration is the misalignment of the illumination spot (from the light source) and the collection spot (from the spectrophotometer); this can render an MFT run void, exposing the object to high-intensity light without the collection of relevant data.

To guard against vibration, placement of the MFT and the object on a stable surface is key. A vibrationally damped steel optical bench or floor-mounted table can be beneficial, though some users successfully utilize tables with brake mechanisms. Note that large objects may be positioned on a stable surface (e.g., cart or table) separate from the MFT. For tripod-mounted MFTs, it is necessary to attach sufficient weights to the tripod to restrict movement. One may choose to place the MFT computer on a desk independent from the instrument to limit physical movement of the MFT or the object; this assumes sufficient slack in the attached USB cables to the spectrophotometer and digital camera. A common source of vibration and shock is passersby who bump into the table or apparatus, including the fiber optic cables from the test head; foot traffic in the vicinity of the MFT should be restricted, and erecting temporary barriers can forestall any mishaps. Consideration should also be given to vibration emanating from adjacent instrumentation or spaces.

It is equally important to ensure that objects are easily accessible in the space where the MFT is located. This may necessitate double doors to accommodate carts and sufficient working area when testing larger objects. Since transferring objects to the MFT can pose complications, particularly if removed from the museum, one might choose to bring the MFT to the objects, with consideration given to careful packaging of the instrument and backup components for transit, and sufficient time for performance checks after arrival (fig. 4.2); in addition to facilitating object access, this has the benefit of more readily engaging collection staff with the technique.

Additional parameters of concern include air movement and light. Wind or internal air movement from HVAC systems or instrumentation (some MFT components may have cooling fans) can be directed toward the test head and object, potentially disrupting readings. Of particular vulnerability is movement of the fiber optic cables, which will affect light transfer to the sample and spectrophotometer; this can be mitigated by erecting a barrier between the object and the air source. As mentioned earlier, air movement will impact freely hanging textiles and will need to be addressed before conducting MFT on these vertical surfaces (fig. 4.2). While the impact of ambient light will be masked during MFT runs by its high-intensity light, excessive light exposure of the sample surface before and after MFT should be limited, particularly for fugitive colorants such as BW1, 2, and 3. If conducting MFT in a non-climate-controlled space, it may also be prudent to record ambient temperature and relative humidity conditions for future reference.

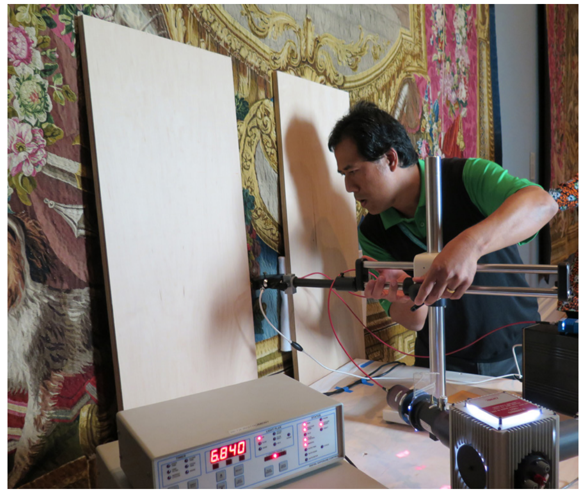


FIGURE 4.2 MFT analysis of a hanging tapestry conducted in the gallery. Image by Christine Lee © 2021 J. Paul Getty Trust.

Lamp Start-up and Intensity

The first step in the MFT start-up protocol is to power on the light source, which should then be allowed to thermally equilibrate. Xenon-arc lamps, used in most Whitmore MFTs, are typically warmed for 30 to 60 minutes, though some users suggest as little as 20 minutes and as long as 2 hours; during this time, the xenon gas pressure within the bulb increases and temporal, spatial, and spectral stability can be affected. Radiometer or photometer measurements of light intensity can determine when it has stabilized; note that one may need to maximize the reading by slight adjustments in the position of the light beam into the radiometer or photometer. (See Sidebar: Radiometric and Photometric Units.) Over time, the intensity of the xenon-arc light source can diminish due to deterioration of the lamp. Lamp lifetimes will vary roughly between 500 and 1,500 hours based in part on power consumption, and its performance trajectory can be tracked by daily light-intensity measurements. When performance diminishes, the power supply to the lamp may be increased as compensation, though other strategies such as alignment of the optical lenses (discussed below) should be explored first. For a 75W lamp, manufacturers suggest a limited increase to 80W but levels up to 90W and 100W have been used. It is also suggested that the ferrules (or base) of the xenon-arc bulbs and their brass sockets are occasionally inspected for corrosion (note that the pressurized bulb should be carefully handled with gloves and goggles should be worn), as this can result in failure of the power supply regulation (Ford, pers. comm. 2020).

Radiometric and Photometric Units

Light intensity is reported by radiometers in terms of watts (radiant flux) or W/m^2 (irradiance) and by photometers in terms of lumens (lm, luminous flux) or lux (lm/m^2, illuminance). Radiometers measure light across the electromagnetic spectrum, while photometers measure visible light (between roughly 400 and 700 nm) weighted at each wavelength based on the sensitivity of the human eye. For light source characterization, it is suggested that radiometric units are reported as it reflects the actual power received at the surface, but the common use of lux in the cultural heritage field merits the continued use of photometric units. Assessment of the spectral power distribution (SPD) of the light source with a spectrophotometer provides a more complete depiction, and given a radiometric calibration of the spectrophotometer, one can calculate the luminous flux from the SPD.

Legacy Whitmore MFTs employ a xenon-arc lamp that resides within a housing containing a series of movable optical lenses (collector, reflector, and condenser) (fig. 4.3). After thermal equilibration has been reached, these lenses can be adjusted by rotating knobs to maximize light intensity; this is an iterative process, and one should consult the standard operating procedure before making adjustments. A comparison of day-to-day light intensity (following warm-up) as measured by a radiometer or photometer can indicate if the current lens alignment is sufficient (i.e., similar levels are observed) or adjustment is required (i.e., lower levels are observed). If the MFT has been used recently and not moved, it is likely that the optical lenses within the lamp housing will need only minor adjustment or none at all. Note that if the MFT is transported to a new location, time should be set aside to readjust the optical lenses. In addition, the fiber coupler plate, which is the attachment point for one end of the illumination fiber optic cable, can be manually positioned to maximize light intensity.

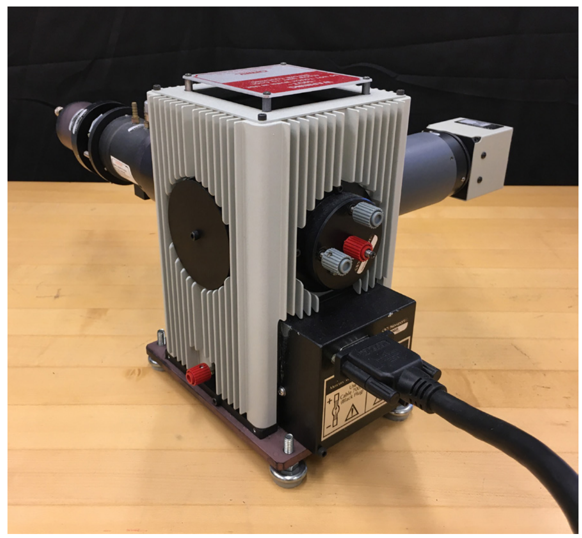


FIGURE 4.3 Xenon-arc housing for Whitmore MFT from front (left) and rear (right). On the left image are tubes connected to the detector/digital exposure controller (left side) and the condenser assembly/filter holder/fiber coupler plate (right side). The image on the right shows the rear reflector assembly above the power connection; the lamp base and rear reflector assembly have lamp adjustment knobs for X, Y, and Z directions for tilt and focus. Images by Vincent Laudato Beltran.

Many Whitmore MFTs incorporate a digital exposure controller to stabilize the xenon-arc light source. The controller setup positions a sensor in the light path that constantly monitors intensity and adjusts the power supply output accordingly (fig. 4.3, left image). Use of a digital exposure controller simplifies calculation of light dosage during a run given a well-defined spot size. This calculation is the product of the illuminance (units of lux or lumens/square meter) and the exposure time (units of hours), with the former determined by dividing the luminous flux (units of lumens) by the area of the illumination spot. The digital exposure controller also allows one to reduce the intensity of the light source to a fixed level to improve day-to-day comparison of MFT results and preserve lamp life; a number of users choose to set the intensity to ~600 mlm, as this typically allows for a reasonable response from BW3. As noted in the previous chapter, those employing compact xenon-arc light sources will typically omit use of the exposure controller, as it is expected that their short-term stability is sufficient for MFT analysis.

In some respects, the use of LEDs as an MFT light source simplifies operation. LEDs permit a shorter period of equilibration (~10 minutes), and, while LEDs will deteriorate over time, this occurs at a much slower rate than that of xenon-arc lamps. The LED package is designed to focus its light; thus, they do not require the optical lenses needed by some xenon-arc sources for collecting and redirecting light. While not typically paired with an exposure controller, the intensity of the LED responds linearly with amperage and can be controlled by a driver, allowing one to easily adjust and attenuate the current up to a threshold value, protecting the light source (fig. 4.4). However, some users suggest caution when operating LEDs at low voltages as its spectral power distribution may shift slightly. Given the variability in SPDs between different LED lamps, the specific SPD of the MFT LED light source should be recorded with a spectrophotometer, and measurement of daily intensity should be done with a radiometer or photometer. As discussed in the previous chapter, MFT results when exposed to the characteristic troughs and peaks of a specific LED SPD may not represent the worst-case scenario of a broadband xenon-arc light source, though more research is needed on this topic.

FIGURE 4.4 LED lamp (left) and driver (right). Image by Vincent Laudato Beltran.

For both xenon-arc and LED light sources, light intensity can be reduced by placement of a neutral density filter in the optical path. This decreases the intensity at all wavelengths with minimal distortion of the spectral power distribution of the light source. Neutral density filters are often characterized by their optical density (OD); OD values of 1, 2, 3, and 4 will reduce transmittance to 10%, 1%, 0.1%, and 0.01%, respectively, of the original light intensity. Attenuation is achieved by absorptive glass or the addition of a thin metallic layer (typically Inconel); the latter is directional and must be used with the reflective surface facing the light source (arrows may be printed on the filter edge to guide orientation). (See Sidebar: Cautious MFT Assessment Using an ND Filter.) Note that the use of a filter requires its positioning in the light path, but options for filter placement may be limited or absent depending on the design; some users choose to employ in-line fiber optic filter mounts to expand filter capacity or, if blocking light, act as a shutter.

Cautious MFT Assessment Using an ND Filter

A reduction in light intensity can be helpful when cautiously exploring unfamiliar or suspected light-sensitive objects with MFT. Instead of immediately exposing the object to high-intensity light, one can use a neutral density filter to reduce intensity by 75% to 90% during an MFT run. Background and reference spectrums will also be collected at this reduced level, but the BWs may show relatively slow change. Should the object be extremely light sensitive (much higher than BW1), this conservative protocol will slow the color change and allow the user more time to end the MFT run and prevent undue damage. If the low-intensity MFT run reveals little change in the unknown sample, one can then repeat MFT using the typical high-intensity light.

Alignment

Whitmore MFT

Before each MFT run, it is necessary to align the illumination and collection spots to ensure that data collected by the spectrophotometer are from the area exposed to the high-intensity light source. With the illumination and collection lens assemblies fixed in the test head at a 0/45 geometry (i.e., illumination is normal to the surface, and data collection is 45° from normal), alignment is achieved by raising or lowering the test head (fig. 4.5). Assuming the sample surface is horizontal, it may also be helpful to use a bullseye level positioned on the test head to verify that illumination is normal to the surface. (Note that the bullseye level should be affixed to the test head or removed when not in use to avoid its falling on the sample.)

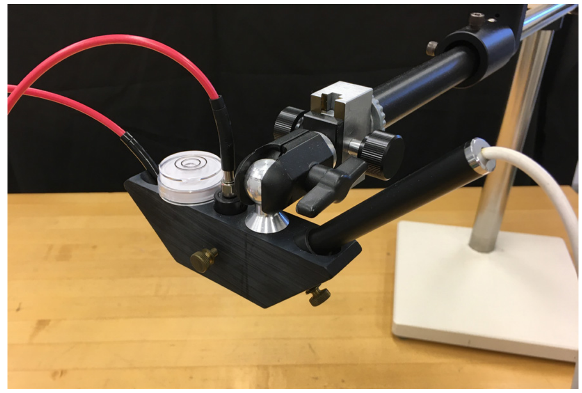


FIGURE 4.5 Triangular MFT test head containing the illumination barrel and fiber optic (middle), the collection barrel and fiber optic (left), and the pencam (right). Positioned on the test head is a bullseye level that ensures the light beam is vertical to the sample surface, assuming a level sample. The knobs behind the test head allow for fine vertical adjustment. Image by Vincent Laudato Beltran.

Alignment of the illumination and collection spots can be determined when the maximum detector counts or highest peaks in the reflectance spectra are observed in the spectrophotometer software. As the two spots become increasingly aligned, one will observe a steady increase in detector counts or spectrum peak height. This may require removal of the neutral density filter from the light path, exposing the surface to full light intensity, and initiation of continuous spectra collection, allowing one to quickly see results when adjusting the test head height. Since a surface is being exposed to full-intensity light, a number of users choose to verify proper alignment via maximum detector counts only at the start of the day on a non-artwork sample (e.g., white reference standard) to avoid unnecessarily exposing an object to high-intensity light. (Subsequent alignment checks might rely on use of a secondary light source, as described in the next paragraph.) If one chooses to do this alignment step on artwork, it should be conducted rapidly to minimize any color change.

An alternative or supplementary alignment method entails detaching the collection fiber optic cable from the spectrophotometer and attaching it to a low-intensity light source (i.e., fiber optic continuity tester, tungsten halogen lamp), projecting an elliptical spot (due to its 45° angle) from the collection lens assembly onto the sample. The test head is then adjusted vertically until the collection spot visually overlaps with the circular illumination spot. When this technique is used, the neutral density filter is inserted into the light path (with the shutter open), resulting in a low-intensity illumination spot on the sample surface. Given the small diameters of the light spots, use of a pen camera or digital microscope can allow for improved viewing of this overlap (fig. 4.6). Rotation of the illumination and collection lens assemblies (after loosening their set screws)

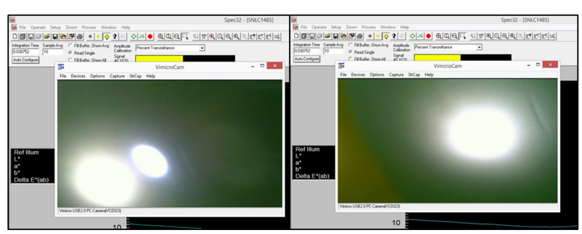


FIGURE 4.6 Pen camera images of misaligned (left) and aligned (right) illumination and collection spots. Note that the diameter of the collection spot (left spot in left image) is larger than that of the illumination spot. Image by Ayanna Lynch, GCI/GRI Marrow Undergraduate Intern.

may also affect spot alignment, though the extent is limited. Once alignment has been verified, turn off the second light source and securely reattach the collection fiber optic cable to the spectrophotometer. Note that the illumination and collection fiber optic cables should be assessed regularly to ensure that their SMA connections are firmly attached (loose connections allow for light loss) and that light is being transmitted through the fiber; excessive bending or flexing of the fiber optic cables can compromise their integrity.

Following alignment of the illumination and collection spots, users should also periodically assess the focus of the illumination spot. The ideal illumination spot has sharp edges and a minimum diameter (typically 0.5 mm or less); when this spot is defocused, resulting in a hazy halo around its perimeter, light intensity and fading rates will be reduced. Focusing of the illumination spot is achieved by vertical adjustment of the illumination lens assembly. For Whitmore MFT test heads, this requires loosening the set screw, raising or lowering the illumination lens assembly in the test head, and resetting the set screw once focus is achieved. Adjustment of the illumination spot is best done on a flat uniform surface, such as a white standard, and use of a pen camera or digital microscope can provide a clearer view. The diameter of the light spot can be roughly determined by exposing a highly light-sensitive material (e.g., Sunprint paper) to full intensity light, and examining the resulting spot with a microscope; note that the size of the spot may increase with duration. More accurate assessments of spot size can direct the illumination spot onto an image sensor such as a charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) sensor (Schilling, pers. comm. 2021).

Automated MFT and Retroreflective and Contact Probes

For automated MFTs (fig. 4.7), the alignment of the illumination and collection spots is automatically assessed. In practice, the user manually moves the motorized test head below the ideal focus position and then initiates an autofocusing procedure. This is conducted at a fractional power setting, which is typically defaulted to ~5% of full power.

In contrast, retroreflective and contact MFT probes do not require alignment, as their illumination and collection paths are inherently aligned. While any angle can be employed for a noncontact retroreflective probe, some users position the probe 45° to normal, mimicking the 0/45 geometry employed by the Whitmore and automated MFTs, while others have chosen to shift this angle between 15° and 35° from normal. In any case, MFT readings on samples and standards must employ the same angle to facilitate comparison of results.

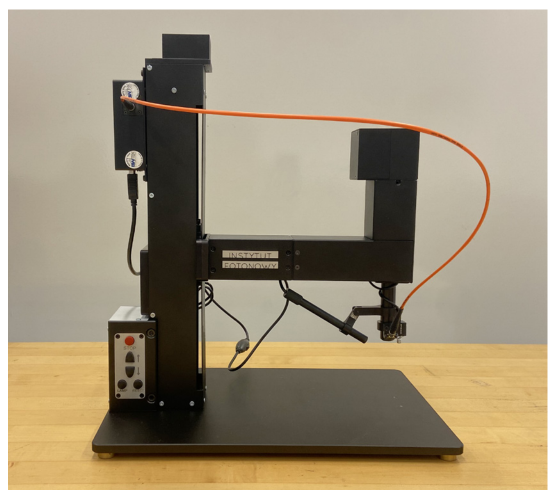


FIGURE 4.7 Automated MFT developed by Instytut Fotonowy. Image by Vincent Laudato Beltran.

As described in the previous chapter, there are several types of contact probes that have been adapted to MFT. The "6 around 1" contact MFT probe (central illumination port surrounded by six collection ports) is aligned by using a Mylar guide with scribed cross-hairs. It is necessary to provide a small gap (~1–2 mm) between the end of the bifurcated fiber optic cable and the object, which may be defined by additional Mylar sheets or a black collar extending from the end of the fiber optic cable. This gap allows for reflection of the light beam to the perimeter collection ports. For the two contact MFT probes described by Pesme et al. (2016), the angled fiber holder is positioned on the sample surface using a scribed Mylar sheet, while positioning of the ball lens probe is visually guided by a low-intensity spot, after which it is lowered until it gently contacts the sample surface. Use of a contact probe in noncontact mode is less efficient due to loss of signal and possible probe vibration; however, if contact is unacceptable, multiple tests should be conducted using a fixed air gap between the contact probe and the surface to examine the resulting error.

Integration Time and Sample Averaging

Following alignment of the illumination and collection spots, the user can begin to define the operational settings of the spectrophotometer. An initial parameter to address is integration time; this is analogous to a camera shutter speed and controls the amount of light to which the detector is exposed. An appropriate integration time (typically in units of μsec) should maximize the signal without saturating the detector. To determine this parameter, a white reference sample is positioned under the MFT test head, the illumination and collection spots are aligned, and the sample is exposed to full-intensity light (the shutter in the light path is opened and the neutral density filter removed). The user may then initiate an automated function in the spectrophotometer software to define integration time; this seeks to maximize detector counts at ~80% of spectrophotometer capability when exposed to full intensity light. Note that analysis of fluorescent samples is complicated by both the reflected light and the emitted fluorescence (Connors-Rowe, Morris, and Whitmore 2004), and MFT analysis of these sample types will need to be considered carefully.

Once the integration time is determined, the sample averaging parameter can be defined. This specifies the number of spectra to average when saving spectral data files and viewing a spectrum onscreen. This is particularly useful when the spectrum appears unstable, as a higher sample averaging value will reduce jitter in the trace. In practice, MFT users typically average between 5 and 25 spectra depending on the stability, with 10 being a common value. It is also suggested that samples exhibiting rapid color change should use a sample averaging value as low as 3.

Record of Operating Conditions

During instrument set-up, the user should document the MFT operating conditions in a daily log. This data can be valuable for evaluating MFT performance (e.g., long-term drift, diminished light intensity) and signaling when a more thorough examination of the instrument is needed (e.g., lamp replacement, check of fiber optic cables, mirror adjustment, or lens positioning). Note that some spectrophotometer software can record select operating conditions within the sample metadata. Daily parameters to consider recording include the following:

- Date, operator, and purpose
- Mode (power- or intensity-controlled)
- Lamp hours (daily, cumulative)
- If employing a digital exposure controller:
  - Pre-controller maximum light intensity (from radiometer or photometer) and watts (from power supply)
  - Controller μA (after adjusting light intensity to chosen level) and range light position (indicates proximity of light intensity to boundary conditions)
  - Post-controller light intensity (from radiometer or photometer) and watts (from power supply)
- Spectrophotometer integration time (μsec), peak detector counts, and sample averaging
- Temperature and relative humidity (if operating in fluctuating environmental conditions)

Background and Reference Calibration

Before MFT data can be collected, the spectrophotometer must be calibrated with respect to background conditions and a white reference. The background (or dark) spectrum represents the 0% reflectance signal when the sample surface is not exposed to the light source, though this spectrum should include ambient light commonly present during analysis. For Whitmore MFTs, the path from the light source can be blocked by closing the manual shutter knob located at the fiber coupler plate (where the illumination fiber optic cable is attached); other MFT designs may employ a shutter mechanism elsewhere in the light path. During background calibration, a white reference sample may be positioned beneath the test head in preparation for the subsequent collection of the reference spectrum. Alternatively, some users position the collection spot on a matte black surface or over a void (e.g., off the edge of a table), and others choose to defocus the collection spot such that it is more than two focal lengths from a reflective surface. Acquired at the beginning of an analysis day, the background spectrum will be subtracted from the collected data, removing unrelated background signals. It is important that the background spectrum be blacker than any dark color tested or subsequent spectra may go below 0% reflectance, resulting in failed color calculations (Whitmore 2019).

The next calibration step involves collection of a reference spectrum on a white reference sample to define 100% reflectance across the visible wavelength region. A common reference sample is a Spectralon® white diffuse reflectance standard, which exhibits reflectance of ~99% and is chemically inert and environmentally stable. Other white reference options are barium sulfate or magnesium oxide coatings, white opal glass, and Millipore filters. As with any standard, care should be taken to maintain a clean and smooth surface so as not to alter its reflectance properties. Collection of the reference spectrum requires alignment of the illumination and collection spots on the white reference and its exposure to full intensity light (i.e., shutter fully open with neutral density filter removed). After collection, verify that the spectrum of the white reference sample produces a horizontal line at 100% reflectance; if it does not, repeat acquisition of the reference spectrum. The reference spectrum should be reassessed periodically throughout the day (every ~1 to 1.5 hours, though shorter intervals are also common), as drift may result in an undulating, slanted, and/or translated reference spectrum. Some spectrophotometer software can also calculate luminous flux (units are lumens) when collecting the reference spectrum, which may be used to evaluate the stability of the light source over time.

Calibration of spectrophotometer wavelength should be addressed intermittently, though this may require shipment of the unit to the manufacturer. The wavelength calibration procedure uses an elemental light source with characteristic emission peaks at specific wavelengths (e.g., mercury-argon, neon, krypton) to determine if they align with the resulting spectrum. If they are misaligned, one can determine the wavelength shift and apply a correction in the spectrophotometer software. Verification of wavelength calibration may be particularly important following transit of the spectrophotometer.

Data Collection

Colorimetry

The following colorimetric parameters relate to MFT practice and are discussed in greater detail in chapter 2. The calculation of CIE L*a*b* colorimetric coordinates from the spectral data requires definition of a reference illuminant and observer angle. Many MFT users employ standard illuminant D65 (overcast daylight with a CCT of 6,500 K) and the CIE 1931 2° Standard Observer function for their colorimetric calculations, and their continued use will promote comparison of MFT data among users.

Following the collection of MFT spectral data and calculation of their CIE L*a*b* coordinates, the color difference or ΔE between the initial spectrum and a subsequent spectrum can be determined. The first color difference formula was presented by CIE in 1976 and defined as the Euclidean distance between two points in CIE L*a*b* color space; this metric is typically shown as ΔE^*_{ab}. Issues with perceptual nonuniformities in CIE L*a*b* color space resulted in the addition of various corrections in 1994 (ΔE^*_{94}) and 2000 (ΔE^*_{00}). While one can use any of the three color difference metrics, CIE recommends use of the ΔE^*_{00} metric due to its improved representation of color discrimination by the human eye. Further, calculation of the three color difference metrics can occasionally result in varying Blue Wool equivalence classifications, so use of the more accurate ΔE^*_{00} should be relied on when assessing risk. Note that ΔE^*_{ab} continues to be commonly reported in the literature, in part due to its ease of calculation, and may be the only color difference metric calculated by the spectrophotometer software; thus, it may be prudent to report color difference in terms of both ΔE^*_{ab} and ΔE^*_{00}.

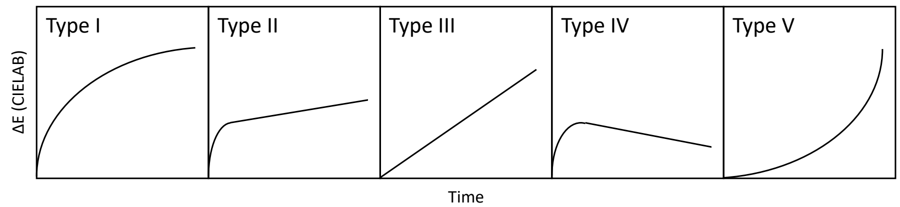
Data Logging

For each run, the MFT user must define in the spectrophotometer software the data collection interval and test duration. The data collection interval specifies the frequency in which averaged spectra are saved to the file. The original 1999 paper by Whitmore, Xun Pan, and Baillie stated a data collection interval of 6 milliseconds, but current MFT users extend this interval from several seconds to one minute, with 30 and 60 seconds being common. This choice represents a balance between coverage of the MFT run and the collection of a reasonable number of data files. However, one may occasionally encounter samples that exhibit such rapid color change (as evidenced from the near real-time ΔE^*_{ab} or ΔE^*_{00} shown by the spectrophotometer software) that the run is terminated before sufficient data are collected (or, in the case of exceedingly fast change, before a second averaged spectrum is collected). In this instance, the user will typically conduct a second MFT run on a different location of the same color but significantly shorten the data collection interval to ensure capture of the color change behavior. Data collection intervals on the order of several seconds emphasize color change behavior during the earliest stages of the MFT run, when the fastest fading rates are often recorded; the consequence, of course, is the collection of a large number of data files, though the testing time might also be reduced.

The test duration is one of the parameters that defines when to cease the MFT run. MFT test durations typically range from 5 to 30 minutes. Durations on the lower end (5 to 10 minutes) are typical, due to the need to examine a large number of test sites in a limited period. As previously mentioned, samples found to be particularly fugitive (~BW2 or less) should be retested in a different location of the same color; this subsequent test can be stopped early once it is determined that it tracks the previously observed color change behavior. Similarly, MFT runs for samples appearing to be more lightfast than BW3 may also be ceased before the end of the test as a means of saving time. Note that short test durations have the potential to miss a delayed color change, though this may be a nonissue as most colorants display plateauing (Type I and II) or continuous (Type III) color change (Crews 1987; Giles 1965; Druzik and Pesme 2010) (fig. 4.8); some users have reported rare instances of more atypical color difference behavior (Type IV or V curves), which should be flagged for the MFT community.

When testing artwork, the MFT user must also predefine a color difference threshold at which exposure of the test site to high-intensity light will be blocked and the test stopped; this is intended to protect the object from incurring visible change from MFT. The selection of a color difference threshold varies among

FIGURE 4.8.
Color difference curve shapes. From Giles 1965.



users, but commonly reported values are ΔE^*_{ab} of 5 and ΔE^*_{00} of 3. Higher threshold values may be appropriate for visually complex artwork such as textiles, while evenly colored smooth surfaces easily marred by visible discoloration might merit a more conservative threshold value.

For most Whitmore MFTs, the collection of data by the spectrophotometer will stop once the test duration is reached, but exposure of the sample to high-intensity light will continue. Light exposure ceases only when a neutral density filter is inserted into the light path or the shutter is manually closed. In contrast, the automated MFT will mechanically close the shutter at the conclusion of a run, with end test conditions defined by time, light dose, or a color difference threshold. Note that use of an electronic shutter is supported by the spectrophotometer software (Spec32 by Control Development, now Perkin Elmer) used by many Whitmore MFTs, but this adaptation is rarely incorporated.

Blue Wool Standards

The color change behavior of an artwork as determined by MFT is typically defined by comparison to the behaviors of Blue Wool Standards 1, 2, and 3, which represent colorants with high light sensitivity (Michalski 2018). Recall that the BW scale approximates a geometric progression, with each BW roughly twice as lightfast as the preceding one. When characterizing their performance, one may conduct multiple MFT runs of BW1, 2, and 3 to examine the variability of each and define their relative color difference behavior. (Note that one needs to compare the same color difference metric—ΔE^*_{ab}, ΔE^*_{94}, or ΔE^*_{00}—for all samples.) While MFT users have occasionally included BW4 as a reference, its color change behavior is thought to be dependent on the presence of UV and there is concern about its relevance when exposure is limited to the visible light region (Tao and Whitmore 2010; Hattori, Yoshizumi, and Crews 2012). Due to the number of tests needed to adequately characterize the color change behavior of BW1, 2, and 3 (some call for a minimum of three runs each), a user might consider dedicating up to a day to conduct MFT runs on these samples. This process should also be carried out when an MFT has been inactive for an extended period (e.g., weeks to months) or when lighting or environmental conditions have changed significantly.

Ideally, the standard deviation for each BW will be small and the color difference curve for BW2 will slot roughly equidistant between that of BW1 (highest color difference) and BW3 (lowest color difference). If either is not the case, additional testing is needed to assess if a previous MFT run may have been anomalous or if that specific BW card or fabric is responding atypically and should be replaced. It may be helpful to compare new MFT BW results to those for previous BW Standards whose performance is trusted. However, given a limited on-site supply of BW Standards possibly from the same manufacturer and batch and an expectation of longevity if handled carefully, replacement of a BW card or fabric should be a careful decision.

Once a BW Standard has been well characterized and assuming the MFT is in regular use, one may choose to intersperse single MFT runs of BW1, 2, and 3 with testing of artwork or other samples. If the MFT results for the BWs align with previously collected data, the user can be confident that the current testing conditions are similar to those when the BW Standard was initially assessed. Note that the MFT setup (i.e., light intensity, geometry, spot size) used to assess BWs should be similar to that for the object or sample; particular consideration should be given to the positioning of fiber optics during testing, as cables that are supported by the table may transmit light differently than those that are freely hanging. A BW Standard can be run at the beginning and/or the end of the day when artwork is being organized and during convenient breaks. (Some MFT users do not routinely run BW Standards if the instrumental conditions are similar to prior days.) As previously mentioned, the textured BW surface necessitates careful positioning of the light spot on the top of a thread, which may be indicated by a "twinkling" phenomenon; use of a pen camera or digital microscope can be helpful for determining location (fig. 4.9). Beyond BW standards, MFT testing of readily available light-sensitive material (e.g., commercial colored paper, markers) can provide another gauge of daily instrument performance, and there is ongoing research in the conservation field to develop an alternative lightfastness standard.

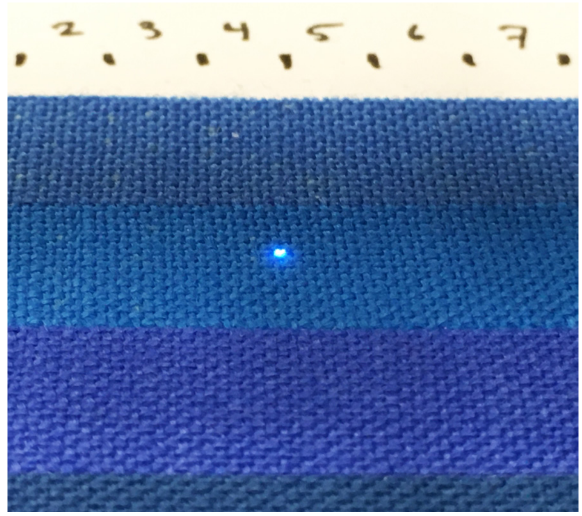


FIGURE 4.9 MFT light spot positioned on a Blue Wool (BW) 2 Standard, with BW1 and BW3 above and below. The numbers written above on the mounting card aid in recording the location of measurement. Image by Vincent Laudato Beltran.

To ensure the extended use of BW Standards, care should be taken when handling. During testing, it is suggested that, aside from the current test site, the standard be covered to limit unnecessary light exposure. Users should also avoid touching the BW fabric. When not in use, the standard should be appropriately stored in the dark; some users place them in a Mylar pocket and then in a Photographic Activity Test (PAT) approved paper folder. Each BW standard should be paired with key information such as dates of purchase and first use, supplier, batch number, and a unique identifier (which may be added to the MFT data filename). Use of a grid system can guide location selection and facilitate testing across the entirety of the BW Standard.

Protocol

While a number of the individual MFT data collection steps have been described thus far, this section elaborates on the practical order and pace at which these are conducted. The following protocol is based on the use of a Whitmore MFT and organized by three successive objectives—positioning of the light beam, maximizing reflectance, and initiating the run—each followed by comments. Note that this assumes that the topics presented above have already been addressed, including sample and site selection, vibration mitigation, maximizing and stabilizing light intensity, defining integration time and sample averaging, and conducting background and reference calibrations.

Positioning the Light Beam

- Close the shutter to block the light path to the sample.
- Position the sample beneath the test head; ensure that MFT components (e.g., fiber optic and USB cables) do not touch the sample surface.
- Insert the neutral density filter into the light path and then open the shutter fully, resulting in a dim spot on the sample.
- Position the light spot on the desired test area; a pen camera or digital microscope can aid with positioning and record images of the test area.

- Close shutter.

Comments

- As mentioned previously, textured surfaces such as BW Standards require that the light spot be positioned on the top of a thread. This can be highlighted by a "twinkling" effect when moving the sample laterally.
- For LED lamps, light intensity can be reduced or increased by adjusting the current on the LED driver. Some drivers have a trigger mode that can act as a shutter, though some users have suggested this may have an impact on stability.

Maximizing Reflectance

- In the spectrophotometer software, choose continuous scanning and y-axis auto scaling to allow for real-time visualization of the spectrum.

The following three steps should be conducted rapidly to minimize impact on the sample.

- Open the shutter and remove the neutral density filter from the light path; this will result in full intensity light on the sample.
- Adjust the vertical position of the test head to maximize reflectance as seen in the software interface.
- Reinsert the neutral density filter into the light path, close the shutter, and stop continuous scanning.

Comments

- As discussed previously, a number of MFT users choose to maximize reflectance only on a non-artwork sample at the start of the analysis day. For subsequent MFT runs, an alternative or supplemental alignment method disconnects the fiber optic cable from the spectrophotometer and attaches it to a low-intensity light source (e.g., fiber optic continuity tester, tungsten halogen lamp); this produces dim collection and illumination spots (the neutral density filter is inserted in the MFT light path) on the sample surface that can be visually aligned by vertical adjustment of the test head. Once aligned, be sure to securely reattach the fiber optic cable to the spectrophotometer and turn off the secondary light source.
- When maximizing reflectance, one may insert a neutral density filter in the light path (with the shutter open), resulting in a dim spot and minimizing light exposure of the sample. However, this may be an issue when maximizing the signal for darker objects, in which case the neutral density filter can be removed.

Initiating the Run

- Ensure that the shutter is closed, and remove neutral density filter.
- Set up data logging and colorimetric parameters, the colorimetry window (where real-time color difference or ΔE is shown), and allow for continuous scanning.

The following three steps should be conducted rapidly to ensure maximum data collection after exposing the sample to light.

- Open shutter, which exposes the sample to high-intensity light.
- Reset the onscreen ΔE to zero by defining reference L*a*b* values from the current spectrum.
- Initiate data collection.

During the run:

- Watch the onscreen ΔE. If it exceeds the predefined ΔE threshold, stop the MFT run by inserting the neutral density filter into the light path, closing the shutter, and terminating data collection.
- Verify collection of the first several spectrum files.
- Show the initial spectrum onscreen for comparison to evolving spectra.
- After collection of the last spectrum, stop light exposure of the sample by closing the shutter. This can be followed by reinsertion of the neutral density filter into the light path and termination of continuous scanning.

Comments

- Do not walk away from the MFT when testing artwork.
- The MFT setup used to assess Blue Wool standards should be similar to that for the object or sample; this includes positioning of the fiber optics during testing, as cables supported by the countertop may transmit light differently than those allowed to hang freely.
- Observation of a parallel spectral shift across the visible region may indicate potential movement in the test head or sample during the MFT run. If movement is due to loosening of the adjustment mechanism, allowing the test head to shift under its own weight, one may explore tightening of the stage.
- Observation of a jog in a relatively smooth color difference time series can also indicate movement in the test head or sample.
- One can employ a Perl script (programming language adept at processing text) to monitor real-time ΔE and readout colorimetric data for analysis by external software.
- Some users choose to begin continuous acquisition of data before exposure of the sample to high-intensity light. This allows for the collection of information during the earliest stages of light exposure when the rate of color change may be at its highest (data collected before light exposure are discarded) and likely entails use of a small data collection interval (~1 second) to maximize coverage.
- Consider setting a timer that alerts the user near the end of an MFT run, so the shutter can be closed (avoiding unnecessary light exposure on the object) after collection of the last spectrum.

Data Analysis

Following the collection of spectral and colorimetric information during a series of MFT runs, data analysis is typically conducted using programs separate from the spectrophotometer software. These data can be organized in a variety of ways to facilitate comparison and interpretation, and the results for each object are summarized in a report.

Software

Due to the need to examine numerous MFT data files for multiple color areas on an object, protocols were developed to compile and organize these results. Whitmore developed a suite of Excel macros (using "Visual Basic for Applications" programming) to extract and visualize spectral and colorimetric data; this also allowed for some automation and flexibility in configuring inputs and outputs. Use of Whitmore's Excel macros remains common among MFT users. In 2006, Spectral Viewer was developed at the GCI by Lionel Keene. This MFT analysis software employs a graphic user interface to facilitate spectral and colorimetric comparisons and is currently being updated by J. P. Brown at the Field Museum, Chicago (fig. 4.10). The automated MFT employs its own custom software that incorporates both data analysis and hardware control (e.g., shutter, spectrophotometer).

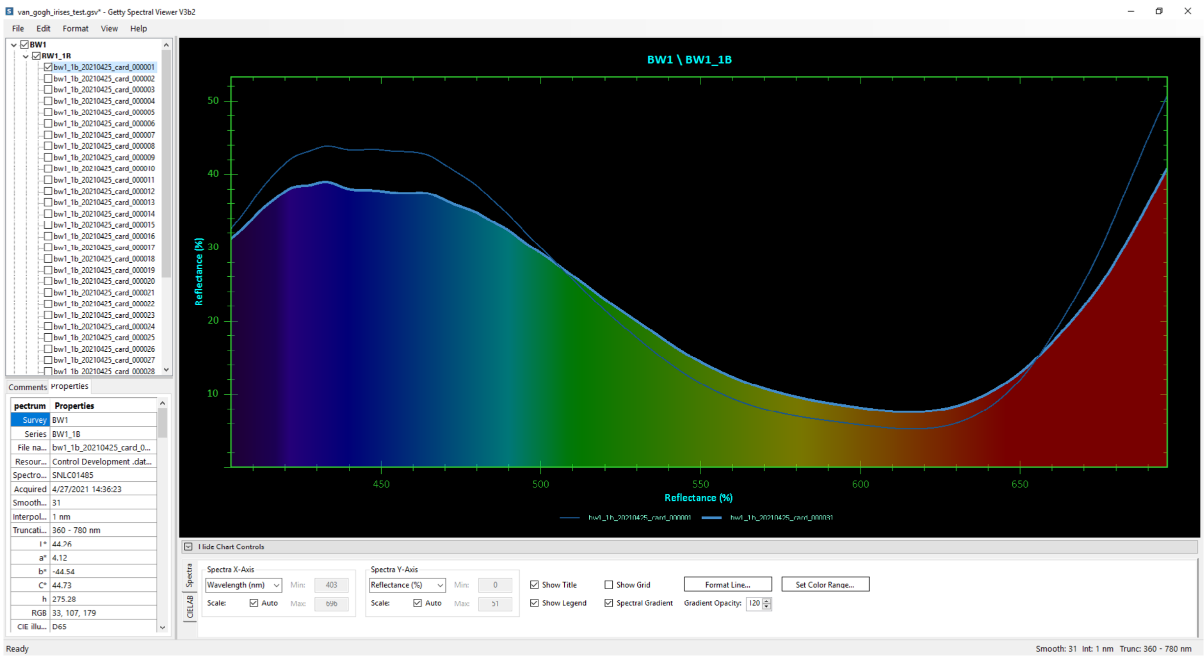


FIGURE 4.10 Initial (thin line) and final (thick line) spectra collected during an MFT run as shown in Spectral Viewer software, Version 3, Beta 2 (developed by JP Brown, Field Museum).

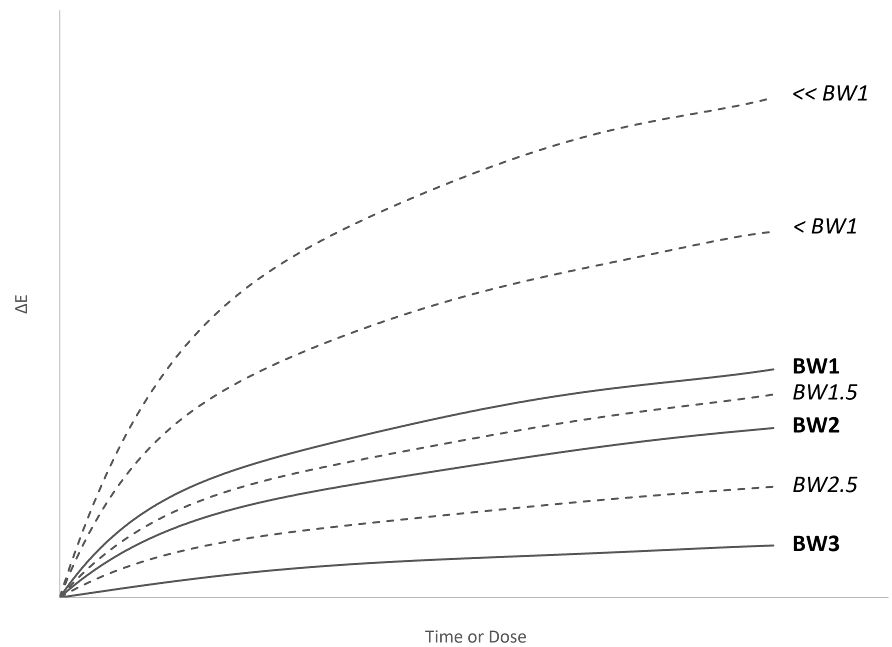
Data Visualization

Spectra are the fundamental information collected by a spectrophotometer, and it is important to examine its evolution during an MFT run. A common visual compares the initial and final spectra of a test area, emphasizing how and at which wavelengths change occurred (fig. 4.10). For example, increasing and decreasing reflectance at specific wavelengths may indicate color fading and darkening, respectively, while a spectrum trending toward horizontal can suggest a graying behavior (Whitmore 2019). Examination of spectra might also suggest testing errors; as previously mentioned, parallel shifts across the entirety of the spectrum could indicate movement of the sample or test head during the MFT run, requiring retesting of that color. Liang et al. (2011) advocated for the advanced exploration of MFT spectra, as this can provide more insight into degradation processes than reliance on colorimetry alone; a proposed approach is to calculate the difference in reflectance (final minus initial) across the visible region and determine the rate of change of the spectrum for narrow wavelength ranges (25 nm or 50 nm windows).

Given its focus on color perception, MFT data analysis emphasizes the assessment of colorimetric parameters calculated from the spectral data. Time series plots are used to show the progression of variables such as L*, a*, b*, ΔE^*_{ab}, and ΔE^*_{00} for a specific sample. For colors with replicate analyses, average values and standard deviations can be included. If the light intensity during the MFT run is known (and assuming it is constant), time may be replaced with light dose on the x-axis; however, one should resist the temptation to extrapolate MFT data collected at high-intensity light levels to low-intensity gallery lighting, as reciprocity may not hold.

The overlay of color difference time series for BW standards and test locations allows one to define BW equivalence (BWE). Color difference values recorded at the end of the test are commonly used to classify BWE; some users also choose to report the BWE at midpoints during the MFT run as this may differ from the BWE determination at the end of the run (Tse 2019). One can also define BWE at specific thresholds, such as when the curve reaches a ΔE^*_{00} of 1.5, approximating a JND (Pretzel 2008; Michalski and Druzik 2012). Bar charts offer an alternative display of BWE; colors may be used to indicate similarities between the samples and BW Standards. If the color difference of the sample lies between that of two BW Standards, its BWE can be characterized by intermediate BW steps (e.g., BW1.5, BW2.5) (see, e.g., del Hoyo-Melendez and Mecklenburg 2010; Druzik and Pesme 2010; Tse 2019) (fig. 4.11). Note that use of finer BWE intervals (e.g., BW1.4, BW2.2) should be done with caution as it may imply a higher level of accuracy than is present. Prestel (2017) suggested that comparison of the rate of color change (first derivatives of the color difference curves) of samples and BW Standards might be a more accurate means of assigning BWE. With respect to the object, its overall light sensitivity is typically defined by its most fugitive component (i.e., if the most light-sensitive colorant on an object has a BW2 equivalence, the overall object light sensitivity is also BW2); however, discussions among conservation and curatorial colleagues may suggest that decisions about acceptable light exposure be adjusted if the color change of its most vulnerable colorant is thought to have a minimal impact on the overall significance of the object.

FIGURE 4.11 Color difference curves for BW1, 2, and 3 and suggested curves for intermediate and less than BW1 behavior. Adapted from Druzik and Pesme 2010.

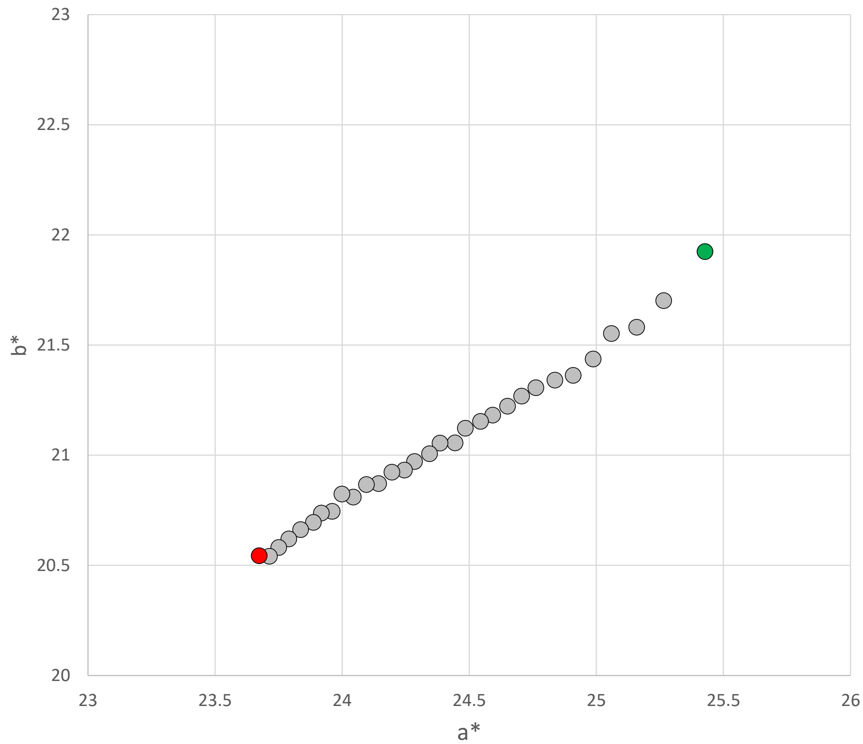


While ΔE quantifies the extent of color change, the direction of color change during an MFT run can be described by shifts in L*, a*, and b*, which correspond to the light-dark, red-green, and yellow-blue axes, respectively. Categorizing the overall change in these variables between the initial and final MFT data files provides some insight into how the color might evolve, though this should be verified by real-time color monitoring. The plotting of a* versus b* is a typical visualization used to track the path of color change of a sample during an MFT run (fig. 4.12 and appendix 5). (Note that other color spaces, such as Luminance-Chroma-Hue (Lch), can also be used to explore color change.)

Reporting

The MFT analysis of a specific object should be detailed in a report containing data tables and selected visualizations, as well as discussion of the implications for lighting policy (see chap. 5). While the report structure will differ among MFT users, the following is a summary of the various components that might be

FIGURE 4.12 Color change of an orange sample in a*-b* space (CIELAB), indicating that it is becoming less red (a*) and less yellow (b*). The green and red circles denote the initial and final data collected, respectively.



included (appendices 4 and 5 present an object screening case study from the Getty Research Institute and a sample MFT report by Bruce Ford, respectively).

- Object name, artist, accession number, year of creation, materials
- Image of object and map of MFT test locations
- Verbal summary of results and their implications for display
- Summary colorimetry table for all tested colorants, including ΔL*, Δa*, Δb*, Δc, Δh, ΔE^*_{ab}, ΔE^*_{00}, and BWE for ΔE^*_{ab} and ΔE^*_{00}
- Summary color difference (ΔE^*_{ab} and ΔE^*_{00}) bar chart for samples and BW Standards
- Summary color difference (ΔE^*_{ab} and ΔE^*_{00}) time series plot for samples and BW Standards
- For each test area: image of location on object, a* versus b* plot, initial and final spectra plot, time series of L*, a*, and b*
- MFT operator, key instrument details (e.g., light source, filters, measurement geometry, standard illuminant, standard observer), operating conditions (e.g., light intensity, spot size, lamp SPD), BW Standard information (e.g., source, batch no., date purchased)
- Location and filenames of MFT data for samples and BW Standards

The inclusion of brief descriptions of various topics associated with MFT (paired with key references) can also be beneficial for readers inexperienced with the instrument, color science, and lighting policy terminology. These topics might include:

- Description of the instrumentation
- Limitations of and uncertainty associated with MFT
- Colorimetric concepts (e.g., L*, a*, b*, ΔE^*_{ab}, ΔE^*_{00})
- Lighting policy concepts (e.g., BW standards, JND, Museum Lifetime)
- Example of lighting policy guidelines

Beyond the examination of one object, the organization of MFT analyses on numerous objects and research samples in a searchable database can be a useful resource for understanding broader trends; a notable example is the MFT database developed by Season Tse at the Canadian Conservation Institute. Access to MFT data from multiple institutions may allow one to revisit published lighting guidance for various materials, which can be beneficial for those without access to MFT. Such an effort, however, should not detract from the unique ability of MFT to provide insight into the light sensitivity of an object with a specific material composition and exposure history and guide decision making on how it is displayed during exhibition.

Conclusion

This chapter details the practical steps of planning and conducting an MFT analysis. Though much of this information can be applied to any MFT, users of a specific instrument should review its standard operating procedure and reflect on how it aligns or differs from what is described here. As previously stated, the goal of this chapter is not to create a uniform protocol but to explore the rationale for the various choices made by MFT users and to provide guidance for those considering the addition of MFT to their preventive conservation tool kit.

References

Connors-Rowe, Sandra A., Hannah R. Morris, and Paul M. Whitmore. 2005. "Evaluation of Appearance and Fading of Daylight Fluorescent Watercolors." *Journal of the American Institute for Conservation* 44 (2): 75–94.

Crews, Patricia Cox. 1987. "The Fading Rates of Some Natural Dyes." *Studies in Conservation* 32 (2): 65–72.

Druzik, Jim. 2010. "Oriel Microfading Tester (MFT): A Brief Description." In *Textile Specialty Group Postprints, vol. 20, AIC Annual Meeting, Milwaukee, WI, 11–14 May 2010*. Washington, DC: AIC.

Druzik, Jim, and Christel Pesme. 2010. "Comparison of Five Microfading Tester (MFT) Designs." In *Textiles Specialty Group Postprints, vol. 2, AIC Annual Meeting, Milwaukee, WI, 11–14 May 2010*. Washington, DC: AIC.

Ford, Bruce, and Jim Druzik. 2013. "Microfading: The State of the Art for Natural History Collections." *Collection Forum* 27 (1): 54–71.

Ford, Bruce, and Nicola Smith. 2017. "A Reality Check for Microfade Testing: Five Examples." In *ICOM-CC 18th Triennial Conference Preprints, Copenhagen, 4–8 September 2017*, ed. Janet Bridgland, art. 1508. Paris: International Council of Museums.

Giles, C. H. 1965. "The fading of colouring matters." *Journal of Applied Chemistry* 15, no. 12 (December): 541–550.

Hattori, Hika, Kunio Yoshizumi, and Patricia Cox Crews. "Wavelength Sensitivity of AATCC Blue wool Lightfastness Standards under Light Radiation." *Dyes and Pigments* 92 (3): 936–41.

Liang, Haida, Rebecca Lange, Andrei Lucian, Paul Hyndes, Joyce H. Townsend, and Stephen Hackney. 2011. "Development of Portable Microfading Spectrometers for Measurement of Light Sensitivity of Materials." In *International Council of Museums, Committee for Conservation (ICOM-CC) Triennial Conference, 2011*. Lisbon: ICOM-CC.

Michalski, Stefan. 2018. "Agents of Deterioration: Light, Ultraviolet and Infrared." www.canada.ca/en/conservation-institute/services/agents-deterioration/light.html; accessed January 7, 2021.

Michalski, Stefan, and Jim Druzik. 2012. “The Lighting of Easel Paintings.” In *Conservation of Easel Paintings*, ed. J. H. Stoner and R. Rushfield, 678–92. New York: Routledge.

Pesme, Christel, Andrew Lerwill, Vincent Beltran, and James R. Druzik. 2016. “Development of Contact Portable Microfade Tester to Assess Light Sensitivity of Collection Items.” *Journal of the American Institute for Conservation* 55 (2): 117–37.

Prestel, Thomas. 2017. “A classification System to Enhance Lightfastness Data Interpretation Based on Microfading Tests and Rate of Colour Change.” *Coloration Technology* 133: 506–12.

Pretzel, Boris. 2008. “Now You See It, Now You Don’t: Lighting Decisions for the Ardabil Carpet Based on the Probability of Visual Perception and Rates of Fading.” In *International Council of Museums, Committee for Conservation (ICOM-CC) Triennial Conference, 2008*, Volume II, 759–765. New Delhi: ICOM-CC.

Tao, Chong, and Paul M. Whitmore. 2010. “Development of a Microfading Tester for Light Exposures including Near Ultraviolet Wavelengths.” In *Textiles Specialty Group Postprints, AIC Annual Meeting, Milwaukee, WI, 11–14 May 2010,* vol. 20. Washington, DC: AIC.

Tse, Season. 2019. “Microfade Testing for Heritage Institutions: A Canadian Experience.” *Studies in Conservation* 64 (6): 337–51.

Whitmore, Paul M. 2019. “MFT User’s Guide, Version 1.1.” March 24. Unpublished.

Whitmore, Paul M., Xun Pan, and Catherine Bailie. 1999. “Predicting the Fading of Objects: Identification of Fugitive Colorants through Direct Nondestructive Lightfastness Measurements.” *Journal of the American Institute for Conservation* 38 (3): 395–409.

5. LIGHTING POLICY FRAMEWORK AND ROLE OF MFT

Christel Pesme and Mark Benson

In addition to enhancing our understanding of the light-induced color change behavior of a specific collection item, the microfading tester can play a role in the broader context of lighting policy development for a heritage collection. This chapter seeks to expand the scope of this document by exploring a decision-making framework for lighting policy based on concepts such as value-based collection care and risk assessment that are currently being developed and applied in the cultural heritage field. Such an approach permits collection stewards to adjust the level of control of light exposure based on the extent of acceptable light-induced damage of an object.

The unique predictive capacity of MFT significantly reduces the uncertainty associated with light sensitivity assessments. The resulting data support collection stewards by offering a prospective approach in which light risk is mitigated by budgeting an object's light exposure over its lifetime. This approach optimizes the balance between present and future access to a collection subset identified as vulnerable to light and allows for flexible lighting scenarios that support the viewing experience of an item.

Figure 5.1 presents a summary of the decisions that can be used to formulate lighting recommendations for display, broadly categorized as "Assessing Value at Risk to Light," "Quantifying Risk to Light," and "Managing Light Risk." This framework emphasizes the need for careful consideration of the item, collection, and institution, which is followed by the potential for MFT to significantly inform the management of light risk associated with display.

The proposed framework is also a methodological tool to help collection stewards set priorities based on the needs of the collection and the institution and guide development and implementation of display recommendations. While not all the steps

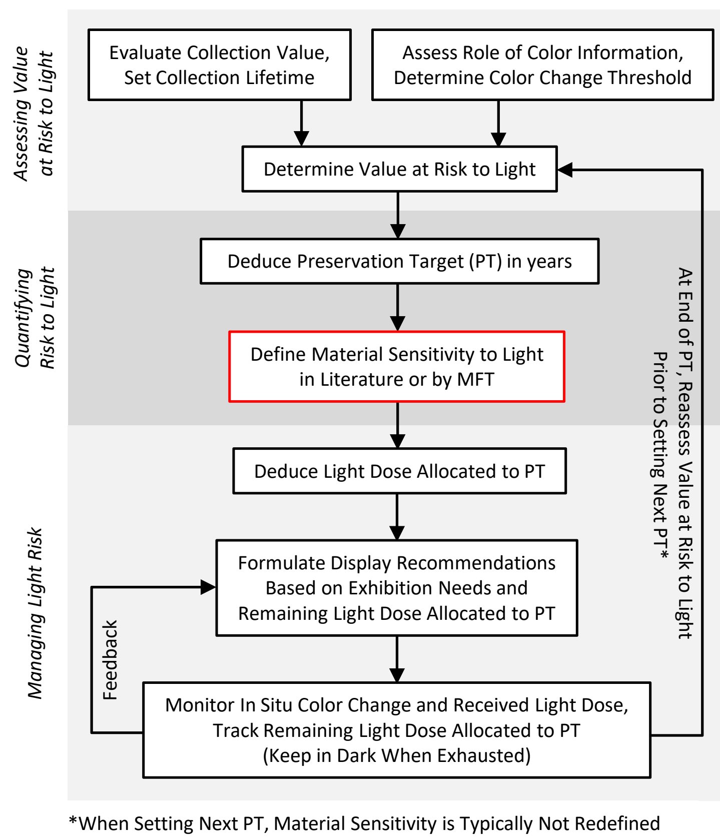


FIGURE 5.1 Decision diagram for defining lighting recommendations for display of an item and/or a collection that is vulnerable to light. The step highlighted in red incorporates MFT analysis.

described in figure 5.1 may apply to specific situations, the general structure of the decision diagram will aid in documenting the motivations for the choices made.

Assessing Value at Risk to Light

For collection care, risk is related to damage that can be defined as a loss of value (Ashley-Smith, Derbyshire, and Pretzel 2002). Light risk corresponds to the loss of cultural value induced by the exposure of the collection item to light. This is dependent on the color change resulting from the item's exposure to light, how much this change would reduce its cultural value and future use, and the importance and usability of the item for the institution.

This section begins by summarizing the parameters involved in light-induced color change. It then provides context for the management of light risk as part of a larger value-based collection care framework. Central to this process are the concepts of collection value and the associated targeted collection lifetime and value at risk to light. The latter depends on the importance of color as a value-determining feature and is relevant for collection items that are likely vulnerable to light. Further, it is shown how assessing the relative value at risk to light aids in identifying priorities for light risk mitigation at the collection level.

Light-Induced Color Change

When collection items are exposed to light, the main material alterations consist of color change at the surface and, if UV is present, weakening and yellowing of the support and chalking of the media. Exposure to IR and the conversion of visible light and UV into heat will result in elevated object temperatures, which may cause local desiccation, distortion, or cracking.

Color change is often the main criterion used in the conservation field to quantify material deterioration induced by light exposure. Color measurement and its subsequent monitoring during and after display are typically based on nondestructive portable techniques that are relatively simple but labor-intensive. Use of these techniques can be complicated by the need to remove objects from their housing and the difficulty of matching the same locations of measurement when monitoring color change. While light-induced color change is typically irreversible and cumulative, in exceptional cases it can be reversible to some extent (e.g., Prussian blue, iron gall ink); exhibition of such material must be managed separately from the broader collection.

Color change induced by light exposure depends on the light dose received and, if within the range of gallery light levels, follows the reciprocity principle, which states that material response is determined by total light exposure. For example, color change induced by 3 months of exposure at 100 lux is equivalent to the change induced after 6 months at 50 lux, all other conditions being equal. Light dose is commonly expressed in units of lux-hours or Megalux-hours, with 1 Megalux (Mlux) equivalent to 1 million lux. The spectral power distribution (SPD) of the light source will also affect color change (Saunders 2020).

Brokerhof, Ankersmit, and Ligterink (2017) provide specific examples of the relationship between visible light, UV, IR, and other agents of deterioration and their associated synergetic effects. (The Canadian Conservation Institute's [CCI's] 2017 webpage "Agents of Deterioration" provides information on primary threats to heritage.) For instance, increasing temperature will accelerate chemical reactions, including those induced by exposure to light, and light-induced deterioration will increase at higher levels of relative humidity. Figure 5.2 summarizes the main parameters determining material color change induced by museum gallery lighting.

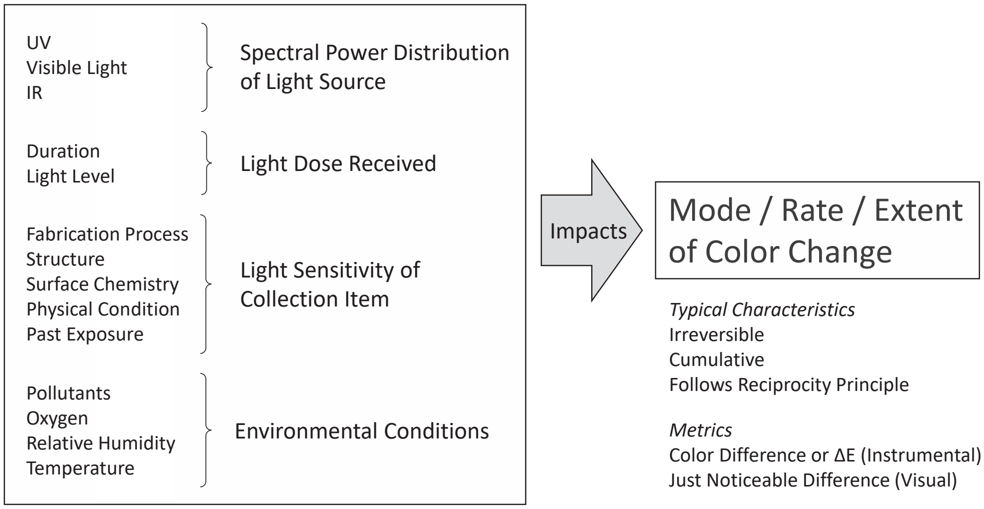


FIGURE 5.2 Parameters impacting light-induced color change.

However, assessing light-induced deterioration using only color change poses two caveats. First, any light-induced deterioration resulting in structural weakening of the support or change in appearance beyond color, such as gloss, may be underestimated. Second, color change resulting from exposure to other agents of deterioration (e.g., pollutants) may be overlooked if the risk assessment is not carefully carried out.

Value-Based Collection Care

Over the past twenty-five years, the concept of heritage care is transforming from a material-based approach to a significance- or value-based approach (ICOMOS 1994; Keene 2002; Avrami et al. 2019). This change in thinking developed from the growing recognition that heritage items comprise intertwined tangible and intangible features, with the latter rarely being fully embodied or contained by the former (*Australia ICOMOS Burra Charter*, 2013). An item's cultural "significance is seen as the accretion of everything that has happened to it physically (including repairs and conservation) and the accumulation of different values" (Pye 2016). Originally developed for the field of immovable heritage, this approach is increasingly being applied to collection care. Recognizing that collection value only becomes effective during interaction with its intended audience, it is expected that collection stewards will promote access to collections and their associated data as they increase in overall cultural value and if proper care is implemented.

Value-based collection care seeks to support rational decisions concerning staff effort and allocation of resources so as to develop value, increase short- and long-term accessibility, and enhance use of the collection (Brokerhof, Ankersmit, and Ligterink 2017; Brokerhof, Bülow, and Kemp 2017). Increasingly using cost-benefit analysis methodology and drawing on sustainability principles, this approach considers not only the value placed on cultural heritage and the people involved with it but also the impact that collection use has on people, institutional operations and finances, and the environment (Henderson, Waller, and Hopes 2020).

The implementation of value-based collection care integrates value assessment and risk management and requires assessment of item significance to further monitor collection value. As cultural values change with perspective (synchronic change), assessing the significance of an item will require research, consultation, discussion, and negotiation between all stakeholders, as values may be in conflict. Various methods using combinations of valuation criteria have been developed in the heritage field to analyze, assess, and specify significance, value, and meaning (Russell and Winkworth 2009; Bülow 2010; Cultural Heritage

Agency 2014; Reed 2018). The main methods currently applied in the field for movable collections are described by Ankersmit and Stappers (2017).

Ideally, each collection item should have a statement of significance, defined as "a reasoned, readable summary of the values, meaning, and importance of an item or collection" (Russell and Winkworth 2009, 11). This statement should be signed and dated as significance is not fixed in time (diachronic change). While item-specific statements have been adopted in certain regions, application has been uneven in the field. It should also be noted that the musealization process (the removal of an object from its natural or cultural context for exhibition in a museum) and further uses and associated care of the item in a cultural heritage institution will likely affect its cultural significance and values (Rubio 2020).

Estimating Collection Value of an Item

The mission statement, collecting policy, and collection plan of the cultural heritage institution define the institution's profile (e.g., museum, archive, library), while also determining the collection anatomy and indicating associated uses and expected types of access. In this text, "collection value" is proposed as a working concept, understanding that it will be determined by the collecting institution on the basis of an item's cultural significance, its relative importance within the collection, and its expected usability (Häyhä, Jantunen, and Paaskoski 2015). On the other hand, collection value will likely determine decisions regarding its interpretation, use, and care by the holding institution. Taylor and Cassar (2008) refer to the relationship between the valuation of an item, its representation and use within the institution, and the care provided to it as "symbiotic."

Estimating the relative collection value of an item using broad categories (i.e., high, medium, lower) will help prioritize intervention related to its care. Assessment results can be used as guiding criteria for establishing an item's position of importance for recovery in an emergency plan and will likely play a role when assessing the insurance value of an item. While most institutions do not explicitly formulate rankings, items considered the most valuable are often indicated obliquely; for instance, they may be labeled as the "treasures" of the collection and their usage via loans or in-house exhibitions will reflect their status. Formalizing the ranking of collection value, systematically or for specific items, will depend on the practices of each institution. Value classification systems can be implemented nationwide, as has been done in the Netherlands since the 1990s (Reuss, Scott, and MacKinnon 2005).

Collection value is related to an item's cultural significance and will vary in time with changes in communities, culture, politics, science, and the environment. Collection value will increase or decrease depending on the use of the item by the institution and the quality of the care provided, and therefore needs to be regularly reassessed and updated. The practice of assessing and ranking collection value should be seen as a dynamic process that will continue to develop and adapt as circumstances of and demands on the collecting organization change (Brokerhof, Bülow, and Kemp 2017). The frequency of such a reassessment is connected with a preservation target, which is discussed below.

Setting a Collection Lifetime for an Item

To help manage risks associated with the use of a collection item, the collecting institution may want to set a targeted collection lifetime (Saunders 2020). This term can be defined as the length of time for which the collection item will continue to be meaningful and usable, corresponding to its "serviceable life" in the collection.

Targeted collection lifetime(s) should be tailored to each institution and collection type. This ideally results from a collaborative decision-making process within the institution as it establishes a commitment regarding collection stewardship and the resources allocated to it. The collection lifetime associated with an item will likely vary according to collection value: as a general rule, the higher the collection value, the longer the targeted collection lifetime.

Collection care can then be understood as the careful management of the collection value of an item throughout its targeted collection lifetime in a way that is consistent with and sustainable for present and long-term uses and functions (Lithgow 2011).

Assessing Value at Risk to Light of an Item

When analyzing the negative consequence of an item exposed to a specific agent of deterioration, the value at risk rarely corresponds to its total collection value. Value at risk is instead the proportion of total value that might be lost in the type of event/exposure considered. It should be noted that this might be further refined by studying the damage function, which quantifies the sensitivity of an item to the agent of deterioration (largely the focus of conservation scientists) and considers the impact of material change on the cultural value of the item, which may be more difficult to ascertain and remains understudied (Ashley-Smith 2013; Strlič, Thickett, Taylor and Cassar 2013; Brokerhof, Ankersmit, and Ligterink 2017).

With the main light-induced effect on materiality consisting of color change at the surface, value at risk to light corresponds to the portion of the cultural value that would be negatively affected by color change. Consequently, the value at risk to light should be assessed only for items identified as likely to be vulnerable to light, either due to their light sensitivity (i.e., items in pristine condition, unknown behavior, suspected high light sensitivity) or potential exposure to high light levels.

Assessment of the value at risk to light can be achieved based solely on the estimation of collection value, with a higher collection value associated with a greater value at risk to light. Alternatively, one may want to take a more in-depth look at the role played by color information in collection value. This is especially relevant for high-value items for which visual perception is important. Assessments of the role of color information in collection value may have less relevance depending on the nature of the collection or specific collection item. It is easy to recognize that an artist's intended visual aesthetic value relying on excellent color discrimination will likely be significantly impacted by color change. Tolerance to such change may be larger for an item where collection value is dependent on the informational content conveyed, such as text readability that is based on the contrast between the text and the support and requires a high level of contrast acuity. Alternatively, an item with a high collection value and an aesthetic quality relying on a sensory rather than visual experience may not be vulnerable to color change.

It is proposed to use three broad categories—important, average, and smaller—to evaluate the role that color information plays in the collection value of the item. As a general rule, value at risk to light will be greatest for a high collection value item in which color is an important value-determining feature.

Determining Relative Value at Risk to Light for a Collection Subset

Collection stewards may wish to determine the relative value at risk to light for a subset of the collection identified as vulnerable to light to help set priorities regarding mitigating light risk. Table 5.1 presents nine categories that can be used to assess the relative value at risk to light of a collection item. The categories used to assess collection value of an item are high (H), medium (M), and lower (L), while those used to evaluate the role of color are important (I), average (A), and smaller (S). Each combined category of relative value at risk to light can then be defined by two letters, the first corresponding to the item's collection value and the second to the ranking of the role of color information. 'HI' corresponds to collection items with high collection value and for which color information plays an important role; this also represents the category of items with the highest value at risk, requiring the most attention and care. On the other end of the scale, LS corresponds to collection items with the lowest value at risk to light.

TABLE 5.1 Matrix showing relative value at risk to light based on an item assessment of collection value and role of color information.

		Collection Value		
		High (H)	Medium (M)	Lower (L)
Role of Color Information	Important (I)	HI	MI	LI
	Average (A)	HA	MA	LA
	Smaller (S)	HS	MS	LS

The processes of risk analysis and value estimation that underlie the determination of the relative value at risk to light for the collection can be complex and resource-intensive. A careful analysis of the expected gains versus the efforts involved is therefore recommended prior to engaging in the process for the collection subset identified as light-sensitive. This decision will depend on the nature and size of the collection, the current condition, access level, expected use, and capacity of the cultural heritage institution. It can be expected that most items stored in archives will have a high or medium *Collection value* with an average role of color information, whereas color information is expected to play an important role for most items in a visual art museum collection.

Quantifying Light Risk

The management of light risk at the collection item level should ensure its effective and sustainable use and access for present and future stakeholders. This requires managing its value at risk to light over the targeted collection lifetime set by the holding institution. This section discusses determination of the total loss of value at risk to light and a preservation target, which is the time frame for which a just noticeable difference (JND) is allowed.

Establishing a set of broad categories of value at risk to light for the collection and deducing preservation targets accordingly permits setting priorities to guide the selection and implementation of cost-effective mitigation strategies. The level of light risk control should be adjusted according to the value at risk category and resources allocated to protect items for which light exposure may induce greater damage. This process improves the overall balance between short- and long-term access to the collection and can help prioritize the selection of collection items to examine with MFT.

This section also examines the process by which literature- or MFT-based assessments of an item's light sensitivity help quantify the preservation target and support the development of a prospective approach to the mitigation of light risk for the collection.

Assessing the Total Loss of Value at Risk to Light

Estimating the change in color after which an item's value at risk to light would be entirely lost can be a sensitive task. Attempts at quantification may easily result in a misleading interpretation that would reinforce "the falsehood that lighting guidelines are, should, or could ever be based on solely objective criteria," not fully acknowledging that "lighting decisions legitimately depend on perceptual, social and institutional criteria, as well as scientific" (Ford and Smith 2011, 81). This idea of a more holistic understanding of item lifetime was explored by Fenech et al. (2013), who crafted a value-based psychophysical approach that includes stakeholder workshops; the results, which focused on archival collections of color photographs, indicated that the nature of the image itself (e.g., fading profile, extent of detail) was the most prominent factor in the assessment of the change in color that would mark its end of life.

Assessing the maximum color change after which a collection item is no longer fit for its expected use should be coupled with the evaluation of the role of color information. This process provides an opportunity to reinforce collaboration and improve mutual understanding among the various stakeholders involved in the use and care of the collection. Discussions between curators, conservators, and collection managers and consultations with external stakeholders—for example, artists, representatives of the originating community, and visitors—allows for the explicit formulation of a commonly agreed upon target for the item's presentation and preservation. This also benefits the institution by increasing accountability and transparency in its decision-making and aiding in the identification of resources needed to reach the agreed target.

Threshold of Maximum Color Change

Assessment of the maximum light-induced color change threshold was first used by Lafontaine (1980) to assess the suitability of felt-tip pens as artistic material. Ashley-Smith, Derbyshire, and Pretzel (2002) proposed use of this concept to quantify the change in appearance after which an item would have reached the end of its life as a collection item and is no longer fit for display; this was set at 10 successive JNDs from its original appearance. (As noted in chapter 2, the JND is a context-dependent quantity for which a difference can be perceived by more than ~50% of viewers.) In addition, Michalski (2018) refers to an "almost total fade," which is the threshold after which a colored sample has lost most of its color; this roughly corresponds to a minimum of 30 successive JNDs from its original appearance, assuming a saturated color. (For paler colors and items with low contrast, an almost total fade may occur at a lower successive JND threshold.) These different thresholds are not contradictory but rather reflect a change in scale and interpretation. In the first case posed by Ashley-Smith, Derbyshire, and Pretzel (2002), the color change induced on the item surface marks the end of its life as a collection item as it is assumed that the role of color information is large and its value at risk to light and collection value are the same. Michalski's term "almost total fade" refers to the fading of a colored sample with no associated meaning. The two thresholds—10 and 30 successive JNDs—underlie the relationship between the extent of color change and the role of color in conveying information or triggering a meaningful experience.

The Light Damage Calculator developed by the CCI can aid in the determination and communication of the acceptable maximum color change for a collection item (Tse 2019). This interactive online tool provides visual simulations of the anticipated impact of select lighting scenarios for different colorants. The estimated color change is based on scientific results obtained by aging studies of various artists' materials in light accelerated aging chambers. For a specific item with known dyes or pigments in the CCI database, the Light Damage Calculator can be used to select various lighting scenarios and assess their impact. The tool can also generate a scale of color change that serves as a reference for estimating the color change threshold(s) marking the total loss of value at risk to light. Figure 5.3 presents visual simulations of a saturated red alizarin paint corresponding to color differences of 16, 24, 32, 40, and 48 ΔE^*_{ab}, as determined by the CCI Light Damage Calculator. Note that a JND is thought to correspond to a ΔE^*_{ab} of approximately 1.6. The corresponding number of successive JNDs associated with each computed color change is also indicated. As already mentioned, in the case of a pale desaturated reference, color and the associated information may likely be lost after a smaller color change. Similarly, digital simulations of the light-induced change of an image have also been used to examine acceptable color change (see Sidebar: Digital Simulation of Overall Faded Appearance).

Reference Color					
CCI Light Damage Calculator Simulation					
Successive JNDs	~10	~15	~20	~25	~30
ΔE^*_{ab}	~16	~24	~32	~40	~48
Dose, UV removed (Mlux-hours)	80.3	118.3	156.2	197.1	239.4

FIGURE 5.3 Levels of change from a reference red alizarin paint as modeled by the CCI Light Damage Calculator.

Digital Simulation of Overall Faded Appearance

It has been acknowledged that the JND concept is well suited to measure visual ability but is less suited for assessing the viewer's perception of change in an image, with the unacceptability threshold being largely image dependent (Richardson and Saunders 2007). To address this complexity, digital image processing techniques have been used to simulate various extents of light-induced change of an image's overall appearance. These visual simulations were then used to carry out psychophysical studies on unacceptability thresholds (Fenech et al. 2013).

A project focused on *The Bedroom* by Van Gogh, one of the recently conserved paintings at the Van Gogh Museum, provides an example of how digital simulation of an item's appearance can be used. Data obtained during accelerated light aging experiments on historically reconstructed samples were used to generate two series of digital visual simulation: a study of the various stages of appearance leading to the painting's current state (Geldof et al. 2018; Berns 2016) and a simulation of its predicted appearance when subject to continued light exposure (Hendriks, Brokerhof, and van den Meiracker 2017). The latter series was used to form an opinion on how much light-induced color change over how many years was acceptable for the collection item. Assessments were done by relevant stakeholders including museum visitors, with the results used to formulate display recommendations for the painting (Hendriks, Brokerhof, and van den Meiracker 2017). While promising, such an approach requires extensive research and investment of resources, and application is likely limited to items with high collection value on a case-by-case basis.

Morris and Whitmore (2007) have proposed using imaging software to incorporate fading colorimetric data obtained during MFT analysis to simulate the predicted overall change in appearance of sensitive collection items. Several authors have explored this idea (del Hoyo, Świt, and Sobczyk 2018; Pesme 2016); however, additional research is required before applying this method more systematically, particularly with respect to the correlation of the color change observed in the gallery and predicted by MFT (Barro et al. 2020).

Setting a Preservation Target for Light Exposure

Once the light-induced color change threshold (after which an item is no longer fit for its expected use) has been determined, the next step is to manage this change to optimize the balance between present and future access to the collection. Since light-induced color change is typically irreversible and cumulative, this threshold may be budgeted over the targeted collection lifetime. This results in a preservation target for light exposure expressed in years and is defined as the period of managed use (e.g., storage, study, reproduction, display, or lending) during which a JND is allowed for a collection item. An item with a collection lifetime set to 500 years and a color change threshold of 20 successive JNDs will have a preservation target equivalent to 25 years (500 divided by 20). It should be noted that the preservation target can alternatively be expressed as the acceptable number of JNDs within a given period of time.

Broad Categories of Value at Risk to Light for the Collection

To manage light risk for a light-sensitive subset of the collection, collection stewards may wish to establish broad categories of value at risk to light by rearranging the nine categories described in table 5.1 into a limited and more manageable number. This will streamline the process and reduce the time required for implementation. The preservation target will then be deduced for each of the resulting categories of value at risk to light to optimize the balance between short- and long-term access.

Table 5.2 summarizes the various parameters involved in establishing categories of value at risk to light for the collection and deducing the associated preservation targets for light exposure. In this example, the collection value categories are again defined as High, Medium, and Lower (as in table 5.1), and their targeted collection lifetimes are defined as 500, 300, and 150 years, respectively. In contrast to table 5.1, the role of color information has been assessed using only two categories; the Smaller category is retained, while the Larger category combines both the Important and Average roles of color information. When color information plays a Larger role (including low-contrast colors), a change of color corresponding to 10 successive JNDs has been chosen as the maximum threshold beyond which an item is no longer fit for its expected use. When color information plays a Smaller role, the maximum color change threshold was set at 20 successive JNDs. This results in three broad categories of value at risk to light. Category A corresponds to items with High collection value and for which color information plays a Larger role. Category B encompasses a broader collection subset, corresponding to items with High collection value and a Smaller role for color information, as well as items with Medium collection value. Category C includes items with Lower collection value. In the case of items with Medium (Category B) and Lower (Category C) collection values, color information is conservatively assumed to play a Larger role.

TABLE 5.2 Categories of value at risk to light and associated preservation target (PT) for items identified as likely to be vulnerable to light. Note that color information is assumed to play an important role for Medium and Lower collection values. The original table 5.1 categories of relative value at risk to light are shown in parentheses, and the prioritization of resource allocation is also indicated. *The PT for Category B was set to 30 years (300 years/10 JNDs) to ensure the highest level of protection within this item grouping.

			Collection Value & Target Lifetime		
			High (H)	Medium (M)	Lower (L)
Color Information	Role	Total Loss	~500 years	~300 years	~150 years
	Larger, includes Important (I) & Average (A)	~10 JNDs	Category A PT = 50 years (HI, HA) *1st Priority*	Category B PT = 30 years (MI, MA, MS) *3rd Priority*	Category C PT = 15 years (LI, LA, LS) *4th Priority*
	Smaller (S)	~20 JNDs	Category B PT = 30 years* (HS) *2nd Priority*		

Resources to be allocated to the mitigation of light risk for light-sensitive collections can be prioritized using the broad categories of value at risk to light shown in table 5.2. Category A represents items for which it is the greatest priority to implement the maximum level of care; these items bear the highest value at risk to light and will likely be the most frequently requested for display due to their High collection value. The second priority is Category B items with High collection values, as these may be in higher demand for display than Category B items with Medium collection values. Table 5.3 presents brief descriptions of collection items in the three categories of value at risk to light shown in table 5.2.

TABLE 5.3 Examples of collection items in each category of Value at Risk to Light as defined in table 5.2.

Category of Value at Risk to Light	Examples of collection items
A	**Collection Value:* High, *Role of color information:* Important or Average Includes unique visual art items from renown artists relying on color appearance, most valuable colored archival material
B	**Collection Value:* High, *Role of color information:* Smaller Includes unique visual art items from renown artists, most valuable archival material for which color information plays a smaller role **Collection Value:* Medium, *Role of color information* assumed to be important Includes visual art items and archival material of lesser value
C	**Collection Value:* Lower, *Role of color information* assumed to be important Includes documents for which information value is not color dependent and susceptible to fading (e.g., maps)

The method of organizing collection items into a limited set of categories of value at risk to light, as shown in table 5.2, is flexible and can accommodate the nature of the collection and the specific priorities, resources, and capacity of the cultural heritage institution. Some institutions may streamline the process by choosing a single preservation target without determining collection value or forgoing evaluation of the role of color information and employing a single threshold of maximum color change. These various options help collection stewards simplify the assessment process to establish an adequate number of relevant categories of value at risk to light for the collection. The cultural heritage field would benefit from further discussion on the application of this categorization method for a range of collections and institutions.

Reassessing the Preservation Target over an Item's Collection Lifetime

Setting a preservation target during which a JND is allowed for a collection item is by definition an iterative process that will be revisited regularly over an item's collection lifetime. After a preservation target is exhausted and before a subsequent preservation target is set, collection stewards should take the opportunity to reevaluate both the collection value and the value at risk to light. For instance, collection value of an item may have increased due to newly acquired knowledge on the artist's technique, a successful conservation treatment, its presence in an important exhibition, or its relation to recently acquired items. Alternatively, unacceptable damage may have occurred, resulting in an item's decreased usability and collection value. Note that the devaluation of an item's collection value should be closely regulated; such a decision will likely require multiple approvals (up to the director level) and may have an impact on subsequent care of the item. Reassessment of collection value and value at risk to light may be needed prior to the end of the current preservation target when confronted with an exceptional and/or unpredictable event that has a significant impact on these parameters.

When reassessing categories of value at risk to light, it is recommended that the past appearance of the collection item act as a reference to avoid “shifting baseline syndrome.” This circumstance can occur when subsequent generations of collection stewards are unaware of the original item condition and recalibrate values based on its existing condition; this will result in a larger change in the item than originally prescribed (Brokerhof, pers. comm. 2021).

The concepts of collection lifetime and preservation target are sometimes criticized as overly static and pessimistic and placing in opposition the preservation of an item and its use (Henderson, Waller, and Hopes 2020). By focusing on risks related to unwanted material change induced by light exposure, insufficient consideration is given to the positive gain in cultural significance and collection value resulting from an item's public display (Taylor and Cassar 2008). However, this may be mitigated by intentionally coupling the iterative processes of defining the preservation target and reassessing collection value; this reflects more accurately the dynamic and symbiotic relationship between how items are valued, used, and cared for within the institution. By managing light risk of an object over successive preservation targets—that is, durations shorter than the targeted collection lifetime—one can readjust as needed the balance between short-, mid-, and long-term access to the collection. This methodology also strengthens decision-making accountability and allows for consistent evaluation of collection care.

Assessing Material Sensitivity to Light

Light sensitivity assessment has largely been based on information about different artists' materials available in the literature. However, with the development of MFT, object-specific information on sensitivity to light can now be obtained. Both methods result in the assignment of a Blue Wool equivalence (BWE) to the item. As discussed earlier, the BWE allows one to relate the light sensitivity of an item to a specific Blue Wool Standard and its associated JND dose. Once the BWE of the tested collection item is obtained, the next step of the risk management process is to deduce the light dose allocated to its preservation target.

Literature-Based Light Sensitivity Assessment

Light sensitivity has traditionally been assessed using color change data obtained by aging samples in accelerated aging chambers and published in the relevant literature. Numerous publications have provided general light level recommendations, such as 50 lux for objects especially sensitive to light and 200 lux for those more lightfast (Thomson 1978). Many of these publications also provide categories with the estimated light sensitivity of specific media and materials linked to BWE—with and without UV—and the approximate Mlux-hours needed to induce a JND (CIE 2004 [Technical Report 157]). Table 5.4 shows an example of color change information categorized by light sensitivity and BWE. It should be noted that while the text in table 5.4 is careful to state that "most" or "many" examples of a media type exhibit a particular light sensitivity, the practical application of these qualifiers is to assume that all examples of the said media type behave in a uniform manner.

Once the light sensitivity of a colorant and its BWE have been determined, it becomes possible to deduce the light dose allocated to the preservation target; this corresponds to the light dose assumed to induce a JND on the equivalent BW. Table 5.5 presents approximate light doses associated with BW1, 2, and 3. Those established by Michalski (1987) have been commonly used and represent averages based on a literature compilation of available data from light accelerated aging tests; it should be noted that "the uncertainty in each dose estimate ranges approximately to the estimates of the adjacent Blue Wool" (Michalski 2018). Table 5.6 illustrates how these traditional JND light doses are typically used in the conservation field to assess the duration and intensity of light exposure on an item (Michalski 2018). Some collection stewards have begun to use more conservative estimates of the JND light dose for BW1, 2, and 3, which are shown at right in table 5.5; these are based on unpublished studies of BW during mild light accelerated aging tests (less than 40,000 lux with UV excluded) carried out at the CCI (Tse, pers. comm. 2021). This difference in JND light doses for high-sensitivity BWs poses additional uncertainty for decision-making on lighting policy, particularly for BW1 whose revised light dose is reduced by 66% compared to the traditional light dose. While this should be the subject of further research, the use of either JND light dose supports a risk management approach to light.

TABLE 5.4 Materials grouped by light sensitivity (Michalski 2018).

No Sensitivity	Low Sensitivity	Medium Sensitivity	High Sensitivity
Materials that do not change colour due to light. (These materials may change colour due to ageing or pollutants.)	Materials rated ISO Blue Wool #7, #8 (and higher).	Materials rated ISO Blue Wool #4, #5, or #6.	Materials rated ISO Blue Wool #1, #2, or #3.
Most but not all mineral pigments. The "true fresco" palette, a coincidence with the need for stability in alkali. The colours of true glass enamels, ceramics (not to be confused with enamel paints). Many monochrome images on paper, such as carbon inks, but the tint of the paper and added tint to the carbon ink are often high sensitivity. Paper itself must be cautiously considered low sensitivity. Many high-quality modern pigments developed for exterior use, automobiles.	Artists palettes classified as "permanent" (a mix of truly permanent AND low-light sensitivity paints, e.g. ASTM D4303 Category I; Winsor and Newton AA). Structural colours in insects (if UV blocked). A few historic plant extracts, especially indigo on wool. Silver/gelatine black-and-white prints (not resin coated paper) assuming all UV blocked. Many high-quality modern pigments developed for exterior use, automobiles. Vermilion (blackens due to light).	Alizarin dyes and lakes. A few historic plant extracts, particularly madder-type reds containing primarily alizarin, as a dye on wool or as a lake pigment in all media. It varies throughout the range of medium and can reach into the low category, depending on concentration, substrate, and mordant. The colour of most furs and feathers. Most colour photographs with "chrome" in the name, e.g. Cibachrome, Kodachrome.	Most plant extracts, hence most historic bright dyes and lake pigments in all media: yellows, oranges, greens, purples, many reds, blues. Insect extracts, such as lac dye and cochineal (e.g. carmine) in all media. Most early synthetic colours such as the anilines, all media. Many cheap synthetic colourants in all media. Most felt tip pens including blacks. Most red and blue ballpoint inks. Most dyes used for tinting paper in the 20th century. Most colour photographs with "colour" (or "color") in the name. e.g. Kodacolour, Fujicolour.

TABLE 5.5 Estimated light doses (UV filtered) resulting in 1 JND for BW1, 2, and 3.

Blue Wool Standard	Traditional JND light dose (lux-hour, Michalski 1987)	Revised JND light dose (lux-hour; Tse, pers. comm., 2021)
BW1	300,000	100,000
BW2	900,000	600,000
BW3	3,000,000	2,400,000

TABLE 5.6 Estimated time to reach a JND based on illuminance and light sensitivity, assuming use of traditional JND light doses presented in table 5.5. Adapted from Michalski 2018.

	Approximate time to reach a JND (assuming display of 8 hours/day or 3000 hours/year)		
Illuminance (lux, no UV)	High Sensitivity BWE1 - 3	Medium Sensitivity BWE4 - 6	Low Sensitivity > BWE7
50	18 months–20 years	20–700 years	300–7000 years
150	6 months–7 years	7–200 years	100–2000 years
500	7.5 weeks–2 years	2–70 years	30–700 years

The main limitation of managing light risk based on published guidelines is the lack of accuracy when assessing the light sensitivity of a specific item. Absent scientific study, this method relies on a visual observation of the object surface to estimate the material composition of the artwork; this is required to assign a BWE using a resource similar to that in table 5.4. Even if the assessment of material composition is correct, the light sensitivity of an item depends on additional parameters including:

- Chemistry of the absorbing species
- If pigments and colorants are mixed with others and their respective concentrations
- Dye aggregation and particle size distribution
- Presence of metal ions or impurities
- Chemical and physical structure of the substrate
- Presence of glazing or coating
- Surface state
- Previous light exposure of the material (Saunders 2020)

Light sensitivity assessments that are not object specific are limited in their capacity to integrate the chemical complexity of the item surface and its past light exposure history. This can result in large uncertainty with respect to a BWE, which is most problematic for items with the highest light sensitivity.

Comparison of Literature- and MFT-Based Light Sensitivity Assessments

It is inevitable that one will encounter collection items whose lightfastness is either unknown or not widely published. Considering the numerous parameters that contribute to an object's lightfastness, even a wealth of published data on a medium or material may present significant uncertainty with respect to judging the light sensitivity of a specific object. However, it remains appropriate and necessary to consider and apply published guidelines and standards on lighting recommendations if that is the only available resource for assessing light sensitivity, as imperfect recommendations are preferred over conjecture.

In contrast, MFT presents an opportunity to reduce this uncertainty by the collection of object-specific data on light sensitivity. The following examples show the straightforward but significant difference between implementation of lighting policy with and without MFT. The first example focuses on ballpoint pen ink, which is representative of a medium type more commonly found in library and archival collections. The second example highlights watercolors, a medium that is familiar in museum or fine art collections. Both of the selected media are generally categorized in the literature as light sensitive.

Example 1: Ballpoint Pen Ink

Libraries, special collections, and archives contain a wealth of rare historical objects that are made accessible to the public. However, it would be a misconception to assume that the only access to these collections is reading rooms and digital formats. Increasingly, these materials are being used for physical exhibitions (Chen, Pickle, and Waldroup 2015). In 2010, the Association of Research Libraries (ARL) conducted a survey to determine the number of academic libraries actively mounting exhibitions; all but one of the seventy-nine respondents reported the development of exhibitions based on their collections, and a majority have a designated space within the library for this purpose (George 2010).

For conservators and collections managers, exhibiting these materials requires information on their lightfastness. Unfortunately, many of the media and materials found in archives are not well studied. These materials can be unfamiliar to conservators or considered "non-artistic" and, therefore, may not be included in published lightfastness categories. These types of materials can make up a significant part of an archive and, if exhibited, may be at risk of irreversible damage.

The ballpoint pen is a common and inexpensive writing implement used since the mid-1950s. The ink formulations used in ballpoint pens have varied through the years, resulting in unpredictable lightfastness (Ellis 1995). The inks discussed in this example were samples purchased and prepared in 2019 for a larger study on real-time color change of library and archival materials at the Getty Research Institute (GRI).

The four colored inks were removed from the pens and applied to an archival paper substrate and tested with a Whitmore MFT; as described in previous chapters, this instrument employs a xenon-arc light source and a noncontact 0/45 measurement geometry (i.e., light is introduced normal to the sample surface, and reflected light at an angle of 45° is collected by the spectrophotometer).

Figure 5.4 shows the BWEs assigned with and without the use of MFT. Represented are four ballpoint pen inks: red, purple, blue, and black. In the absence of MFT data, all inks have been assigned a BWE of less than BW1 (or more sensitive than BW1). As previously mentioned, light sensitivity assessments without the use of MFT are largely based on display recommendations from published sources, if available. In this case, there exist several published references to ballpoint pen ink and its sensitivity to light (it should be noted that none of these sources specifically address the lightfastness of the purple ballpoint pen ink).

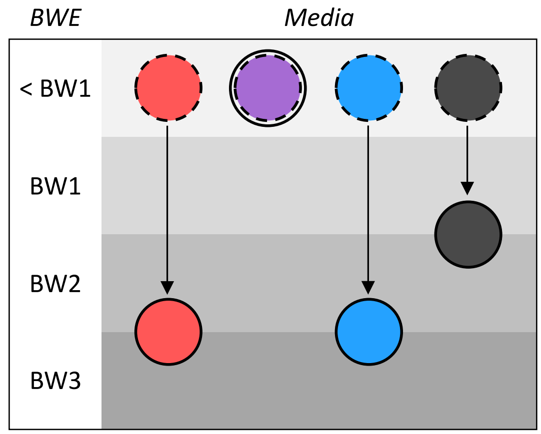


FIGURE 5.4 Blue Wool equivalence (BWE) for ballpoint pen ink based on published guidelines (dashed borders) and MFT data collected for these specific ink samples (solid borders). Note that published display recommendations were not available for the purple ink; thus, its BWE was assumed to be < BW1.

- The Library of Congress places these inks in the "Very light sensitive" category, with recommendations to "avoid display and limit use if possible" (www.loc.gov/preservation/care/light.html).
- The CCI warns that "most red and blue ballpoint inks" have a "high sensitivity" to light (this is the basis for the ballpoint ink recommendation in table 5.4). (www.canada.ca/en/conservation-institute/services/agents-deterioration/light.html).
- A published MFT study of black, red, and blue ballpoint pen inks by Ford (2018) demonstrates that the sensitivity of these inks can range widely from significantly more sensitive than BW1 to more lightfast than BW3.

If basing the light sensitivity assessment on these published sources and especially considering the 2018 work by Bruce Ford, the sensitivity of these four inks could vary considerably. In an effort to minimize risk, most conservators and collection managers would take a conservative position and assume all were potentially more sensitive than BW1. Even when MFT data is available for the media, the inks tested in the Ford (2018) study may not reflect the fugitivity of the specific inks in this example. Ford (2018, 31) concludes that without MFT, "the only safe general exposure recommendation is to not display important documents or works of art containing ballpoint pen inks, or, if so, for very short periods (weeks/exhibition rather than months)."

At the GRI, MFT analysis was conducted on the four inks, and figure 5.4 indicates how the BWEs have been reassigned based on these results. While all of the inks remain in the "High Sensitivity" category corresponding to BW1-3, three of the four inks were found to be more lightfast than BW1. The red and blue inks corresponded to a BWE of 2.5, while the black ink showed a BWE of 1.5. The purple ink was identified by MFT as corresponding to a BWE less than BW1. These results show that the purple ink merits a more conservative recommendation, while a more flexible approach to lighting can be taken with the less sensitive inks. The ability to go beyond the "High Sensitivity" category and refine the assignment of BWEs for specific inks allows the conservator to present options for access to the most lightfast material in the group rather than prevent access based on preconceived notions about a media type.

Example 2: Watercolors

The effect of light on watercolor paintings is well documented. George Field's *Chromatography*, published in 1885, warns about the effects of light on watercolors and includes a list of pigments affected by light exposure. This sparked a spirited debate about the exposure of watercolors in museums, which was followed in 1888 by a comprehensive investigation and report by Russell and Abney (Bromelle 1964). These events resulted in significant changes in the production and marketing of watercolors; manufacturers were now motivated to include information about the lightfastness of their pigments. The debate and experimental results helped establish the importance of a permanent palette and furthered the understanding of the fragility of watercolor paintings (Cohn 1977).

In recent years, numerous publications have discussed the impact of light on watercolors and posed recommendations for their display (e.g., Thomson 1986; CIE 2004; Michalski 2018). These resources assist collection care staff by alerting them to risks for potentially light-sensitive objects but assume that the medium is characterized accurately and its color change behavior is uniform. As seen in the previous example, display lighting decisions based on information from the literature may differ from those based on in situ light sensitivity assessments.

This example focuses on MFT analysis of four hand-colored woodblock prints prepared for a 2014 exhibition at the GRI. Based on its transparent appearance, the hand-coloring was assumed to be a watercolor; no other technical analysis was conducted on these objects. With each item comprising multiple colorants, the most sensitive colorant or site typically defines the overall BWE. Figure 5.5 shows the assigned BWE based on literature resources and MFT data collected for these objects.

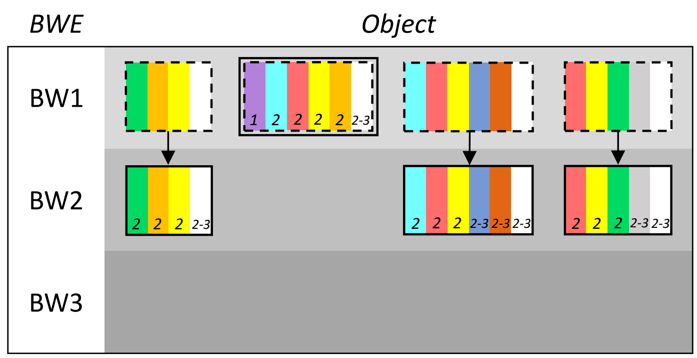


FIGURE 5.5 Blue Wool equivalence (BWE) for watercolors based on published guidelines (dashed borders) and MFT data collected for these specific hand-colored prints (solid borders). The colors in each group represent those present in each print, including the white paper substrate. The BWE as determined by MFT is shown for each color.

As previously mentioned, there are numerous sources that discuss the light sensitivity of watercolors, which may be relied on by conservators and institutions for their assessments.

- Thomson (1986) categorizes watercolors as "especially sensitive" to light and recommends a maximum illuminance of 50 lux.
- The Library of Congress categorizes watercolors as "very light sensitive" and recommends a maximum illuminance of 3 foot-candles (30 lux) (www.loc.gov/preservation/care/light.html).
- Ashley-Smith, Derbyshire, and Pretzel (2002) categorize watercolors as "sensitive," with an ISO BWE of 4 or below.
- Colby (1992) places watercolors in "Category 1, Sensitive," with an ISO BWE of 3 or lower.
- CIE Technical Report 157 (CIE 2004) categorizes watercolors as having "medium responsivity" to light with an ISO BWE between 4 and 6.

Considering these published sources, the degree to which watercolors are sensitive can be difficult to interpret. The inconsistency of the terms used to describe the categories and the broad assignment of BWE contribute to uncertainty when assessing the light sensitivity of watercolors. This variation in guidance ultimately results in conservators taking a precautionary position when making display recommendations; with this in mind, the watercolors in this example were assigned a BWE of BW1 (fig. 5.5).

MFT analysis of these objects was conducted at the GRI and showed that only one of the four hand-colored prints was as light sensitive as estimated (fig. 5.5). Of the sites tested with MFT, the purple watercolor indeed exhibited a BW1 equivalence; only one print contained this color. For the remaining three prints, the most sensitive colorants tested were the turquoise, red, orange, yellow, and green watercolors; each showed a BW2 equivalence. The blue, brown, and grey watercolors and the paper substrate had a BWE between BW2 and BW3. While these prints remain in the "High Sensitivity" category, the MFT results allow for a more flexible approach when negotiating access, particularly for those with BW2 and BW3 equivalences.

These two examples demonstrate the challenge of relying on the conservation literature to estimate object light sensitivity and the advantage conferred by the additional information provided by MFT. Given their broad scope, published guidance estimating the sensitivity of a material type will always have some uncertainty when relating to a specific object. The first example showed three of four inks that were determined by MFT to be more lightfast than estimated by the literature. The second example showed a similar result for watercolors, as well as the variability in light sensitivity that can occur within a single multicolored object. These disparities in light sensitivity assessments based on material-based recommendations and object-specific MFT analysis can unnecessarily restrict access to more lightfast collection materials while potentially contributing to the overexposure of the most light-sensitive items in collections.

Refining BWE for Highly Light-Sensitive Items

For conservators and collections managers, the uncertainty associated with literature-based light sensitivity assessments based on broad generalizations for specific media can result in lighting recommendations that limit flexibility. The consequences of this rigidity may be restricted access to collection items for exhibition or loan or lighting conditions and/or display durations that compromise the viewing experience. Collection stewards are aware that the objects in their collections do not respond uniformly to light; thus, it is rarely possible to group collection items into like material sensitivity categories without compromising the long-term preservation of a subset of the collection and unnecessarily reducing flexibility for others (Colby 1992).

MFT provides data that are specific to the surface of the object, allowing users to take into account its material complexity and exposure history. A primary function of MFT is to discriminate collection items that are light sensitive from those that are light stable (greater than BW3). Moreover, within the "High Sensitivity" category encompassed by BW1, 2, and 3, MFT allows for a more nuanced classification of light sensitivity and implementation of light mitigation strategies. This is an important step forward in the preventive conservation field as it significantly reduces the uncertainty associated with light sensitivity assessments (Ford and Druzik 2013), allowing one to focus on the management of light risk when most necessary (i.e., when an item' s BWE is less than BW3). In addition, the unique predictive capacity of the MFT provides collection stewards with data to support a prospective approach that mitigates light risk by identifying an object's light sensitivity and budgeting its light exposure over its targeted lifetime.

As previously discussed, once the BWE of the collection item is obtained by MFT or literature research, the next step in the process is to deduce the JND light dose associated with its preservation target. It should be emphasized that the color change at the object surface is expected to be just noticeable once the light dose allocated to the preservation target has been exhausted. At this point, the item should be in dark storage for the remainder of the duration set by the preservation target. When nearing the end of the preservation target, the item's value at risk to light should be reconsidered and a subsequent preservation target set accordingly.

Setting Priorities for Item Testing with MFT

MFT analysis can be a time-consuming endeavor, and it is unlikely that all collection items thought to be light sensitive will be tested. It is possible to extend the results obtained from MFT analysis of a specific collection item to other similar items in the collection. While time-efficient, this assumes a uniform response among this collection subset, which, as mentioned earlier, may not always be the case.

It is recommended that collection items be prioritized for examination by MFT. An efficient tiered approach would be to align MFT priorities with the highest categories of value at risk to light, which would aid in establishing manageable testing plans. Using the categories shown in table 5.2, the highest priority for MFT analysis would be objects in Category A, which encompasses items with high collection value and important or average roles of color information. The next priority for MFT analysis would be high-value objects from Category B, which is then followed by medium- and lower-value items in Categories B and C, respectively. If such a testing plan is implemented, the resulting number of items to be examined by MFT will be dependent on the anatomy (by materiality) and value distribution of the collection and the approach taken when establishing broad categories of value at risk to light.

While providing light sensitivity information that is specific to an object, MFT data are also associated with some uncertainty. As discussed in chapter 3 and in the report from the 2018 MFT Experts Meeting (Beltran 2019), potential issues involve reciprocity, Blue Wools, SPD, and unexpected color change behavior. When communicating with stakeholders about MFT, it is important that one carefully consider its various sources of uncertainty to ensure a rational interpretation of MFT data. This dialogue can be supported by subsequent in situ color change monitoring of objects previously analyzed by MFT when possible; this offers the opportunity to assess the accuracy of MFT results in comparison to the real-time change observed during exposure to gallery lighting.

Managing Light Risk Associated with Display

Assuming an appropriate level of collection care, gallery exhibitions offer institutions a means of promoting its collection and increasing its cultural value, as well as bolstering its reputation. However, exhibition of an object simultaneously subjects it to the deteriorating effects of light, resulting in cumulative and irreversible damage. This section discusses the consideration of light requirements and risks during the exhibition development process and presents examples of display recommendations for light-sensitive objects that offer flexibility in defining lighting scenarios to optimize the balance between short- and long-term access.

Displaying Collection Items

The amount of light exposure received by an item and its resulting light risk will vary significantly based on different collection item types and their frequency and mode of use. For example, though display practices regarding archival material have recently shifted toward increasing gallery display, most archival collection items will rarely be exposed to light and if they are, only for brief periods; physical access to archival materials, collected and preserved as historical sources and evidence, is often limited to study room appointments for scholars and researchers. In contrast, visual art collection items are expected to be on physical display in a gallery to offer sufficient access; as a result, such items will be exposed to light for extended durations. Collection managers recognize that the frequency of loan requests and/or selection for in-house or touring exhibitions varies significantly between collection items, often based on their cultural significance or collection value.

Physical display of a collection item in a gallery setting is a valuable means of access for viewers, as it provides the most direct and often richest experience. The preparation of an exhibition is commonly supported by art historical research by the curatorial team; this task develops the exhibition narrative and contributes to new interpretations that can further enrich the cultural significance of the item. This period also provides an opportunity for the conservator to deepen and refine their understanding of the selected items while preparing them for safe display. Exhibition publicity and any associated articles and catalogs benefit the valuation of the collection items selected for display and their importance within the collection.

Once a collection item has been selected for public display in a gallery, the exhibition design team develops and implements strategies to support the curatorial team's exhibition narrative, offer a rewarding experience of the item for visitors, and ensure its safe presentation. Satisfying access needs requires lighting conditions that allow the item on display to be visible by the audience such that its embodied meanings and values are properly conveyed and richly experienced.

Ensuring proper visibility of an item on display depends on the interplay of several parameters, including color, reflectance, and visual complexity. Ideally, the light level and quality are tailored to render the appearance of the item as intended by the artist; this supports the visual perception of subtleties in shape, texture, gloss, color, and contrast and enhances the curatorial interpretation and exhibition narrative. Further, the lighting exhibition design should be inclusive by accommodating the diversity of visual performance of its visitors and offer the flexibility to adjust light levels required for various visual tasks (e.g., special programs accompanying the exhibition, security lighting, gallery cleaning and maintenance).

Michalski (1997, 2018) proposed the following lighting adjustments to ensure optimum viewing of a collection item on display, though adoption of any of these must be balanced by preservation needs.

- A benchmark Illuminance of 50 lux allows a young viewer to distinguish color and details.
- To see details on a dark surface (i.e., with low reflectance), up to 3 times more light is required.
- Up to 3 times more light is required to see low-contrast details.
- Up to 3 times more light is required to perform complex time-limited tasks or see very fine details.
- Up to 3 times more light is required to accommodate older viewers, as they are likely to need more light than younger viewers to achieve a similar viewing experience.

While application of all the above adjustments would result in an illuminance of ~4,000 lux, the intention is to emphasize consideration of these individual factors for each lighting situation. Assuming sufficient adaptation, illumination at 250 lux will allow most visitors to see most object types reasonably well; at 500 lux, all but the very old will see objects well (Saunders 2020).

Saunders (2020) discusses various parameters involved in the selection of a light source for gallery display. These include dependence on the lighting technology available in an institution and the energy consumption and associated cost of exhibition lighting. Additional criteria are reductions in the carbon footprint and optimization of the SPD of gallery lighting to induce minimal damage and improve the visual experience;

the latter is a particularly important research topic in the museum lighting field and may be supported by advances in LED technology (Druzik and Michalski 2012; Garside et al. 2017; Padfield, Vandyke, and Carr 2013).

Formulating Display Recommendations

The physical display of an item in a gallery inherently places it at risk of light-induced damage. The primary strategy for mitigating this risk is to manage the light dose received by the item by formulating display recommendations that reduce the intensity and/or duration of exposure while maximizing and optimizing access.

The formulation of display recommendations provides an opportunity for collaboration among all stakeholders involved in collection item display and a better understanding of the risks related to light. Recommendations for display should include information on the light sources to be used during display (Garside et al. 2017). This may include obtaining the SPD of the lamp and quantification of its UV component, which is often presented in units of microwatt/lumen. Though atypical, a maximum damage index may be described for the light source. Additional strategies for mitigating light risk are limiting the level of oxidizing substances (i.e., pollution, oxygen) in the environment surrounding the object and lowering the temperature and/or relative humidity. Operational capacity and economic and ecological considerations will also play a role in the formulation of display recommendations (Saunders 2020).

Recommendations on the intensity of light and duration of exposure during display can be informed by budgeting the light dose allocated to the preservation target, which is based on the reciprocity principle. Light levels ranging from 50 to 250 lux typically assure satisfactory visibility of the item while on display, though lower levels may prove challenging for older visitors. Once a light level is chosen, a duration of exposure (hours) is multiplied by the light level to determine the resulting light dose (lux-hours or Mlux-hours); this is then compared to the preservation target light dose. In addition to public display, the exposure duration should account for all periods when the item is illuminated, including conservation treatment, research-based activities, reproduction, exhibition setup/removal, security and custodial activities, and special after-hours events in the gallery. It is important that the light dose received by each item during exhibition is recorded and the remainder of its preservation target light dose updated accordingly. Once the preservation target light dose is reached, the item should be kept in the dark for the remainder of the duration, after which a subsequent preservation target can be established.

The following section presents two examples of managing light risk based on the preservation target concept. While they differ in terms of the time frames considered, both approaches offer flexibility in selecting lighting scenarios for display. This allows the stakeholders involved in exhibition preparation to explore and negotiate appropriate options for balancing short- and long-term access. It should be noted that the effectiveness of these approaches increases with the accuracy of the BWE assessment and, to a lesser extent, the JND light dose.

Impact of Exhibition Lighting Scenarios

Applying the reciprocity principle, a range of gallery lighting scenarios may be proposed for an individual exhibition. These options can accommodate special visual requirements or short periods of increased lighting, assuming the light dose allocated to the preservation target is not exceeded. Table 5.7 presents various exhibition lighting scenarios and their expected impact on the future display of various collection items based on the preservation target light dose determined at the time of assessment. In this example, the three items were examined by MFT at the same time: the light sensitivity of items 1 and 2 corresponded to a BWE of BW1, while item 3 had a BW3 equivalence. Items 2 and 3 have remained in the dark since being examined by MFT, and their preservation target light doses are assumed to be 100,000 and 2,400,000 lux-hours, respectively (table 5.5). In contrast, following MFT analysis, item 1 has been on display, during which it received a light dose of 50,000 lux-hours; thus, the remainder of its *Preservation Target* light dose is limited to 50,000 lux-hours (100,000 minus 50,000 lux-hours).

TABLE 5.7 Assessing the impact of exhibition lighting scenarios on future object display. The column highlighted in green shows the remainder of each object's preservation target light dose for the given lighting scenario. Note that the BWE of each object was determined by MFT at the same time. *Following MFT analysis, item 1 was exhibited and exposed to a light dose of 50,000 lux-hours.

Exhibition Lighting Scenarios					Item Information			Impact on Future Display
Scenario	Hours of Exposure/ Week	Expected Light Level (lux)	Expected Exhibition Duration (weeks)	Expected Light Dose During Exhibition (10^3 lux-hrs/exh)	Item	BWE (determined by MFT)	Light Dose Allocated to PT (10^3 lux-hrs)	Remaining % of Light Dose Allocated to PT
A	54	50	24	64.8	1	1	50*	< 0% (Not Allowed)
					2	1	100	35%
					3	3	2400	97%
B	54	150	24	194.4	1	1	50*	< 0% (Not Allowed)
					2	1	100	< 0% (Not Allowed)
					3	3	2400	92%
C	54	150	6	48.6	1	1	50*	< 2% (After exhibition, remain in dark until end of PT)
					2	1	100	51%
					3	3	2400	98%

Table 5.7 shows several exhibition lighting scenarios that exhaust the remaining light dose allocated to the preservation target. Focusing on item 2, lighting scenario B results in an expected exhibition light dose of ~0.2 Mlux-hours (194,400 lux-hours), which exceeds the preservation target light dose of this item (0.1 Mlux-hours) and is thus not allowed. However, scenarios A and C pose alternative lighting options—scenario A lowers the intensity from 150 to 50 lux, and scenario C shortens the duration from 24 to 6 weeks—that reduce the exhibition light dose such that the current exhibition needs of item 2 may be satisfied while preserving the potential for its future display. Adoption of this approach during exhibition planning allows curators and exhibition managers to anticipate item rotations and explore alternative display options. An application of this approach is also shown in an MFT case study in appendix 4.

Formulating Long-Term Display Recommendations

Display recommendations can be formulated by budgeting the light dose allocated by the preservation target over extended periods. This provides flexibility by accommodating exhibition planning and long-term operational needs, including factors such as the number of light-driven changeovers expected for items selected for permanent in-house exhibition or items frequently requested for display or loan for traveling exhibitions with multiple venues.

Table 5.8 presents display recommendations (updated from Ford and Smith 2010, 2011) implemented at the National Museum of Australia (NMA). Described by Ford and Smith (2011), this is one of the first examples of the incorporation of MFT into an institution's existing lighting policy. This pragmatic approach allowed the NMA to address two concerns regarding their prior lighting policy: the order of magnitude difference in light sensitivity between BW1 and BW4 and the assumption that all objects are equally at risk at all times.

TABLE 5.8 Decadal lighting recommendations based on lightfastness and significance. The colored boxes represent levels of light damage risk, with red indicating the most vulnerable objects. Assumed are 3,000 hours of annual exposure (UV filtered) and BWEs based on use of ΔE^*_{00}. Courtesy of Bruce Ford, National Museum of Australia.

Blue Wool Equivalent (BWE)	1	1.5	2	2.5	3	3.5	4
Lightfastness (Mlux-hours/JND)	0.2	0.6	1.0	1.8	3.0	5.5	10.0
Light Level (lux)	Up to 50 lux		50 – 80 lux*		50 – 80 lux*		Lighting as Required*
Display High Significance	Individually Decided		2 Years/Decade		5 Years/Decade		Period of Exhibition
Display Normal Significance	Individually Decided (2 Years/Decade)		5 Years/Decade		Period of Exhibition		Period of Exhibition

**Minimum consistent with good display*

Prior to the adoption of MFT at the NMA, items presumed to be "sensitive" to light—from BW1 to BW4—were assigned a BW2 equivalence with suggested display at 50 lux for 2 years/decade or 10 years/50 years. The latter time frame aligns with an assumed preservation target of 1 JND per 50 years; it should be noted that the NMA has not developed consensus on a JND threshold or how long objects should last (Ford, pers. comm. 2021). By using MFT, the NMA has collected object-specific data that refine assessments in the "sensitive" category and "separates the fast from slow faders" (Ford, pers. comm. 2021). While some items were shown to be highly fugitive (~BW1 or less), the majority of NMA objects examined with MFT proved more lightfast than BW2, expanding options for their display and guiding rotation strategies.

Significance is a key component of the NMA display recommendations. This is related to the importance of color for an object and its collection value, with the latter including the cultural values embodied by an object, the availability of duplicates or alternatives, the history of exhibition and loans, and the projected significance of the object. The two categories of significance—high and normal—shown in table 5.8 may also correspond to varying degrees of value at risk to light. By taking into account the significance of individual objects, resources can be concentrated on protecting those items that are the most light sensitive and likely to be displayed.

Lighting recommendations for the most vulnerable objects, emphasized by the red regions in table 5.8, are to be "individually determined"; the lighting scenario approach described in table 5.7 represents one means of doing so. The suggested display of more lightfast objects is 2 years/decade (BW1.5–2.5 and high significance) and 5 years/decade (BW1.5–2.5 and normal significance; BW2.5–3.5 and high significance). However, implicit in any institutional lighting policy is the idea that guidelines may be revised in the future; this may be due to acceptance of a different tolerance for change (e.g., changing total loss threshold or collection value) or a more nuanced understanding of the accuracy associated with MFT (e.g., revised JND light doses for BW standards).

The NMA's development of lighting recommendations demonstrates how the management of light risk using the preservation target concept can be adapted to meet the specific needs of an institution and its collection. In addition to refining the museum's light sensitivity assessments using MFT and introducing a significance component, the selected intervals of 2 and 5 years aligned with "the NMA's existing exhibition durations and periodic light-driven changeover intervals," providing a level of familiarity and continuity for collection stewards (Ford, pers. comm. 2021).

Key Implementation Factors

Determining display recommendations by budgeting the light dose allocated to the preservation target permits one to design various lighting scenarios that can improve the viewing experience of an item and ensure its long-term preservation. While the efficacy of this light risk management method is improved by the incorporation of MFT, additional factors play a significant role in ensuring an effective implementation.

- Setting a preservation target for light exposure as a collaborative process involving relevant stakeholders across the institution. This decision-making process should be documented and recorded in the Collection Management System (CMS).
- Documentation of the preservation target and BWE of the collection item in a database, preferably in a searchable field in the CMS. If determined by MFT, the analysis report should be readily available. This information is useful when selecting items for exhibition display and highlights potential rotations or other needs associated with light sensitivity to be considered during the exhibition planning phase.
- All information associated with lighting should be recorded, including the measured light level during exhibition, the light source type with pertinent performance information (e.g., UV component, SPD), the calculated exposure light dose, and the cumulative light dose during display. When considering study room access, one may determine an average light dose during use and multiply it by the number of accepted consultation requests tracked in the system. Light exposure during nonpublic display should also be tracked and accounted for, including periods in lighted storage, conservation labs, and imaging studios.
- The percentage of the preservation target light dose used for each exhibition should be calculated, and its remainder carefully tracked. This bookkeeping exercise can be done manually or automatically in the CMS (fig. 5.6). Automated tracking of light dose within the CMS may allow for warning indicators when 90% of the light dose allocated to the preservation target has been reached.
- Once the preservation target light dose is exhausted, the item should be kept in the dark until the end of the duration set for the preservation target.
- Once the duration of the preservation target has been reached, the item's collection value can be reassessed and adjusted if necessary and as regulated by institutional policies; the subsequent preservation target is set based on a reassessment of the item's value at risk to light.

Object Information	*Inventory Number*	2014_321	Assigned at acquisition		
	Collection Value Ranking	High	Assigned at acquisition		
	Role of Color Information	Lower	Assigned at acquisition		
	Category of Value at Risk to Light	C			
	Targeted Lifetime (years)	500			
	Preservation Target (PT, years)	50			
	Assessed Blue Wool Equivalence (BWE)	2	MFT, June 2015 (see report)		
	Light Dose Allocated to PT (lux-hours)	600,200	Through 2064		
	Light Dose/Decade (lux-hours)	60,000	Through 2024		
Object Use	*Description*	*Light Source*	*Dates*	*Light Dose (lux-hours)*	*% of Light Dose Allocated to PT Already Used*
	Photo Lab - Reproduction	MR16	May 1 2014	6,000	0.8
	In House Exhibition - Lalala	MR16	Jan 1 2015 - Jul 1 2015	64,800	12
	In House Exhibition - Lelele	LED Warm	Jan 1 2017 - Apr 1 2017	32,400	17
	Conservation Lab - Treatment	UV Filtered Daylight	May 4 2018 - May 25 2018	10,000	19
	Touring Exhibition (Loan) - Lilili	LED Warm	Venue 1: Jan 1 2019 - Apr 1 2019	32,400	24
		LED Warm	Venue 2: May 1 2019 - Aug 1 2019	32,400	30
Tracking Light Dose	*Light Dose Since Acquisition (lux-hours)*	178,000			
	Light Dose Received in Current PT (lux-hours)	178,000			
	% of Remaining Light Dose Allocated to PT	71%			

FIGURE 5.6 Automated tracking of cumulative light dose received and percentage of remaining light dose allocated *to* current preservation target.

Conclusion

The process of determining lighting recommendations for collection items is complicated by the numerous aesthetic and preservation variables at play. This chapter suggests a framework for considering and documenting these decisions, in which MFT can play an important role. Assessing the light sensitivity of valuable collection items with MFT can allow for a more prospective approach and added confidence in decision-making regarding the management of light risk and object access. MFT assessment may be prioritized for items of high value (especially when color plays an important role) and identified as likely to be vulnerable to light (e.g., in pristine condition, lacking information on light sensitivity, suspected to be light sensitive, potentially subject to high light levels).

The following is a summary, first introduced in figure 5.1, of the process of formulating display recommendations for a collection item or collection subset vulnerable to light. Similar to this document's description of MFT practice, the motivation for this decision-making framework is not to present a "single, ideal path" but to describe the basis for variations in method. It should be reiterated that some of the individual steps in this framework may not apply to all situations, and the specific context of each institution and collection should be considered.

Assessing Value at Risk to Light

- Determine the collection value of the item and define how long the item is expected to continue to be meaningful and useable (i.e., targeted collection lifetime). Evaluate the role of color information, focusing on items with high collection value and assessing the acceptable color change threshold corresponding to its almost total loss.
- Determine the category of value at risk to light of the item.
- Document the decision-making process and planned reassessments.

Quantifying Light Risk

- Deduce the preservation target in terms of a time frame for reaching a JND or the number of accepted JNDs within a given time frame, using relevant categorization systems of value at risk to light.
- Assess the light sensitivity of the item by MFT or through literature research.
- Record the selected preservation target and light sensitivity assessments in the collection database.
- Once the preservation target is exhausted, reassess the collection value and value at risk to light and set the duration for the subsequent preservation target accordingly.

Managing Light Risk

- Deduce the light dose allocated to the preservation target by considering the targeted collection lifetime and the categorization of value at risk to light.
- Formulate display recommendations for a chosen time frame (e.g., exhibition, annual, decadal) by (a) evaluating the benefit to collection value against the associated risks of light exposure, (b) assessing the light level required to ensure satisfactory visibility of the item, and (c) deducing the duration of exposure (which cannot exceed the remainder of the preservation target).
- Record the light dose received by the object during exhibition (including from other uses involving light exposure), record the relevant performance information of the light source, and monitor the remaining percentage of the preservation target display life.

- Once the light dose allocated to the preservation target is exhausted, keep the collection item in the dark until the end of the preservation target.
- Revise recommendations as needed; whenever possible, assess the in situ color change of the item and compare to the change predicted by MFT.

References

Ankersmit, Bart, and Marc H. L. Stappers. 2017. *Managing Indoor Climate Risks in Museums*. Cham: Springer International.

Ashley-Smith, Jonathan. 2013. "Deliverable 4.2: Report on Damage Functions in Relation to Climate Change." www.climateforculture.eu/index.php?inhalt=furtherresources.projectresults; accessed December 1, 2020.

Ashley-Smith, Jonathan, Alan Derbyshire, and Boris Pretzel. 2002. "The Continuing Development of a Practical Lighting Policy for Works of Art on Paper and Other Object Types at the Victoria and Albert Museum." In *ICOM-CC 13th Triennial meeting, Rio de Janeiro, 22–27 September 2002: Preprints*. London: James & James.

Australia ICOMOS International Council on Monuments and Sites. 2013. *The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance.*

Avrami, Erica, Susan MacDonald, Randall Mason, and David Myers, eds. 2019. *Values in Heritage Management: Emerging Approaches and Research Directions*. Los Angeles: Getty Conservation Institute. www.getty.edu/publications/resources/virtuallibrary/9781606066195.pdf.

Barro, Lisa, Katherine Sanderson, Silvia A. Centeno, and Beth Saunders. 2020. "The Exhibition and Characterization of Seven Salted Paper Prints." *JAIC* 59 (3–4): 171–85.

Beltran, Vincent Laudato. 2019. "Advancing Microfading Tester Practice: A Report from an Experts Meeting Organized by the Getty Conservation Institute, March 13–15, 2018." Getty Conservation Institute, Los Angeles.

Berns, Roy S. 2016. *Color Science for the Visual Arts: A Guide for Conservators, Curators, and the Curious*. Los Angeles: Getty Conservation Institute.

Brokerhof, Agnes W., Janien Kemp, and Anna E. Bülow. 2017. "Value Management Scan: Setting Priorities in Management and Care of Collections." In *ICOM-CC 18th Triennial Conference Preprints, Copenhagen, 4–8 September 2017,* ed. Janet Bridgland, art. 1306. Paris: International Council of Museums.

Brokerhof, A., B. Ankersmit, and Frank Ligterink. 2017. *Risk Management for Collections*. Amsterdam: Cultural Heritage Agency of the Netherlands

Bromelle, N. S. 1964. "The Russell and Abney Report on the Action of Light on Watercolors." *Studies in Conservation* 9: 140–52.

Bülow, Anna E. 2010. "Collection Management Using Preservation Risk Assessment." *Journal of the Institute of Conservation* 33 (1): 65–78.

Canadian Conservation Institute (CCI). 2017. "Agents of Deterioration." Government of Canada. www.canada.ca/en/conservation-institute/services/agents-deterioration.html.

Chen, Amy H., Sarah Pickle, and Heather L. Waldroup. 2015. "Changing and Expanding Libraries: Exhibitions, Institutional Repositories, and the Future of Academia." Council on Library and Information Resources.

Cohn, Majorie B. 1977. *Wash and Gouache: A Study of the Development of the Materials of Watercolor.* Cambridge, MA: Center for Conservation and Technical Studies, Fogg Art Museum.

Colby, Karen M. 1992. "A Suggested Exhibition Policy for Works of Art on Paper." *Journal of the International Institute for Conservation—The Canadian Group* 17: 3–11.

Crawford, B. H. 1973. "Just Perceptible Colour Differences in Relation to Level of Illumination." *Studies in Conservation* 18 (4): 159–66.

del Hoyo-Meléndez, Julio M., Pawel Świt, and Joanna Sobczyk. 2017. "Measuring Photostability through Glass: The Application of Microfading Spectrometry to the Study of Framed Pastel Artworks." *Coloration Technology* 134 (6): 411–22.

Druzik, James R., and Stefan W. Michalski. 2012. *Solid-State Lighting for Museum*. Ottawa and Los Angeles: Canadian Conservation Institute and Getty Conservation Institute.

Ellis, Margaret Holben. 1995. *The Care of Prints and Drawings*. Lanham: Rowman & Littlefield.

Fenech, Ann, Catherine Dillon, Konstantinos Ntanos, Nancy Bell, Mark Barrett, and Matija Strlič. 2013. "Modelling the Lifetime of Colour Photographs in Archival Collections." *Studies in Conservation* 58 (2): 107–116.

Ford, Bruce. 2018. A microfading survey of the lightfastness of blue, black and red ballpoint pen inks in ambient and modified environments. *AICCM Bulletin*, 39:1, 26-34, DOI:10.1080/10344233.2018.1515809

Ford, Bruce, and Jim Druzik. 2013. "Microfading: The State of the Art for Natural History Collections." *Collection Forum* 27 (1): 54–71.

Ford, Bruce, and Nicola Smith. 2010. "Protecting the Most Important, Most Exhibited and Most Fugitive Museum Objects from Light-Fading." *Textile Specialty Group Postprints* 20: 157–86.

______. 2011. "The Development of a Significance and Risk Based Lighting Framework at the National Museum of Australia." *AICCM Bulletin* 32: 80–86.

Garside, Daniel, Katherine Curran, Capucine Korenberg, Lindsay MacDonald, Kees Teunissen, and Stuart Robson. 2017. "How Is Museum Lighting Selected? An Insight into Current Practice in a UK Museum." *Journal of the Institute of Conservation* 40 (1): 3–14.

Geldof, Muriel, Art Ness Proaño Gaibor, Frank Ligterink, Ella Hendriks, and Eric Kirchner. 2018. "Reconstructing Van Gogh's Palette to Determine the Optical Characteristics of His Paints." *Heritage Science* 6 (17). ttps://doi.org/10.1186/s40494-018-0181-6.

George, Lee Anne, ed. 2010. *SPEC Kit 317: Special Collections Engagement*. Washington, DC: Association of Research Libraries

Häyhä, Heikki, Sari Jantunen, and Leena Paaskoski. 2015. *Analysing Significance*. Publications of Finnish Museums Association No. 75. www.museoliitto.fi/doc/verkkojulkaisut/AnalysingSignificance.pdf.

Henderson, Jane, Robert Waller, and David Hopes. 2020. "Begin with Benefits: Reducing Bias in Conservation Decision-Making." *Studies in Conservation*. https://doi.org/10.1080/00393630.2020.1787638.

Hendriks, Ella, Agnes W. Brokerhof, and Kees van den Meiracker. 2017. "Valuing Van Gogh's Colours: From the Past to the Future." In *ICOM-CC 18th Triennial Conference Preprints, Copenhagen, 4–8 September 2017*, ed. Janet Bridgland, art. 1306. Paris: International Council of Museums.

ICOMOS. 1994. *Nara Conference on Authenticity in Relation to the World Heritage Convention, Nara, Japan, 1–6 November 1994*.

International Commission on Illumination (CIE). 2004. *Control of Damage to Museum Objects by Optical Radiation*. Technical Report 157. Vienna, Austria: CIE.

Keene, Suzanne. [1966] 2002. *Managing Conservation in Museums*. London: Routledge.

Lafontaine, Raymond H. 1980. "The Lightfastness of Felt-Tip Pens." *Journal of the International Institute for Conservation—Canadian Group* 4: 9–16.

Library of Congress. Collections Care: "'Which Things Are Most Sensitive to Light?' (and display recommendations)." www.loc.gov/preservation/care/light.html.

Lithgow, Katy. 2011. "Sustainable Decision Making: Change in National Trust Collections Conservation." *Journal of the Institute of Conservation* 34 (1): 128–42. DOI:10.1080/19455224.2011.582457.

Cultural Heritage Agency. 2014. "Assessing Museum Collections: Collection Valuation in Six Steps." Cultural Heritage Agency of the Netherlands, Amersfoort. https://english.cultureelerfgoed.nl/publications/publications/2014/01/01/assessing-museum-collections; accessed December 12, 2020.

Michalski, Stefan. 1987. "Damage to Museum Objects by Visible Radiation (Light) and Ultraviolet Radiation (UV)." In *Lighting in Museums, Galleries and Historic Houses*, 3–16. London: Museums Association, UKIC, and Group of Designers and Interpreters for Museums.

———. 1997. "The Lighting Decision." In *Fabric of an Exhibition, Preprints of Textile Symposium 97*, 97–104. Ottawa: Canadian Conservation Institute.

———. 2018. "Agent of Deterioration: Light, Ultraviolet and Infrared." Government of Canada. www.canada.ca/en/conservation-institute/services/agents-deterioration/light.html; accessed February 17, 2021.

Morris, Hannah R., and Paul M. Whitmore. 2007. "Virtual Fading of Art Objects: Simulating the Future Fading of Artifacts by Visualizing Micro-Fading Test Results." *JAIC* 46 (3): 215–28.

Padfield, Joseph, Steve Vandyke, and Dawson Carr. 2013. "Improving Our Environment." www.nationalgallery.org.uk/paintings/research/improving-our-environment; accessed December 21, 2020.

Pesme, Christel. 2016. *ExPres: Exhibiting while Preserving—Development of an App. Allowing Visualization of the Digitally Simulated Effects of Light on Artwork Appearance*. ICOM-CC PMWG, Amsterdam.

Pye, Elizabeth. 2016. "Challenges of Conservation: Working Objects." *Science Museum Group Journal* 6. Available at http://journal.sciencemuseum.ac.uk/browse/issue-06/challenges-of-conservation/.

Reed, Caroline. 2018. "Reviewing Significance 3.0: A Framework for Assessing Museum, Archive and Library Collections' Significance, Management and Use." The Collections Trust. Available at https://collectionstrust.org.uk/wp-content/uploads/2018/01/RevSig3-Introduction-1.pdf; accessed December 18, 2020.

Reuss, Margrit, Graeme Scott, and Fiona MacKinnon. 2005. "Conservation of Exhibition: Making a Maintenance Programme Work." In *Preprints of ICOM-CC 14th Triennial Conference, The Hague*, vol. 2, ed. Janet Bridgland, 693–99.

Richardson, Clare, and David Saunders. 2007. "Acceptable Light Damage: A Preliminary Investigation." *Studies in Conservation* 52 (3): 177–87.

Rubio, Fernando Domínguez. 2020. *Still Life: Ecologies of the Modern Imagination at the Art Museum*. Chicago: University of Chicago Press.

Russell, Roslyn, and Kylie Winkworth. 2009. "Significance 2.0: A Guide to Assessing the Significance of Collections." Collections Council of Australia Ltd. www.arts.gov.au/sites/g/files/net1761/f/significance-2.0.pdf; accessed December 2020.

Saunders, David. 2020. *Museum Lighting: A Guide for Conservators and Curators*. Los Angeles: J. Paul Getty Trust.

Strlič, Matija, David Thickett, Joel Taylor, and May Cassar. 2013. «Damage functions in heritage science." *Studies In Conservation* 58 (2): 80–87.

Taylor, Joel, and May Cassar. 2008. "Representation and Intervention: The Symbiotic Relationship of Conservation and Value." In *Conservation and Access: Contributions to the London Congress, 15th–19th September 2008*, 7–11. London: IIC.

Thomson, Garry. 1986. *The Museum Environment*. 2nd ed. London: Butterworth-Heinemann.

Tse, Season. 2019. "Microfade Testing for Heritage Institutions: A Canadian Experience." *Studies in Conservation* 64 (6): 337–51. DOI: 10.1080/00393630.2018.1527984.

6. CONCLUSION

From its first mention in a September 21, 1994, lab book entry by conservation scientist Paul Whitmore (Druzik 2010) to its current use at over seventy cultural heritage institutions around the world, the origin and evolution of the microfading tester has been unique. While other common scientific techniques in cultural heritage were transferred from broader external fields of study with robust technical and didactic support, MFT emerged from within the cultural heritage field as an innovative means of investigating in situ light sensitivity and managing light risk. Though commercially produced instruments and kits are available (primarily from Newport Oriel and Instytut Fotonowy), the small market share of MFT has limited the typical breadth of support observed for other scientific techniques employed across multiple disciplines. As a consequence, it is incumbent on the cultural heritage field itself to provide the necessary support to cultivate and expand use of the technique. This document represents a contribution to this effort, seeking to establish a baseline of knowledge about MFT.

Light plays an integral role in facilitating access to a collection item while simultaneously acting as an agent of deterioration. Determining the balance between access to and protection of an object and/or collection has been a significant focus of lighting policy discussions. Lighting decisions have previously relied on light sensitivity assessments using mockup samples and/or color comparisons of objects before and after display; this information is integrated in published guidance on the light sensitivity of various classes of artists' materials. However, these approaches may not produce data that are representative of an item's specific material composition and display history. MFT addresses this issue by providing a means of assessing the light sensitivity of an object.

MFT exposes the object surface to an intense and focused light spot and monitors the resulting visually imperceptible change. The color change behavior of the item is then compared to that of ISO Blue Wool Standards, allowing one to categorize objects by their light sensitivity and mitigate the risk associated with light exposure. Most commonly employed as a lightfastness screening tool, MFT offers important information to the exhibition development team when choosing an object for display, as one may opt for a more robust object or facsimile if it fulfills a similar curatorial need. The potential that some items may be more lightfast than previously thought can also present significant financial and time savings by reducing the need for precautionary object rotations. For items identified by MFT as highly light sensitive but deemed necessary for inclusion in an exhibition, this offers an opportunity to delineate an evidence-based lighting policy that considers short- and long-term display needs, object significance, and the potential loss of value due to color change. Thus, MFT can support sustainable practice by allowing an institution to focus its resources on the objects most in need.

While MFT reduces the uncertainty regarding the light sensitivity of specific objects, this should also be considered within the uncertainty associated with lighting policy decisions. Once the MFT results are used to align the color change behavior of an object with Blue Wool (BW) 1, 2, or 3, a light dose associated with a just noticeable difference (JND) of that BW is used to scaffold lighting decisions. However, as shown in chapter 5, there exists a range of light doses thought to incur a JND for these BWs. In addition, the increasing use of LEDs instead of broadband xenon-arc light sources for MFT poses concern regarding the impact of different spectral power distributions on the resulting MFT data. With the increasing accessibility of hand-held color monitoring instruments, there is an opportunity to compare real-time color change of objects during gallery conditions to the predictions made by MFT; such case studies will continue to establish the reliability of the technique and prompt collective research if the in situ and predicted color change diverge. Despite these uncertainties (which will likely be a focus of research in the near future), MFT continues to be an important light sensitivity assessment technique and risk management tool as it provides crucial data on which the discussion of lighting policy hinges. As summarized by conservation scientist Bruce Ford, "Uncertain data is better than none. With data, everything becomes negotiable" (pers. comm. 2020).

In addition to its role in assessing lightfastness to inform display decisions, MFT can be employed in a research capacity to examine color change behavior for different classes of artists' materials exposed to a range of environmental conditions. This work can be conducted on bespoke sample sets or mine "big data" from the voluminous MFT analyses of different objects conducted in the field; the latter can take advantage of MFT databases developed by institutions such as the Canadian Conservation Institute and the Getty Conservation Institute. Such efforts have the potential to refine existing guidance on the light sensitivity of different material classes that may benefit collections without access to MFT.

It is hoped that this document can further the development of a self-sustaining MFT user community. The MFT Institution Directory (appendix 1) may be helpful in this regard, promoting regional networks of MFT expertise that can offer guidance to prospective, new, and expert users. From this rich dialogue could emerge a demand for hands-on and virtual training workshops for conservators and scientists, sessions or meetings focused on MFT that might also extend to collection managers, and research that further defines the technique's boundaries. Accessibility to MFT should also be considered, as not all institutions or private collectors will have the staff, budget, and/or demand to acquire an instrument; this could be addressed by supporting MFT use at regional conservation centers and by key private conservators or conservation scientists, the inclusion of MFT in mobile conservation science laboratories, and the allotment of MFT time by larger cultural heritage institutions to small and mid-size museums and private conservators.

References

Druzik, Jim. 2010. "Oriel Microfading Tester (MFT): A Brief Description." In *Textile Specialty Group Postprints, vol. 20, AIC Annual Meeting, Milwaukee, WI, 11–14 May 2010*. Washington, DC: AIC.

Appendix 1
Microfading Tester Institution Directory

This directory is part of the Getty Conservation Institute's collaborative efforts to advance microfading tester practice in the cultural heritage field. It seeks to identify MFT practitioners around the world (fig. A1.1), in the hope of developing regional networks of expertise to support prospective, new, and expert users. Listings are grouped by region and country and include institution, city, and MFT type.

Five MFT types are distinguished:

- *Whitmore MFT*: based on original design by Paul Whitmore
- *Retroreflective MFT*: employs noncontact measurement head in which light from lamp and reflected light to spectrometer travel on same path
- *Automated MFT*: design that automates operation
- *Contact MFT*: employs measurement head that touches sample surface
- *Custom MFT*: design based on general MFT principles

FIGURE A1.1.
Map of MFT locations (hollow circles indicate multiple institutions with MFT). Map by Savannah Novencido.

ASIA AND OCEANIA

Australia
National Museum of Australia, Bruce Ford (Canberra)
Whitmore MFT

Museums Victoria (Melbourne)
Whitmore MFT

China
Beijing Jiayuanwenbo Technology Limited (Beijing)
Automated MFT

M+ (Hong Kong S.A.R.)
Whitmore MFT

New Zealand
Auckland War Memorial Museum (Auckland)
Whitmore MFT

Unversity of Otago (Dunedin)
Whitmore MFT

Qatar
Qatar National Library (Doha)
Automated MFT

Singapore
Heritage Conservation Centre, an institution of the National Heritage Board (Jurong)
Whitmore MFT

Taiwan
National Taiwan Museum of Fine Arts (Taichung)
Automated

EUROPE AND UNITED KINGDOM

Austria
Landessammlungen Niederösterreich (St. Pölten, NÖ)
Automated MFT

Renee Riedler
Custom Contact MFT

Czech Republic
National Library of the Czech Republic (Prague)
Whitmore MFT

Denmark
Det Kongelige Bibliotek (Royal Danish Library) (Copenhagen)
Whitmore MFT

Bevaringscenter Fyn (Conservation Center Funen) at Langelands Museum (Rudkøbing)
Automated MFT

Conservation Center Vejle/Odense City Museum (Vejle/Odense)
Automated MFT

France
Centre de Recherche et de Restauration des Musées de France (Paris)
Contact MFT

Centre de Recherche sur la Conservation / CNRS - Muséum national d'Histoire naturelle - Ministère de la Culture (Paris)
Whitmore MFT, Automated MFT

Musée du quai Branly - Jacques Chirac (Paris)
Contact MFT

Germany
Christel Pesme (Berlin)
Custom Contact MFT

Rathgen-Forschungslabor, Staatliche Museen zu Berlin - Preußischer Kulturbesitz (Berlin)
Whitmore MFT

Staaliche Akademie der Bildenden Künste Stuttgart / Laboratory for Archaeometry and Conservation Science (Stuttgart)
Automated MFT

University of Fine Arts, Dresden (Dresden)
Whitmore MFT

Netherlands
Cultural Heritage Agency of the Netherlands (Amsterdam)
Custom MFT

Norway
National Library of Norway (Oslo)
Automated MFT

National Museum (Oslo)
Automated MFT

Poland
AGH University of Science and Technology (Krakow)
Automated MFT

National Museum in Krakow (Krakow)
Whitmore MFT, Custom MFT

Muzeum Śląskie w Katowicach (Silesian Museum in Katowice) (Katowice)
Automated MFT

The Inter-Academy Institute of Conservation and Restoration of Works of Art (Warsaw)
Automated MFT

Slovenia
Heritage Science Lab Ljubljana/
University of Ljubljana (Ljubljana)
Automated MFT

Sweden
Jacob Thomas (Gothenburg)
Retroreflective MFT, Automated MFT, Transmission MFT

Nationalmuseum (Stockholm)
Automated MFT

Riksantikvarieämbetet (The Swedish National Heritage Board) (Visby)
Retroreflective MFT

Switzerland
Kunstmuseum Basel (Basel)
Automated MFT

Swiss National Library (Bern)
Automated MFT

Museum zu Allerheiligen Schaffhausen (Schaffhausen)
MFT Forthcoming

United Kingdom
British Museum (London, England)
Whitmore MFT, Automated MFT

National Archives (London, England)
Retroreflective MFT

Tate Gallery (London, England)
Custom MFT

University College London, Institute for Sustainable Heritage (London, England)
Retroreflective MFT

Nottingham Trent University (Nottingham, England)
Automated Retroreflective MFT, Custom MFT

Science Museum Group, National Collections Centre (Swindon, England)
Automated MFT

National Galleries Scotland (Edinburgh, Scotland)
Whitmore MFT

NORTH AMERICA

Canada
Canadian Conservation Institute (Ottawa)
Whitmore MFT

United States
California

Academy Museum of Motion Pictures (Los Angeles)
Automated MFT

Getty Conservation Institute/Getty Research Institute (Los Angeles)
Whitmore MFT, Contact MFT, Automated MFT

Los Angeles County Museum of Art (Los Angeles)
Contact Whitmore MFT

Colorado

Clyfford Still Museum (Denver)
Automated MFT, Retroreflective MFT

Connecticut

Institute for the Preservation of Cultural Heritage, Yale University (New Haven)
Whitmore MFT

Delaware

Winterthur/University of Delaware (Winterthur)
Whitmore MFT

Illinois

Art Institute of Chicago (Chicago)
Automated MFT

Field Museum (Chicago)
Retroreflective MFT

Indiana

Indianapolis Museum of Art at Newfields (Indianapolis)
Whitmore MFT

Massachusetts

Museum of Fine Arts, Boston (Boston)
Whitmore MFT

Straus Center, Harvard Art Museums (Cambridge)
Whitmore MFT

New Mexico

Georgia O'Keeffe Museum (Santa Fe)
Whitmore MFT

New York

Buffalo State (Buffalo)
Whitmore MFT

Metropolitan Museum of Art (New York)
Whitmore MFT

The Museum of Modern Art (New York)
Automated MFT

New York Public Library (New York)
Whitmore MFT

Whitney Museum of American Art (New York)
Retroreflective MFT

Oklahoma

Gilcrease Museum (Tulsa)
Automated MFT

Pennsylvania

Philadelphia Museum of Art (Philadelphia)
Automated MFT

Texas

Menil Collection/Museum of Fine Arts (Houston)
Whitmore MFT

Virginia

Virginia Museum of Fine Arts (Richmond)
Whitmore MFT

The Colonial Williamsburg Foundation (Williamsburg)
Whitmore MFT

Washington

Seattle Art Museum (Seattle)
Automated MFT

Washington, DC/Maryland

National Archives and Records Administration (College Park, MD)
Whitmore MFT

Museum Conservation Institute, Smithsonian (Suitland, MD)
Whitmore MFT

Hirshhorn Museum and Sculpture Garden (Washington, DC)
Whitmore MFT

Library of Congress Preservation Research and Testing Division (Washington, DC)
Whitmore MFT, Automated MFT

National Gallery of Art (Washington, DC)
Whitmore MFT

United States Holocaust Memorial Museum (Washington, DC)
Retroreflective MFT

Appendix 2
Glossary

0/45 Geometry Reference to the alignment geometry of the illumination and collection beams, with 0° indicating that light (from a xenon-arc or LED source) is arriving perpendicular or normal to the sample surface and 45° denoting the angle (from normal) at which diffuse reflected light from the surface is collected by the spectrophotometer.

Almost Total Fade Concept defining the threshold after which a colored sample has lost most of its color. For saturated colors, this roughly corresponds to 30 JNDs, though this may occur at lower thresholds for paler colors and items with low contrast.

Automated MFT An MFT type that automates various steps in the MFT process, including alignment of the illumination and collection spots, opening and closing of the shutter, and initiation of spectral data collection and resetting the ΔE value in the spectrophotometer software. Such an instrument has been developed by Instytut Fotonowy.

Background or Dark Calibration A calibration step defining the 0% reflectance signal for the spectrophotometer. This can be subtracted from the collected data, removing unrelated background signals.

Bifurcated Fiber Optic A Y-shaped assembly consisting of two fiber optics. Bifurcated cables can be employed with contact or retroreflective MFT probes, with the single ends attached to the light source and spectrophotometer and the joined end connected to the probe.

Blue Wool Equivalence Categorization of light sensitivity of a sample during accelerated aging tests based on the color change behavior of Blue Wool Standards. Given concerns about reciprocity breakdown, this method provides a means of bridging the results produced during high-intensity MFT light exposure and the expected behavior of the material while on gallery display.

Blue Wool Standard (ISO) An ISO standard for lightfastness consisting of eight dyed wools of increasing stability, with Blue Wool (BW) 1 being the most fugitive and BW8 the most lightfast. The wool sample with the higher number reference is approximately twice as resistant to light-induced color change as the preceding reference. The three most sensitive swatches—BW1, 2, and 3—are thought to represent high light sensitivity colorants. Note that BWs can be presented as loose weaves or mounted on a card.

CIE Acronym for the Commission International de l'Eclairage (International Commission on Illumination), which is a nonprofit organization whose objective is to provide an international forum for all matters relating to the science, technology, and art of color and light. The CIE provides recommendations and standards for colorimetry, illumination, and photometry.

Collection Lifetime The length of time (in years) for which a collection item continues to be meaningful and usable, corresponding to its "serviceable life" in the collection. This decision is driven by material, ethical, and resource considerations for each institution and collection type. As a general rule, the higher the cultural significance, the longer the collection lifetime. The term "museum lifetime" is interchangeable with collection lifetime, but the latter is used in this document because it is a more inclusive term.

Collection Value A working concept based on an item's cultural significance, its relative importance in the collection, and its expected usability. Collection value is defined by the institution and will likely influence decisions regarding an item's interpretation, use, and care. Since it can vary with changes in communities, culture, politics, science, and the environment, an item's collection value should be regularly reassessed and updated.

Color Difference (CIE) The calculated distance between two points in CIELAB color space. The initial color difference calculation introduced by the CIE in 1976, denoted as ΔE^*_{ab}, was defined as the Euclidian or straight-line distance between two points. Subsequent refinements of the calculation were introduced in 1994 (ΔE^*_{94}) and 2000 (ΔE^*_{00}) to address issues of perceptual nonuniformity in CIELAB space, with the latter considered most accurate.

Color Difference Threshold The predetermined color difference, or ΔE value, at which exposure of the sample surface to high-intensity light will be blocked and the MFT run stopped. This is intended to protect the object from incurring visible change from MFT. Selection of a color difference threshold varies, but commonly reported values are a ΔE^*_{ab} of 5 and a ΔE^*_{00} of 3.

Color Temperature The behavior of an idealized thermal black-body radiator that absorbs radiation of all frequencies and emits black-body radiation that is dependent on that object's temperature. In practice, color temperature is defined for light sources that approximate black bodies, with values above 5,000 Kelvin (K) considered "cool" (bluish) and those below 3,000 K considered "warm" (yellowish).

Colorimeter An instrument that measures tristimulus values, which correlate with the human perception of color. Colorimeters incorporate an internal light source that shines onto a sample, with the reflected light passed through red, green, and blue filters. While useful for color assessment, colorimeters lack the ability to collect spectral reflectance data appropriate for more complex color analysis.

Contact MFT Probe An MFT measurement head that is in gentle contact with the sample surface (typically through a Mylar template). While not requiring alignment of the illumination and collection spots, potential drawbacks of the contact probe, beyond contact itself, include an inability to test through glazing, the need for a flat surface, and the lack of visibility of the test area during testing.

Digital Exposure Controller A component of the original Whitmore MFT design that continuously monitors light intensity and adjusts the power supply output to maintain a constant intensity. This allows MFT to assess small color differences and eases calculation of light dose during a run. The unit also permits the reduction of the intensity of the light source to a fixed level to improve day-to-day comparisons of data and preserve lamp life.

Fiber Optic Continuity Tester A tool that transmits light through a fiber optic to verify its light throughput. In addition to assessing fiber integrity, this can be used during the MFT setup to denote the collection spot and aid in its alignment with the illumination spot. Alternative low-intensity light sources, such as tungsten halogen lamps, can be used for this purpose.

Fiber Optics Flexible glass fibers used to transmit light between its two ends. For MFT, fiber optics are used to transmit light from the light source to the sample and from the sample to the spectrophotometer. The original Whitmore MFT design used illumination and collection fiber with diameters of 200 and 600 μm, respectively, providing tolerance when aligning the illumination and collection spots.

Grey Scale (ISO) A means of assessing the extent of color change and staining. The Grey Scale (ISO 105-A02) consists of nine pairs of nonglossy neutral gray colored chips. A value of 5 indicates no difference between the standard and sample, while a value of 1 indicates the most difference. Note that the chip pairs also denote half steps of change (i.e., 4/5, 3/4, 2/3, and 1/2).

Infrared (IR) Radiation wavelengths from 700 to 1000 nanometers, existing just beyond the visible spectrum. Though possessing a reduced photon energy compared to the visible region, IR is filtered from MFT xenon-arc light sources to limit excessive heating of the sample surface.

Integration Time Analogous to camera shutter speed, this controls the amount of light to which the detector in the spectrophotometer is exposed and is typically expressed as microseconds, or μsec. An appropriate integration time maximizes the signal (or counts) without saturating the detector.

ISO Acronym for the International Organization for Standardization, which is an independent, nongovernmental organization that develops international standards, technical reports, and specifications to support quality and safety assurance in world trade. While their purview is broad, the ISO often collaborates with the CIE on the development of lighting standards.

Just Noticeable Difference (JND) A statistical measure by which the smallest difference between two stimuli is perceptible to 50% (or more) of observers. In the conservation field, the JND has been used to quantify the perceptible change in color appearance under specific viewing and lighting conditions. In colorimetric terms, it is suggested that 1 JND equates to a ΔE^*_{00} of approximately 1.5, though this value may be larger for visually complex artworks.

L*a*b* Color Space (CIELAB) A three-dimensional color space introduced by CIE in 1976 and derived from CIEXYZ. The lightness value, L*, represents black at L* = 0 and white at L* = 100. The a* axis represents green in the negative direction and red in the positive direction, and the b* axis represents blue in the negative direction and yellow in the positive direction. a* and b* values of 0 represent true neutral grey.

Lens An optical device that focuses or disperses light using refraction. In the original Whitmore MFT design, two pairs of convex or converging lenses are used to converge light rays (from the light source) onto the sample and the collecting fiber (to the spectrophotometer). The choice of lens also informs the working distance between the sample and test head, allowing for noncontact MFT analysis.

Light Damage Calculator An interactive online tool developed by the Canadian Conservation Institute (CCI) that provides visual simulations of the anticipated impact of select lighting scenarios for different colorants. The estimated color change is based on scientific results obtained by accelerated light aging studies of various artistic materials.

Light Dose The cumulative light exposure on a surface, typically in units of lux-hours. The light dose or total exposure is the product of the illuminance (lux or lumens/m^2) and exposure time (hours). Note that large light doses may be expressed in Megalux-hours, which is equivalent to 1 million lux-hours.

Light Emitting Diode (LED) A semiconductor light source that has largely superseded incandescent lights in many galleries due to its energy efficiency and extended lifetime. MFT users have explored LEDs as an alternative to xenon-arc light sources due to their interest in obtaining results for LED-specific spectral power distributions. Note that LEDs are not broadband light sources, as their SPD contains characteristic peaks and troughs.

Lightbox An enclosure in which samples are exposed to light for the purposes of aging studies. Typically used for mock-up samples, experiments can vary the light source, the light intensity, and the duration of exposure, and color change may be assessed at different time intervals. Note that the light intensity within a lightbox is typically several orders of magnitude less than MFT.

Microfading Tester (MFT) An analytical technique that exposes the object surface to an intense and focused light spot and monitors the resulting visually imperceptible change. Developed by Paul Whitmore and introduced to the field in the mid-1990s, MFT can determine the in situ light sensitivity of a collection item. MFT data can inform lighting decisions that mitigate the risk of light damage for highly sensitive objects while expanding access for those items revealed to be more lightfast than expected.

Munsell Color System A three-dimensional color classification system that was a precursor to CIE color space. Introduced in 1905 by Albert H. Munsell and subsequently refined, the Munsell System of Color Notification was based on measurements of human visual responses to color and was the first to define the relationship between hue (color family), chroma (color intensity), and value (lightness).

Neutral Density Filter A filter that reduces the intensity at all wavelengths of light with minimal distortion of the spectral power distribution of the light source. Neutral density filters are characterized by the optical density, with values of 1, 2, 3, and 4 decreasing transmittance to 10%, 1%, 0.1%, and 0.01%, respectively, of the original light intensity.

Pen Camera (Digital Microscope) A digital camera that can be mounted in the MFT test head next to the illumination and collection assemblies to magnify the view of the test site, document the test location, and assist with alignment of the illumination and collection spots.

Photometer An instrument for measuring the intensity of visible light (between 380 and 700 nm) weighted at each wavelength based on the sensitivity of the human eye. Photometers report light intensity as the luminous flux (lumens [lm]) or illuminance (lux [lm/m^2]). In contrast, radiometers measure light intensity across the ultraviolet, visible, and infrared regions without bias toward the human visual system.

Preservation Target The period of managed use (e.g., storage, study, reproduction, display, lending) during which a light-induced JND is allowed for a collection item. Typically expressed in years, the preservation target can alternatively be stated as the number of acceptable JNDs within a given period of time.

Radiometer An instrument for measuring the intensity of light across the ultraviolet, visible, and infrared regions without bias toward the human visual system. Radiometers report light intensity as the radiant flux (watts [W]) or irradiance (W/m^2). In contrast, photometers measure light intensity in the visible region weighted at each wavelength by the sensitivity of the human eye.

Reciprocity A material response that is a function of exposure (or dosage), which can be defined as the product of intensity and time. If reciprocity holds, a similar response should be observed for the same exposure, whether the intensity is low and the duration is extended or the intensity is high and the duration is brief. Reciprocity is not an intrinsic material property but rather a response of a material to a test condition.

Reference Calibration A calibration step defining 100% reflectance across the visible wavelength region for the spectrophotometer. The reference spectrum is commonly collected on a Spectralon® white diffuse reflectance standard and is reassessed periodically throughout an analysis day.

Retroreflective Probe An MFT measurement head that returns the reflected light from the sample surface along the same path as the illumination beam, providing a wider depth of focus and eliminating the need to align illumination and collection spots. While the angle of measurement is flexible, most users maintain a 45° angle between the sample and the probe.

Role of Color Information The role of color or object appearance in conveying the cultural value of an object. This role varies depending on the nature of the collection item and informs the type of visual tasks needed to adequately perceive an object and its necessary lighting conditions.

Spectral Power Distribution (SPD) A visualization of a light source's power output at each wavelength across the visible region and into the ultraviolet and infrared, often referred to as its fingerprint. The strength and distribution of the emitted energy varies for each light source, which is important when evaluating lighting for display.

Spectral Viewer Free software developed at the Getty Conservation Institute that employs a graphic user interface to facilitate spectral and colorimetric comparisons of MFT data. This complements the use of an Excel Macro suite developed by Paul Whitmore to examine MFT data.

Spectrophotometer A device that examines a material's reflection or transmission behavior by measuring spectra that show light intensity as a function of wavelength. MFT incorporates a spectrophotometer to continuously collect spectral reflectance data when the object is exposed to a focused and high-intensity light spot; colorimetric values can then be calculated from the fundamental spectral data.

Standard Illuminant Theoretical standards that are used in colorimetric calculations to compute the tristimulus values of reflected or transmitted object colors under specified conditions of illumination and allow for the comparison of colors measured with different light sources. While the CIE has defined a range of standard illuminants, D65 is a common standard daylight illuminant for color and lighting studies, including MFT.

Standard Observer Experimentally determined color matching functions or tristimulus values (denoted as x, y, and z) corresponding to the sensitivity of long, medium, and short cone photoreceptors in the human eye. While the CIE has described functions for a Standard 2° Observer and a Standard 10° Observer, with the angles corresponding to the field of view for the observer, the former is typically employed in MFT colorimetry calculations.

Ultraviolet (UV) Radiation wavelengths from 100 to 380 nanometers, just beyond the visible spectrum. Possessing a higher photo energy than the visible region, UV can cause damage when absorbed by cultural heritage material by inducing photochemical reactions that can weaken the support. UV is often filtered from a xenon-arc MFT light source so that it more closely resembles gallery lighting conditions.

Value at Risk to Light The proportion of an object's collection value that might be lost when exposed to light, which depends on the importance of color as a value determining feature. Value at risk to light is relevant for collection items likely vulnerable to light, with the main light-induced effect on materiality consisting of surface color change.

Visible Light Radiation wavelengths from 380 to 700 nanometers corresponding to that which is visible by the human eye. This region is a continuous spectrum encompassing seven principal colors, which together create white light, and is the primary focus of MFT analysis.

Whitmore MFT A colloquial term for an MFT largely based on the initial blueprint introduced in 1999 by Paul Whitmore, Xun Pan, and Catherine Bailie. Since no off-the-shelf unit existed, the Whitmore design merged discrete components to create an MFT: a xenon-arc light source, a digital exposure controller, filters, fiber optics, illumination and collection lens assemblies positioned in a 0/45 geometry (allowing for noncontact operation), and a spectrophotometer.

Xenon-Arc A type of gas discharge lamp that produces an intense white light commonly used in daylight simulation studies. In addition to its brightness, xenon-arc lamps were selected as the primary MFT light source due to their continuous spectral power distribution (representing the worst-case scenario), high color temperature, small filament and directionality, and long-term stability (when employed with a feedback monitoring loop).

XYZ Color Space (CIEXYZ) A mathematically determined additive color space based on Standard 2° Observer color matching functions. Introduced by CIE in 1931, CIEXYZ color space transformed visible light to an approximation of what the human eye perceives using three values to characterize color. Subsequent color spaces, including CIELAB, were derived from CIEXYZ.

Appendix 3
Colorimetry Calculations

CIELAB from CIEXYZ

$$L^\star = 116\, f\left(\frac{Y}{Y_\mathrm{n}}\right) - 16$$
$$a^\star = 500\left(f\left(\frac{X}{X_\mathrm{n}}\right) - f\left(\frac{Y}{Y_\mathrm{n}}\right)\right)$$
$$b^\star = 200\left(f\left(\frac{Y}{Y_\mathrm{n}}\right) - f\left(\frac{Z}{Z_\mathrm{n}}\right)\right)$$

where, being $t = \frac{X}{X_n}, \frac{Y}{Y_n}$, or $\frac{Z}{Z_n}$:

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \dfrac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$
$$\delta = \tfrac{6}{29}$$

X, Y, Z describe the color stimulus considered, and X_n, Y_n, Z_n describe a specified white achromatic reference illuminant.

From Wikipedia (CIELAB Color Space)

1976 Color Difference (ΔE^*_{ab}) from CIELAB

Given two colors in CIELAB color space, (L_1^*, a_1^*, b_1^*) and (L_2^*, a_2^*, b_2^*), the CIE76 color difference formula is defined as:

$$\Delta E_{ab}^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}.$$

$\Delta E_{ab}^* \approx 2.3$ corresponds to a JND (just noticeable difference).[12]

From Wikipedia (Color Difference)

1994 Color Difference (ΔE^*_{94}) from CIELAB

Given a reference color (L^*_1, a^*_1, b^*_1) and another color (L^*_2, a^*_2, b^*_2), the color difference is

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2}$$

where:

$$\begin{aligned}
\Delta L^* &= L^*_1 - L^*_2 \\
C^*_1 &= \sqrt{{a^*_1}^2 + {b^*_1}^2} \\
C^*_2 &= \sqrt{{a^*_2}^2 + {b^*_2}^2} \\
\Delta C^*_{ab} &= C^*_1 - C^*_2 \\
\Delta H^*_{ab} &= \sqrt{{\Delta E^*_{ab}}^2 - {\Delta L^*}^2 - {\Delta C^*_{ab}}^2} \qquad = \sqrt{{\Delta a^*}^2 + {\Delta b^*}^2 - {\Delta C^*_{ab}}^2} \\
\Delta a^* &= a^*_1 - a^*_2 \\
\Delta b^* &= b^*_1 - b^*_2 \\
S_L &= 1 \\
S_C &= 1 + K_1 C^*_1 \\
S_H &= 1 + K_2 C^*_1
\end{aligned}$$

and where k_C and k_H are usually both unity and the weighting factors k_L, K_1 and K_2 depend on the application:

	graphic arts	textiles
k_L	1	2
K_1	0.045	0.048
K_2	0.015	0.014

Geometrically, the quantity ΔH^*_{ab} corresponds to the arithmetic mean of the chord lengths of the equal chroma circles of the two colors.[16]

From Wikipedia (Color Difference)

2000 Color Difference (ΔE^*_{00}) from CIELAB

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}$$

Note: The formulae below should use degrees rather than radians; the issue is significant for R_T.

The k_L, k_C, and k_H are usually unity.

$$\Delta L' = L^*_2 - L^*_1$$

$$\bar{L} = \frac{L^*_1 + L^*_2}{2} \quad \bar{C} = \frac{C^*_1 + C^*_2}{2}$$

$$a'_1 = a^*_1 + \frac{a^*_1}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a'_2 = a^*_2 + \frac{a^*_2}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$\bar{C}' = \frac{C'_1 + C'_2}{2} \text{ and } \Delta C' = C'_2 - C'_1 \quad \text{where } C'_1 = \sqrt{a'^2_1 + b^{*2}_1} \quad C'_2 = \sqrt{a'^2_2 + b^{*2}_2}$$

$$h'_1 = \text{atan2}(b^*_1, a'_1) \mod 360^\circ, \quad h'_2 = \text{atan2}(b^*_2, a'_2) \mod 360^\circ$$

$$\Delta h' = \begin{cases} h'_2 - h'_1 & |h'_1 - h'_2| \le 180^\circ \\ h'_2 - h'_1 + 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 \le h'_1 \\ h'_2 - h'_1 - 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 > h'_1 \end{cases}$$

Note: When either C'_1 or C'_2 is zero, then $\Delta h'$ is irrelevant and may be set to zero. See Sharma 2005, eqn. 10.

$$\Delta H' = 2\sqrt{C'_1 C'_2}\sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h'_1 + h'_2)/2 & |h'_1 - h'_2| \le 180^\circ \\ (h'_1 + h'_2 + 360^\circ)/2 & |h'_1 - h'_2| > 180^\circ, h'_1 + h'_2 \\ (h'_1 + h'_2 - 360^\circ)/2 & |h'_1 - h'_2| > 180^\circ, h'_1 + h'_2 \end{cases}$$

$$T = 1 - 0.17\cos(\bar{H}' - 30^\circ) + 0.24\cos(2\bar{H}') + 0.32\cos(3\bar{H}' + 6^\circ) - 0.20\cos(4\bar{H}' - 63^\circ)$$

$$S_L = 1 + \frac{0.015\left(\bar{L} - 50\right)^2}{\sqrt{20 + \left(\bar{L} - 50\right)^2}} \quad S_C = 1 + 0.045\bar{C}' \quad S_H = 1 + 0.015\bar{C}'T$$

$$R_T = -2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}}\sin\left[60^\circ \cdot \exp\left(-\left[\frac{\bar{H}' - 275^\circ}{25^\circ}\right]^2\right)\right]$$

From Wikipedia (Color Difference)

Appendix 4
MFT Case Study:
Screening Material for Exhibition

Mark Benson

The rapid and predictive nature of the microfading tester makes it an ideal tool for screening collection material for lightfastness prior to display. The MFT allows the user to obtain data for multiple locations on multiple objects in a relatively short time. The color change behavior of the artwork can then be compared to that of Blue Wool standards to inform lighting decisions. For over a decade, the Getty Research Institute has been using MFT as a preventive conservation tool.

The GRI rotates multiple exhibitions throughout a year in an exhibition space of approximately 3000 ft^2. Light is necessary to access and engage with the exhibited material but is also a destructive force for many materials. A balance must be struck between providing sufficient light to properly see each object and limiting the extent of damage to the object during light exposure. The MFT has proven to be a valuable tool in assisting GRI conservators with (a) identifying objects requested for exhibition that are highly sensitive to light and (b) informing potential combinations of light level and display duration. This process allows for flexibility when collection care staff discuss lighting scenarios for each object.

EXHIBITION

In 2019, the GRI mounted the exhibition *Bauhaus Beginnings*. The exhibition was on view for 124 days between June 11 and October 13. It included over 200 works from the Bauhaus school, many of which focus on the fundamental principles of color and the interactions among colors (GRI 2019). Due to the important role of color in many of these works, there was significant cultural value at risk due to light exposure during display. The large amount of color media required a careful survey to select potentially sensitive works for MFT.

Assuming that all objects are of relatively high value, an ideal MFT protocol to assess light sensitivity would be to test all colors and the substrate for every object. However, given a large volume of material and limited time, this is impractical. The initial visual survey and selection of items for screening by MFT is largely based on several factors. Priority is given to any media type generally accepted to be light sensitive in the conservation literature or materials whose color change behavior is unknown (and not included in published guidelines). In addition, item selection can be guided by previous MFT and lightbox experiments with various types of media, as well as consultation with the exhibition curators. While MFT experience can be helpful when selecting collection items for testing, caution should be given to the use of previous MFT results to inform lighting recommendations for similar media or material, as light sensitivity depends on multiple parameters that are specific to each object. (This is discussed further in chapter 5.). After careful consideration, 40 items from the *Bauhaus Beginnings* material were selected for MFT.

MFT ANALYSIS

MFT analysis of the Bauhaus exhibition was carried out using a Whitmore MFT as described and pictured in figure 3.1. The light source is a 75-watt xenon-arc lamp with ultraviolet and infrared minimized; light intensity was measured with a photometer at ~525 millilumens (mlm). A total of 116 sites were examined across the 40 items. The number of sites per object ranged from 1 to 13 and was based on the number of distinct colors (including the substrate) on each object. The testing was completed over nine days in November and December 2018, allowing sufficient time before the exhibition to interpret the data, discuss the results with curators, and agree on item selection and a safe and acceptable lighting scenario for each.

Figure A4.1 shows one of the collection items from the *Bauhaus Beginnings* exhibition examined by MFT. This print by Lothar Schreyer, an instructor at the Bauhaus, is identified in the library record as a "hand-painted lithograph," which was supported by visual examination of the print. The black colorant appears printed, evenly applied, and opaque. In contrast, the red, blue, and white colorants are unevenly applied and translucent in places, suggesting application by hand. The print is signed and dated in graphite at the bottom right corner.

Often used as colorants for colored prints, watercolor and gouache are generally accepted as sensitive to light (e.g., CIE 2004; Saunders 2020). As a result, any object with hand coloring is prioritized for MFT screening at the GRI. In addition, previous MFT tests at the GRI of various types of water-based paint suggest that their lightfastness can vary significantly. The uncertainty in color change behavior associated with this media further supported its analysis by MFT.

MFT at the GRI begins with a series of runs on ISO Blue Wool (BW) Standards 1, 2, and 3, which define high light sensitivity. As discussed in chapter 2, BW Standards are a series of eight dyed wools used as a metric for lightfastness. With respect to MFT, the BWs are used as an internal calibration by which one can classify the color change behavior of sensitive materials.

At the start of testing, three 15-minute runs are conducted for BW1, 2, and 3 to characterize their performance. Color difference, or ΔE, is visualized for each set by showing the average color difference and standard deviation over time. For each subsequent MFT analysis day, an additional 15-minute run is carried out for each of the three BWs and compared to the initial BW series to ensure that the testing conditions have not changed; these are generally conducted at the beginning of the day and during breaks. If the MFT is inactive for an extended period or relocated, the three 15-minute runs are repeated for the high-sensitivity BWs.

FIGURE A4.1 Hand-painted lithograph by Lothar Schreyer, part of the Bauhaus Beginnings exhibition. Red circles indicate MFT test sites. Photo: Getty Research Institute, Los Angeles (2012.PR.4) © Michael Schreyer.

For the Schreyer print, a decision was made to focus on testing of the blue and red paint and the paper substrate; this was based on the earlier assumption that they are the least lightfast. Since it is generally accepted that the black printing ink and the graphite inscription were relatively lightfast (e.g., CIE2004), they were not tested. While white pigments are also generally considered stable (e.g., CIE 2004), sparse MFT data for this colorant had been collected at the GRI; thus, MFT was also carried out on the white paint. If time permits, any media not tested during the initial round can be tested.

The length of the MFT runs for the Bauhaus material typically ranged between 5 and 10 minutes, with spectral data collected every 30 seconds. The focus when conducting MFT runs is less about maintaining a consistent duration than on collecting sufficient data to confidently establish a BW equivalence (BWE). The selected durations also allow for analysis of a large number of test sites in a limited time window. The GRI MFT protocol defines a ΔE^*_{ab} (color difference based on the 1976 CIE calculation) threshold of 2.5 at which a run will be terminated to prevent any detectable color change on the print; this is based on the near real-time ΔE^*_{ab} displayed onscreen in the Spec32 software for the Control Development spectrophotometer. It should be noted that there is always the potential that shorter MFT durations may not detect delayed color changes (see chapter 4), though this appears to be a rare occurrence.

Figures A4.2 and A4.3 show the MFT results for the Schreyer print. Figure A4.2. compares the initial and final spectra of the red hand coloring and shows shifts in L*, a*, and b*. Spectral change is greatest between 400 nm and 500 nm, while the changes in CIELAB indicate that the test site is becoming lighter (increasing L*), less red (decreasing a* and above 0), and less yellow (decreasing b* and above 0). Figure A4.3. shows a time series of ΔE^*_{94} for the for the 3 colorants, substrate, and BW1, 2, and 3. (Note that this analysis used an earlier version of the GCI's Spectral Viewer software that was limited to either ΔE^*_{ab} or ΔE^*_{94}, with the latter based on the 1994 CIE calculation; a newer version of the software includes ΔE^*_{00}, which is the recommended color difference calculation.) Focusing on the relative positioning of its final data point compared to the BWs, the red paint has a ΔE^*_{94} just below that of BW1; for an object in which color plays a central role, it was decided to take a conservative position and assign the red colorant a BWE of BW1. As its most sensitive colorant, the red watercolor determines the overall BWE for the print. The BWE represents a starting point for discussion with curators about the MFT light sensitivity assessment and how these results might inform the formulation of appropriate lighting scenarios.

LIGHTING SCENARIOS

Consideration of lighting regimes for the Schreyer print is based in part on the light dose associated with 1 JND (ΔE^*_{00} of 1.5) for BW1 and the preservation target, which is the duration over which this JND is allowed. Using the more conservative revised JND light dose for BW1 from table 5.5, this item can be exposed to approximately 100,000 lux-hours before reaching a JND. At the GRI, the preservation target is used to visualize different scenarios and communicate the impact of different lighting options to curators and other stakeholders.

Table A4.1 shows four display scenarios at varying light levels and their respective calculations for determining how much of a 50-year preservation target will be consumed. For light-sensitive items with the highest significance to the collection, one might consider allowing access for only a portion of the exhibition; scenario 4 reduces exhibition time from 18 weeks to 9 weeks at 50 lux. In this scenario, the print can be swapped with a similar print at the midpoint of the exhibition, distributing exposure across two objects. Alternatively, the print can be replaced at 9 weeks with a facsimile, though this is often a less popular choice.

A discussion with the curator revealed that the Schreyer print is part of a larger portfolio of works

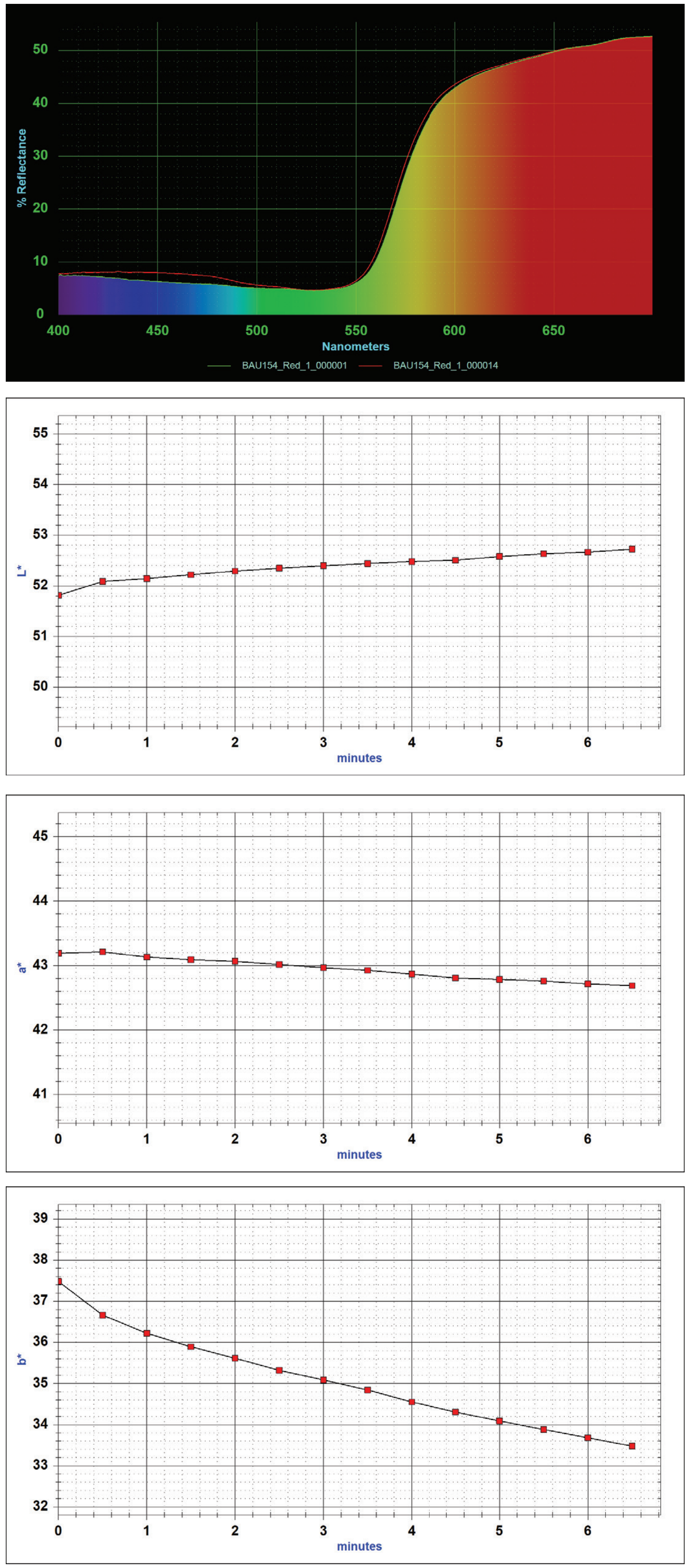


FIGURE A4.2 A) Initial and final spectra and temporal changes in B) L*, C) a*, and D) b* for the red hand coloring on the Schreyer lithograph.

FIGURE A4.3 Color difference time series for the Schreyer lithograph and BW1, 2, and 3.

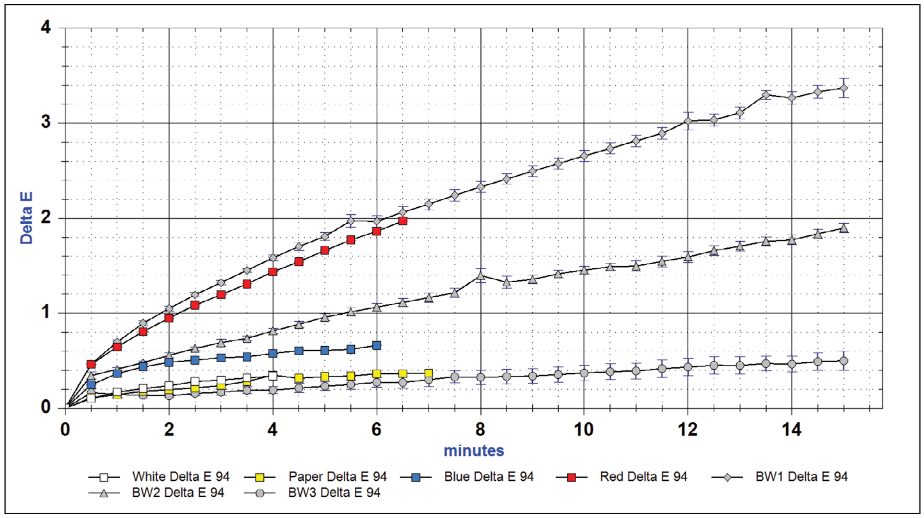


TABLE A4.1.
Lighting scenarios for the Schreyer lithograph assuming a BW1 equivalency and a 50-year preservation target.

Exhibition Lighting Scenarios					Item Information			Impact on Future Display
Scenario	Light Level (lux)	Hours of Exposure/ Week	Weeks/ Exhibition	Expected Light Dose during Exhibition (lux-hours)	BWE (determined by MFT)	Preservation Target (years)	Light Dose Allocated to PT (lux-hours)	% of Preservation Target used
1	30	54.5	18	29,430	1	50	100,000	~30%
2	50	54.5	18	49,050	1	50	100,000	~50%
3	70	54.5	18	68,040	1	50	100,000	~70%
4	50	54.5	9	24,525	1	50	100,000	~25%

called "Erste Mappe: Meister des Staatlichen Bauhauses in Weimar." This "Erste Mappe," or first folder, was created at the Bauhaus in Weimar, Germany, and consists of 14 prints by the masters of the Bauhaus. These portfolios were sold to raise funds for the school, and the GRI copy of the "Erste Mappe" is complete and in excellent condition. Acquired in 2012, the Lothar Schreyer print had not been requested for exhibition or loan until the *Bauhaus Beginnings* exhibition. Outside of the GRI reading room, the curator does not anticipate a high volume of requests for this object in the future.

Given this context, Scenario 1 was chosen to display the Schreyer print. The decision to display this print for the duration of the exhibition at 30 lux balanced the important role of the print for the exhibition with its high sensitivity to light. The overall BWE was slightly greater than BW1, and, at 30 lux, we expect to use less than 30% of the 50-year PT during the display period. The relatively simple, harder-edge composition of the Schreyer print allowed it to be displayed at 30 lux (lower than the GRI standard of 50 lux for works on paper) and still be viewed satisfactorily.

Figure A4.4. shows the BWE for the 40 Bauhaus items tested by MFT. With the exception of three items, all of the material is considered highly sensitive; however, over 60% of the items tested are more lightfast then BW2, allowing for significantly more flexibility with lighting recommendations. Light levels can be adjusted depending on the sensitivity of the object and the amount of light needed for proper viewing. The MFT results for each item are recorded in the object record of the collection database along with the exposure light dose (reported in lux-hours) during the exhibition. If the object is to be included in subsequent exhibitions, the light dose for future display periods will also be recorded and monitored to ensure that the risk of light damage is properly managed. It is also important to note that the MFT analysis of the Bauhaus material represents an example of how the testing and decision-making process associated with MFT and exhibitions can be approached. As circumstances evolve for various exhibitions and loans, the MFT protocol can be adjusted to account for the needs of the collection and the available resources to conduct testing.

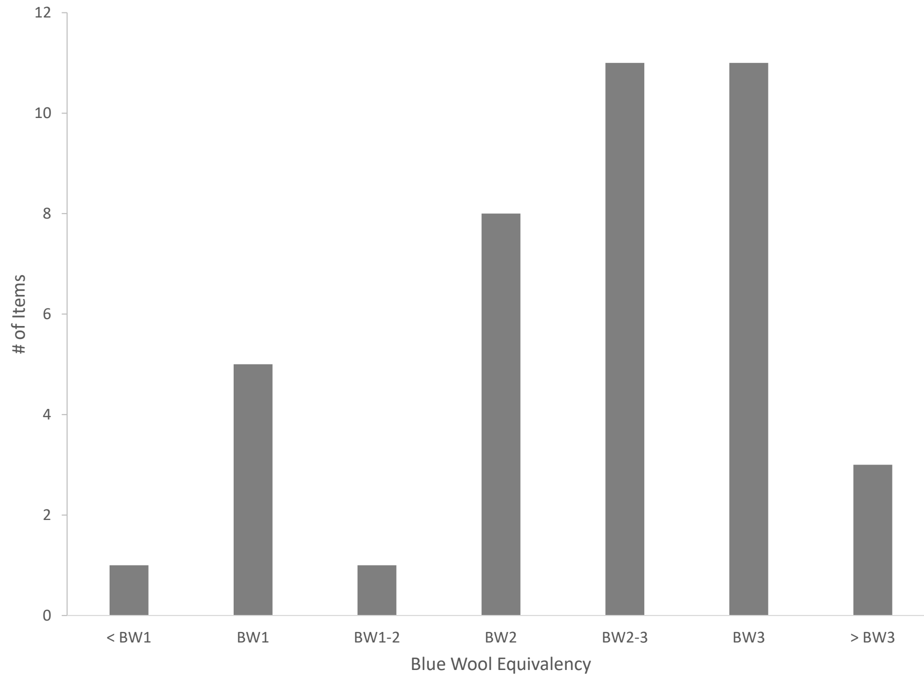


FIGURE A4.4 Overall BWEs for 40 *Bauhaus Beginnings* items tested by MFT.

CONCLUSION

At the GRI, the development of appropriate lighting scenarios for the Bauhaus material, including the Lothar Schreyer print, is dependent on effective communication between the conservator and the curator. The conservator conveys their understanding of an object's light sensitivity, in this case based on MFT, and the implications in terms of risk from light exposure. The curator provides a nuanced understanding of the object's role in current and future exhibitions and the collection, as well as its overall collection value. To fully understand the "value at risk" for an object, it is necessary to establish and maintain this communication with the various stakeholders and work toward a mutual understanding that balances both preservation and access.

REFERENCES

Getty Research Institute. 2019. *Bauhaus Beginnings*. www.getty.edu/research/exhibitions_events/exhibitions/bauhaus/beginnings/explore.html.

International Commission on Illumination (CIE). 2004. *Control of Damage to Museum Objects by Optical Radiation*. Technical Report 157. Vienna, Austria: CIE.

Saunders, David. 2020. *Museum Lighting: A Guide for Conservators and Curators*. Los Angeles: J. Paul Getty Trust.

Appendix 5
Sample MFT Report

by Bruce Ford

Micro-fading report

www.microfading.com

Object:

Maker:
Accession No:
Materials and media
Collection:
Collection type:
Year of production
Exhibition:
Test Date:
Operator:
Requested by:

Summary

The least lightfast dye within **the curtain (1-9)** is yellow (7), which faded at a rate equivalent to greater than BW1 (CIE76) under the test conditions (Endnotes 1 & 2). This is equivalent to approximately 0.1 Mlux h/JND (4-6 months at 50 lux) or less (Endnote 2). It is at the least stable end of the range of lightfastness (BW1 or worse to BW3) for colourants described in the CIE standard for museum lighting as having "high responsivity to light" for museum purposes (CIE 2004). Green (4) and orange-yellow (2) are also very fugitive and it is very likely they both contain the same yellow dye: G = Y+C and OY = Y+R. The exception is the yellowish beige background (6), which is not dyed with the fugitive yellow. The colours in which yellow is probably a component all darken and lose chroma – further evidence that their fading is largely driven by the response of the yellow dye.

Normally the light-sensitivity of this fabric would render it suitable for about 2- 4 months/decade display at 50 lux. Its sensitivity to light absolutely rules out out hanging the curtains inside the caravan within the Main Hall with any of the windows or doors open, bearing in mind that the constantly changing pattern of direct and reflected sunlight within the hall itself is complex, let alone within a partially exposed enclosure like the caravan with the door open and/or windows uncovered. Replica or replacement fabrics are the obvious solution here.

The red cushion (10, BW2-3) could withstand the equivalent in lux hours of 2 years/decade at 50-100 lux, but it should not be exposed to direct sunlight or strong reflected sunlight, which in the main hall can reach hundreds and in some places thousands of lux. Without logging (electronically or using a BW dosimeter), it would be impossible to estimate the annual cumulative exposure of any particular location inside the caravan, although it is a simple matter to at least check for direct sunlight using Sunseeker or Sun Surveyer apps for Android and Iphone.

The vinyl bench seat (11, >BW4) is probably pigmented and as far as light-fading of the colourant is concerned can withstand indefinite exposure, however it would be imprudent to expose it to direct sunlight which will eventually cause depolymerisation of the plastic which would probably first become visually apparent as decreased surface reflectivity, which can look like fading.

1

Figure 1 Test positions: cushion left insert, vinyl bench cushion right insert.

	CIE76			CIE2000							
Colour	BW Range	BW Equivalent	ΔE76	BW Range	BW Equivalent	ΔE2000	ΔL*	Δa*	Δb*	ΔC	Δh
BW1			12.2			4.5	3.8	-3.7	11.0	-10.9	6.2
BW2			6.0			1.8	1.0	-1.0	5.9	-5.7	3.0
BW3			2.7			0.8	0.6	-1.1	2.4	-2.6	0.7
BW4			1.0				0.0	0.3	1.0	-1.0	-0.4
1 curtain grey	BW4	3.8	1.4	BW3-BW2	2.3	1.6	0.0	1.2	-0.6	-0.1	-4.8
2 curtain orange-yellow	BW2-BW1	1.5	9.3	<BW1	<BW1	5.7	-4.3	-4.3	-7.0	-7.6	4.8
3 curtain magenta	BW4	3.9	1.3	>BW3	>BW3	0.4	0.0	-1.2	-0.5	-1.2	0.2
4 curtain green	BW3	2.8	3.5	BW2	1.8	2.4	-1.9	-0.2	-2.9	-2.4	4.0
5 curtain cyan	BW4-BW3	3.6	1.7	BW3-BW2	2.5	1.3	-0.1	0.9	-1.5	-1.7	1.6
6 curtain beige	BW4-BW3	3.7	1.6	BW3	2.9	0.9	0.5	-0.8	-1.3	-1.4	1.0
7 curtain yellow	BW2-BW1	1.1	11.8	<BW1	<BW1	6.5	-5.9	-5.5	-8.7	-9.4	5.0
8 curtain "black"	>BW4	>BW4	0.5	>BW3	>BW3	0.6	-0.2	0.5	-0.1	0.4	-2.7
9 curtain dark blue	>BW4	>BW4	0.5	>BW3	>BW3	0.5	-0.1	0.5	-0.1	0.4	-2.0
10 cushion red	BW3-BW2	2.7	3.7	BW3-BW2	2.4	1.4	-0.1	-2.8	-2.4	-3.6	-1.0
11 vinyl seat	>BW4	>BW4	0.4	>BW3	>BW3	0.3	-0.4	-0.1	-0.1	-0.1	-0.1

Table 1. Colour change summary. See last page for CIELAB diagram and Endnote 2 for a discussion of CIE76 vs CIE2000 results.

4

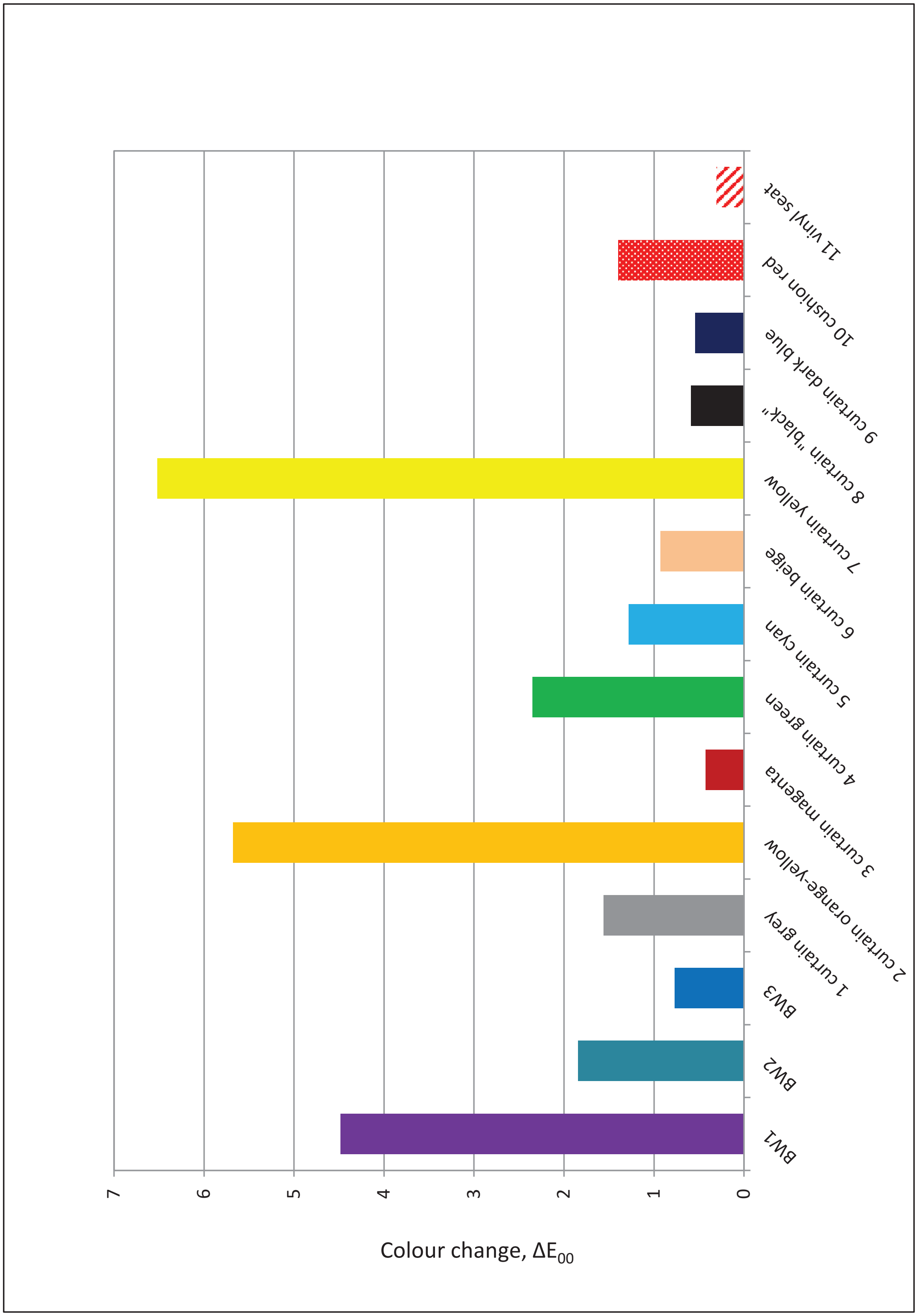


Figure 2. Relative colour change rates , CIE2000

5

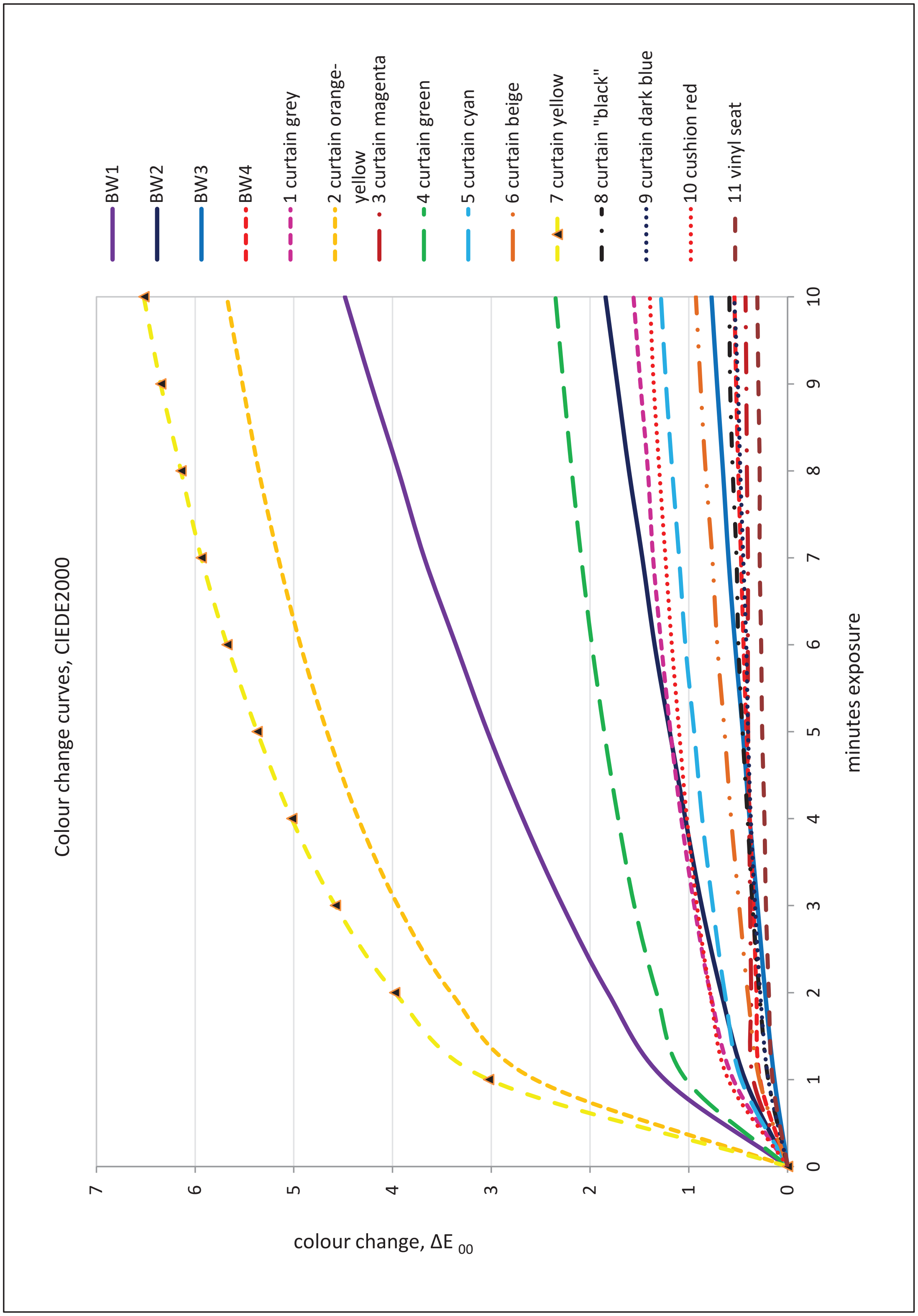


Figure 3. Colour change curves, CIE2000

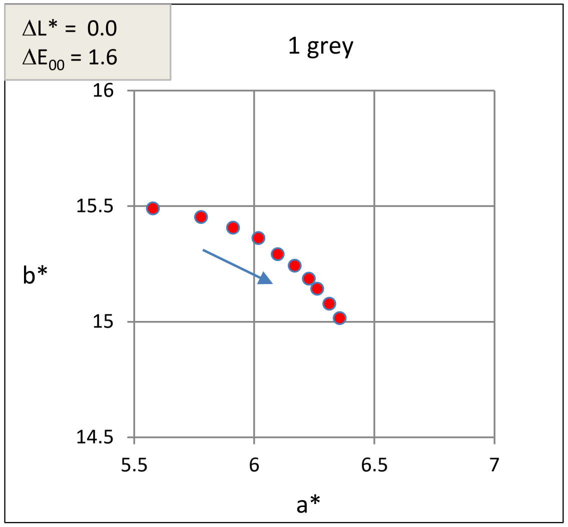
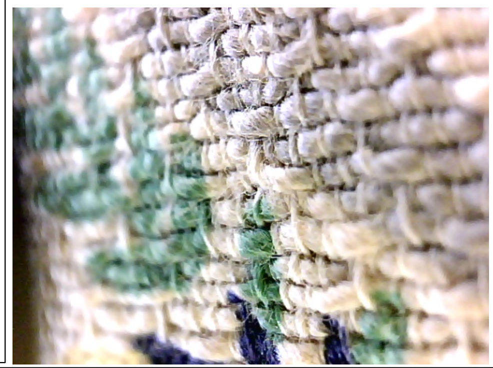
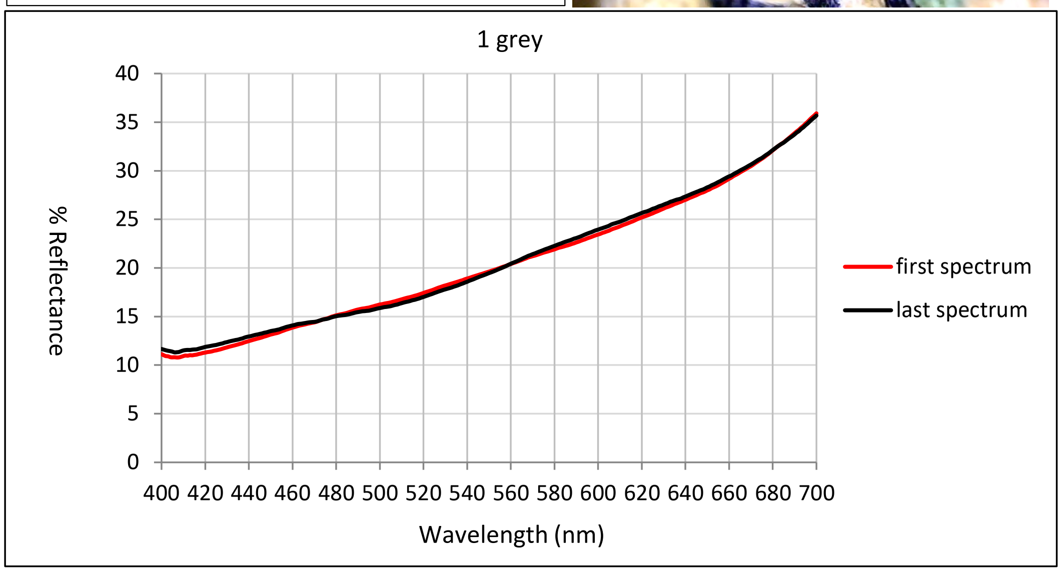


Figure 4. Curtains grey (1): mostly hue shift, redder.





6

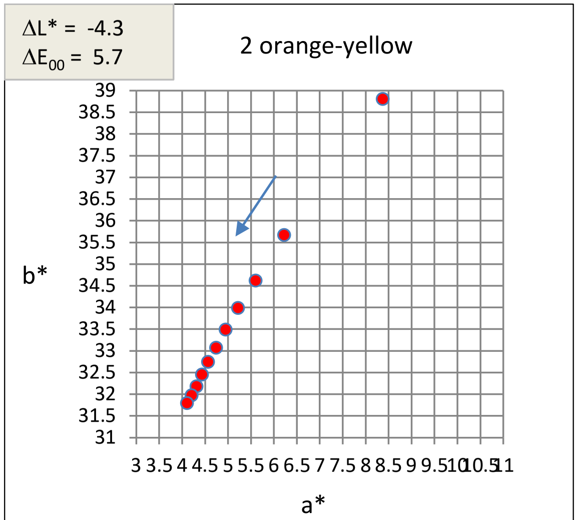
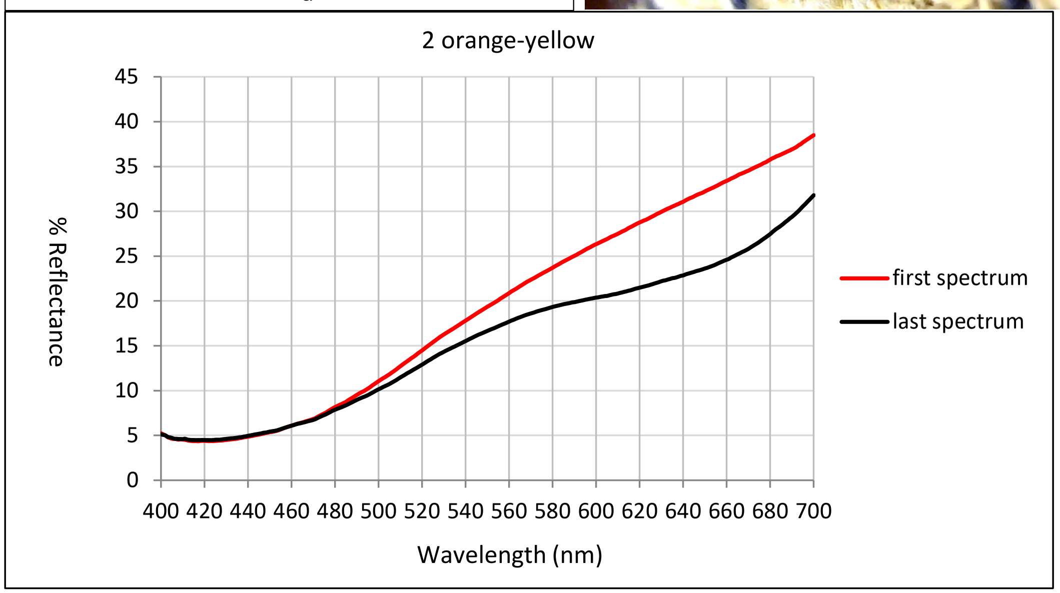


Figure 5. Curtains orange-yellow (2): darker, chroma loss, hue shift. It has lost a lot of reflection in the yellow (G+R) region of the spectrum, indicating the fading of yellow in a mixture. See Figure 10, yellow.



7

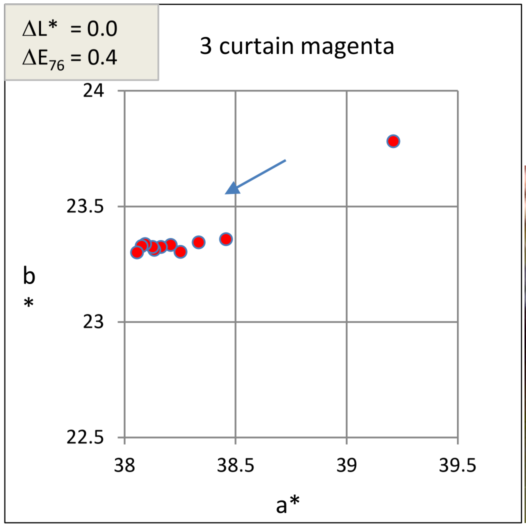
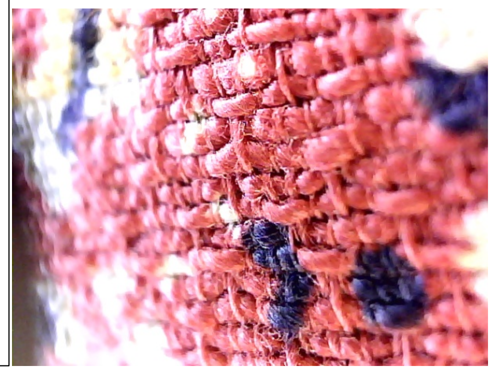
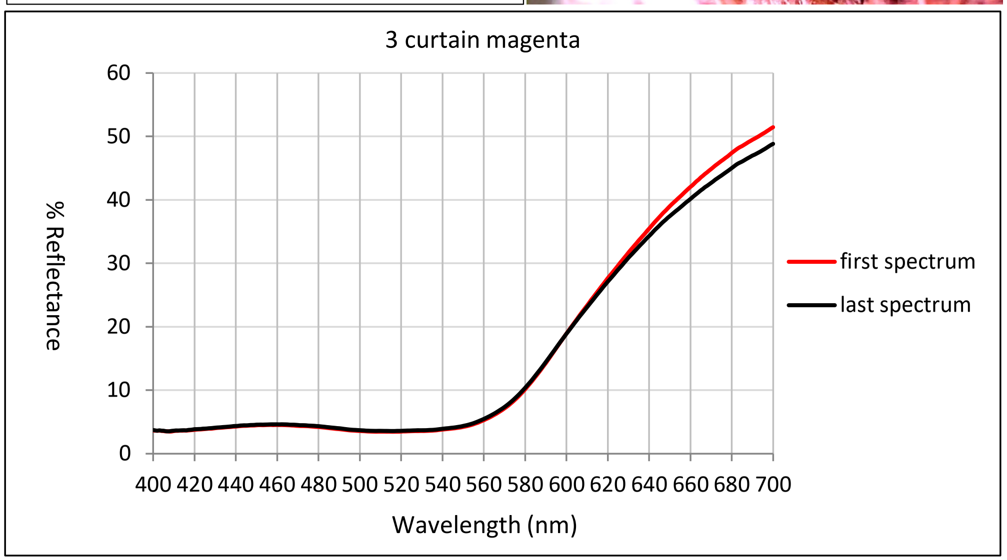


Figure 6. Curtain red (3): chroma loss.





8

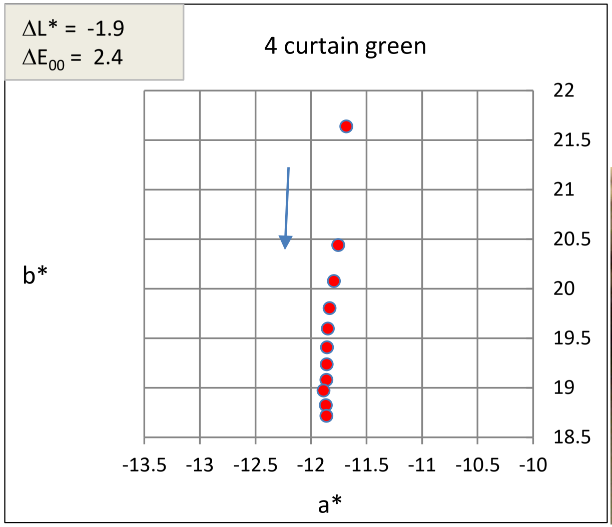
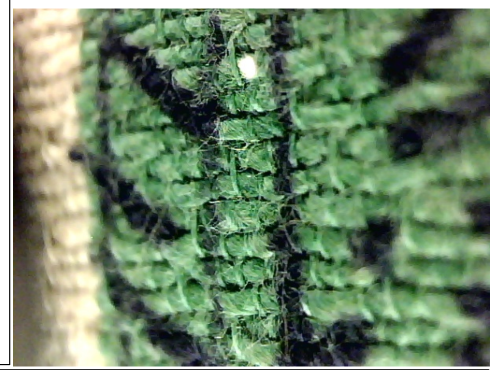
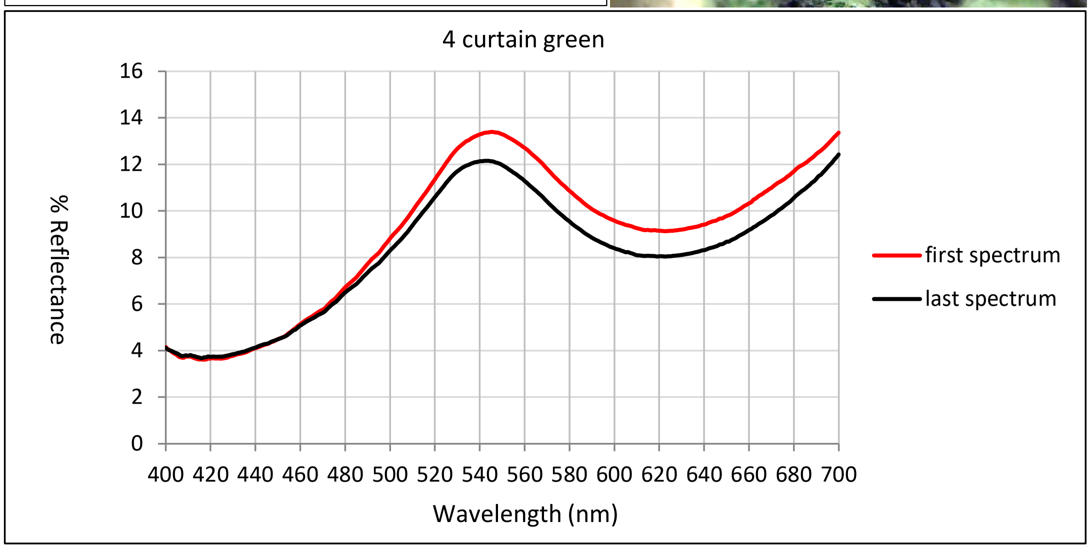


Figure 7. Curtain green (4): darker, loss of chroma (less yellow). The green is almost certainly a mixture of the yellow and cyan dyes. See Figure 10, yellow.





9

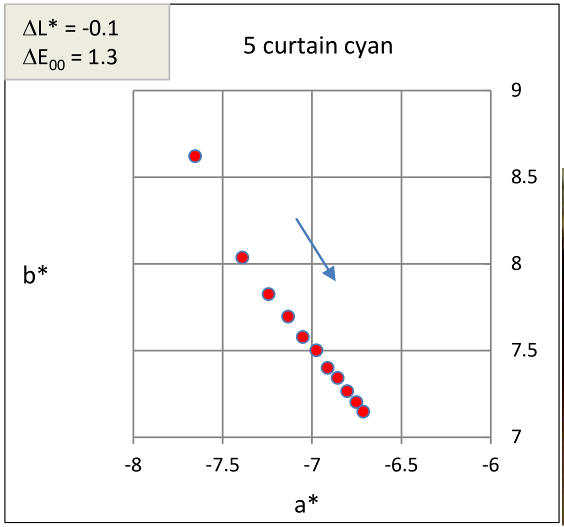
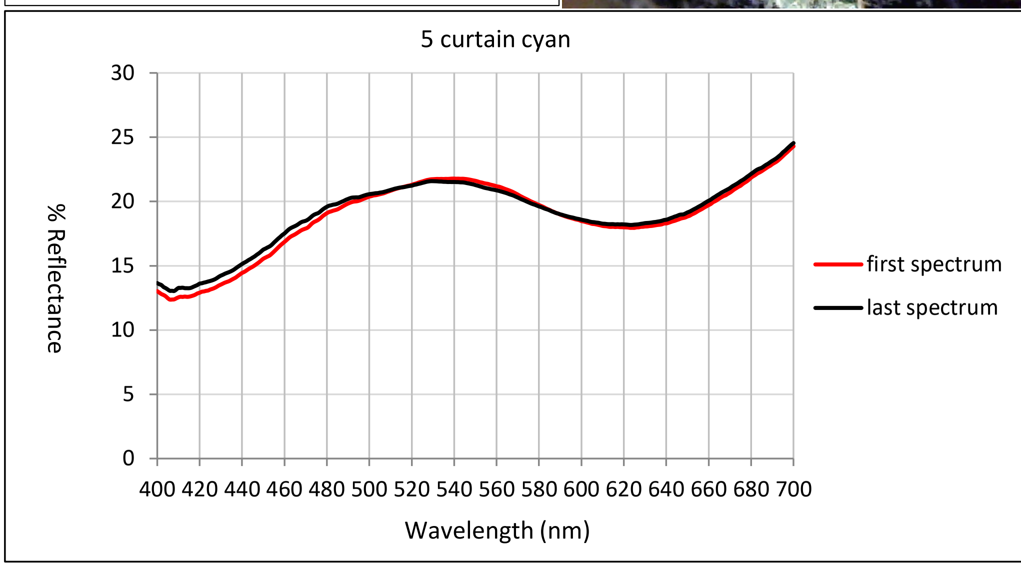


Figure 8. Curtain cyan (5): chroma loss (less green).



10

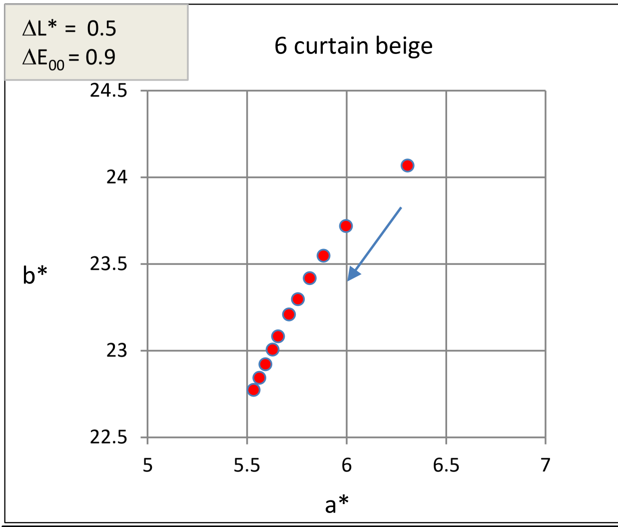
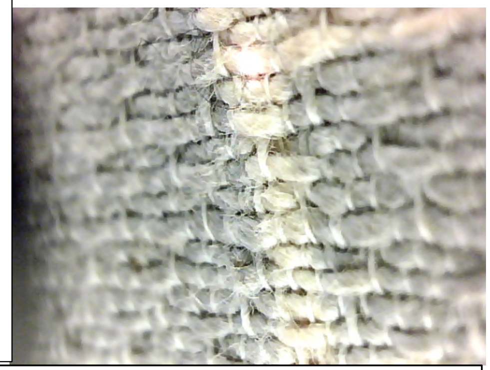
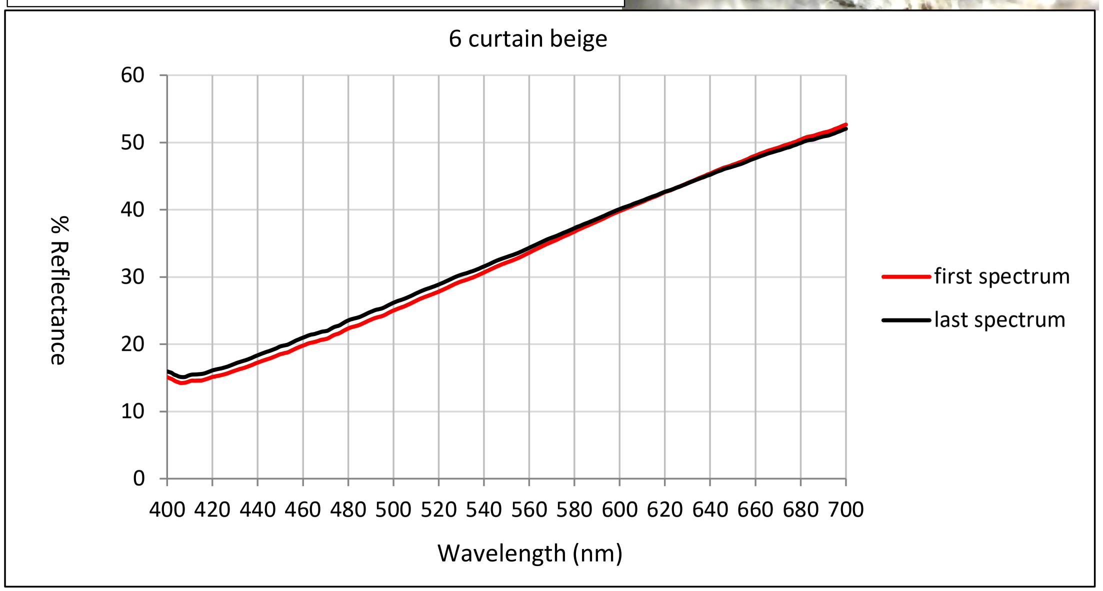


Figure 9. Curtain beige (6): lighter, less yellow. This does not contain the other yellow dye (7), and is probably the background fabric colour upon which the other dyes are printed.





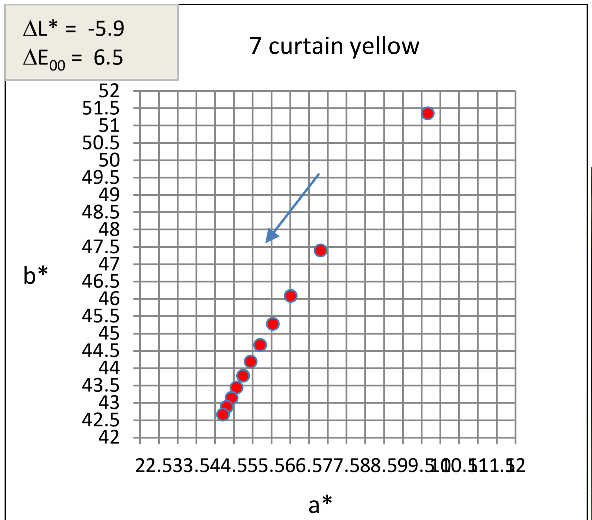
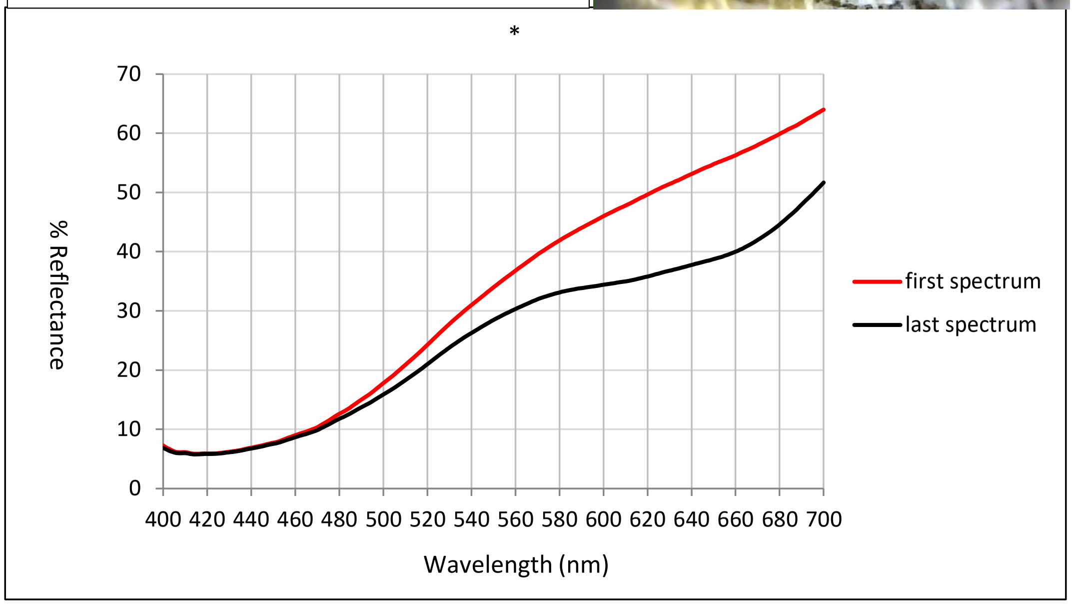


Figure 10. Curtain yellow (7): mostly faded out, but still close to BW1. It would have faded faster when it was new. This is the most fugitive component in green (C+Y) and orange (R+Y)



12

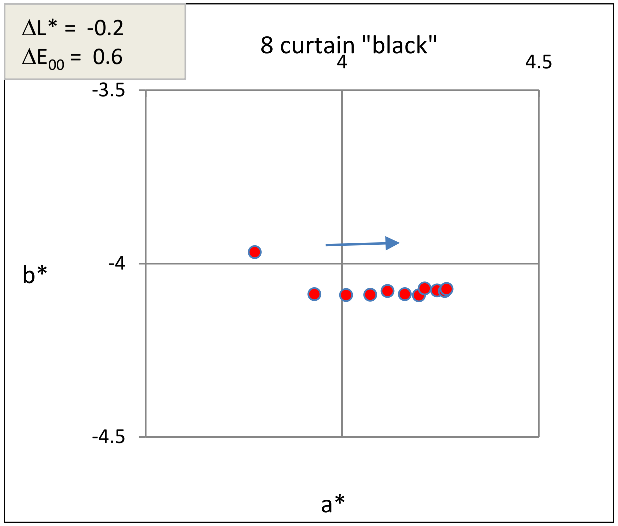
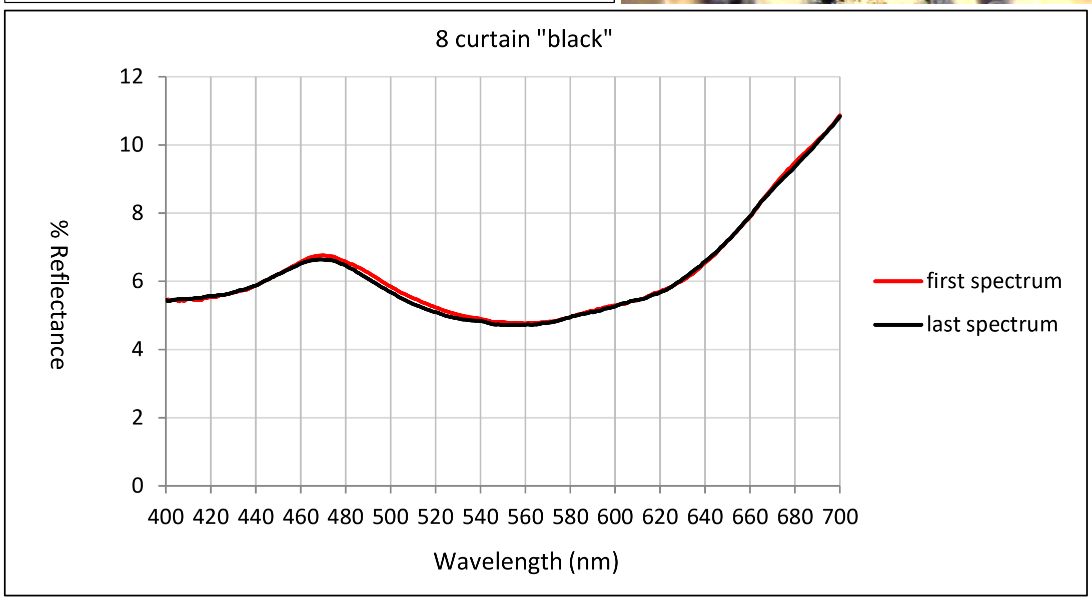


Figure 11. Curtain “black” (8): really a very dark blue (C+M), see Fig. 12 & 15 spectra.



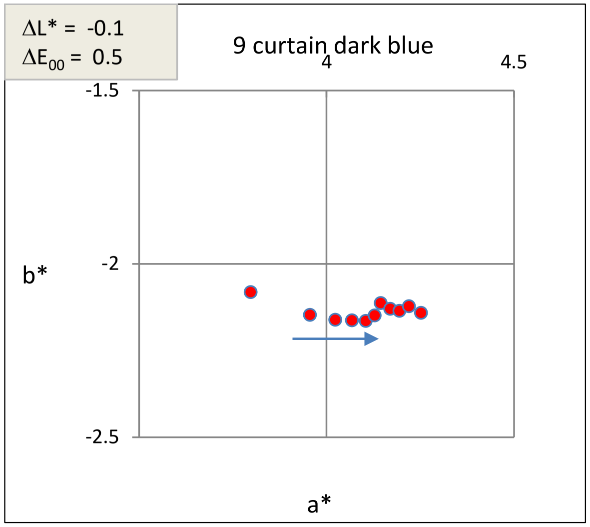
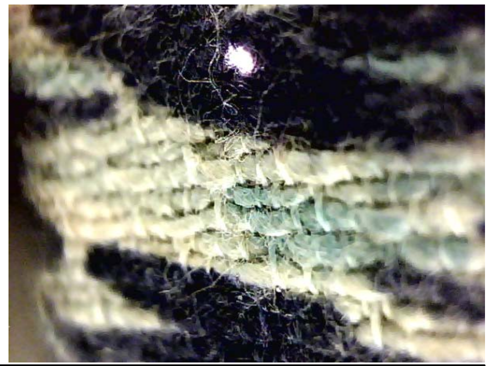
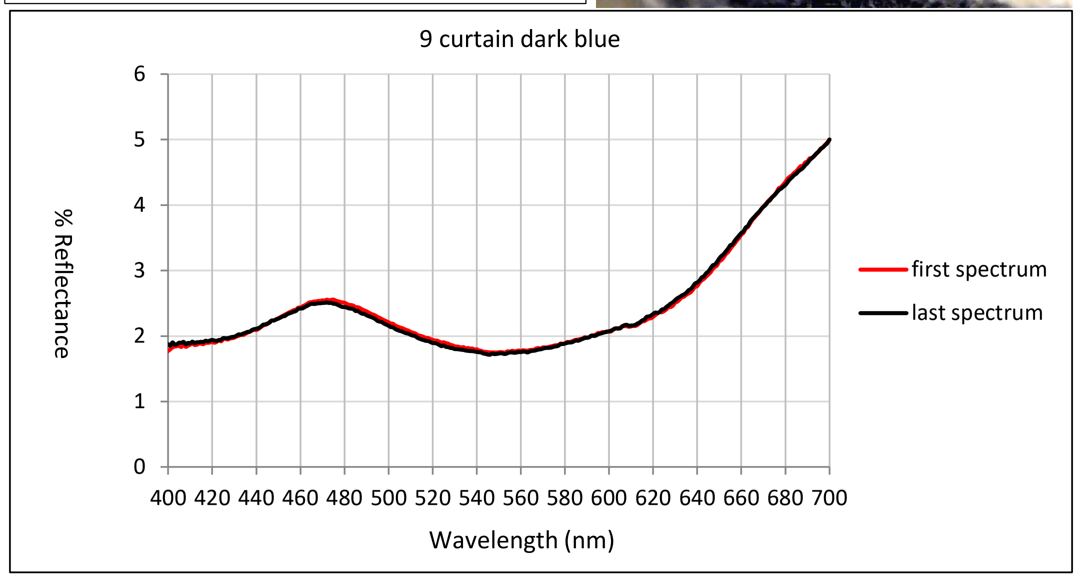


Figure 12. Curtain dark blue (9): same as "black" Figure 11. More obviously dark blue because of the surrounding colours.





14

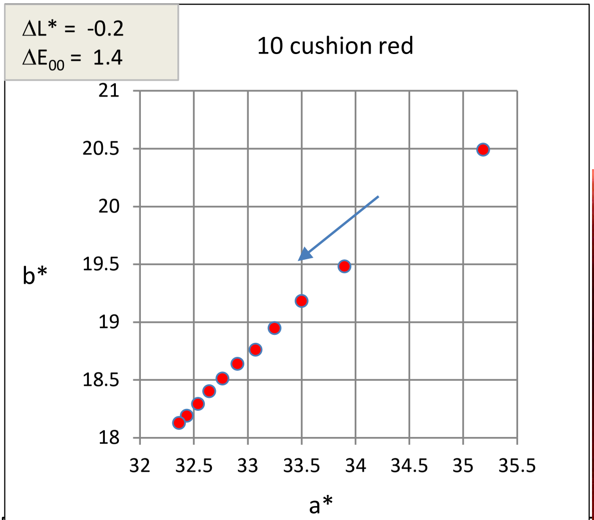
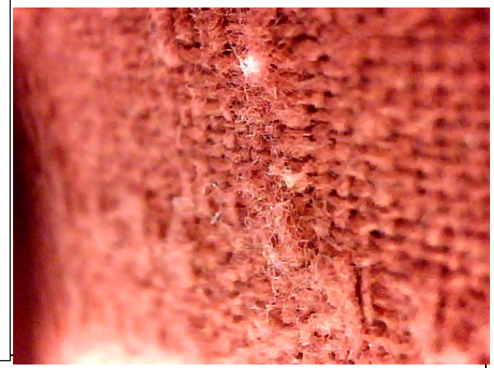
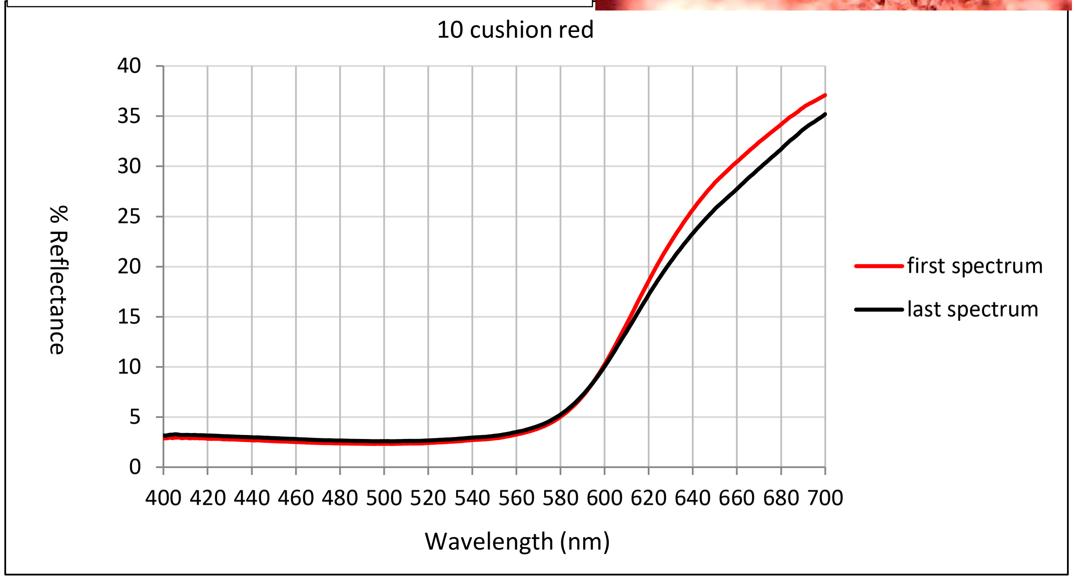


Figure 13. Cushion red (10): slight darkening, chroma loss





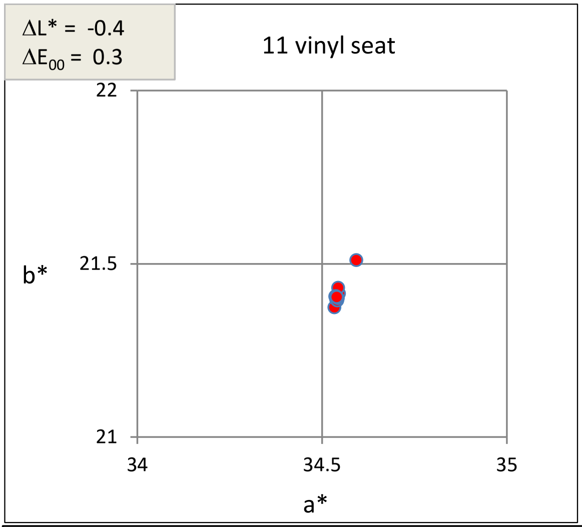
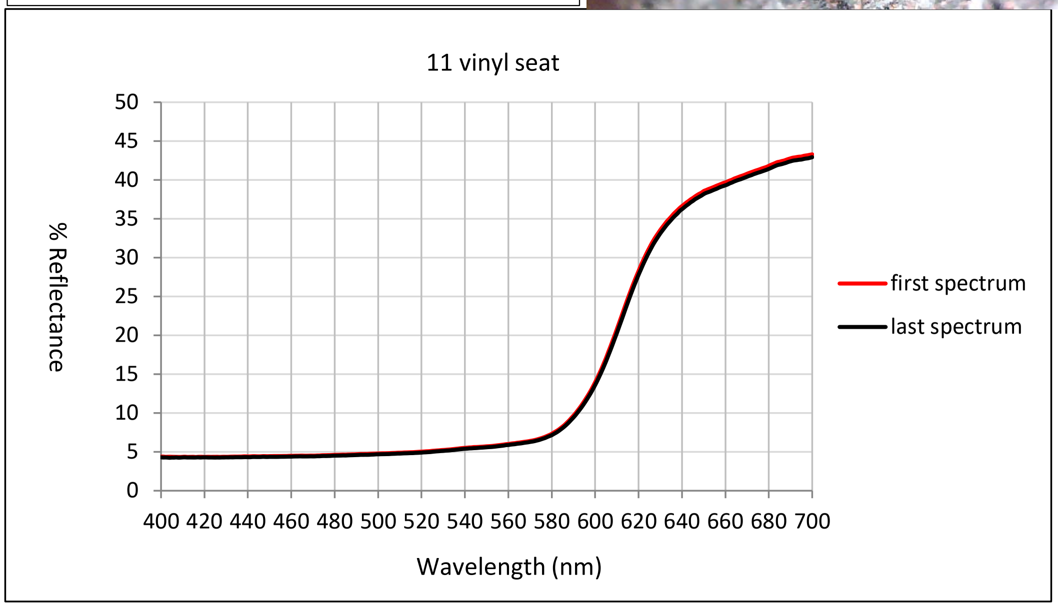


Figure 14. Vinyl bench seat red. Little if any response (lightfast). The very small initial change is probably bleaching of the yellowed plastic.



16

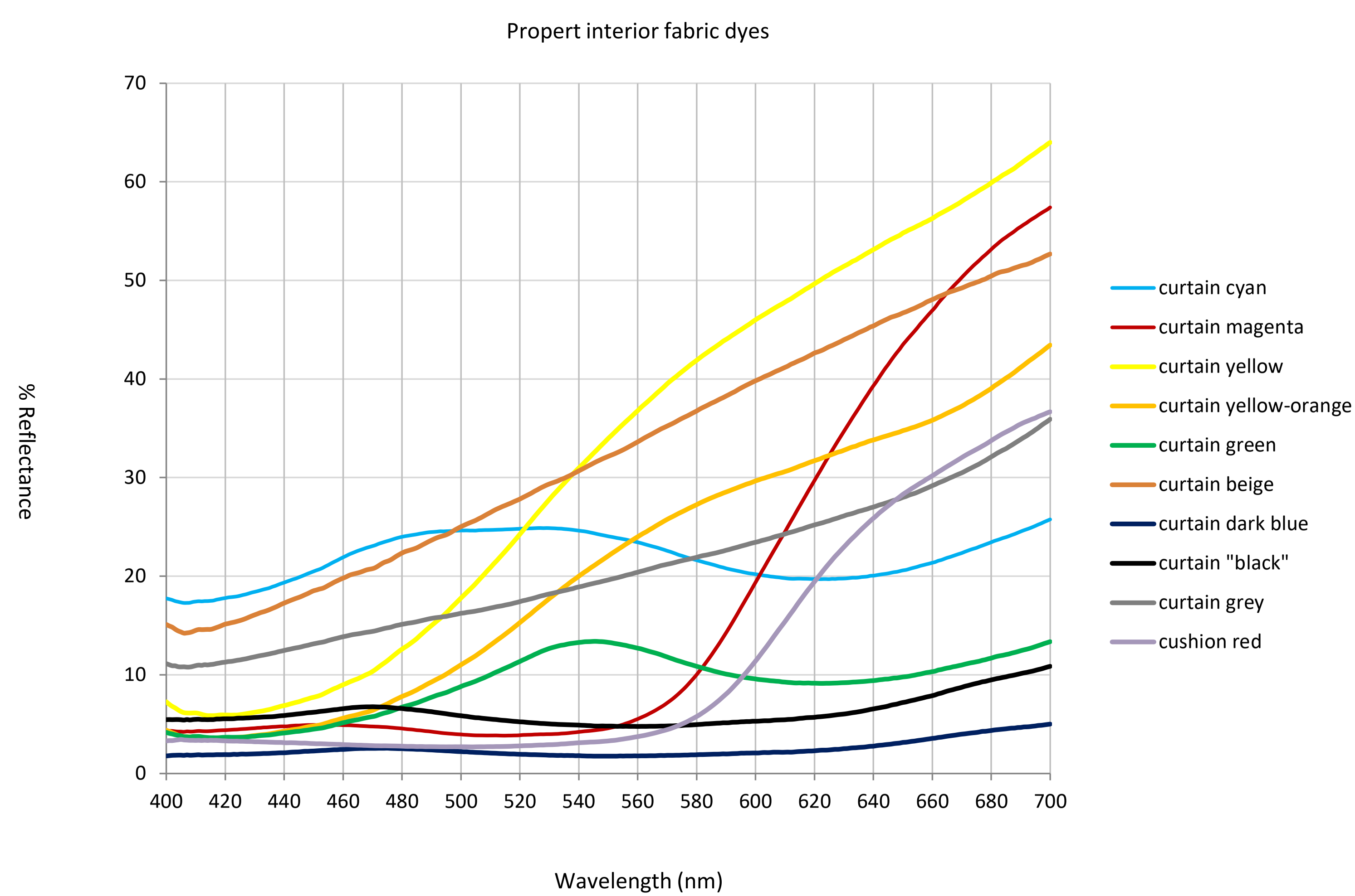


Figure 15. Dye spectra. It is probable that only three dyes were used for the image colours – cyan, magenta and yellow. Green is a mixture of yellow and cyan and yellow-orange a mixture of red and yellow, dark blue (“black”) may be all three.

17

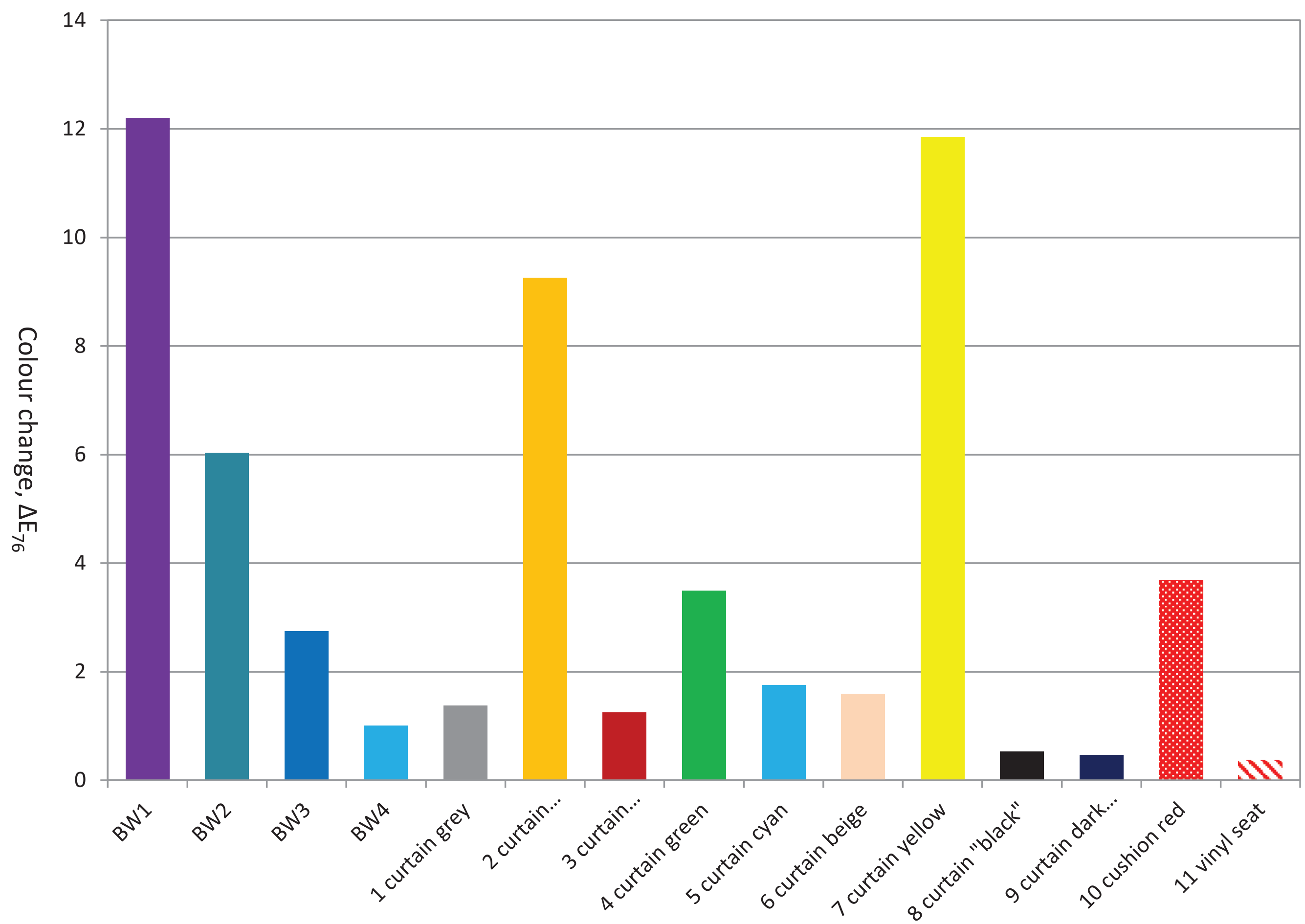


Figure 16. Relative colour change rates , CIELAB (CIE1976)

18

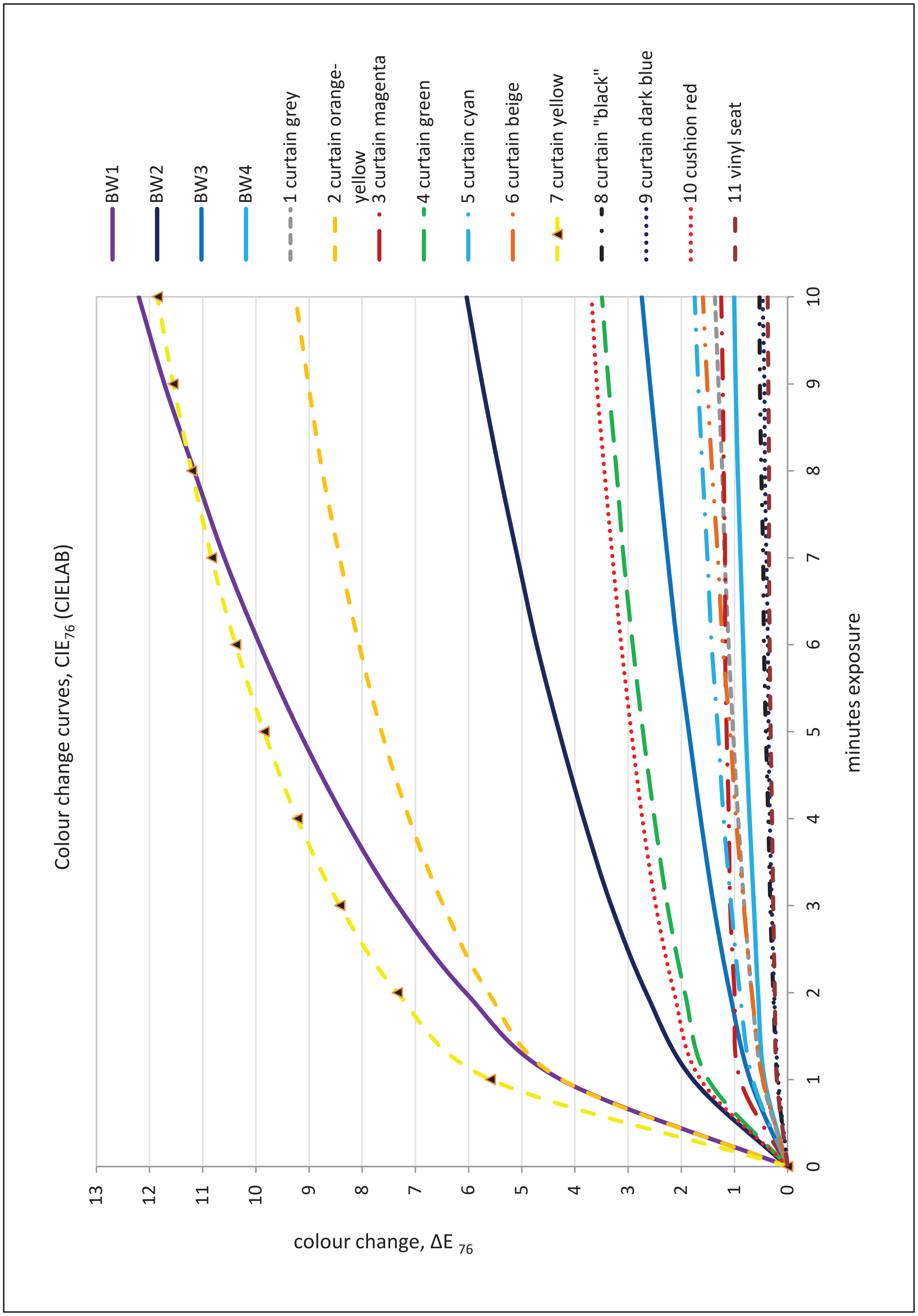


Figure 17. Colour change curves, CIELAB (CIE1976)

Endnote 1
Microfade testing is an accelerated test method and there are uncertainties surrounding the correlation between what is observed at very high intensities and what is likely to occur on display and during subsequent storage (Whitmore et al 2000). It is a semi-quantitative risk assessment tool rather than necessarily predictive. The results in this case apply only to UV-free light.

Endnote 2
For the purposes of this report colour change (ΔE) has been calculated using the CIE's 2000 (CIEDE2000) colour difference formula which replaced the earlier and much simpler 1976 (CIE76 or CIELAB) equation. Relative fading rates using the latter calculation are also provided in Table 1 and Figures 16 & 17. While much of the accelerated and ambient fading instrumental data in the conservation literature has been calculated using CIELAB, CIEDE2000 is likely to be more representative (CIE 2001). The ability of an "average observer" to notice differences between blues was exaggerated by a factor of about two in CIELAB. This affects the relative fading rates of the ISO Blue Wools (BWs) used as internal standards and other colourants not affected by the revision to the same degree. There are many other colour difference equations, all of which will give different results - for example CMC, S-CIELAB, and a proposed I* (I-star) metric for photographs (McCormick-Goodhart 2007).

Michalski's estimates of cumulative eexposure (megalux hours, Mlux h) resulting in a just noticeable fade or difference (JNF or JND) for each of the BWs (CIE 2004) are themselves approximations with an estimated maximum error of ± 1 BW step (Michalski 2010). Therefore absolute predictions of the response of a colourant to a particular exposure (mlx-h) are possibly uncertain to a similar extent. The most recent (unpublished) research by the CCI and GCI indicates that for BWs 2-5 Michalski's estimates are reasonable, but the lightfastness of BW1 is overestimated by as much as a factor of two or three (Druzik 2016).

Endnote 3
Microfading cannot predict post-exposure colour changes that may occur in undyed and unpigmented fibres and paper because only the immediate photochemical response is measured and not the effect of concurrent and subsequent thermal (oxidative) yellowing reactions (Feller 1994). Light exposure accelerates subsequent yellowing of paper via a thermal (non-photochemical or "dark") mechanism involving residual photochemical reaction products. Thermal discolouration depends heavily on temperature, chemical processing of fibres, pH, exogenous and endogenous pollutants, prior conservation treatments and so on. To further complicate matters, ultraviolet directly yellows, rather than bleaches, groundwood paper and most natural fibres like wool. For example the rapid discolouration of newspaper in sunlight is the result of UV (<400nm) yellowing outpacing visible (>400nm) light bleaching.

Endnote 4
The NMA assumptions (Ford BL & N Smith 2009) are based on those of the V&A Museum (Ashley-Smith et al 2002): that is works should last for at least 500 years in a coloured form; a Just Noticeable Difference (JND) = 1.6ΔE and 10 JNDs signal the effective end of coloured life for an object. This may sometimes be a conservative estimate because approximately 30ΔE represents complete fading, but for low chroma colours it seems reasonable. The absolute fading rates of the BWs are taken from CIE157 (2004), see Endnote 2. CIE157 recommends colourants less lightfast than BW3 be exposed only half as much as the V&A's 2 years/decade at 50lux recommendation.

The NMA further makes a judgement based on a significance test as to whether the object/collection is likely to be in strong demand for exhibition in the future (i.e. at higher risk of fading over time) and adjusts recommended exposures accordingly. Objects judged more likely to be in continuing demand are displayed more conservatively (Ford BL & N Smith 2009) .

References
Ashley-Smith, J, Derbyshire, A & B Pretzel 2002, The continuing development of a practical lighting policy for works of art on paper and other object types at the Victoria and Albert Museum, *Preprints of the 13th triennial meeting of the ICOM Committee for Conservation in Rio de Janeiro*, vol.1, pp. 3-8.

CIE 2004, *CIE157-2004*, *control of damage to museum objects by optical radiation*, Vienna: Bureau Central de la Commission Internationale de l'Éclairage.

CIE. 2001. Improvement to industrial color difference evaluation, *CIE technical report 142-2001.* Vienna, CIE Central Bureau.

Druzik J.M., Getty Conservation Institute (GCI), personal communication, 18th November 2016

Feller, RL. 1994. *Accelerated ageing: photochemical and thermal aspects*. Research in Conservation No. 4, GCI.
http://www.getty.edu/conservation/publications_resources/pdf_publications/accelerated_aging.html

Ford, B & N Smith, 2009, The development of a significance and risk based lighting framework at the National Museum of Australia, *AICCM Bulletin* vol. 32 pp. 80-86.

Michalski, S., Canadian Conservation Institute (CCI), personal communication, 10th October 2010.

Refs ctd.

McCormick-Goodhart, M. 2007. *An introduction to the I* Metric*. Aardenburg Imaging and Archives.

Tse, S. 2016. Personal communication.

Whitmore, PM, Bailie, C & S Connors 2000, Micro-fading to predict the result of exhibition: progress and prospects, in *Tradition and Innovation: Advances in Conservation*, ed. A. Roy and P. Smith, pp. 200-205. London: IIC.

The Canadian Conservation Institute website has an excellent general introduction to light and museum collections: http://www.cci-icc.gc.ca/resources-ressources/agentsofdeterioration-agentsdedeterioration/chap08-eng.aspx

For a complete list of references to microfading and its applications see http://www.microfading.com/resources.html

Blue wool equivalent (BWE)	1	1.5	2	2.5	3	3.5	4
Lightfastness (Mlux h/JND)	0.2	0.6	1.0	1.8	3.0	5.5	10

Light level (lux)	up to 50 lux	50 - 80 lux*	50 - 80 lux*	lighting as required*
Display high significance	individually decided	2 years/decade	5 years/decade	period of exhibition
Display normal significance	individually decided (2 years/decade)	5 years/decade	period of exhibition	period of exhibition

*minimum consistent with good display

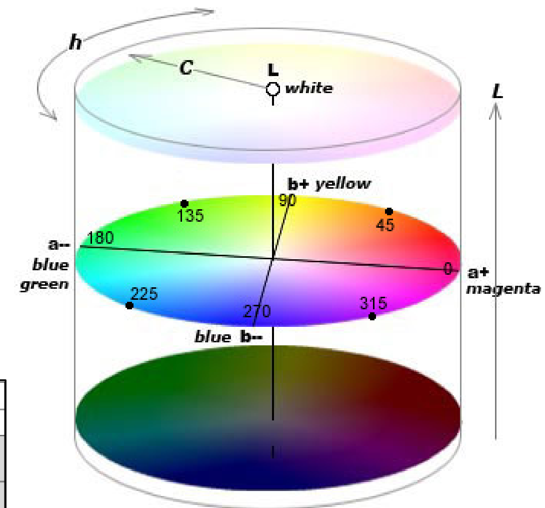
Figure (a) Appendix NMA lighting guideline

BW4-2 taken from Michalski's BWFS estimates from *Running A Museum, a practical handbook* ICOM 2004. *http://portal.unesco.org/culture/en/ev.php-URL_ID=36646&URL_DO=DO_TOPIC&URL_SECTION=201.html More recent estimates of BW1 put it at about 0.1-0.2 Mlux h/JND (UV-free), less lightfast than Michalski's estimate (Druzik 2016)*

Instrument Settings

Luminous flux (mlm)	~650
Spot lux (megalux)	~ 6-8
Spot diameter (mm)	0.4

Figure (b) Appendix. Simplified L*a*b* colour space



L* a* b* and L C h are different ways of describing the same shift in CIELAB space

L* = Lightness
a* = red-green axis
b* = yellow-blue axis

C = vividness (chroma)
h = hue angle anticlockwise from red (0)

21

About the Authors

Vincent Laudato Beltran is an associate scientist at the Getty Conservation Institute and active in the Conservation Institute's Preventive Conservation group and Managing Collection Environments Initiative. Since joining the GCI in 2002, he has participated in a range of research and teaching efforts on topics such as environmental management in hot and humid climates, environmental data analysis and visualization, packing case performance during transit, and mechanical characterization of historic materials. He organized and moderated the 2018 MFT Symposium and Experts Meeting held at the Conservation Institute and authored its summary report, *Advancing Microfading Tester Practice,* which is available online. He holds a B.S. in general chemistry from the University of California, Los Angeles, and an M.S. in oceanography (geochemistry) from the University of Hawaii at Manoa.

Christel Pesme is a collection care specialist trained in paper conservation at the University Paris 1-Sorbonne. She has lectured extensively on the use of MFT to formulate display recommendations and developed numerous MFT workshops for conservators. Introduced to MFT in 2004 during a Conservation Institute graduate internship with Jim Druzik, Christel joined the GCI's Preventive Conservation group in 2008, contributing to the development of a portable MFT prototype and conducting light sensitivity assessments for the Getty Research Institute and the J. Paul Getty Museum. She returned to Europe in 2012 where she worked as a private preventive conservator and MFT consultant. In 2017 she became the Senior Conservator at the M+ Museum in Hong Kong and led efforts to develop collection care practice and establish their conservation staff and laboratories until departing in 2020.

Sarah K. Freeman is an associate conservator in the Paper Conservation Department of the J. Paul Getty Museum. She earned her M.A., C.A.S. in art conservation at the State University College at Buffalo, and a B.S. in art history from the University of Wisconsin, Madison. Her interests include preventive care of photographs and experimental photography. Sarah has participated in research and non-destructive analysis on photographs in the museum's collection, which includes extensive holdings of 19th- and 20th-century photography from all over the world. She has presented and published on the use of the MFT to assess light sensitivity of photographs, technical studies on 19th-century photographic processes, and mounting and storage of large format prints.

Mark Benson is an assistant conservator in the Getty Research Institute's Conservation and Preservation Department and has worked in museums and special collections for fifteen years. He earned an undergraduate degree in art history from the University of California, Los Angeles, and is pursuing his M.A. in preventive conservation at Northumbria University, Newcastle. His role at the Research Institute is focused on preventive conservation policies and procedures with an emphasis on light sensitivity assessments, integrated pest management, and managing collection storage environments. Mark is currently working on a series of experiments pairing color monitoring and microfading to investigate differences between real-time and accelerated color change for various types of media commonly found in library and special collections.

Getty
Conservation
Institute

getty.edu/conservation