"VIRTUAL FADING" OF ART OBJECTS: SIMULATING THE FUTURE FADING OF ARTIFACTS BY VISUALIZING MICRO-FADING TEST RESULTS

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ABSTRACT—The authors examine the importance of visualizing the color changes of colorants exposed to visible light, and use this information to create a "virtually faded" art object. The color information collected during lightfastness measurement (as CIE L*a*b* values) with a micro-fading tester can be transformed to RGB values, and color swatches representing the original and faded colors displayed on a computer monitor. Such demonstration of the appearance changes can help to visualize the degree of color change and the precise nature of that change, which may not be simple lightening of the color but could also include hue or chroma changes. Judging the visual impact of a light-induced color change requires viewing the altered color in its context within a particular image. Digital renderings of paintings were created with Adobe Photoshop and Matlab, using a number of fugitive colors, the fading characteristics of which had been recorded with prolonged micro-fading tests of 100–1920 minutes in duration depending on the light dosage required for the color to no longer be changing. Based on this information describing the appearance of each of the colors as it changes with light exposure, simulations of the "virtually faded" painting were generated, representing the image appearance with incremental light exposure. Such virtually faded simulations can offer insight into the severity of particular light-induced color changes, allow targeting of crucial color areas that might warrant tracking in a color monitoring program, and inform discussions about the "end of exhibition life" of an object and appropriate exhibition rotation policies.

TITRE—La décoloration virtuelle des objets d'art: simuler la décoloration future des artefacts en visualisant les résultats de tests de micro-décoloration RÉSUMÉ—Dans cet article, on discute de l'importance de visualiser les changements de couleur des colorants lorsqu'ils sont exposés à la lumière visible, et on utilise ces informations pour créer un objet d'art ≪décoloré virtuellement≫. L'information recueillie sur la couleur, lors d'essais de solidité à la lumière (sous le modèle CIE L*a*b*) à l'aide d'un testeur de micro-décoloration, peut être transformée en valeur RGB, et les échantillons de couleurs originales et décolorées peuvent être présentés sur un écran d'ordinateur. De telles démonstrations d'un changement d'apparence peuvent aider à visualiser le degré de changement de couleur et la nature de ce dernier, qui peut être non seulement un simple pâlissement de la couleur, mais aussi un changement chromatique ou de tonalité.

Juger de l'impact visuel d'un changement de couleur causé par la lumière requiert l'examen de la couleur altérée dans son contexte, au sein même d'une image. Dans cet article, on illustre cette approche. Grâce à Adobe Photoshop et Matlab, on a créé des peintures numériques en utilisant un certain nombre de couleurs fugaces dont la décoloration caractéristique a été compilée à l'aide de tests prolongés de micro-décoloration. La durée de ces tests variait de 100 à 1920 minutes selon la dose de lumière requise pour que la couleur ne présente plus aucun changement. Grâce à cette information, qui décrit l'apparence de chacune des couleurs au fur et à mesure qu'elles changent suite à leur exposition à la lumière, on a créé des simulations d'une peinture ≪décolorée virtuellement≫ de façon à montrer son apparence suite à une exposition prolongée à la lumière. De telles simulations peuvent élargir nos connaissances sur la sévérité d'un changement de couleur particulière, ce qui permet de cibler des zones de couleurs sensibles qui méritent un suivi lors d'un programme de contrôle de la lumière et aussi d'alimenter les discussions sur la ≪durée de vie d'exposition≫ d'un objet et sur les politiques adéquates de rotation des expositions.

TITULO—"Decoloración virtual" de los objetos artísticos: simulación de la futura decoloración de los artefactos mediante resultados de pruebas de microdecoloración RESUMEN—Este trabajo examina la importancia de visualizar los cambios de color en los colorantes cuando se los expone a la luz visible y utiliza esta información para crear un objeto artístico "virtualmente decolorado". La información sobre el color recogida durante una medición del efecto de la luz (utilizando valores de L*a*b* CIE) en un reactivo para micro-decoloración, puede ser transformada a valores RGB, y se pueden mostrar en el monitor de una computadora como muestras de color que representan los colores originales y los decolorados. Tales demostraciones de los cambios de apariencia pueden ayudar a visualizar el grado de cambio en el color y la naturaleza precisa de ese cambio, que puede no ser simplemente aclaramiento del color, sino que podría también incluir cambios en el matiz (hue) o la intensidad del color (chroma). Para juzgar el impacto visual de un cambio de color inducido por la luz, es necesario ver el color alterado en su contexto, dentro de una imagen en particular. Este enfoque se ilustra en este trabajo. Las representaciones digitales de los cuadros fueron creadas con Adobe Photoshop y Matlab, usando una cantidad de colores fugaces cuyas características de decoloración habían sido registradas con pruebas prolongadas de micro-decoloración de una duración de 100–1920 minutos, dependiendo de la dosis de luz requerida para que el color dejara de cambiar. Usando esta información que describe la apariencia de todos los colores a medida que cambien con una exposición a la luz futura, se generaron simulaciones de los cuadros “virtualmente decolorados,” que representan la apariencia de la imagen con una futura mayor exposición a la luz. Tales simulaciones “virtualmente decoloradas” pueden ofrecer una percepción de la severidad de algunos cambios de color inducidos por la luz, permitiendo dirigirse a algunas zonas de colores cruciales, que podrían justificar un seguimiento en un programa de control, e informar las consideraciones sobre el “fin de la vida de exhibición” de un objeto y las políticas apropiadas de rotación de exhibiciones.

TÍTULO—“Descoloração virtual” de objetos de arte: simulação do futuro descoloramento de artefatos através da visualização de resultados de testes de micro-esmaecimento RESUMO—Este artigo examina a importância da visualização das modificações da cor dos corantes quando expostos à luz visível e utiliza esta informação para criar um objeto artístico “virtualmente esmaecido descolorado.” A informação sobre a cor recolhida durante a medição dos parâmetros da luz (com valores $L^*a^*b^*$ da *CIE*) com um analisador de micro-esmaecimento pode ser transformada em valores *RGB*, e amostras de cor representantes do original e cores descoloração podem ser exibidas num monitor de computador. Tais demonstrações das modificações de aparência podem auxiliar na visualização do grau da mudança de cor e na natureza precisa dessa modificação, a qual pode não ser só uma simples iluminação da cor mas que também pode incluir uma alteração de tom. Avaliar o impacto visual de uma alteração cromática induzida pela luz requer uma observação da cor no seu contexto e numa imagem específica. Este procedimento é ilustrado neste artigo. Apresentações digitais de pinturas foram criadas com *Adobe Photoshop* e *Matlab,* utilizando um número de cores fugidias com características de esmaecimento descoloração que foram registradas através de testes de micro-esmaecimento descoloração prolongados de 100–1920 minutos de duração, dependendo da dosagem de luz requerida para a cor não sofrer mais alterações. Com esta informação descrevendo a aparência de todas as cores conforme mudam com uma futura exposição à luz, simulações de pinturas “virtualmente descoloridas” foram criadas, representando a aparência da imagem após uma maior exposição à luz. Tal simulação de “‘descoloração virtual” pode oferecer compreensão acerca da severidade das alterações da cor induzidas pela luz, permitir classificar áreas coloridas cruciais justificando um programa de monitoramento da cor e informar discussões sobre o “fim da vida em exposições” de um objeto e políticas corretas de rotatividade de objetos em exposições.

1. INTRODUCTION

Fading due to light exposure is a serious concern for the long-term preservation of colored art objects, books, and archival materials. Appropriate lighting design for galleries, acceptable light exposure doses for types of objects, and exhibition rotation schedules for sensitive objects, are all measures intended to control the damage associated with light exposure. With a few exceptions, these prescriptions are developed from prior experience with collections of similar objects. For instance, watercolors and woodblock prints, textiles, and photographs, having been observed to be prone to fading damage, are considered classes of light-sensitive objects. Consequently, they are exhibited with low light levels and at infrequent intervals. The drawback to this collections management approach is that it addresses average (or most common) risks and is not tailored to the individual needs of particular objects. Not every watercolor is extremely light-sensitive, for example. Conversely, an object that belongs to a class that is considered relatively resistant to fading changes—an oil painting, for example—might actually be more light-sensitive than the norm. It could have been created using some unusually unstable material, or it could be in an exceptionally pristine condition that leaves it much more vulnerable to fading damage due to light exposure. Assessing the light sensitivity of a particular object through conventional examination or identification of its constituent materials remains very difficult.

The advent of digital cameras has allowed for digital rendering of art objects at specific instances in time (Lossau and Liebetruth 2000). Emphasis has been placed on creating an accurate color representation of the object (Berns 2001; Martinez et al. 2002; Liang et al. 2005; Saunders 2006). This allows one to determine its current condition, provide a comparison for changes that occur before and after treatment, and provide a method for tracking color change from exhibition of the object. By tracking the color changes that occur over time, one can get a better understanding of the light-sensitive pigments on an object and potentially alter exhibition policies to better reflect the object’s sensitivity rather than using generic categories to assess an object’s stability. However, tracking the changes of an object through its natural course of aging can take a very long time, during which the object is subject to significant damage if careful exhibition conditions are not strictly followed.

To address this problem of determining the light sensitivity of an individual object on a more realistic time scale, an instrument has been developed that makes direct measurements of color change upon exposure to visible light, which indicate the tendency of the color to fade. This device, called a micro-fading tester, has been described in detail previously (Whitmore et al. 1999). Briefly, this instrument continuously measures the reflectance spectrum of a tiny area on a colored object (approximately 0.4 mm diameter), using very intense visible light (the focused output of a filtered xenon arc lamp) as the probe. If a material is prone to fade, exposure to the probe beam will cause the reflectance spectrum to change. The amount of the color change that occurs during the exposure is indicated by the color difference (CIE ΔE) calculated from the collected reflectance spectra, and the rate of color difference produced can be compared to the performance of fading reference standards (ISO Blue Wools) to describe the lightfastness of the colored material. Since its development, the micro-fading tester has been used successfully to determine the light sensitivity of many different types of artifacts (Bowen et al. 2002; Whitmore 2002; Druzik and Whitmore 2004; Connors et al. 2005).

However, there is much color information collected by the micro-fading tester that is underutilized when only evaluating the numerical CIE ΔE information. The reflectance spectra collected during the test lend themselves to examination for the changes in optical absorption or scattering that occurred. The individual color components (the L^*, a^*, and b^*) used to calculate the color difference as a measure of *how much* the color changed can also be analyzed to give a more detailed description of *how* the color changed. This is particularly instructive in cases where the color did not fade in the conventional sense—increasing in lightness towards white—but instead changed hue, as might occur during the fading of one component of a mixed color, or darkened, as has been observed for pigments such as vermilion or red lead (Druzik and Whitmore 2004).

In addition to the more detailed description of light-induced color change that can be derived from the raw spectral or color data in the test, the numerical view of the data is limited, in that it expresses fundamentally visual changes in numerical terms. The development of this quantitative language of color is a triumph of the field of color science. Yet for many users whose experience with these quantities is limited, it is a difficult challenge indeed to understand how large a visual difference is indicated by a ΔE of 15, for example, or a hue shift of some particular amount. The micro-fading tester has “observed” the color change, but that perception has been translated into the numerical language of color. While the information is present in the data, it takes an experienced color analyst to visualize the change in his/her “mind’s eye.” Or as the noted color scientist Deane Judd put it, “Perceptions can only be experienced: description is only a faint reminder of prior experience” (Judd and MacAdam 1979, 516).

There is a final limitation of the fading test results that prevents an easy interpretation of the finding in terms of the severity of the color change, that is, the visual impact of the light-induced color change on the aesthetic of the overall image or artifact. Fading tests are done on areas of color, treated as tiny scientific samples divorced from any context. As pointed out by color scientists, however, the surrounding areas of color can affect the perceived appearance of a color (Jameson and Hurwitz 1959; Judd 1962) and color change. Furthermore, the function of the color area in an image or as part of an object can vary widely, and alterations of that color can have profoundly different effects on the perceived “image loss.”

This paper illustrates how one can more fully utilize the detailed color information recorded by the micro-fading tester. Procedures are described that allow the visual display of the color areas before and after a fading test to gain insight into the magnitude and nature of the light-induced color changes after a given light exposure dose. Finally, by inputting the fading test results of individual color areas to manipulate an image of the object using an image-editing software program such as Adobe Photoshop, one can generate the future appearance of an object after it will have suffered color changes from additional light exposure. Such a simulation, while only approximate, can highlight problematic color areas that, by virtue of their light sensitivity and critical importance to an image, would become the targets for a color monitoring program. These virtually faded images can also form the basis for a more informed debate about the expected exhibition life of an object and about a sensible rotation policy for exhibition of light-sensitive objects. There are many different means to create the visual appearance of colors from the data acquired in fading tests, and the procedures presented here are not meant to be prescriptions. The following cases are meant simply as demonstrations of the value of presenting measured color data in visual formats.

2. DISPLAYING COLOR CHANGES FROM REFLECTANCE SPECTRA

As described above, the micro-fading tester measures and stores reflectance spectra during the exposure of a color area to intense visible light. By simple calculations described in many color science textbooks (Berns 2000; Johnston-Feller 2001), one can reduce the spectral data (reflectance at each wavelength) to color coordinates in any of a number of systems, such as tristimulus values (X, Y, Z) or the CIE L*a*b* system. In order to recreate that color, one needs to translate the color coordinates into the language used for computer displays, projectors, or printers. Typically, monitors use red, green, and blue (RGB) values to define the colors, corresponding to the three color phosphors used in the screens, and printers will use CMYK values or other systems, corresponding to the inks used to create a print. For the demonstrations described here, RGB values were used to create images on a computer monitor, and these displays are approximately translated to the color images on the pages of this article. It should be noted that care must be taken to calibrate the color display used (see Appendix for details).

The value of displaying the colors is illustrated in the following example. Micro-fading tests were performed on two green colors, one composed of a green colorant and the other a mixture of a blue and yellow colorant. For the purposes of this demonstration, the fading tests were continued to rather large light doses, in order to generate easily perceived changes in the colors. One would, of course, rarely test an art object to cause such easily observed faded areas. The color differences for the two green materials are shown in figure 1. Strictly based on the ΔE information, these two colors show similar light sensitivities, with the rate of color change initially high, gradually slowing to a very low rate at the end of the test. This is the extent of the information provided from the color difference results, which have conflated the L*, a*, and b* changes into a single numerical value.

However, the L*, a*, and b* values for each spectrum measured were recorded in the data file during the micro-fading test, and these provide the full description of how the color changed during the light exposure. The L*, a*, b* values can thus be extracted from the fading test data files and processed using an algorithm in Matlab (Mathworks, Version 7.04, see Appendix for algorithm) that converts them to red, green, and blue values. With the RGB values for each measurement during the fading test, the colors at each stage during the light exposure can be displayed. Figure 2a was created in Microsoft PowerPoint (see Appendix for details) and shows swatches of color as a function of light exposure during the tests of the two green colors. Swatches have been created at about

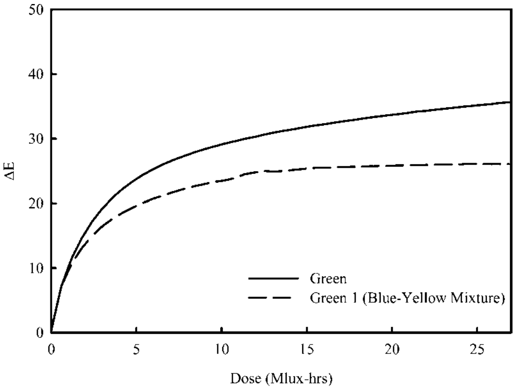

Fig. 1. Color difference (ΔE) as a function of dose for two green colors at large exposure doses. The solid line is the result for a single green colorant, and the dashed line for a mixture of blue and yellow.

Table 1. Light-Sensitive Colors Used to Create the Virtually Faded Images and Conditions for Fading Experiments

Color	Material	Mixture composition	Time of fading test (minutes)	Collection interval (minutes)
Burnt Orange	Radiant Water Color[1]		1020	5
Hyacinth Blue	Radiant Water Color[1]		100	1
Pumpkin	Radiant Water Color[1]		1920	5
Tapestry	Radiant Water Color[1]		850	10
Magenta	Gouache[2]		260	5
Blue	Marker[3]		150	5
Green	Marker[3]		420	5
Lime	Marker[3]		265	5
Pink	Marker[3]		300	5
Wisteria	Marker[3]		254	1
Green 1	Marker[3] + Gouache[2]	Blue + Spectrum Yellow	225	5
Purple 1	Gouache[2]	Magenta + Turquoise Blue	120	2
Purple 2	Marker[3] + Gouache[2]	Blue + Spectrum Red	1420	5
Red	Gouache[2]	Geranium + Spectrum Yellow	1520	5

1. Dr. Ph. Martin's Concentrated Radiant Water Color Series C.
2. Winsor Newton designer gouache.
3. Crayola marker.

the same color difference (ΔE) for each of the two greens. A plot of the L*, a*, and b* values as a function of dose for both greens is shown in Figure 2b to delineate the color changes that are seen in the swatches. Comparing the progressive changes in color for the two samples, one sees that, despite the similar fading rates (color difference over time), the two greens have followed very different courses of fading. The green color composed of a single colorant (top row of figure 2a) increased in lightness and seems to fade "on shade," that is, without a significant hue shift (increase in only a*, or greenness, see figure 2b). The mixed green, however, shows a pronounced shift in hue from green to yellow, a result of the preferential reaction of the blue component in the mixture (increase in both the a* and b*, see figure 2b). By tracking the color change visually instead of only monitoring the numerical ΔE values (fig. 1) or the numerical changes in the a* and b* values (fig. 2b), one can get a better sense of the nature and severity of the color change produced from light exposure. Without viewing the data as color swatches, the very different fading that occurred between the two green colors might have been missed.

3. COLOR CHANGES IN CONTEXT

The fading of a colorant can have various effects on an image, ranging from severe to minimal, depending on where in the object the changing color occurs. Figure 3 illustrates this phenomenon, using as an example the fading of the mixed green color, green 1, of the previous illustration, in three different contexts. (Art pieces shown throughout this paper are digital renderings of paintings. Initial and faded colors used in these renderings were generated using the L*a*b* values collected from micro-fading test results of actual paint samples prepared on watercolor paper. Table 1 provides a list of all colors used throughout these analyses and table 2 describes the specific colors used in each study object that was created.) The top row in figure 3 shows three images before fading has occurred due to light exposure. In each case, only green 1 reacts to light exposure, losing the blue of the blue/yellow mixture, while all other colors on the object are unchanged. The lower row of images shows how the objects would appear after the blue has been completely lost from the green color mixture.

In the first image of the series (fig. 3a), the green color occurs in a very minor position in the composition, and its fading, while a distortion of the artist's original intent, affects the interpretation of the picture in a rather insignificant way. In the second and third images (figs. 3b and 3c), the image is a picture of a target, and the green is used as the background in figure 3b and in the rings of the target in figure 3c. When the green of figure 3b fades to yellow, there is a significant loss of contrast between the background and the target, which is a more substantial image loss than seen

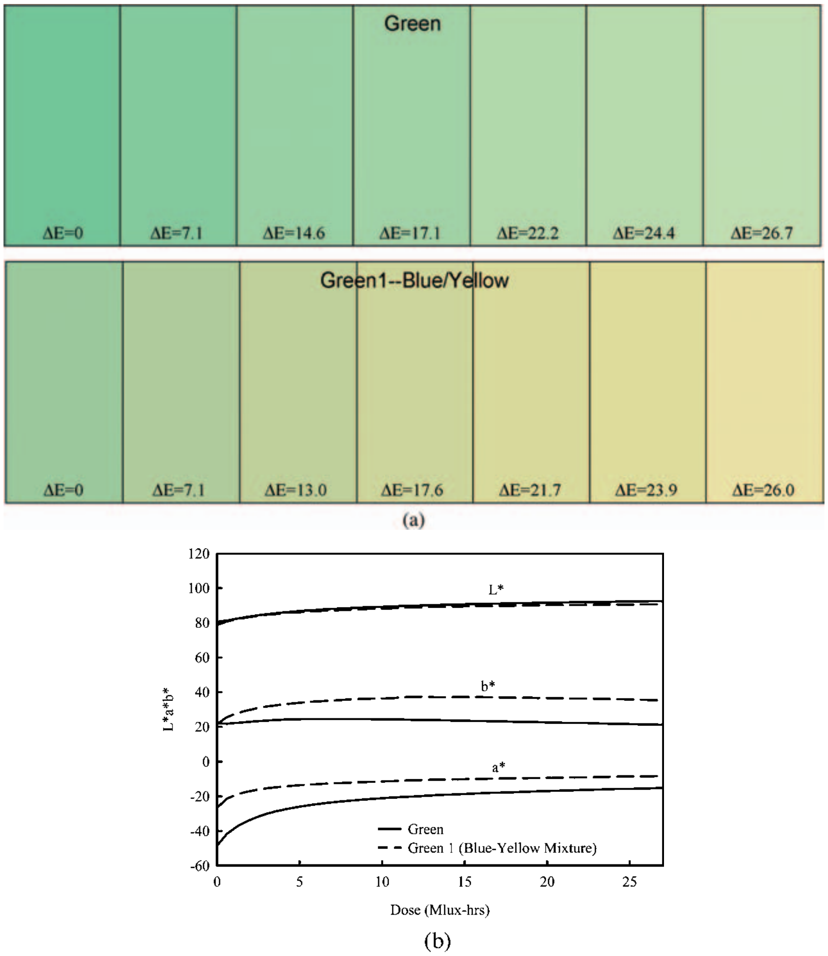

Fig. 2. Fading of two green colorants (Green and Green 1 in table 1) as a function of light dosage using data collected with the micro-fading tester: (a) Color swatches generated from the calculated RGB values (the color pairs are shown at comparable ΔE values); (b) L*, a*, and b* values. The pure green colorant, Green, fades "on shade" with an increase of value, while the mixed green, Green 1, shifts hue as the blue component fades from the mixture.

in figure 3a. However, the image can still be read as a target. In figure 3c, when the green color fades, the rings of the target completely disappear. The image is now one of a yellow circle on a purple background, instead of a target. Fading of the green to an equivalent degree has had a much more profound effect in figure 3c than in figures 3a or 3b. Since awareness of the context plays such a significant role in determining the extent of damage due to color fading, promoting this awareness was the motivating factor behind creating the methodology for visualizing the actual color change on an object.

4. VIRTUAL FADING OF OBJECTS

The fundamental steps in creating the predicted appearance of virtually faded objects are straightforward. First, micro-fading tests are performed on all the color areas of the object. Sometimes the virtual fading simulation is used to examine the effect of a particular light exposure dose, such as the outcome from a specific exhibition condition. In such a case, fading tests are done for a period that produces the equivalent light dose of interest. In other cases (as will be discussed below), one seeks to examine changes that will occur

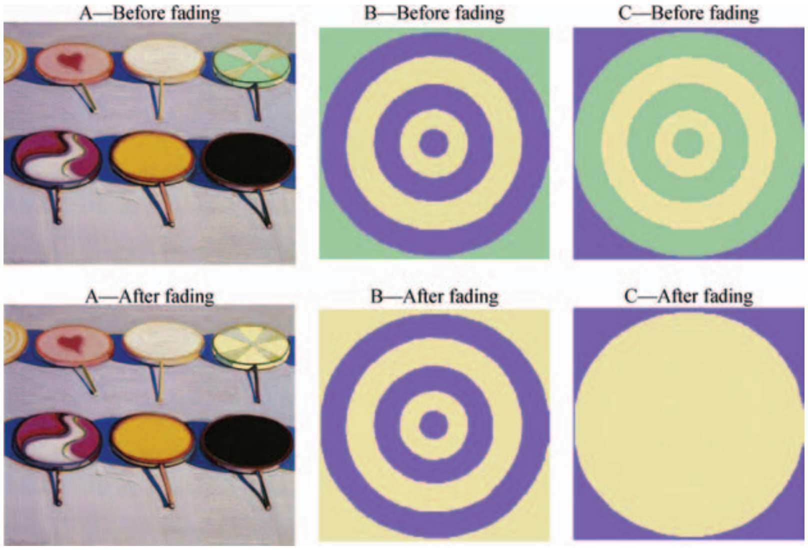

Fig. 3. Three examples of image change of digitally simulated art objects, Seven Suckers and Target, caused by the fading of a mixed green before light exposure, 0 Mlux-hrs, and after 26.3 Mlux-hrs light exposure, demonstrating the importance of color changes in context.

Table 2. Colorants Used to Create Rendering of Virtually Faded Art Objects*

Study Object	**Artist**	**Figure**	**Color**	**Location**
Seven Suckers	Wayne Thiebaud	3A	Green 1	Upper right sucker
Target	Jasper Johns	3B	Hyacinth Blue	Outer rings
			Green 1**	Background
			Faded Green 1	Inner rings
		3C	Green 1**	Outer rings
			Hyacinth Blue	Background
			Faded Green 1	Inner rings
Double Gray Scramble	Frank Stella	5	Hyacinth Blue	Outer 3 squares
			Green	Next square
			Tapestry	Next 2 squares
			Pumpkin	Next square
			Burnt Orange	Inner 3 squares
Woman with a Flower	Pablo Picasso	6	Magenta	Outer face
			Wisteria	Inner face
			Tapestry	Hair
			Pumpkin	Flower
			Green 1**	Upper Leaf
			Green	Lower Leaf
			Purple 2	Branches
			Green/Lime	Alternating stripes on collar
			Burnt Orange	Breasts
			Red	Claw on shirt
			Wisteria	Right arm
			Blue	2 shirt triangles
			Hyacinth Blue	Inner shirt
			Purple 1	Left arm
			Pink	Left body
			Lime	Right body

* The images were created from scanned pictures of the original artwork. The parameters for the listed colors were digitally inserted into specified locations of each image for purposes of the virtual fading simulation.

** Only Green 1 is fading with dose while the other colors remain unchanged.

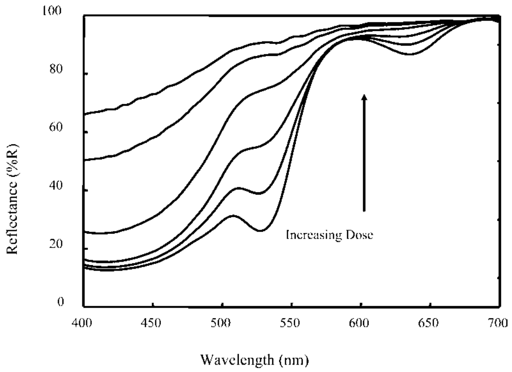

Fig. 4. Micro-fading test results for an orange color at long light exposure doses: 0, 0.6, 3.6, 28.6, 114.6, and 229.2 Mlux-hrs. The test was stopped when the ΔE was no longer changing.

after very large light doses, projecting color changes occurring far into the future. For that purpose one must do prolonged fading tests that will reproduce these very large light doses. Naturally these tests will also create significant fading changes on the test areas on the object. While severe fading from this testing would occur only in these very tiny areas, leaving perceptible damage equivalent to the removal of a pigment sample, one should still be prudent in such examinations of collections materials. For the purpose of illustration, all the fading tests were performed on the color samples prepared on watercolor paper to very large exposure doses, until there was no more change in the ΔE with light exposure. The colors produced during the course of the prolonged fading tests were then used to digitally "paint" the renderings of the digitally simulated art works. An example of the spectral change occurring during such an "ultimate" fading test is shown in figure 4. Once fading tests have been performed on each of the colors, the RGB values can be calculated for each color as a function of light exposure, using the software formula in Matlab for converting L*a*b* values to RGB, as described in the Appendix.

These RGB fading test results are now used to alter the colors in a digital image of the object, thus creating the virtually faded appearance of an object. While it is straightforward to capture such an image of an artifact in its current "original" state with a digital camera or scanner, it is usually necessary to "unify" the colors first, that is, to alter the image so that the colors are uniform in each color area. The reason for this step is that the fading tests have been performed on only selected small spots within each color area, and one must assume these test spots to be representative in color and fading behavior of the larger areas. If the test spots are not representative of the larger area,

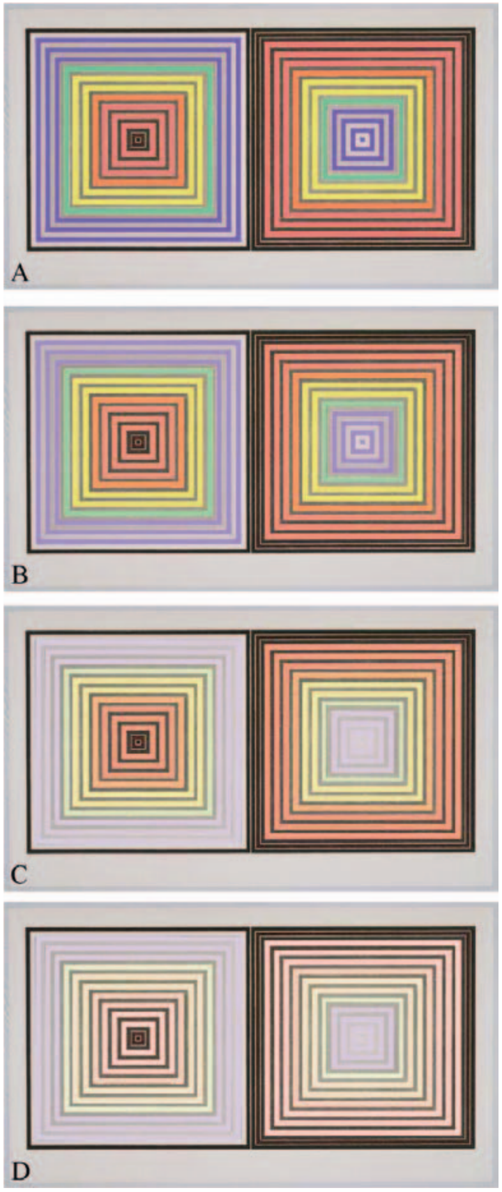

Fig. 5. A series of virtually faded images of the digitally simulated art object Double Gray Scramble as a function of light dose: (a) 0 Mlux-hrs, (b) 1.8 Mlux-hrs, (c) 21.5 Mlux-hrs, and (d) 181 Mlux-hrs.

Fig. 6. Virtually faded images of the digitally simulated art object Woman with a Flower used to visualize the end of exhibition life of an object. Light doses are: (a) 0 Mlux-hrs, (b) 1.8 Mlux-hrs; (c) 8.4 Mlux-hrs, and (d) 229 Mlux-hrs.

such as in areas having poorly blended or scumbled color mixtures, or if the image itself is comprised of many small but unique color areas (an area having a gradation in tone, for example), the procedure described here will not be easily implemented or will produce only very gross renditions.

Once a digital image of the object has been captured and the colors unified, one proceeds to alter that image by repainting each of the color areas with the colors that were measured at a given light dose during the fading tests. This can be done in any of a variety of ways using image manipulation software. An automated procedure using Adobe PhotoShop and Matlab is described in the Appendix.

An example of this image manipulation is shown in figure 5. The four images show an object at different stages of fading as a function of light exposure. The initial image in figure 5a shows the object in its current state, prior to light exposure. The image is a pair of nested squares. The nested squares on the left side progress through the color spectrum from purple to orange moving toward the center; the opposite progression from orange to purple comprises the set of squares on the right side. Through appropriate use of the initially bright colors within the nested squares an optical illusion is created to give the piece spatial depth. As the colors fade (shown in figures 5b–d) the balance of the different colors is lost and the optical illusion is altered. This illustrates that as visible light alters the colors, the image is changed in a much more complex way than simply the gradual lightening of an image. Essentially, the delicate balance between hue, value, and intensity of color as well as the proper proportion of space allotted to each color creates a very complex, and easily distorted, visual whole.

Therefore, through the creation of such virtually faded images, the light-induced appearance change of an image can be evaluated. The color changes that are most important to the reading of the image might thus be identified, and these may or may not be the locations where the fading is most rapid. These critically important color areas could then become the targets for color monitoring programs designed to track the color changes that most significantly affect the appearance of an object.

5. THE "END OF EXHIBITION LIFE" FOR AN OBJECT

To some extent, decisions of exhibition policy for light-sensitive artifacts rest on some estimation of the light dose that an object can withstand before its aesthetic value has been reduced to some trivial residual. This assessment of the object's lifespan is then apportioned to briefer exhibition periods separated by longer intervals, in order to increase the number of years over which an object can be shown. These rotation schedules are almost always vexing negotiations. A central reason for this difficulty is the poor grasp of the quantities involved. For example, how much light can an object withstand until the end of its exhibition life? What is actually going to be lost as the object suffers unavoidable damage from light exposure, and can one be more specific about the appearance change that will effectively make an object "unexhibitable"?

This paper cannot offer any prescriptions to resolve these debates, for they are fundamentally curatorial judgments based on many factors, only one of which is the object's light sensitivity. However, the virtually faded images that may approximate the future appearance of an object, especially as it becomes exceedingly faded and nears the state of being at the end of its exhibition life, may be helpful aids to making these judgments. If one could visualize the future appearance, and determine the changes that will have the greatest impact on the image aesthetic and that will ultimately establish the endpoint for its exhibition life, one might be in a position to make better estimates of maximum tolerable light doses and appropriate rotation schedules.

This analysis is illustrated with the series of images shown in figure 6. (See table 2 for details of the colors used to create images from a study object.) The first image (fig. 6a) represents the current state of an object, in this case a painting on paper, before further light exposure. The final image in the sequence (fig. 6d) illustrates the appearance after all colors in the object have faded to their ultimate color according to the micro-fading tests (229 Mlux-hrs light exposure). The intermediate images, figures 6b and 6c, are the simulated appearance at intermediate light doses.

In the image portrayed, the colors in the different areas fade at different rates, which is a typical situation for multicolored objects. The blues, purples, greens, and pinks fade quite rapidly, leaving behind the yellow, orange, and red colors that fade much more slowly. In this image, the colors in the lower half of the object are fading very quickly, so that by the time the object has been exposed to 8.4 Mlux-hrs of visible light (fig. 6c), the entire lower portion of the image has essentially faded to its final color. One might reasonably argue that this extent of damage can be called the end of the object's exhibition life. However, at this stage the upper half of the image, which is the abstract rendition of a woman's face, is still recognizable, and the colors in that portion have not been completely lost until a much greater light dose of 229 Mlux-hrs (fig. 6d). One could also reasonably argue that this degree of fading is the end of exhibition life, and the object would have a much longer exhibition life than the prior judgment. Certainly there is no simple or unique resolution to such a debate. But by creating these virtually faded images that will provide a reasonable approximation of the future appearance of an object, one can begin to debate more specifically the severity of change from certain exposure conditions, the acceptable appearance changes over time, and the different results of particular exhibition rotation schedules.

6. ADVANTAGES AND LIMITATIONS OF VIRTUAL FADING OF OBJECTS

Creating a virtually faded image using data collected with the micro-fading tester provides a simple way of visualizing the potential changes that can occur to a piece of art from exposure to visible light. Because the micro-fading tester provides results of color fading under accelerated aging conditions, the data is collected on a relatively quick time scale (days as opposed to years required for light damage from natural aging to become evident.) The manual processing time for creating a set of images that comprise the change in the art object as a function of light dosage can be extensive. This requires converting all the data into RGB values from L*a*b* values, inputting each faded color into a single image at a specific light dosage and repeating the color change for each subsequent recorded light dosage. However, by creating an automation sequence in Matlab software, the process time is greatly reduced to a matter of minutes.

Since fading tests are performed on only a single point within a color region, the color changes may under- or overestimate the amount of fading that can occur for the entire area. Also, spot testing assumes the color regions to be uniform rather than retaining the rich color texture present in many actual images. Therefore, this type of image simulation works best when performed on materials that have large areas of uniform color, such as Color Field paintings or woodblock prints, so that the digital renderings using spot test data faithfully capture the essential color and image attributes.

There are also limitations associated with displaying the virtually faded images on a computer monitor or color printer. If the color is outside the gamut of the display or output device, as would be the case for fluorescent paints that have a very high value or saturated colors with very high chroma, the monitor will be unable to accurately display the color. Under these conditions, the RGB values will be truncated to fall within the gamut of the monitor or printer. While this is a limitation for the appearance of the initial image prior to light exposure, as the fading progresses the colors will probably eventually fall within the gamut of the monitor or printer and be appropriately displayed.

The examples presented in this study provide extreme conditions of light exposure where the colorant has reached a negligible level of color change with further light exposure. Such light exposure tests will create very small but detectible faded spots, whose size is comparable to the damage left by removal of a pigment sample. Care needs to be taken to minimize the effect of this damage on an art object.

7. CONCLUSIONS

The creation of the micro-fading tester has brought about the ability to non-destructively test the light-sensitivity of colors on artifacts. However, reducing the fading information to changes in a single ΔE value, which is all that is necessary to assess stability, does not allow full advantage to be taken of all the other color information that is acquired during the tests. This paper shows some of the utility of examining the color data. By displaying color swatches generated using the data, it is much easier to envision the degree of change in a given color, and how that color is being altered from visible light exposure. Placing the faded colors in the context of the tested image permits more sophisticated judgments to be made of the severity of fading damage to the image, and not just to its constituent colors. Finally, the creation of virtually faded images from the micro-fading tester data can show the changes from a specific light exhibition condition or the progressive changes that will occur over the life of an object. Such future appearances can inform otherwise difficult determinations of appropriate exhibition and acceptable fading damage.

APPENDIX: EXPERIMENTAL

Rather than taking measurements directly on valuable art objects, color samples were painted on hot press watercolor paper and tested with the micro-fading tester. All the colors that were used for creating virtually faded images were chosen from very light-sensitive designer gouaches (Winsor & Newton), color markers (Crayola), and Dr. Ph. Martin's Radiant Concentrated Water Colors Series C. Dye solutions were obtained from the ink of the color markers by drawing the color on paper and washing with water. The water was mostly evaporated to concentrate the color. The last four colors in table 1 were a mixture of two colors created by mixing the two components previously dissolved in water. The first component listed for the mixture is light-sensitive, while the second component of the mixture is relatively light-stable. The light intensity for the micro-fading tester was set to 900 millilumens to reduce the time required to reach the final faded color for all the colors (typical light intensity for micro-fading tests is 600 millilumens). Each of the colors was quickly tested to roughly evaluate the light-sensitivity. In order to reduce the amount of data, the data collection time for each color was then chosen so that color information for the very fugitive colors was captured at frequent intervals, while the changes to the more stable colors were recorded less frequently. The total test times and collection intervals for each color tested in this study are listed in table 1. In many of the fading experiments for individual colors, to reach the point where the color was no longer changing required more than 7 hours, a time period long enough to cause concern for instrumental drift. To address this concern, at the end of each experiment the light intensity was remeasured; the drop in intensity for all the colors was less than 3.3%. Therefore, the color change due to long light exposure was significantly greater than the fluctuations in lamp intensity, which were determined to have minimal affect on the L^*, a^*, and b^* values.

To convert $L^*a^*b^*$ values stored in the fading test data files to RGB values, the following algorithms in Matlab were used. The calculation requires the $L^*a^*b^*$ values derived from the spectral data to be calculated using CIE Illuminant D65 for the proper conversion of the data to RGB values. The $L^*a^*b^*$ values were first converted to standard RGB (sRGB) color space, a standard color space in the color industry (IEC 1999), and then to the RGB value, calculated by multiplying the sRGB value by 255, the maximum value for RGB. (See table 3.) In Matlab, the command "makecform" creates a color transformation and the command "applycform" applies the color transformation. (See table 3.)

Prior to creating color swatches and virtually faded images using the color data obtained from the micro-fading tester, the color monitor was calibrated with commercial instrumentation and software (X-rite Monaco Optix). Colors with known RGB values are displayed on the screen and the RGB values are collected with a colorimeter that is attached to the monitor. The system will profile the current color conditions of the monitor and apply a correction which ensures that the colors are displayed appropriately. Once the monitor has been calibrated, the RGB values collected from the micro-fading tester representing the color fading as a function of time are assured color accuracy in their display.

Many commercial software packages will allow the input of RGB values to display color. In figure 2a, the color swatches were created in Microsoft PowerPoint software by inputting the RGB values calculated as a function of light exposure. The swatches were created by drawing empty (without any color fill) rectangles on the page. Then the desired colors

Table 3. Matlab Transform Commands for a Color Called lab_color

Command	Function
cform = makecform('lab2srgb')	transforms L* a* b* to sRBG
rgb_color = applycform(Lab_color, cform)	applies the color transform on the color in L* a* b* to create a color in sRBG

were defined for the "fill color" button (paint bucket), by selecting the "more fill colors, custom" tab. The RGB color calculated from the L*a*b* measurements at a specific light dosage was entered, then the paint bucket control was used to fill the rectangle with the color. A new color was created for each subsequent light dosage, and other swatches in the series were filled to display the color changing as a function of light dosage.

To render the virtually faded images shown in figure 6, a digital image was captured and altered using Adobe PhotoShop. First the color areas were unified by selecting each region in the image of a similar hue and reducing it to a single color, the initial color measured in that area in the micro-fading test. In Adobe PhotoShop, the magic wand tool was used to define the region of interest, the fill color was defined with the appropriate RGB value, and the region was filled using the paint bucket tool. In order to automate the repainting of the image for the sequence of light exposure doses, individual masks were created for each color in the image to be altered. Each mask mapped the color area of interest as white, while the remainder of the image in the mask was left black. This created a binary map that could be used to indicate the color regions to be updated at each light exposure. These masks were saved as JPEG files and were imported into Matlab for analysis.

A single look-up table was compiled listing the RGB values as a function of light dosage for each color. Rather than creating images for every measured point in the fading test, virtually faded images were created only for those measurements that showed a significant change ($\Delta E > 1$) in at least one color. Also, since the collection intervals were not the same for all of the colors, at some doses their colors had not been measured. When this occurred, unmeasured colors were kept at their previous RGB values for that image. When a color reached the end of its fading—for example the blue had finished fading at 150 minutes—the color information from the last data point was used until the end of the virtually faded image series.

To create a virtually faded image at a given light dose, a Matlab program was created that chooses a pixel from the image and determines whether the first color is present at that location by looking up that pixel location in the first mask. If the mask pixel is black, the chosen color is not present. If the color of that mask pixel is white, indicating the presence of that color at that image location, the program then looks up the appropriate RGB for that color at that light dose from the look-up table and replaces the original pixel color with that new (faded) color. Once each pixel in the mask has been analyzed, a new image, called "temp_image," is created in which all regions of a specific color have now been changed to the new RGB value for the specified light dosage. This process is repeated for the next mask, which will analyze and alter the current temp_image, rather than the original. After all masks have been analyzed in this way, an image will have been created in which all the areas have been changed to their color at a specific light dosage.

At this point, the first two images of a series have been created, a "before fading" image and a "light dosage one" image. The program now increments to the data set gathered for the next light dosage in the series ("light dosage two"). The same procedure is applied to compare each pixel in the different color masks and adjust the appropriate pixels to the new faded colors to create the light dosage two image. In this way, the fading data set is translated from a set of numbers describing the course of fading to a series of images whose colors are changed as a function of light dosage.

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SOURCE OF MATERIALS

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