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A Study on the Human Ability To Detect Soot Deposition onto Works of Art

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Works of art can become soiled due to the deposition of airborne black soot particles within museums and art galleries. The soot particle deposition rates are already known for many environments, but knowing the levels of carbon particle coverage at which humans can detect image darkening is also important. Therefore, in this work, human subjects have been tested to determine their ability to detect soiling by black carbon particles deposited onto specially prepared samples having colored backgrounds. The results show that certain observers are able to detect that a sample is becoming soiled once surface coverage by black carbon particles has reached 2.4% if the soiled samples and clean samples are placed directly adjacent to each other, producing a sharp dividing line (an "edge-to-edge" comparison). Observers can detect the presence of soiling with greater than 90% accuracy during an edge-to-edge comparison on most backgrounds when soiling levels reach approximately 3.6% surface coverage by black particles. If the comparison between soiled and clean samples must be made with samples that are separated from each other by a neutral gray area, soiling is only detected with 100% accuracy once coverage by black particles has reached 12.0% surface coverage. These results show that a greater accumulation of black carbon than was previously thought is required to produce a visibly soiled surface.

Introduction

Air pollution is an unfortunate result of a modern society. One form in which air pollution is manifested is through particulate matter that is introduced into the atmosphere by factories, internal combustion engines, and burning of fossil fuels to produce energy. Particles suspended in the atmosphere are continuously deposited onto all exposed surfaces. As many of these particles are not transparent, they will alter the appearance of the exposed surfaces. This is especially apparent when soot, consisting mostly of fine black elemental carbon particles, is deposited onto surfaces. The microscopic black particles will absorb light that would usually be reflected back by the exposed surface. This has the effect of making the exposed surface appear darker.

The problem of darkening of surfaces by deposited soot is especially critical in museums and art galleries. Most pieces of art in these institutions are exposed to the atmosphere and, therefore, to airborne soot. The art objects are often very valuable, and great care must be taken to preserve the appearance of each piece for future generations. The cleaning of works of art is difficult, expensive, and in some cases, impossible; thus, it is extremely important to minimize the rate of particle deposition within buildings housing works of art. Some museums protect sensitive objects in air-tight glass cases, but this can alter the appearance of the art and is inappropriate in many situations. As an alternative to the use of sealed display cases, museums and art galleries often install complex air filtration systems into their heating, air conditioning, and ventilation systems to reduce the concentration of airborne particles that can enter the building from outside or that are generated by the occupants inside the building. Unfortunately, soot particles are found in very small particle sizes of a few tenths of a micrometer in diameter and, due to their small size, can pass through many of the filters used in common ventilation systems (*1, 2*). Many museums, especially those found in historic buildings or private residences, lack any air filtration systems at present. Thus, many museums must consider how to deal with the problem of deposited soot particles soiling their collections.

Soot is extremely difficult, and many times impossible, to remove. It can settle into the pores of stone sculptures or form a thin adhesive layer on the stone surface. Acidic components of the soot particles can also cause decay, and when the soot is impossible to remove, this decomposition is virtually impossible to stop (*3*). Soot can also promote the corrosion of metals (*3*). Often other forms of pollution, such as SO_2 (also produced by combustion), begin the process of degradation by chemically reacting with the surface and changing its physical properties, making it easier for soot particles to adhere (*4*). Soot often cannot be removed from a surface without damaging the art under the soot, and thus the damage is permanent. While the present study will focus on the appearance of soot deposits, the human ability to detect the visual effects of other types of particles would be an interesting subject for future research.

The rates of particle deposition onto interior surfaces within many museums as well as the identities and amounts of the components of aerosol material in museum environments have been studied extensively (*1, 2, 5−7*). It was found that black particle coverage of exposed vertical surfaces within southern California museums proceeded at a rate of 0.08−2.7 μg of black carbon (m of surface)$^{-2}$ day^{-1}, depending on the location of the museum and the sophistication of its ventilation system. Translation of these particle deposition rates into an estimate of the length of time before an object will appear soiled, however, raises many technical problems even though much research has been conducted on how humans perceive color as well as how the human anatomy quantitatively detects color (*8, 9*). In previous work, Carey (*10*) reported that 0.2% surface coverage of black particles on a white background would be visible to the average human observer. This value was determined by creating rings of 0.1%, 0.2%, 0.4%, and 0.8% surface coverage by randomly placing black dots of 0.1−0.5 mm radii on white and gray papers, holding the papers at a distance from the observer so that the individual dots were not visible, and asking the observer to distinguish between the rings and the background. Later experiments by Hancock et al. (*11*) confirmed this value. Yet, many objects of interest, such as fragile tapestries, often present their soot deposits against a deeply colored background and not a plain white or gray surface. Furthermore, recent technical advances make it possible to

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TABLE 1. Colors Used in the Study

color name	Munsell notation	color name	Munsell notation
white	N 9.5	light red	5R 8/4
dark red	5R 4/12	light green	2.5G 8/6
dark green	2.5G 5/8	light blue	5B 8/4
dark blue	5B 5/8	light yellow	5Y 9/6
dark yellow	5Y 8/12		

create test samples of soiled surfaces that mimic actual fine carbon particle deposits better than the test samples used in previous works by Carey (*10*) and Hancock et al. (*11*).

In the present study, the level of soiling at which a human observer can detect a change in the appearance of white and colored backgrounds is determined. This information can be used in conjunction with known particle deposition rates to predict the length of time that an art object can remain in a certain environment without its appearance noticeably changing due to soiling by deposited soot. Test samples are created that are coated by fine carbon particles at carefully controlled levels of coverage. The optical properties of these samples are characterized quantitatively by reflectance spectrophotometry and optical microscopy. Human subjects are given two tests to determine the extent of surface coverage by black particles necessary to produce a visibly darker image. In the first test system (the solid test), the soiled area is separated from the unsoiled area by a neutral gray buffer. In the second test system (the edge test), the soiled area is immediately adjacent to a clean area on the same surface, producing a sharp dividing line that is more easily seen, a phenomenon known as the Craik−O'Brien−Cornsweet effect (*11*−*13*). It has been shown that the color and pattern of the background against which a color is viewed has a great effect on the appearance of the color (*14*).

Methods

To determine the threshold at which the average human observer can detect that a colored background has been soiled, tests were constructed using samples created by printing fine patterns onto color standards. The samples were analyzed by optical microscopy and by reflectance spectrophotometry. Human subjects taking the tests were asked to differentiate between soiled or half-soiled samples and clean samples. Their responses were noted, and graphs were constructed relating the soiling level to the percentage of responses that were correct.

Sample Creation. To create colored surfaces with simulated soiling, carbon black dot patterns were printed onto Munsell QuickColor color standard sheets (21.5 cm × 28 cm) using a Hewlett-Packard 5Si LaserJet laser printer connected to a personal computer. To simulate soiling on different colored backgrounds, nine different Munsell standard colors were used in this experiment (Table 1). The printed dot patterns were designed using the Adobe Photoshop 3.05 computer program. In Photoshop, an array of different 2 cm × 2 cm sections containing gray-scale images of controlled density were created by shading the desired areas at even K values of 2−20 (Table 2). The K variable in Photoshop controls the percent of coverage by black dots within the image, with $K = 0$ being completely white and $K = 100$ being completely black. For each K value chosen, two types of samples were printed for each colored background. For the solid test system, each 2 cm × 2 cm section was uniformly shaded at the specified K value. For the test studying the Craik−O'Brien−Cornsweet effect, only half of each section (1 cm × 2 cm) was shaded while the adjacent half was left blank, producing a sharp dividing line across the sample. During this process, the print transfer rate was set to 60%, resulting in almost microscopic dots with diameters ranging from 60 to 160 μm.

TABLE 2. Percent Coverage of White Samples by Black Carbon As Determined by Optical Microscopy As Compared to Expected Coverage

K value	expected %	% coverage on white	K value	expected %	% coverage on white
2	1.2	**1.3**	12	7.2	7.0
4	2.4	2.4	14	8.4	9.3
6	3.6	3.6	16	9.6	9.8
8	4.8	5.0	18	10.8	11.0
10	6.0	**5.7**	20	12.0	12.1

Therefore, the theoretical percent coverage of black carbon dots on the colored sheets is actually 0.6 times the K value chosen (Table 2).

The HP LaserJet is designed to print on plain paper. The QuickColor Standards are composed of card stock covered with a thin layer of paint. The toner that is used to create black dots is designed to bond to paper, but in some cases it does not bond correctly to the paint layer of the color standards. Therefore, although most of the samples were printed correctly, some exhibited slight irregularities in their patterns. In particular, the printing onto dark yellow sheets was not consistent enough to produce experimental results that would merit analysis, and this color was eliminated from the study. The printing onto some of the other sheets, such as the light green and light red, contained some inconsistencies at the lowest levels of soiling (Table 3, Figures 2f and 3e), and thus the data at lower levels of soiling for these samples are less reliable than for the other samples studied.

Five darkened rectangles of the same color and shaded at the same K value and five rectangles of the same color standard without any shading were arranged in random order on a matte board having dimensions of approximately 4 cm × 48 cm, with approximately 2 cm of space between each sample. The matte board was painted Munsell Neutral Grey Value 7. Thus, each matte board had 10 samples, and there were 20 boards for each color (one board for each K level for the solid test, one board for each K level for the edge test).

Sample Characterization. Examples of each shaded color standard test strip were examined using a Diano MatchScan II reflectance spectrophotometer to determine the total color difference ΔE between the shaded standard and the unprinted standard of the same Munsell color standard sheet. The percent surface coverage by simulated black carbon of each test strip was determined by optical microscopy for each level of surface coverage for each color. ΔE describes the total color difference between two samples in the three-dimensional CIE $L^*a^*b^*$ color system (*15*) computed using the CIE 2° standard observer (*16*) and illuminant D65. The L^* coordinate represents the lightness of the color (0 being black, 100 being white), the a^* coordinate represents the red−green coloration, and the b^* coordinate represents the yellow−blue coloration:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{1}$$

The reflectance spectrophotometer was used to determine the ΔE value under illuminant D65 for each level of darkening relative to an unprinted sample for each color standard (Table 3). Certain of the sheets shaded at 6.0% coverage were found to be darker than the sheets shaded at 7.2% coverage because of inconsistencies in the printing process used to make the samples.

The percent coverage of dots created by the printer was measured by analyzing the samples using an Olympus Model BH optical microscope. Gray-scale 640 pixel × 480 pixel images of the samples were taken by a video camera mounted on the microscope and stored on a Macintosh personal

TABLE 3. Total Color Difference (ΔE) between Shaded Samples and Clean Samples of the Same Color as a Function of Percent Surface Coverage by Microscopic Black Carbon Dots[a]

	12.0% ($K = 20$)	10.8% ($K = 18$)	9.6% ($K = 16$)	8.4% ($K = 14$)	7.2% ($K = 12$)	6.0% ($K = 10$)	4.8% ($K = 8$)	3.6% ($K = 6$)	2.4% ($K = 4$)	1.2% ($K = 2$)
white	6.29	5.64	4.82	4.49	3.33	2.11	1.99	1.06	0.69	0.40
dark green	5.79	5.41	4.30	3.66	2.71	2.35	1.85	1.75	1.21	0.84
light green	6.67	6.53	5.66	4.94	2.82	3.90	3.64	3.34	3.01	3.00
light yellow	6.45	5.19	3.70	2.96	2.75	1.41	1.36	1.86	1.07	0.80
dark red	5.97	4.85	4.94	2.69	1.10	1.64	1.45	1.29	0.81	1.13
light red	5.51	4.71	3.21	2.08	1.52	1.81	1.30	1.10	0.77	0.89
dark blue	4.42	3.75	3.23	2.01	1.38	0.77	0.51	0.39	0.61	0.50
light blue	5.91	4.81	3.84	2.95	1.52	1.65	1.40	0.98	0.73	0.20

[a] Illuminant D65, 2° observer.

computer. The total fraction of the area covered by black dots was calculated from the images using a computer program written in the C programming language. Actual values were very close to the expected values of 0.6K% coverage (Table 2). Values in bold in Table 2 were calculated using the public domain NIH Image program (developed at the U.S. National Institutes of Health and available on the Internet at http://rsb.info.nih.gov/nih-image/) in those cases where a more closely controlled background subtraction was necessary.

Human Testing. To determine the level of darkening at which the average human observer can just detect a difference between clean and soiled backgrounds, 30 persons were asked to participate in a series of tests that would record the accuracy with which they could distinguish between soiled and unsoiled surfaces at different levels of surface coverage. During the tests, all test strips were viewed inside a Munsell Spectralight lighting booth operated using the daylight setting (color temperature 7500 K) in order to provide a standard lighting environment. Subjects were first given the Farnsworth−Munsell 100 Hue test to determine the quality of their color vision. Out of a total of 30 subjects, 1 had inferior color vision, 11 had superior color vision, and 18 had normal color vision. Subjects were then shown the matte boards, each containing five identical soiled samples and five corresponding unsoiled samples arranged in random order. The boards were presented one board at a time in order of increasing level of surface coverage. All colored backgrounds at each level of surface coverage were presented before moving to darker samples. The observers were placed at 75 cm from the samples. Subjects were first shown an example of clean white samples and soiled white samples so that they understood what they were looking for. The subjects were then asked to identify which tiles of each set of 10 were dark and which were light, and the responses were recorded. Subjects were not told that there were five soiled and five clean samples, so that they would not guess according to this knowledge, but only according to what they saw. As many of the subjects were frustrated because they could not see any difference between tiles having the lowest levels of shading, subjects were informed that they might not see any differences for perhaps the first 40 matte boards. Subjects were also asked to ignore any specks of dust that may have deposited onto the samples during use. After completion of the test system that used fully shaded samples without a visible dividing line, subjects were shown the matte boards with the half-soiled tiles and asked to identify the tiles on which they saw a horizontal or vertical dividing line between soiled and unsoiled areas. Again, the subjects were informed that they might not be able to see any dividing lines on the first 10 boards. Because nearly all subjects were able to detect perfectly all half-soiled tiles on the boards shaded at 4.8% surface coverage, the test did not continue past 4.8% surface coverage unless the subject could not detect the difference between half-soiled and unsoiled samples with perfect accuracy on a certain color background. If the subject could not detect with perfect accuracy half-soiled samples when they were shaded at 4.8% surface coverage on a certain color background, the subject was tested at the next higher level of surface coverage, 6.0%, only for that color. This process continued until the subject could detect all of the half-soiled tiles perfectly for that color background.

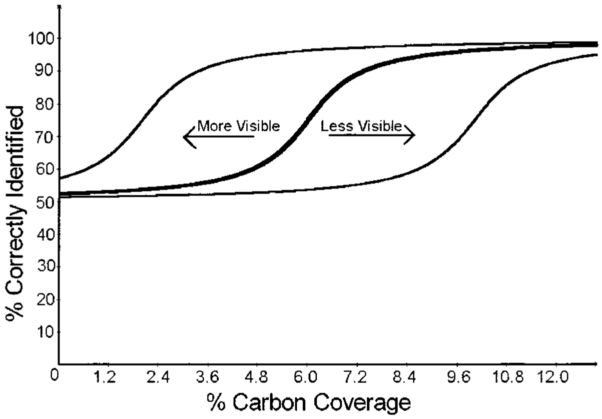


FIGURE 1. Characteristic arctangent curve used to describe the threshold for detection that a sample is soiled.

Data Analysis. For each matte board, the number of correct responses as a percentage of total responses was calculated for each subject. Then the percent correct averaged across all observers was calculated for each matte board. For both test systems, eight graphs, one for each color remaining in the test sequence, were constructed that related percent surface coverage to the percentage of correct identifications averaged over the responses from the population of 30 observers. Error bars represent one standard deviation of the population of responses at each soiling level tested. The graphs were expected to follow a curve similar to that of

$$f(x) = \alpha \arctan((\beta/\pi)(x - \gamma)) + \delta \qquad (2)$$

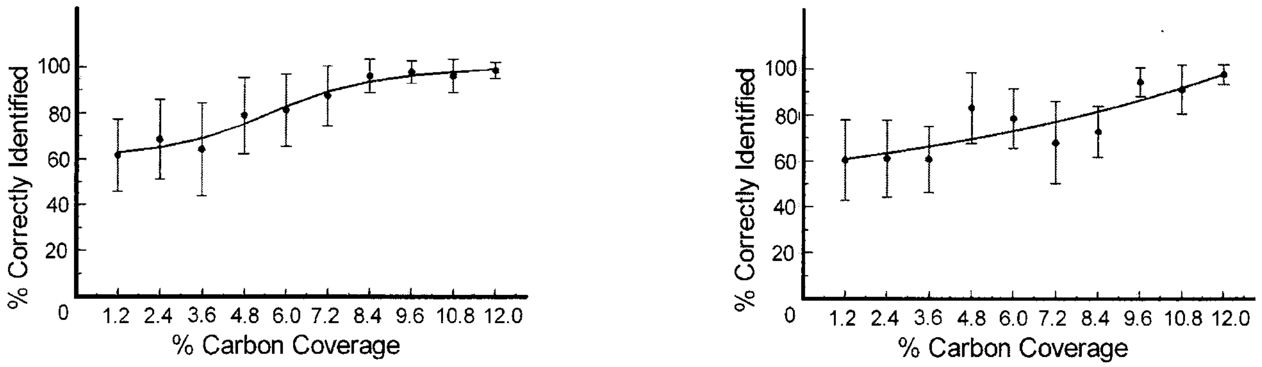
where γ is a constant that describes the location of the threshold at which soiling is just visible. This curve can be used to represent the abrupt transition from a condition when the soiling is imperceptible to a condition when the soiling is visible. In theory, the curve will shift to the left when the average observer can see the darkening better and to the right when the darkening is more difficult to detect (Figure 1). Using Axum, a graphing and data analysis program, the values of parameters α, β, γ, and δ in eq 2 that best fit an arctangent curve to each set of data were selected, and the results are shown in Figures 2 and 3.

Results and Discussion

At the lowest soiling levels studied, the observers' assessment that a particular sample is or is not soiled is correct about

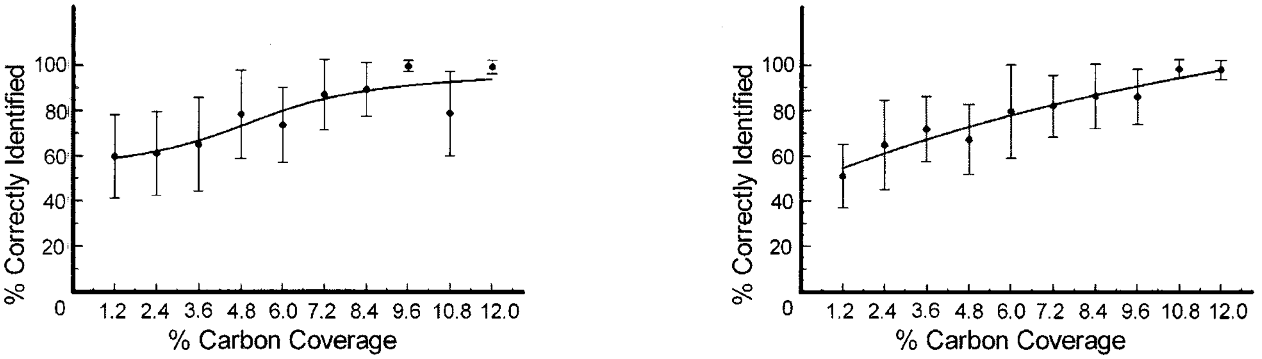
(a) White Solid

(b) Dark Red Solid



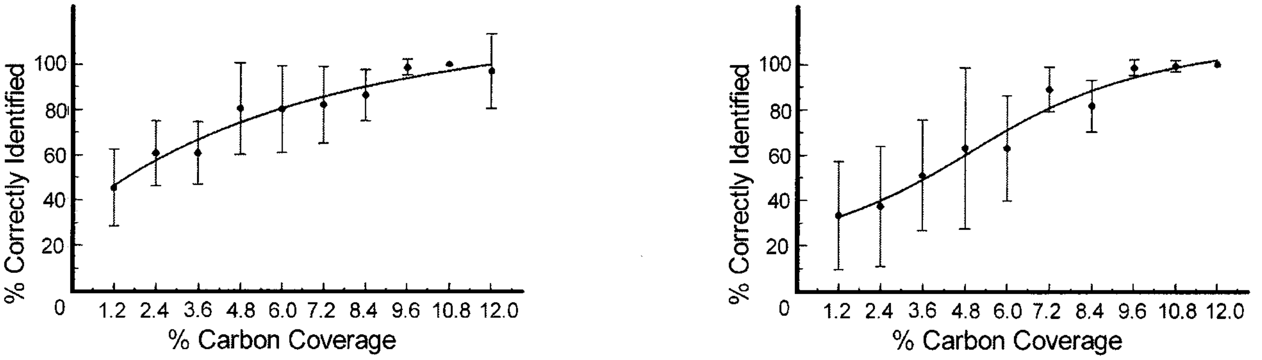
(c) Dark Green Solid

(d) Dark Blue Solid



(e) Light Red Solid

(f) Light Green Solid



(g) Light Blue Solid

(h) Light Yellow Solid

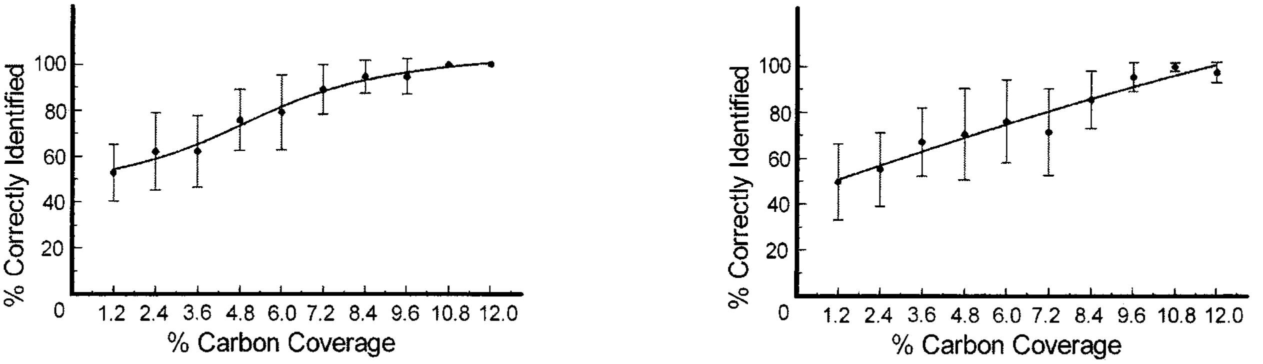


FIGURE 2. Results produced when human subjects were asked to discriminate between soiled and clean tiles when a neutral gray area separated the tiles. The curves fit to the data showed a rather linear increase in soiling recognition as the soiling level was increased.

50% of the time (Figures 2–3), which corresponds to the results expected for a random guess. Clearly a 1.2% surface coverage by microscopic black particles is essentially invisible to the observers under our test conditions. The results from the edge test system are represented nicely by an arctangent curve. This suggests a definite threshold for the ability to discriminate between soiled and clean samples when the soiled area is immediately adjacent to the unsoiled area on the same color chip, providing clear local contrast and producing a visible dividing line (Figures 2–3). The curves

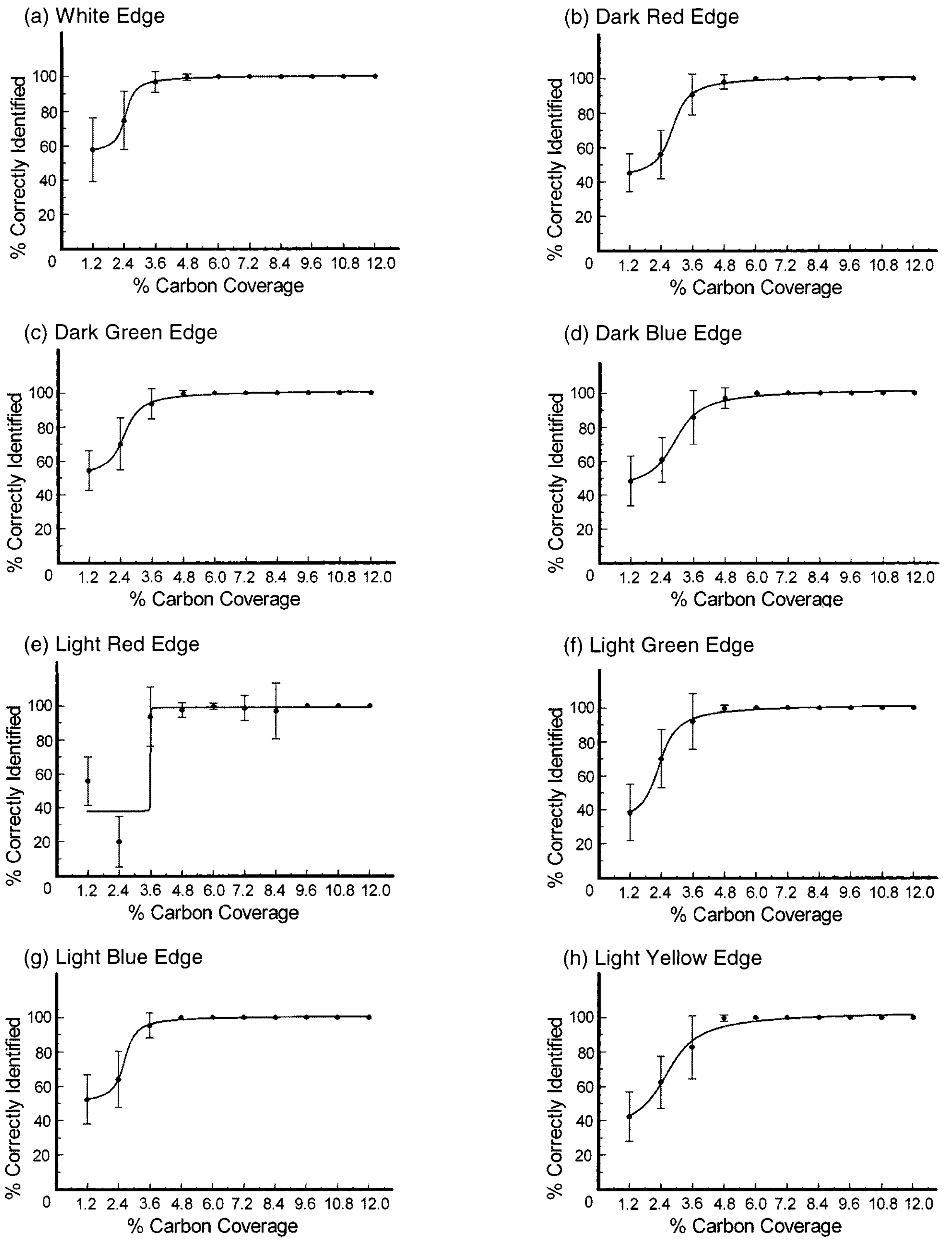


FIGURE 3. Results produced when human subjects were asked to discriminate between soiled and clean tiles when the soiled area was placed directly adjacent to the clean area, producing a sharp dividing line. The curves fit to the data corresponded well to the characteristic arctangent curve and showed definite thresholds for when soiling becomes visible on various backgrounds.

for the tests involving uniformly soiled samples separated by a neutral gray area are more linear and did not show any obvious threshold at which the average observer just begins to see the difference between soiled and clean tiles clearly.

The average percent of correctly identified samples calculated for the data in the solid test system did not always show the continuous increase that would be expected as levels of soiling increased. In some places, these averages were lower for samples with a greater level of surface coverage. Because of the design of the test with uniformly soiled tiles, its results are affected by certain variables that are less important in the edge test, causing greater observer-to-observer variability. For example, the random arrangement of soiled and unsoiled test strips on each matte board was found to have a large effect in certain cases when uniformly soiled samples were viewed. Referring to the graph for the uniformly shaded dark green test (Figure 2c), we see that the average percent of correct responses for 10.8% surface coverage is significantly lower than one would expect. The pattern of color tiles on this particular matte board when chosen at random turned out to be five soiled samples followed by five clean samples, and this was the only matte board that happened to have that pattern. Because the subjects only had one instance in this sequence of samples where they could see a soiled tile followed immediately by a clean tile, it may have been more difficult to determine which tiles were soiled. In general, because the observer had nothing to compare each tile to except other tiles, the observer found that it was much more difficult to identify correctly soiled and clean tiles when they were immediately surrounded only by other similarly soiled or clean samples. In the edge test system, the observer was looking for tiles that were only half soiled; therefore, they always had the opportunity for a side-by-side comparison of the soiled versus clean condition by comparing one side of a tile to the other side.

Thresholds where soiling just becomes visible occur where the curve through the data has a steep slope. Backgrounds on which the soiling is definitely visible at 3.6% surface coverage during the edge test include light blue (Figure 3g) and white (Figure 3a). Some of the darker colors, dark blue, for example, exhibited a less steep threshold, showing that soiling on darker backgrounds can be more difficult to discern. Yet, even on the darker backgrounds, observers are able to see soiling with increased reliability as the amount of soiling increases.

The smallest level of shading at which soiling may be detected with greater than 90% reliability on any background using edge-to-edge comparison is 3.6% surface coverage. This corresponds to a ΔE value of about 1 between clean and soiled samples for the light red, light blue, and white backgrounds (Table 3). Soiling begins to become visible to certain observers at approximately 2.4% surface coverage when making an edge-to-edge comparison. This surface coverage value is 12 times higher than the threshold of 0.2% reported by Carey (*10*) and Hancock (*11*).

These data can be converted into predictions of the time required for a flat vertically oriented work of art hung on a wall and exposed to the indoor atmosphere to become visibly soiled by deposited soot. For example, the area coverage rates by black carbon particles deposited onto vertical surfaces in a variety of southern California museums have been estimated to range from 0.003 to 0.18 $\mathrm{cm^2\ m^{-2}\ day^{-1}}$ corresponding to coverage rates from 3.0×10^{-5} % $\mathrm{day^{-1}}$ to 1.8×10^{-3} % $\mathrm{day^{-1}}$ (*6*). At these rates, it would take approximately 5.4–324 years, depending on the museum studied, for a flat vertically oriented work of art to achieve 3.6% surface coverage by soot and become visibly soiled, if one is able to make an edge-to-edge comparison.

In the case of the test systems involving uniformly shaded samples, 100% reliable identification that the samples are soiled is often not reached until the surface coverage by black carbon reaches 12.0%, corresponding to a ΔE value of roughly 5–7. If an edge-to-edge comparison is not possible and 12.0% coverage is necessary to produce a universally recognized change in color, we predict that it would take approximately 3.3 times longer than in the above example for the artwork to become soiled to that effect. The midpoint in the curves describing the approach to complete detection that soiling is present on a uniformly shaded sample is typically found at about 6.0% surface coverage or a ΔE value of roughly 2. The ΔE values of 1 or 2 at which observers begin to see that the samples are soiled correspond reasonably well to prior expectations of visual acuity based on reports in the literature (*17*).

The main difference between our findings and previous experiments lies in the relationship between the reported surface coverage by black carbon deposited on our samples versus the samples created by Hancock and Carey at the same level of visual detection that the surfaces are soiled. Judging from the descriptions of the prior experiments, Hancock covered his surfaces with visible ink dots and then held the samples at a distance where the dots were reported not to be individually visible. The dots when viewed at close range however did have high contrast against their background, which may have made them easier to detect. Our samples used almost microscopic dots to more closely approximate deposited fine atmospheric soot particles. Our results suggest that higher soot loadings than previously reported can accumulate on objects before they become visibly soiled if the soot particles are microscopic and if the deposit is uniform.

The fact that elemental carbon particle deposits are somewhat more difficult to detect visually than would have been calculated from earlier reports in the literature does not argue that efforts to prevent soiling can be relaxed. In fact, increased attention to this problem may be required. The present findings may mean that management of soiling problems is more difficult than previously expected because the rate of change of the appearance of objects in a museum will be so gradual as to possibly escape the notice of persons who see the collection on a daily basis. Yet the 5-year time horizon for accumulation of visible damage calculated in the earlier example for one unprotected museum in southern California is still far too short a time to be acceptable. Active measures should be taken through the use of particle filtration systems or well-designed display cases or frames to deliberately control black carbon particle deposition rates in museums (*1*).

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