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Topics in Photographic Preservation, Volume 16.
Pages: 47-62
Compiler: Jessica Keister

A Comparative Study of Handheld Reflectance Spectrophotometers

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Presented at the PMG session of the 2014 AIC Annual Meeting in San Francisco, California.

ABSTRACT

This paper addresses the challenges of instrument agreement in color measurement by presenting a comparative study of a group of handheld reflectance spectrophotometers made by two leading companies in the field, Konica Minolta and X-Rite. The project was motivated by the need to replace the spectrophotometer in the Sherman Fairchild Center for Photograph Conservation at The Metropolitan Museum of Art. Measurements were taken using nine instruments on a large selection of samples with the goal of evaluating measurement agreement on a variety of colors, textures, and materials. Results show that instrument agreement depends heavily on factors such as measurement protocol and instrument geometry. However, even with standardization, no two instruments will measure color in exactly the same way. The next step in this project will be to undertake an investigation of methods of standardizing data across instruments.

INTRODUCTION

There is an increasing variety of handheld spectrophotometers available on the market with multiple configurations and price points. Determining the right piece of equipment to use can be challenging, particularly when faced with the problem of data continuity when replacing an older unit. This paper outlines a comparative study of a group of handheld reflectance spectrophotometers manufactured by two leading companies, X-Rite and Konica Minolta. The primary goal of the project was to determine the best instrument to replace the spectrophotometer in the Sherman Fairchild Center for Photograph Conservation at The Metropolitan Museum of Art (The Met). An additional objective was to evaluate the variation in data gathered using multiple spectrophotometers on a set of samples with the goal of better understanding the practical margin of error among this range of instruments.

The group was composed of instruments with 0°/45° and integrated sphere configurations and measurements were taken on a range of samples. For data comparison, The Met's older spectrophotometer was included in the measurements and used as the master instrument against which the test instruments were measured. Samples included the 96 color squares represented on the X-Rite Digital SG Color Checker®, a standard X-Rite ceramic tile, a group of chromogenic photographs, and additional samples with a variety of colors and surface characteristics.

Color Monitoring at The Metropolitan Museum of Art

The photograph conservation lab at The Met began color monitoring using an X-Rite densitometer prior to the 1994 exhibition, "The Waking Dream." By the late 1990's they had also begun to use an X-Rite 968 0°/45° handheld reflectance spectrophotometer, which is still functional in 2015. As a result, the Met has color data on over 400 photographs in the collection, all gathered with the same spectrophotometer. With the instrument no longer supported by the manufacturer, and the software no longer supported by the operating system used by the Museum, the lab needed to replace the spectrophotometer, preferably with one that would agree closely with the current machine.

Given the amount of color data already gathered, the primary concern for this transition related to issues of data continuity. How would the old instrument agree with its replacement? Understanding that an exact match would be impossible, could older data be translated to make it compatible with measurements from the new instrument? There was additional concern regarding software compatibility with current and future operating systems as well as hardware longevity. It was important to find an instrument that might last as long as its predecessor had.

Although the X-Rite 968 spectrophotometer is no longer in production, or supported by the manufacturer, the one used at The Met still provides reliable color data. It has taken consistent readings on its X-Rite calibration tile over the course of several years. This is a metal tile with a ceramic glaze with three color areas: white, brown, and blue. The white is used as the white standard during calibration. The blue and brown areas have been measured periodically since the 1990’s to test for instrument drift, and these measurements have stayed remarkably consistent. The more immediate obsolescence problem had to do with the older X-Rite ColorMaster software, which was no longer compatible with the Museum’s new computer operating system.

In-house Collaboration

In the early planning stages of the project, Scott Geffert, Senior Imaging Systems Manager in The Met’s Photograph Studio became involved. Geffert’s work deals primarily with ensuring that the enormous volume of digital images created in the Photograph Studio are faithful renditions of their subjects and he has incorporated color measurement into his workflow, when possible. This often involves color measurements on the object itself, which he then compares against the values in the digital file and ultimately in the final print. He also has taken on the important task of working towards standardizing the imaging systems and workflows employed in the many conservation labs throughout the museum.

Incorporating the interests of the Photograph Studio with those of Photograph Conservation resulted in an expansion of the project. In all, the full list of research goals grew to include: determining an appropriate replacement spectrophotometer; observing practical differences in instruments and software during testing; evaluating data across manufacturers and instruments in order to develop a set of reference data for future use during image capture in the Photograph Studio.

SPECTROPHOTOMETER BASICS

On the most basic level, spectrophotometers function by reflecting light off of a surface and recording the wavelength distribution of the reflected light. The sample is illuminated with a polychromatic light source and the reflected light is recorded as spectral data by a detector. From the spectral data, tri-stimulus values can be calculated and converted to a number of three-dimensional color spaces. The data presented in this paper is in the CIE L*a*b* color space using the 1976 calculation. (Ohta and Robertson 2005; Johnston-Feller 2001).

Internal Geometry

Hand-held spectrophotometers usually have one of two common internal geometries: 0˚/45˚ or integrated sphere. In 0˚/45˚ instruments, the light source is positioned at a 0 degree angle from the sample and the sensor is 45 degrees from the specular angle. A 45˚/0˚ configuration generates the same results; the light source and sensor are simply switched (fig. 1). The distinguishing characteristic of this configuration is its unidirectional light source, which allows for the exclusion of specular reflectance during measurement.

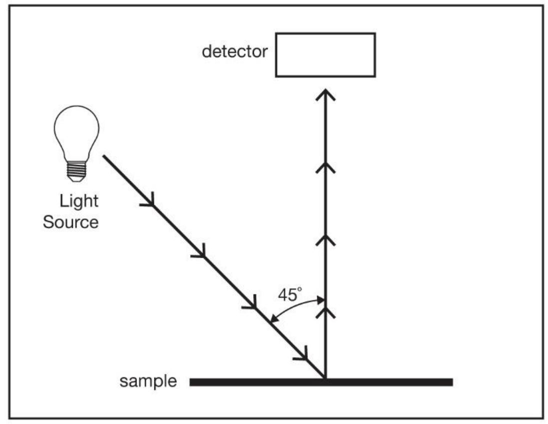

Fig. 1. 45˚/0˚ geometry. A 0˚/45˚ set-up is the opposite of the above configuration. Image: Sarah Meade.

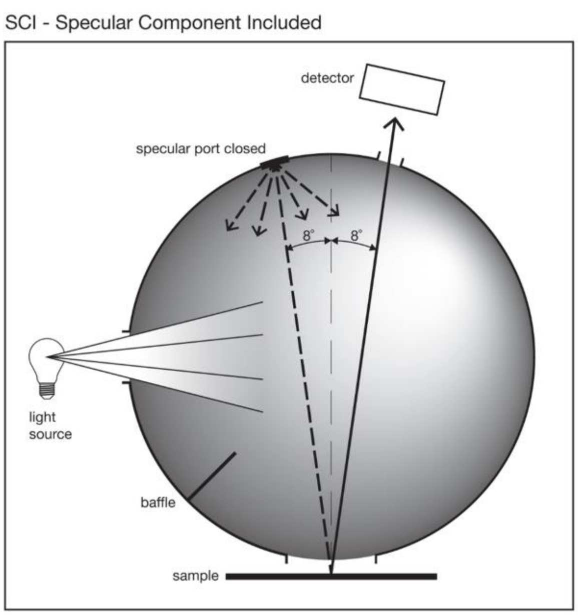

Fig. 2. Integrated sphere: Specular Component Included (SCI). Image: Sarah Meade.

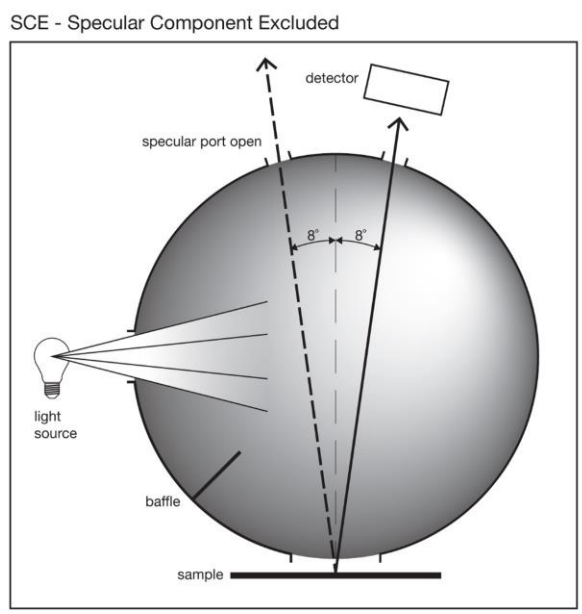

Fig. 3. Integrated sphere: Specular Component Excluded (SCE). Image: Sarah Meade.

Instruments with an integrated sphere geometry (figs. 2, 3) have a spherical cavity coated with a highly reflective white substance – often barium sulfate – and a light source located on the sphere wall. With a baffle preventing the light source from illuminating the sample directly, the light bounces off of the interior of the sphere before it reaches the sample as diffuse light. This is reflected back by the sample as a combination of diffuse and specular reflectance. The highly reflective inner surface of the sphere allows for the combination of diffuse and specular reflectance to reach the sensor, so unlike a 0°/45° instrument, this configuration allows for inclusion of specular reflection from the measured sample. Integrated spheres have a specular port that can be open or closed during measurement. When the port is closed, specular reflection is included in the measurement and the only light lost from the original source is what is absorbed by the sample (fig. 2). This tends to lead to good measurement repeatability, as it includes nearly all of the reflected light, highlighting differences between the colors of samples. However, it also results in lighter color measurements than those produced by a 0˚/45˚ instrument.

When the specular port in an integrated sphere is open, this gap in the sphere acts as a light trap for specular reflectance allowing for its exclusion from the final measurement. Theoretically, this allows an integrated sphere to function like a 0˚/45˚ instrument. In practice, measurements still tend to read slightly lighter than 0˚/45˚ measurements, as it is difficult to exclude 100 percent of the specular reflectance. A 0˚/45˚ geometry is the only configuration that is capable of fully excluding specular reflection.

Standard Illuminants and Observers

The spectral distribution of the light source used for viewing an object has a direct and significant effect on the appearance of color: the same object may look dramatically different under incandescent lights than it does under daylight. Because the light source in a spectrophotometer cannot be changed easily, color data is adjusted mathematically after measurement using a "standard illuminant." Standard illuminants are numerical representations of specific lighting conditions. Defined by the *Commission Internationale de l'Eclairage* (CIE), each illuminant is meant to approximate a real lighting condition. For example, Standard Illuminants A and D65 represent incandescent light (2856k) and average daylight (6500k), respectively (DiCosola 1995; Johnston-Feller 2001, 21; Ohta and Robertson 2005, 92-96). When color measurements are motivated by issues of color matching, such as in-painting in conservation treatment or quality control on a production line, matching the standard illuminant to the final viewing conditions is critical. For measuring color change over time, the specific illuminant used is less important than applying the same one consistently to all data. Using raw spectral data, CIE L*a*b* numbers can be recalculated at any time using a different illuminant.

A "standard observer" is a viewing angle meant to replicate human color perception. Along with the standard illuminant, the standard observer is a numerical component in the calculation of CIE L*a*b* values. The 2 Degree Standard Observer was established in 1931 by the CIE as a way to standardize color measurement data according to the parameters of human color perception. In 1964, the CIE published the 10 Degree Supplementary Standard Observer, which is thought to be a closer approximation of human color perception, though the 2 degree observer is still widely used. As with standard illuminants, selecting the appropriate standard observer depends on the purpose of the color measurement. For comparative measurements taken over time, using the same standard observer consistently is most important. (Johnston-Feller 2001, 23-26; "Understanding Standard Observers…" 2015; X-Rite 2004).

PROJECT METHODOLOGY

Instrument Selection

Representatives from Konica Minolta and X-Rite visited The Met for multiple meetings to discuss their products and instrument recommendations based on the desired applications.

Vendor	Model	Geometry	Description	Light Source	Aperture
X-Rite	968 Spectrophotomter	0˚/45˚	The Met's "legacy" instrument acquired in 1996	Gas filled tungsten	Variable: 4mm, 8mm
X-Rite	964 Spectrophotometer	0˚/45˚	X-Rite's leading 0˚/45˚ instrument: considered closest approximation to the 968	Gas filled tungsten	Variable: 4mm, 7mm, 15mm
X-Rite	eXact Advanced Spectrophotometer (4mm)	0˚/45˚	Newest 45˚/0˚ instrument with updated technology. Lighter than 964 and has an internal white calibration tile.	Gas filled tungsten (UV LED)	Fixed: choice of 2mm, 4mm, 6mm
X-Rite	RM200QC Imaging Spectrocolorimeter	Integrated sphere	Small, user-friendly colorimeter. Only captures tristimulus values (L*a*b*, RGB, XYZ, etc.)	LED array	Variable: 4mm, 8mm
X-Rite	Ci64 spectrophotometer	Integrated sphere	X-Rite's integrated sphere instrument similar in size to the 964	Gas filled tungsten	Variable: 4mm, 8mm, 14mm
Konica Minolta	CM-2500c Spectrophotometer	0˚/45˚	Konica Minolta's leading 0˚/45˚ instrument: equivalent to 968 and 964	Gas filled tungsten	Fixed: 8mm
Konica Minolta	CM-2600d Spectrophotometer	Integrated sphere	Konica Minolta's spherical unit. Same body as CM-2500c	Gas filled tungsten	Variable: 3mm, 8mm
Konica Minolta	FD-7 Spectrodensitometer	0˚/45˚	Newest 0˚/45˚ instrument with updated technology. Lighter than CM-2500c.	LED	Fixed: 3.5mm

Fig. 4. Spectrophotometers included in the study. An X-Rite eXact with a 2mm aperture was also tested, but is not included above. Unless specified, any eXact data is from the 4mm instrument.

Following these meetings, seven instruments were chosen for testing (fig. 4). The selection included both 0˚/45˚ and integrated sphere instruments. The group also included one colorimeter, which was included as an interesting point of comparison: how would the simpler instrument fare against the group of more advanced instruments? If accurate enough, the little colorimeter could be a useful tool in the image capture workflow in the Photograph Studio.

Sample Selection

Samples were selected with the goal of representing a wide spectrum of colors and surface textures. A larger version of the Digital ColorChecker® SG target (DCSG chart) was assembled by hand using unmounted color squares obtained directly from X-Rite (fig. 5). This larger size made it easier to take measurements on the card's 96 color squares. The DCSG chart is a larger version of the Gretag MacBeth ColorChecker® commonly used for photographic documentation in the conservation community. It is also used by professional photographers – including those on staff at The Met – in their image capture workflow. Since there is no published reference data for this chart, this project provided an opportunity to gather reference data for future use in The Met's Photograph Studio.

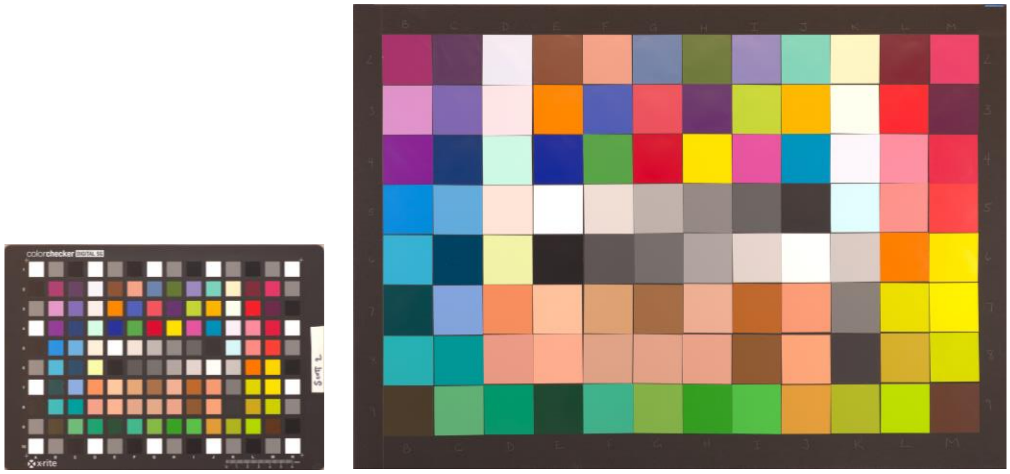

Fig. 5. *Left,* Digital ColorChecker® SG target; *Right,* large-scale hand-made version using larger color squares obtained from the manufacturer.

An additional set of samples was composed of calibration and standardization tiles. Because the main goal was to compare results against The Met's existing spectrophotometer, its calibration tile was included. A set of BCRA (British Ceramic Research Association) tiles lent by X-Rite were also measured. These are ceramic tiles that have become internationally recognized as a leading standard for use in color measurement and standardization.

A final group of samples included a variety of artist materials including a set of chromogenic photographs on three different papers: glossy, matte, and metallic. Sets of textile, painting and paper samples were provided by Met colleagues, with each set including a variety of surface textures.

Measurement Parameters

When devising the protocol for measurements, an effort was made to minimize variables as much as possible. A single operator – the author – took all of the measurements. Following The Met's existing procedure, overlay templates made of polyester film with holes cut out at the measurement sites were used on all samples, ensuring that each instrument measured the same location on each sample. Crosshairs were drawn on the templates at each measurement site, allowing for more repeatable positioning of each instrument.

During measurement, five individual readings were taken and averaged for each measurement site, lifting and repositioning the instruments each time. This practice is critical when comparing measurements taken over time, as it includes the margin of error in the data that results from re-positioning the instrument, making comparison of data sets simpler and – paradoxically – more accurate (Perkinson 2002). Although this study did not involve taking repeated measurements over time, each individual instrument required positioning on the templates, which created a comparable statistical error, so the procedure was employed for this study.

Aperture
Standardizing measurement settings across the range of instruments was challenging. Since The Met's spectrophotometer has always been used with a 4mm aperture, the ideal would have been to evaluate all instruments using this setting. With no single aperture size shared by the entire group, it was standardized as possible. When a 4mm aperture was available, that setting was selected, so all X-Rite instruments were set to 4mm. This was not an option for the Konica Minolta instruments. As a result, the CM-2500c and the CM-2600d were set to 8mm, as this was the only option for the CM-2500c. The FD-7 was used at its fixed aperture of 3.5mm.

Illuminant and Observer
The X-Rite RM200 colorimeter could only be set at a 10 degree standard observer with either illuminant D65 or A. As a result, all instruments were set to illuminant D65 with a 10 degree standard observer.

Software
Konica Minolta's Spectra Magic and X-Rite's Color iQC software were used for most of the readings. Both are designed for industry, however, each product was easy to use and provided the flexibility necessary to use it in a less conventional way, if desired. They had excellent user interfaces including customizable views with spectral and CIE L*a*b* data and a variety of graph formats. They allowed for exporting and calculating data using different illuminants and standard observers. Neither software provided a simple way to record the statistical data for five averaged measurements, though in both cases, there were ways of collecting the data more manually that made this possible and did not add significantly to the measurement time.

RESULTS

Overall Results
Figure 6 shows the average Delta E data from all instruments evaluated against The Met's X-Rite 968 spectrophotometer. When looking at overall average Delta E values across all samples, three distinct categories emerge. The top performing group of instruments is not a surprise. They are the three 0˚/45˚ units that have the most in common with the 968. All have overall average Delta E values under 1, which can be considered relatively close agreement when comparing two different spectrophotometers (Seymour correspondence 2015).

The instruments in the second group all have average Delta E values between 1 and 4. The FD-7 and RM200QC – the two 0˚/45˚ instruments in this group – both use LED light sources, which may account for the wider margin of error, but more research would be needed to confirm this. The FD-7 had inconsistent results with incredibly close agreement on the DCSG chart and greater error on the photograph samples. The RM200QC colorimeter was not expected to perform as well against the 968 or other high-end devices, so its average Delta E of 2.05 exceeded expectations. The other two instruments in this group are the integrated spheres set to exclude specular reflectance (SCE): the X-Rite Ci64 and the Konica Minolta CM-2600d. The general expectation was that integrated spheres set to SCE would perform similarly to the 0˚/45˚ devices, though perhaps with a slightly wider margin of error. This data mostly meets those expectations. On very matte samples, without as much specular reflection, such as textiles and paper, they agreed more closely with the 968. However, samples with any gloss component resulted in more distant agreement of the instruments. This difference in results between matte and glossy samples perfectly illustrates the inability to exclude 100 percent of the specular reflectance when using an integrated sphere. The exception to this would be measurement on a highly smooth, glossy surface, such as a mirror, which will be discussed in more detail later in the Results section.

This trend persists in the data for the third group, the Ci64 and CM-2600d set to include specular reflectance (SCI). Both had an overall average Delta E around 8. The contrast between matte and glossy samples is more extreme as the inclusion of specular reflectance has resulted in even less instrument agreement with the 0°/45° instrument on glossier surfaces. Although the degree of difference from the 968 was unknown at the beginning of the study, this general result is also in line with expectations.

Vendor	Model	Internal Geometry	DCSG (96)	Photo Samples (48)	BCRA Tiles (13)	X-Rite 968 Tile (3)	Painting Samples (6)	Textile Samples (8)	Paper Samples (4)	Overall Average ΔE
X-Rite	964 Spectrophotometer	0˚/45˚	0.75	0.65	0.27	0.34	0.44	0.73	0.46	0.52
X-Rite	eXact Advanced Spectrophotometer	45˚/0˚	0.58	0.95	0.54	0.45	1.01	1.06	0.78	0.77
Konica Minolta	CM-2500c Spectrophotometer	0˚/45˚	0.44	0.56	0.34	0.78	0.82	1.37	1.36	0.81
Konica Minolta	FD-7 Spectro-densitometer	0˚/45˚	0.46	5.66	1.64	0.57	0.63	1.45	1.19	1.66
X-Rite	RM200QC Imaging Spectrocolorimeter	45˚/0˚	2.31	2.25	1.64	1.95	1.63	2.76	1.78	2.05
X-Rite	Ci64 spectrophotometer SCE	Integrated sphere	5.39	3.49	1.4	1.56	5.81	1.2	0.85	2.81
Konica Minolta	CM-2600d Spectrophotometer SCE	Integrated sphere	7.05	4.12	1.91	3.37	5.37	2.78	1.24	3.69
X-Rite	Ci64 spectrophotometer SCI	Integrated sphere	8.79	13.07	9.12	13.07	6.61	1.47	0.79	7.56
Konica Minolta	CM-2600d Spectrophotometer SCI	Integrated sphere	9.91	13.24	9.35	13.8	6.33	2.84	1.19	8.09

Fig. 6. Average Delta E values for all sample groups and test instruments. Delta E values were obtained by comparison with The Met's X-Rite 968 0°/45° spectrophotometer.

Data from the DCSG chart helps to illustrate certain aspects of the various instruments' performance. Figures 11-22 in the appendix each represent the 96 color squares on the DCSG chart as measured by a different instrument. The numerical data in each square is the Delta E value between the 968 and the test instrument. The Konica Minolta CM-2500c and FD-7 agreed very closely to the 968, with an average Delta E value of 0.44 and 0.46 respectively. The X-Rite eXact and 964 were close behind with 0.58 and 0.75 (Figs. 6, 11-13, 15).

Aperture

One factor that may account for the particularly close agreement of the CM-2500c is that at 8mm, the aperture size was twice the size of the 4mm openings of the 968, eXact and 964. A wider aperture measures a larger area of the sample, which can result in greater accuracy by reading a greater amount of reflected light, and effectively averages a larger area of the sample. Even on a flat field of color, like the samples on the DCSG chart, a surface inconsistency or spot in the measurement area could potentially skew a measurement using a very small aperture. With a larger aperture, the blemish would translate as a smaller percentage of the final reading, minimizing the error. This is a significant benefit for highly textured surfaces, like textiles or paintings. For graphic work, like photographs, an aperture as large as 8mm can sometimes be limiting when measuring in a detailed image area. A 4mm aperture works well for reasonably smooth surfaces like photographs and most works on paper. However, smaller apertures may be too limiting for repeatable measurements on most works of art. Comparing two X-Rite eXact instruments with different apertures (Figs. 13, 14) supports this theory. Compared against the 968, the average Delta E of the 4mm instrument is 0.58 while the smaller 2mm aperture agrees less closely with an average Delta E of 0.88. It is more difficult to account for the incredibly close agreement of the FD-7 with the 968, particularly given its slightly smaller, 3.5 mm, aperture size. Considering the inconsistency of agreement from this instrument, more measurements would be needed to understand its unpredictable performance.

When comparing the two spherical instruments to each other, rather than to a 0°/45° instrument, data agreement improves slightly, though perhaps not as much as expected (Figs. 21, 22). Although the reason for this result is not readily apparent, it is most likely that the data would be closer if the apertures had been the same size.

Lightness

The DCSG chart data for the integrated spheres reveal a trend. Portions of columns D and K and rows 5 and 6 on the DCSG chart consistently show the lowest Delta E numbers (Figs. 17-20). These squares are the lightest colors on the chart. This result illustrates a specific characteristic of spectrophotometers: they are most accurate when the light levels are high. Since darker colors reflect less light, they often produce a slightly wider margin of error. The graphs in Figures 7 and 8 plot the CIE L*a*b* values measured by each test instrument on a white and black sample. Focusing on the L* values, it is clear that the splay of data is significantly wider for the black sample than for the white.

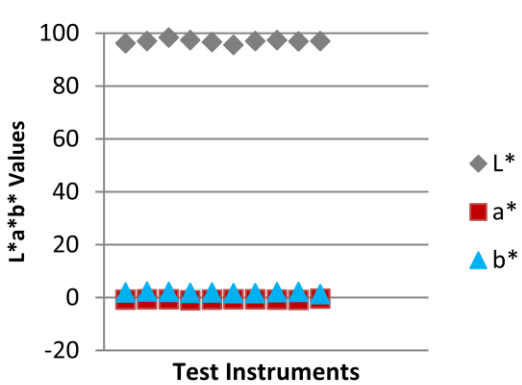

Fig. 7. White square E5 on DCSG chart

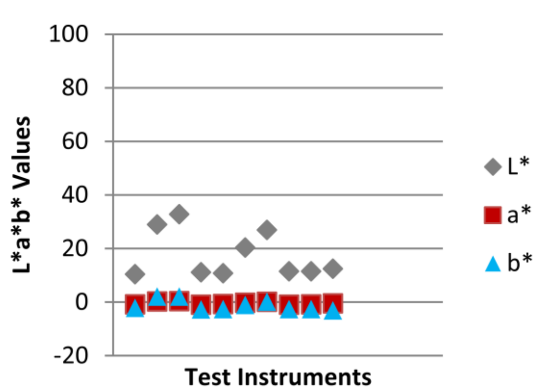

Fig. 8. Black square E6 on DCSG chart

Surface

The photograph samples had particularly interesting data when comparing the glossy and matte samples. Figure 9 charts the average Delta E values for the eight measurement sites on the Fuji glossy and Fuji matte photograph samples. The 0°/45° instruments all showed close agreement between the matte and glossy samples, as did the integrated spheres when set to include specular reflectance. When measured on the SCE setting, the difference between the two samples was significant.

Instrument	Fuji Glossy ΔE	Fuji Matte ΔE	Difference Between Glossy and Matte
X-Rite 964	0.65	0.65	0.00
X-Rite eXact	1.17	1.06	0.11
Konica Minolta CM-2500c	0.55	0.57	0.02
X-Rite RM200QC	1.97	2.06	0.09
Konica Minolta FD-7	5.70	5.71	0.01
X-Rite Ci64 SCE	1.45	6.63	5.18
Konica Minolta CM-2600d SCE	2.00	6.68	4.68
X-Rite Ci64 SCI	11.81	12.93	1.12
Konica Minolta CM-2600d SCI	11.98	11.93	0.06

Fig. 9. Average Delta E values for each test instrument on glossy and matte chromogenic photograph samples. The Delta E values were obtained by comparison with The Met's X-Rite 968 0°/45° spectrophotometer.

This chart may seem to contradict the data in Figure 2, which shows a greater contrast between matte (e.g. textiles) and glossy (e.g. photographs) samples measured using the SCI setting, rather than the SCE. However, the matte photograph sample actually has quite a bit of gloss; it is a glossy, but textured, surface that produces the matte appearance. This is unlike a truly matte textile sample, which does not have a glossy component and so produces diffuse reflectance off its rough surface (fig. 10). When the instruments were in SCE mode, a significant percentage of the specular reflectance off the glossy sample was unidirectional (fig. 10) and escaped through the open specular port. The matte sample also produced specular reflectance, but the textured surface caused more scatter. This would have caused more light to reflect off the interior of the

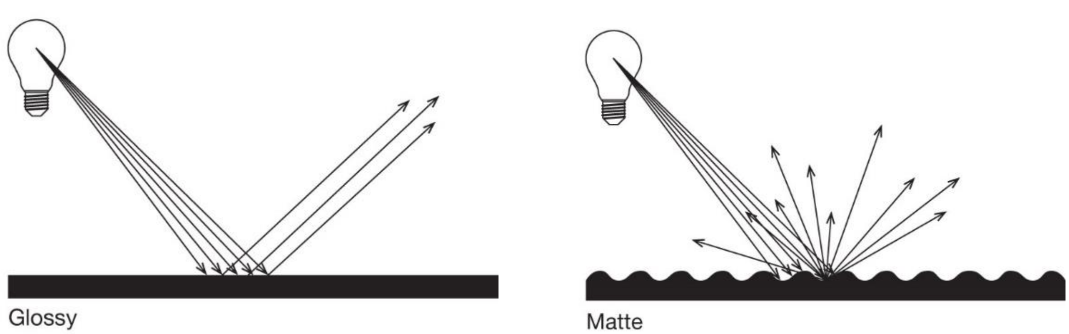

Fig. 10. Specular (left) and diffuse (right) reflectance. Image: Sarah Meade.

sphere, resulting in a lighter measurement overall. Including all specular reflectance with an SCI reading resulted in better agreement since the amount of reflected light being measured remained consistent.

This result is particularly interesting when considering its potential for surface characterization. Using an integrated sphere spectrophotometer, multiple samples could be measured using the SCI setting to identify color differences. SCE measurements could then be taken to evaluate gloss, using the SCI data to correct for color difference.

Ease of Use

All instruments were easy to use. However, some were heavier and more unwieldly than others, which may be a concern when using them to measure art objects. Most of the spectrophotometers had a measurement foot with cross-hairs that could be used to align the instrument with a template. Those that did not have a foot were the X-Rite RM200QC colorimeter and the Konica Minolta CM-2500c and CM-2600d spectrophotometers, and using these instruments without a foot was more difficult and imprecise. The CM-2500c and CM-2600d can both be used with an attachment foot, so they were tested with and without it. Using the attachment foot improved the operation of both instruments, however it is not an original part of their design so the measurement process was still somewhat awkward. The X-Rite 964 and Ci64 were the largest of the group and felt cumbersome at times. With any of these instruments, repeated use and familiarity would undoubtedly improve the fluidity of the measurement process.

Overall, the easiest instruments to use were the lightest ones with an integrated measurement foot. The best in this category were the X-Rite eXact and the Konica Minolta FD-7. Both of these instruments are among the first in a newer generation of handheld spectrophotometers with updated technology and hardware.

It is worth noting here that regardless of which instrument or software is used, the process of measuring color when following a standardized protocol is time-consuming. The author is not aware of any instrument that significantly reduces the amount of time it takes to measure color properly. Shortcuts in the measurement protocol will most likely result in unusable data.

DISCUSSION AND CONCLUSIONS

With numerical color measurements that differ according to so many variables, one might ask what exactly is color and is it even possible to clearly define it using precise numbers? Color exists more as a numerical range, not as an absolute set of values. This concept may seem directly at odds with the purpose of this study and any color monitoring program. However, understanding this seeming limitation means that color can be considered a relative value. In the case of image capture and printing workflows, this requires identification and acceptance of reasonable tolerances in color difference between a measured object and the digital or printed output. For conservators measuring color change over time, it can be even simpler. Using a single instrument and standardized measurement protocol with built-in statistical error makes it possible to directly compare color data without concern for whether the instrument is capturing the exact color of the material. Relative change is the primary focus of this type of color measurement and helps to keep the conservator's purview conveniently – and blissfully – narrow.

The most important aspect in color measurement is consistency in measurement protocol. With this in mind, there were practical limitations preventing The Met from purchasing certain instruments in the group as a replacement for the X-Rite 968. The desire to continue measuring the collection using the same aperture size was the first factor for elimination. This, unfortunately, eliminated the Konica Minolta instruments. A high degree of agreement was also a requirement, so the two remaining contenders were the X-Rite 964 and the eXact, both within a similar range of agreement with the 968. The final criterion pertained to the physical design and the implications for longevity. With its newer technology and lightweight profile, the eXact was selected as the replacement instrument.

FUTURE WORK

The new instrument is now in use in The Met's Photograph Conservation Department. The current practice when taking measurements is to use both instruments in order to acquire overlapping data. Although this is more time-consuming, the benefit of having directly overlapping data is undeniable for data continuity. There is also a plan to make a materials-based color chart including a wide range of photographic processes, colors, and textures. This chart could provide in-house reference data for the Photograph Studio, but would primarily serve as a specialized color reference chart for photographs. Using 968 and eXact data from this chart, the final step in the process will be to devise a mathematical method of standardizing the 968 data with the eXact. This will be carried out in consultation with experts in the fields of color science and applied mathematics and will be made available to the conservation community when it is completed. It is hoped that this stage of the project will not only allow for comparison of data at The Met, but may support continued color monitoring programs at many institutions.

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ACKNOWLEDGEMENTS

The author would like to thank her colleagues at The Met: Scott Geffert, Digital Imaging Specialist, for his deep knowledge of all things color and his significant role in this project; Masahiko Tsukada, Research Scientist, for his time and contributions; Emilia Cortes, Textile Conservator, Isabel Duvernois, Paintings Conservator, and Lisa Conte, Paper Conservator, for providing samples; and the Department of Photograph Conservation, Nora Kennedy, Lisa Barro, Georgia Southworth, and Janka Krizanova. Thank you also to David Albrecht and Bob Balland at X-Rite; Jodi Baker and Greg Rohaus at Konica Minolta; John Seymour, applied mathematician and color scientist; Steven Weintraub, Art Preservation Services; Hannelore Römich, Chairman, Conservation Center, Institute of Fine Arts, New York University; and Philippe Laumont, Laumont Photographics. Special thanks to Sarah Meade.

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Papers presented in *Topics in Photographic Preservation, Volume Sixteen* have not undergone a formal process of peer review.

APPENDIX

Digital ColorChecker SG Target
ΔE calculated against X-Rite 968 spectrophotometer unless otherwise specified

0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5+

	B	C	D	E	F	G	H	I	J	K	L	M
2	0.24	0.25	0.74	0.20	0.55	0.63	0.85	0.76	1.04	0.93	0.71	0.78
3	0.25	0.58	0.66	0.43	0.68	0.64	0.53	1.50	0.54	1.13	0.96	0.80
4	0.96	0.55	0.80	0.73	1.20	0.86	0.81	0.99	0.73	1.02	0.79	0.79
5	0.59	0.74	0.64	0.81	0.79	0.67	0.53	0.49	0.40	1.08	0.65	1.06
6	0.71	0.51	0.74	0.49	0.32	0.42	0.67	0.79	0.98	0.90	0.90	1.11
7	0.98	0.72	0.49	0.64	0.50	0.32	0.62	0.56	0.69	0.44	0.84	1.61
8	0.86	1.36	0.45	0.73	0.62	0.59	0.64	0.46	0.70	0.39	0.72	1.03
9	0.13	1.01	1.29	0.57	1.20	0.95	1.30	1.63	0.64	0.84	1.32	0.22

Fig 11. X-Rite 964 (0°/45°, 4mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	0.34	0.39	0.41	0.29	0.40	0.26	0.63	0.27	0.36	0.35	0.21	0.53
3	0.40	0.43	0.46	0.50	0.54	0.52	0.29	0.67	0.38	0.40	0.44	0.55
4	0.58	0.67	0.48	0.58	0.79	0.44	0.49	0.47	0.57	0.37	0.47	0.49
5	0.56	0.30	0.49	0.50	0.38	0.36	0.31	0.29	0.31	0.40	0.36	0.62
6	0.43	0.46	0.44	0.55	0.25	0.25	0.31	0.34	0.42	0.32	0.46	0.39
7	0.47	0.37	0.42	0.50	0.37	0.33	0.40	0.31	0.43	0.29	0.79	0.51
8	0.33	0.61	0.36	0.57	0.26	0.40	0.31	0.41	0.27	0.24	0.40	0.65
9	0.23	0.48	0.51	0.29	0.48	0.54	1.16	0.88	0.24	0.45	0.73	0.66

Fig 12. Konica Minolta 2500c (0°/45°, 8mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	0.29	0.28	0.31	1.25	0.29	0.26	0.87	0.23	0.65	0.38	0.50	0.62
3	0.39	0.48	0.20	1.14	0.43	0.85	0.83	0.53	0.77	0.61	1.04	0.49
4	0.37	0.37	0.46	0.37	0.61	1.55	0.42	0.35	0.42	0.29	0.55	1.08
5	0.33	0.44	0.21	0.30	0.18	0.18	0.21	0.31	0.95	0.59	0.36	1.01
6	0.53	0.39	0.32	0.69	0.16	0.42	0.16	0.29	0.30	0.28	1.14	0.75
7	0.63	0.32	0.47	0.43	0.08	1.96	0.14	0.95	0.70	0.32	1.13	0.56
8	0.65	1.11	0.27	0.64	0.15	0.23	0.29	0.85	0.51	0.23	1.20	0.53
9	0.65	1.01	1.15	0.56	1.03	0.90	1.15	0.89	0.44	1.16	0.51	1.11

Fig13. X-Rite eXact (0°/45°, 4mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	0.52	0.44	0.68	1.62	0.55	0.60	1.24	0.75	1.08	0.88	0.48	0.59
3	0.74	0.82	0.58	0.80	0.66	0.95	0.64	1.74	1.80	1.09	0.65	0.37
4	1.14	0.58	0.88	0.54	1.11	1.17	0.80	0.87	0.69	0.83	0.62	0.64
5	0.75	0.90	0.55	0.79	0.73	0.60	0.56	0.73	0.99	1.01	0.54	1.09
6	0.89	0.40	0.81	0.74	0.21	0.67	0.63	0.69	0.80	0.71	1.15	1.27
7	1.02	0.83	0.74	0.59	0.52	2.54	0.66	0.73	0.59	0.69	0.87	1.65
8	1.24	1.69	0.75	0.68	0.57	0.58	0.72	0.72	0.88	0.24	2.00	0.82
9	0.37	1.41	1.49	0.96	1.34	1.49	1.76	0.94	0.91	1.70	1.15	0.51

Fig 14. X-Rite eXact (0°/45°, 2mm aperture)

Digital ColorChecker SG Target

ΔE calculated against X-Rite 968 spectrophotometer unless otherwise specified

0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5+

	B	C	D	E	F	G	H	I	J	K	L	M
2	0.39	0.29	0.55	0.32	0.38	0.27	0.60	0.26	0.49	0.54	0.18	0.41
3	0.34	0.34	0.50	0.49	0.27	0.24	0.30	0.78	0.44	0.49	0.34	0.49
4	0.69	0.62	0.49	0.36	0.68	0.66	0.65	0.17	0.39	0.44	0.38	0.39
5	0.33	0.42	0.54	0.56	0.47	0.43	0.38	0.28	0.25	0.40	0.33	0.42
6	0.50	0.23	0.59	0.22	0.29	0.36	0.46	0.46	0.49	0.42	0.40	0.69
7	0.79	0.51	0.46	0.65	0.57	0.33	0.49	0.31	0.67	0.36	0.60	0.66
8	0.46	0.78	0.43	0.74	0.47	0.54	0.42	0.33	0.47	0.25	0.28	0.83
9	0.47	0.71	0.66	0.42	0.29	0.55	0.52	0.65	0.38	0.43	0.57	0.26

Fig. 15. Konica Minolta FD-7 (0°/45°, 3.5 mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	1.78	3.20	0.38	2.12	1.31	0.88	6.10	0.37	0.81	0.91	0.94	3.32
3	1.00	0.84	0.27	3.04	1.62	1.15	3.21	3.70	3.51	0.62	2.25	2.65
4	2.04	3.22	0.60	3.68	3.99	2.91	4.64	2.43	2.98	0.65	1.21	2.36
5	1.83	1.33	0.26	0.73	0.28	0.40	0.27	0.29	2.17	0.69	0.78	1.86
6	1.33	3.71	0.85	1.78	0.35	0.36	0.24	0.24	0.42	0.18	3.03	2.19
7	5.30	0.58	2.62	2.39	0.68	1.44	1.22	3.02	4.38	0.15	9.01	5.34
8	2.12	3.40	1.79	4.52	0.69	0.21	1.69	3.80	2.96	1.42	4.68	6.23
9	2.89	1.07	3.35	3.83	1.65	5.12	8.22	5.18	1.05	5.66	7.89	3.67

Fig. 16. X-Rite RM200QC (0°/45°, 4mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	8.51	10.14	0.09	7.34	2.53	3.10	7.35	1.60	1.86	1.18	8.30	5.97
3	1.60	4.35	0.52	11.14	5.14	4.86	12.35	7.49	10.92	0.72	11.57	9.75
4	8.98	8.28	0.81	8.10	7.98	12.08	10.15	3.92	3.91	0.22	2.21	9.71
5	2.97	2.01	0.79	1.16	0.52	1.11	2.13	3.33	9.18	0.43	3.33	8.85
6	2.01	9.20	1.77	9.75	4.50	3.75	1.79	0.74	0.26	0.86	13.25	8.55
7	12.12	1.49	5.02	2.00	3.10	6.00	2.10	8.90	3.47	2.51	11.91	10.78
8	2.81	4.92	2.43	2.42	2.51	2.10	2.51	8.56	2.98	7.37	7.98	10.95
9	10.71	2.95	4.60	8.92	3.13	4.85	9.41	7.15	6.00	7.07	8.72	9.83

Fig. 17. X-Rite Ci64 SCE (Integrated Sphere, 4mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	6.68	7.52	0.20	11.65	4.03	7.03	12.03	5.50	4.16	0.95	7.68	5.66
3	1.02	3.03	1.31	15.59	11.01	9.68	22.38	10.94	16.04	0.33	9.62	10.30
4	6.73	5.64	1.23	17.65	12.20	19.73	14.71	9.29	8.70	0.26	1.89	9.13
5	2.00	1.27	1.19	0.45	1.86	3.16	5.25	8.27	16.92	0.20	3.32	8.37
6	1.43	6.88	2.23	18.79	9.60	7.53	4.12	2.31	1.31	0.63	13.49	7.58
7	9.49	0.98	6.80	2.59	4.54	9.13	3.54	13.62	5.07	1.97	11.65	10.81
8	1.92	3.29	3.83	3.18	4.02	3.71	4.16	12.53	4.74	6.25	8.18	11.02
9	8.19	2.02	9.77	16.90	6.08	8.06	15.21	11.45	9.41	5.76	6.76	10.49

Fig. 18. Konica Minolta 2600d SCE (Integrated Sphere, 8mm aperture)

Digital ColorChecker SG Target

ΔE calculated against X-Rite 968 spectrophotometer unless otherwise specified

0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5+

	B	C	D	E	F	G	H	I	J	K	L	M
2	13.86	14.98	1.20	11.98	4.17	5.49	10.31	4.77	3.43	1.95	19.08	10.37
3	3.81	7.45	1.29	15.63	8.66	9.16	19.28	11.25	16.36	1.17	17.10	18.69
4	16.09	13.61	1.41	15.41	11.91	19.17	13.43	8.45	6.93	1.34	3.88	14.46
5	5.15	4.00	1.39	0.40	1.41	2.39	4.46	7.48	14.95	1.47	4.89	13.67
6	4.54	15.73	2.73	16.41	8.62	6.26	3.16	1.70	1.00	2.19	19.96	12.90
7	17.74	3.51	7.34	3.18	5.13	8.42	3.52	14.16	5.35	5.00	14.69	16.27
8	5.17	8.36	3.78	4.01	3.88	3.64	3.96	11.86	4.57	12.60	11.93	15.84
9	15.71	6.42	9.54	16.27	5.94	8.31	14.59	11.30	9.78	11.15	11.76	15.07

Fig. 19. X-Rite Ci64 SCI (Integrated Sphere, 4mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	11.45	12.09	0.95	15.19	5.66	8.84	14.12	7.79	5.52	1.64	17.65	9.43
3	2.80	5.64	2.51	18.73	13.50	13.01	26.13	13.89	19.95	0.80	15.00	17.81
4	13.06	10.73	2.68	22.13	15.31	24.56	16.99	12.46	10.88	1.03	3.33	13.51
5	3.95	2.96	2.49	1.69	2.80	4.35	7.12	11.38	20.53	1.10	4.72	12.80
6	3.48	13.10	3.40	22.51	12.66	9.44	5.32	3.24	2.32	1.81	19.44	11.49
7	15.34	2.60	8.89	3.96	6.50	11.09	4.99	17.49	6.89	4.21	14.19	15.52
8	3.88	6.28	5.12	4.88	5.35	5.17	5.51	15.20	6.18	11.05	11.81	15.40
9	13.34	5.12	13.51	21.41	8.32	10.93	19.05	14.57	12.44	9.77	9.61	15.07

Fig. 20. Konica Minolta 2600d SCI (Integrated Sphere, 8mm aperture)

	B	C	D	E	F	G	H	I	J	K	L	M
2	1.86	2.64	0.28	5.08	2.17	3.95	5.22	3.90	2.64	0.40	0.69	0.49
3	0.73	1.34	1.55	4.64	5.88	5.23	10.14	3.79	5.26	0.45	2.01	0.60
4	2.29	2.66	1.70	9.56	4.96	8.44	4.72	5.41	5.00	0.23	0.49	0.71
5	1.01	0.79	1.55	1.55	1.54	2.24	3.31	5.31	8.10	0.39	0.28	0.57
6	0.65	2.34	1.45	9.12	5.40	4.04	2.51	1.74	1.48	0.34	0.46	1.17
7	2.67	0.58	2.27	1.62	2.15	3.69	1.98	5.17	2.29	0.56	0.71	0.52
8	1.00	1.70	1.89	1.81	2.01	2.11	2.13	4.85	2.14	1.13	0.30	0.40
9	2.57	0.98	5.61	8.85	3.42	3.71	6.40	4.89	3.66	1.37	1.99	0.68

Fig. 21. SCE: Konica Minolta 2600d vs. X-Rite Ci64

	B	C	D	E	F	G	H	I	J	K	L	M
2	2.49	2.91	0.35	3.93	1.91	3.36	4.34	3.02	2.32	0.41	1.68	1.09
3	1.09	1.84	1.35	3.33	4.84	4.11	6.97	2.93	3.72	0.44	2.25	1.09
4	3.07	2.89	1.49	6.74	4.02	6.13	3.69	4.01	4.13	0.34	0.68	1.10
5	1.22	1.05	1.38	1.39	1.46	2.05	2.80	4.10	5.84	0.42	0.33	1.00
6	1.06	2.66	1.33	6.15	4.23	3.38	2.25	1.62	1.39	0.47	0.73	1.51
7	2.48	0.92	1.94	1.47	1.87	3.16	1.80	3.78	2.07	0.86	0.70	0.88
8	1.30	2.09	1.68	1.61	1.82	1.87	1.88	4.04	1.91	1.61	0.31	0.57
9	2.54	1.31	4.29	5.75	2.73	3.05	5.00	3.77	2.89	1.44	2.15	0.34

Fig. 22. SCI: Konica Minolta 2600d vs. X-Rite Ci64