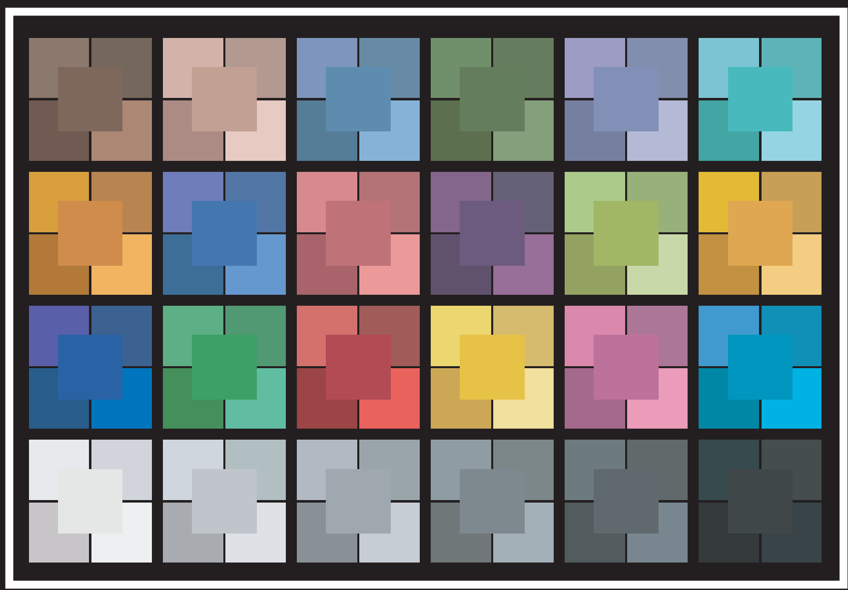
Direct Digital Capture of Cultural Heritage – Benchmarking American Museum Practices and Defining Future Needs

Final Report - 2005



Roy S. Berns and Franziska S. Frey

Rochester Institute of Technology

R·I·T

Munsell Color Science Laboratory
Color Science Building
Rochester Institute of Technology
54 Lomb Memorial Drive
Rochester, NY 14623-5604
Phone: 585-475-7189
Fax: 585-575-4444

This and other reports and further information are available on line at:
http://www.cis.rit.edu/museumsurvey/

Direct Digital Capture of Cultural Heritage – Benchmarking American Museum Practices and Defining Future Needs

---

Roy S. Berns and Franziska S. Frey
Principal Investigators

Mitchell R. Rosen, Erin P. Smoyer, and Lawrence A. Taplin
Researchers

2005

Supported by a grant from
THE ANDREW W. MELLON FOUNDATION

Munsell Color Science Laboratory
Color Science Building
Rochester Institute of Technology
54 Lomb Memorial Drive
Rochester, New York, USA

Table of Contents

Acknowledgments

The authors gratefully acknowledge the support of the Andrew W. Mellon Foundation for this project. We would like to thank the RIT Munsell Color Science Laboratory for the use of their extensive facilities in developing and beta-testing the quantitative testing procedure. Special thanks go to the case study institutions for generously donating their time, facilities and photographers; the respondents for taking time to fill out the survey; and the conference speakers and attendees for their willingness to share their experiences. Thanks to Colleen Desimone and Valerie Hemink for their hard work in support of the Benchmark Conference.

I. Executive Summary

Many museums, archives, and libraries are engaged in direct digital image capture of cultural heritage. This heritage encompasses works on paper, paintings, manuscripts, sculptures, and photographs, among others. Co-investigators R. S. Berns and F. S. Frey have been active in informal and formal evaluations of museum practices and the quality of digital image archives (Berns, 2001; Frey, 1999). Their evaluations revealed a wide range of quality in the digital images being produced by the image archives participating in the study. In order to improve future performance, it was deemed critical to comprehensively benchmark current practices and quality. This project was limited to the United States and excluded the digitization of photographic collections.

The program commenced July 2003 with financial support from the Andrew W. Mellon Foundation. The project had nine major components: 1) developing and posting an online survey of institutional photography departments (Section II); 2) interviewing key digital imaging personnel from a selection of departments; 3) compiling and summarizing documentary standards on imaging quality (Murphy, 2005); 4) developing a quantitative testing procedure (Section III); 5) administering the test at representative institutions (Section III); 6) organizing and holding a conference (Section IV); 7) fully analyzing information and documenting this program (http://www.cis.rit.edu/MuseumSurvey/); 8) disseminating information through publications and presentations (Section VII); and, 9) clearly reporting the findings.

Table I-I lists the key findings (Section V). Table I-II lists suggested future research (Section VI).

Table I-I. The Benchmarking American Museum Project key findings.

Key Findings
Imaging will be mainly digital in the near future.
Museum imaging was output driven (e.g., printed publications and the Internet).
Library and archive imaging was focused on creating semantic-based image archives.
Selection criteria for camera systems were determined primarily by subjective criteria, word of mouth, and technical support rather than objective measures.
It was possible to develop a single experimental procedure to evaluate the objective quality of a camera system.
The ideal photographer has 10–15 years experience photographing cultural heritage and in-depth knowledge in information technology and art history.
Workflows varied widely.
Procedures and workflows were not well documented.
Color management was not used to its fullest capabilities.
Differences in lighting were one of the main factors leading to aesthetic differences in archives.
Aesthetics were often deemed more important than scientific rigor and reproducibility when imaging.
Most institutions included visual editing in their workflow, adding significantly to the total time required from setup to archiving a digital master.
There was not a well-defined digital master that would enable cross-media publishing and that could also be used in scientific imaging.
Digital preservation was still in its infancy.

Table I-II. The Benchmarking American Museum Project suggested future research.

Suggested Future Research
Establish a user group devoted to imaging, archiving, and reproducing cultural heritage.
Hold periodic informal conferences for information gathering and sharing.
Develop a practical characterization test method.
Incorporate characterization data into a metadata structure.
Develop and test a system calibration protocol.
Define quality criteria based on objective and subjective metrics.
Establish a testing service.
Establish an informal imaging inter-comparison.
Research and develop new imaging systems.

II. Survey of American Museums on Digital Imaging for Direct Capture of Artwork

The complete survey including all the tabulated answers can be found at www.cis.rit.edu/museumSurvey/documents/surveyAnalysisReport.pdf. Note that not all the respondents answered all the questions; the actual counts for all the questions can be found along with the tabulated answers.

Introduction

The first stage of this project involved learning about the history, current status, and future of digital imaging within cultural-heritage institutions that use direct digital capture for imaging paintings and sculptures (Klijn and de Lusenet, 2000; Rieger, 2004; Sitts, 2000). No comprehensive survey of this kind had been conducted, and the researchers saw the importance of filling this void. A survey was composed to build a broad picture of the staff, equipment, software, and workflow of American cultural-heritage institutions. One of the goals of this survey was to assist the museum community in modernizing its use of digital imaging and digital images.

"The American Museums Digital Imaging Benchmark Survey" went live on the RIT web site on October 20, 2003, and it was terminated a little less than twelve months later. Over that time, close to 60 surveys were received. International respondents and multiple responses from the same institution were filtered out, leaving a total of 52 surveys from institutions in 22 states. The distribution of the participants within the United States is shown in Figure II-1 below.

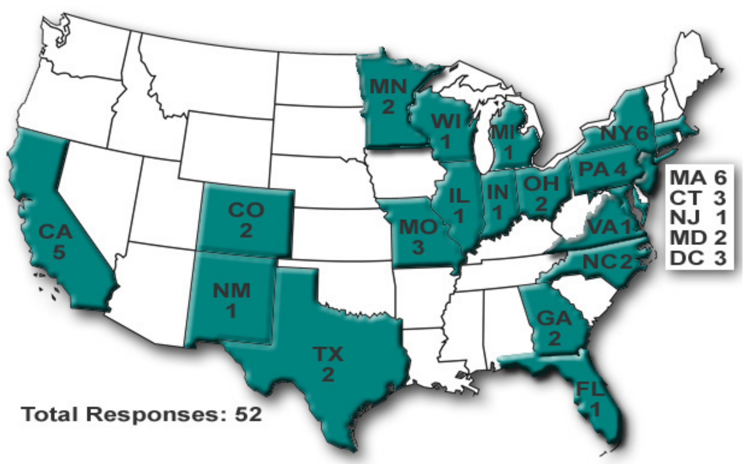


Figure II-1. Distribution of responding institutions from across the United States.

The survey was designed to support the cultural-heritage photographic community by fostering inter-institution communication and being an important first step toward determining effective "best practices." It was also expected that camera and systems developers would benefit by gaining a deeper understanding of the digital photography needs of the cultural-heritage niche.

Research laboratories, too, require the information sought by the survey to help guide them in determining where improvements in the technology are needed.

Answering the 78 survey questions took about one hour. That so many took the time to respond to the questions is testimony that photographic service providers have a strong need for and interest in a better understanding of digital imaging. Participants included many of the major American museums, along with libraries, archives, imaging studios, and consultants.

As mentioned earlier, the research emphasized questions about the use of digital imaging for direct capture of artwork, namely paintings and sculpture. Scanning of photographic prints, negatives, or slides was excluded from this project. Questions were divided into the following ten sections:

I. About You
- General contact information

II. More About You
- Background information on the respondent

III. About Your Staff
- Background information on the respondent's staff

IV. Use of Digital Photography
- Institution's use of and respondent's attitude toward digital photography

V. Imaging Workflow
- Specific information about institution's imaging workflow

VI. Digital Imaging Studio Setup and Equipment
- Detailed hardware and software description of up to five studio setups

VII. Image Editing
- Detailed questions about the modification of images within the workflow

VIII. Color Management
- Details of how color characterization is used within the workflow

IX. Digital Master Files
- Information about how image files are maintained

X. Final Questions
- Where digital photography information is obtained and room for additional comments

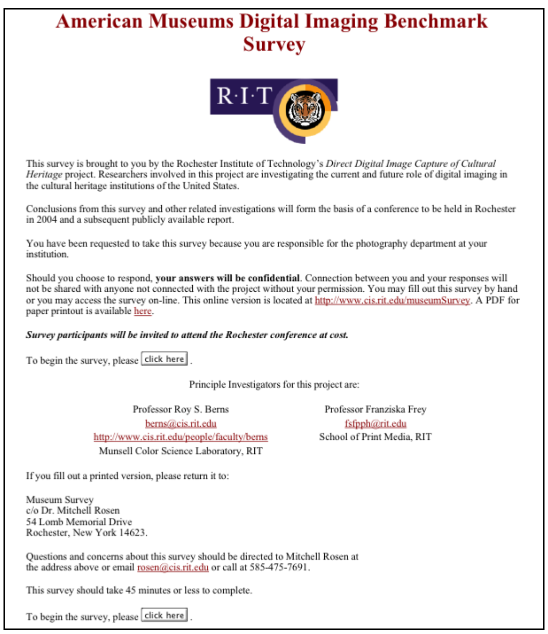
Questions were asked about the backgrounds of respondents and staff and also about studio equipment, capture and editing software, file storage means, color management approaches, and the end-use of images. Questions also covered workflow parameters impacting color, sharpening, compression, lighting, and image processing.

Categories and questions were subjected to several levels of revision prior to the general publication of the survey. Several members of the target population of museum photography studio heads and photographers volunteered their time to beta-test the survey. Their feedback was incorporated into the final revision.

There were five major means used to publicize the survey:

- The survey web site itself
- Direct email
- Listserves and bulletin boards
- Verbal and written announcements at conferences
- Word of mouth

The original homepage can be seen in Figure II-2. Eventually the survey web site grew to become the public face of the project. Figure II-3 shows the homepage as of March 2004.



American Museums Digital Imaging Benchmark Survey

This survey is brought to you by the Rochester Institute of Technology's *Direct Digital Image Capture of Cultural Heritage* project. Researchers involved in this project are investigating the current and future role of digital imaging in the cultural heritage institutions of the United States.

Conclusions from this survey and other related investigations will form the basis of a conference to be held in Rochester in 2004 and a subsequent publicly available report.

You have been requested to take this survey because you are responsible for the photography department at your institution.

Should you choose to respond, **your answers will be confidential**. Connection between you and your responses will not be shared with anyone not connected with the project without your permission. You may fill out this survey by hand or you may access the survey on-line. This online version is located at http://www.cis.rit.edu/museumSurvey. A PDF for paper printout is available here.

Survey participants will be invited to attend the Rochester conference at cost.

To begin the survey, please click here .

Principle Investigators for this project are:

Professor Roy S. Berns
berns@cis.rit.edu
http://www.cis.rit.edu/people/faculty/berns
Munsell Color Science Laboratory, RIT

Professor Franziska Frey
fsfpph@rit.edu
School of Print Media, RIT

If you fill out a printed version, please return it to:

Museum Survey
c/o Dr. Mitchell Rosen
54 Lomb Memorial Drive
Rochester, New York 14623.

Questions and concerns about this survey should be directed to Mitchell Rosen at the address above or email rosen@cis.rit.edu or call at 585-475-7691.

This survey should take 45 minutes or less to complete.

To begin the survey, please click here .

Figure II-2. Survey homepage.

DIRECT DIGITAL IMAGE CAPTURE OF CULTURAL HERITAGE: BENCHMARKING AMERICAN MUSEUM PRACTICES AND DEFINING FUTURE NEEDS

Project Home
The Survey
Conference (Sept. 21-22, 2004)
Research
In the News
Team Members
Links

Project Purpose

Many museums, archives, and libraries are engaged in **direct digital image capture of cultural heritage.** Many more are considering the move. Artifacts to be imaged in this way encompass works on paper, paintings, manuscripts, sculptures, photographs, and many others. This project concentrates on practices of digital photography as they are used for reproducing and documenting paintings and 3D works.

Within the field there is a range of technology used for digital image capture, a range of operator expertise and many potential final destinations of the digital images. Some systems use re-purposed components. Some photographers are new to digital technologies and the majority of equipment and software are fairly new to the market. As a consequence of all these factors, there is a wide range of quality found within and between image databases.

This research project has the goal of determining the status of direct digital imaging practices as used in artwork reproduction workflows of American institutions. The benchmarking includes a survey, on-site case studies documenting current workflows, and a new test method to quantify image quality.

The online survey was launched in October, 2003. As of March, 2004 more than 40 American institutions have completed the survey. From the list of respondents, six institutions were selected for on-site studies: The Museum of Modern Art, The Metropolitan Museum of Art, The Harvard Art Museums, The Harvard Libraries, The Museum of Fine Arts and The Art Institute of Chicago. Each has been visited by members of the research team at least once.

The new test method is being evaluated using the digital photographic systems at the Munsell Color Science Laboratory.

The results of this year-long effort will include written documentation, a two day conference and scholarly publication.

American Museums Digital Imaging Survey Benchmarking Conference

September 21 and 22, 2004
Rochester Institute of Technology

For information click here

Contact:
Mitchell Rosen, Munsell Color Science Laboratory
54 Lomb Memorial Drive, Rochester, NY 14623
rosen@cis.rit.edu
585-475-7691

Project Sponsor :
THE ANDREW W. MELLON FOUNDATION

© 2004 Munsell Color Science Laboratory

Figure II-3. Project homepage (March 2004)

Project team members compiled a list of approximately 30 likely survey participants who were directly contacted through email containing a pointer to the survey. Others received information through less direct means. Listserves, such as Museum Computer Network (MCN), American Institute of Conservation (AIC), Electronic Media Group (EMG), and the Research Libraries Group (RLG), carried announcements, as did bulletin boards like those used for Better Light and Sinar camera systems. The survey also was brought to the attention of the target community at conferences, for example, the 2003 Museum Computer Network Annual Conference and the Archiving 2004 Conference (sponsored by the Society of Imaging Science and Technology).

Table II-I contains a complete alphabetical list of institutions that filled out the survey. Participants included some of the largest and most prestigious institutions in the country, such as the Smithsonian Institution and the Getty Museum, alongside far more modest regional and local institutions like the Missouri Botanical Garden and the Neville Public Museum of Brown County, Green Bay, Wisconsin. The wide range of institution sizes was matched by an equally wide range of institution categories, as shown in Table II-II.

Table II-I. Cultural-heritage institutions that took part in the survey.

Survey Institutions	
Ackland Art Mus., UNC Chapel Hill, Chapel Hill, NC	Library of Congress, Washington DC
American Airpower Heritage Museum, Midland, TX	Hall Library of Science, Engin. & Tech., Kansas City, MO
American Museum of Natural History, New York, MY	Memorial Art Gallery, Rochester, NY
Ancient Biblical Manuscript Center, Claremont, CA	Minneapolis Institute of Arts, Minneapolis, MN
Art Institute of Chicago, Chicago, IL	Missouri Botanical Garden, St. Louis, MO
Boston Photo Imaging, Boston, MA	Museum of Fine Arts, Boston, Boston, MA
Brooklyn Museum, Brooklyn, NY	Museum of Indian Arts & Culture, Santa Fe, NM
Carnegie Museum of Art, Pittsburgh, PA	National Gallery of Art, Landover, MD
Chrysler Museum of Art, Norfolk, VA	Nelson-Atkins Museum of Art, Kansas City, MO
Cleveland Museum of Art, Cleveland, OH	Neville Public Museum of Brown County, Green Bay, WI
Dallas Museum of Art, Dallas, TX	New York State Library, Albany, NY
David Revette Photography, Inc., Syracuse, NY	Princeton University Art Museum, Princeton, NJ
Davison Art Center, Wesleyan U, Middletown, CT	Smithsonian Institution, Washington, DC
Denver Museum of Nature & Science, Denver, CO	Toledo Museum of Art, Toledo, OH
Drexel University, Philadelphia, PA	US Nat. Archives and Records Admin., College Park. MD
Emory University, Atlanta, GA	UC Art Museum/Pacific Film Archive, Berkeley. CA
Friends Hist. Lib. of Swarthmore Col., Swarthmore, PA	U of GA Libraries - Digital Library of GA, Athens. GA
Fruitlands Museums, Harvard, MA	University of Michigan Museum of Art, Ann Arbor. MI
Getty Museum, Los Angeles, CA	University of Minnesota Libraries, Minneapolis. MN
Harvard College Library, Cambridge, MA	University of North Carolina at Asheville, Asheville. NC
Harvard University Art Museums, Cambridge	University of Pennsylvania Library, Philadelphia, PA
Hewlett-Packard Laboratories, Palo Alto	U of South Florida Contemporary Art Museum, Tampa, FL
Huntington Library, San Marino	Wadsworth Atheneum Museum of Art, Hartford, CT
Indianapolis Museum of Art, Indianapolis	Worcester Art Museum, Worcester, MA
Intl. Brotherhood of Electrical Workers, Wash. DC	Yale University Art Gallery, New Haven, CT
Johnson Museum, Cornell University, Aurora, NY	

Table II-II. Categories of respondent institutions.

Category	Count
Archive	2
Camera Manufacturer	1
Library	10
Museum	32
Other Cultural Institution	5
Private Photo Studio	2

Survey Results

Demographics

The first three categories of the survey collected data about the demographics of the participating institutions. Table II-III shows a list of positions the participants held, and Table II-IV shows the divisions under which the participants operated. The wide variety of data was a good indicator that the field was very much in an emerging phase.

Table II-III. Job titles of participants.

Participant Job Titles	
A/V Collections Conservator	Head, Digital Services
Archivist	Imaging Support Specialist
Assistant Registrar	Imaging Tech
Associate Curator	Imaging Technician – Lab Coordinator
Chief Photographer	International Representative-Archivist
Coordinator	Manager of Digital Imaging
Curator	Mgr., Dig. Imaging and Studio Photography Group
Curator of History	Manager/Digital Project Coordinator
Curatorial Assistant	Media Assets Coordinator
Data Specialist	Owner/Photographer
Database Manager	Photographer
Digital Conversion Specialist/ Technology Watcher	Photographer/Editor
Digital Media Manager	Photography Manager
Director of Special Projects	Preservation and Imaging Specialist
Executive Director, Imaging	President/Owner
Freelance Photographer	Registrar
Head	Registrar of Collections/ Manager of Museum Information Services
Head of Digital Services	Research Scientist
Head of Photographic Services	Senior Photographer
Head of Photography	Staff Photographer
Head photographer	

Table II-IV. Institutional departments where participants worked.

Title of Participant's Department	
Anthropology	Intellectual Property
APDI	Journal – Media Relations
Collections	Library
Collections Management	Museum Digitization Project
Collections Management	Imaging and Photographic Services
Collections Support/Photography Services	Imaging Department
Color Imaging and Printing Group	Information Technology
Conservation/Photo Services	Intellectual Property
Curatorial	Journal – Media Relations
Curatorial, Library and Archive	Library
Data Management	Museum Digitization Project
Digital Collections Unit	Photographic Services
Digital Imaging	Photography Studio
Digital Imaging Laboratory, Special Media Preservation Laboratory	Preservation
Digital Media	Preservation and Imaging Services
Digital Services Unit	Preservation Office
Exhibits	Preservation Reformatting Division
Fashion Program	Registrar
Imaging	Research
Imaging and Photographic Services	Research Center
Imaging Department	Special Collections
Information Technology	Visual Resources Collection

The survey participants had worked an average of 9.8 years at the current institution and had held their current position an average of seven years.

Each of the respondents was asked to report his or her educational background. Table II-V summarizes the highest degrees earned by respondents. Those who indicated "Other" specified the following: MBA, Masters in Library Science (2), Bachelor of Industrial Design, high school diploma (2), and photography studies at a renowned institution.

Table II-V. Highest degree earned by respondent.

Degree	***Count***
Ph.D.	3
MFA/MS/MA	18
BFA/BS/BA	18
Other	7

Figure II-4 compares experience in traditional versus digital photography. The median of conventional photography experience was 19 years; the median for digital photography experience was five years.

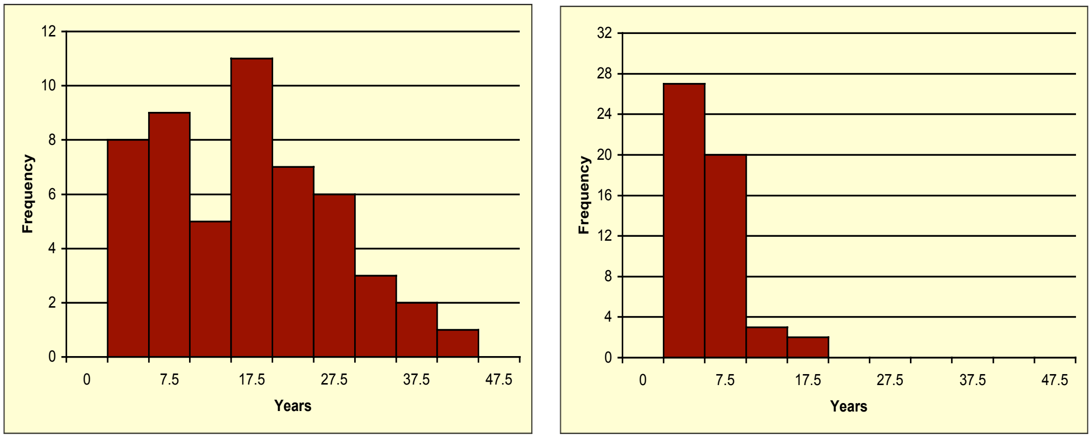


Figure II-4. Histograms of respondents' photography experience. Left: experience with traditional photography. Right: experience with digital photography.

Figure II-5 is a plot of the relationship between length of photography experience and length of digital photography experience. Respondents were grouped in five-year blocks according to how long they had been practicing photography. For each group, the average number of years using digital photography was calculated and displayed (brown curve). The average percentage of photography years spent in the digital medium was calculated and displayed separately (orange curve). The latter curve shows that those who entered the photography field in the last 15 years have spent, on average, at least half that time using digital technology, with a steep increase for those entering recently. Those who have five years or less experience have spent almost all of that time in digital photography.

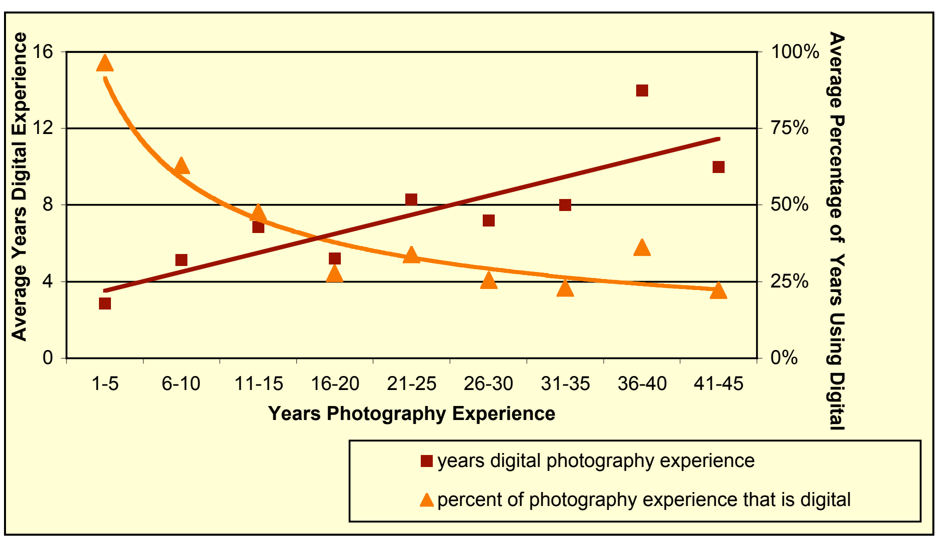


Figure II-5. Comparing length of overall photography experience to digital photography experience. Average years of digital experience shown in brown, average percentage of photographic years spent with digital photography shown in orange.

Survey question 13 asked whether the respondents felt they knew enough about digital imaging on a scale from 1 to 5, where 1 was assigned to “I do not know enough” and 5 to “I definitely know enough.” Figure II-6 shows that 56% responded with a 3 or less. This indicates that many practitioners have a perceived lack of knowledge about the new technologies.

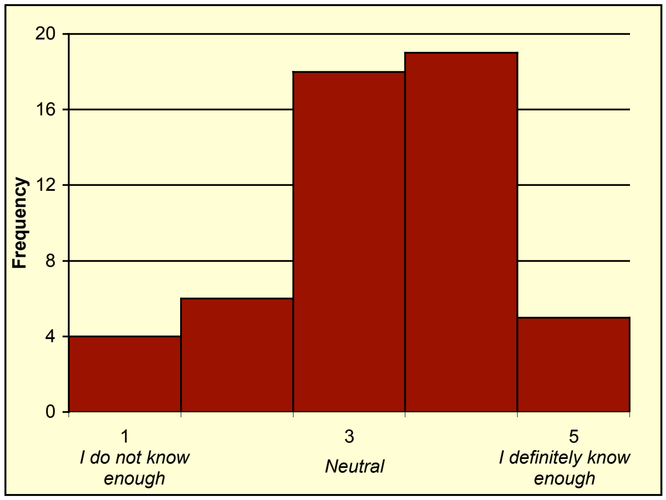


Figure II-6. Histogram of respondent self-described knowledge of digital imaging.

This question demonstrated that respondents were generally uncertain about digital imaging, and the analyses presented in Figures II-4 and II-5 show that they were relatively inexperienced with it. On top of this, it was also shown that institutions were adopting digital technology at a rapid rate. Nevertheless, those surveyed gave strong indication that they were at peace with the emergence of digital photography. Figure II-7 shows that 75% of respondents chose one of the top two positive responses when asked for their comfort level with the digital direction.

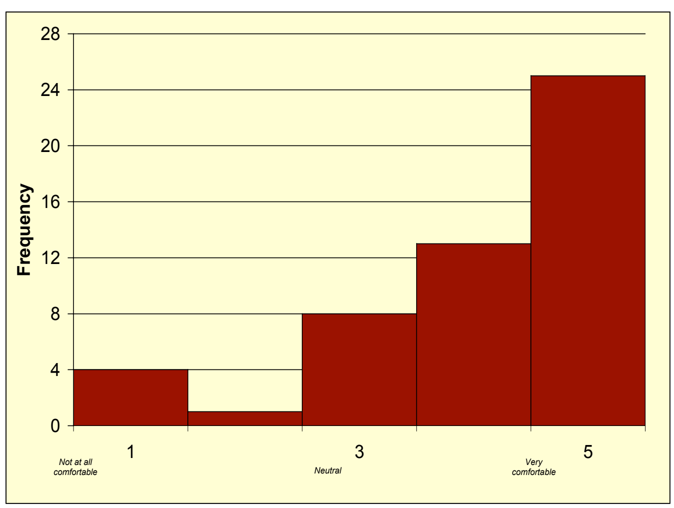


Figure II-7. Histogram of respondent comfort with the institution’s digital photography direction.

The photography departments surveyed had just over four staff members on average. The largest population was 20, and five one-person departments were reported. The survey asked for the academic degrees held by the department staff. Table II-VI shows that photography degrees were the most common. Degrees in other areas, such as art history, graphic design, and "other," were evenly represented. The "other" category included a wide variety of degrees ranging from computer science to a Ph.D. in history. Table II-VII shows the staff categories occupied within the departments.

Table II-VI. Degrees earned by photography department staff.

Degree Area	*Count*
Art History	21
Graphic Design	19
Photography	38
Other	20

Table II-VII. Staff categories within photography department.

Category of Staff	*Count*
Specialized museum staff	27
General museum staff	26
Volunteers (imaging professionals)	3
Volunteers (non-imaging professionals)	14
Outside service	18
Other	15

Institutional Use of Digital Photography

Starting with Section IV, the survey collected specific information about the use of digital imaging within the institution. Survey question 20 asked when digital imaging was first used at the institution. Figure II-8 is a histogram of the responses.

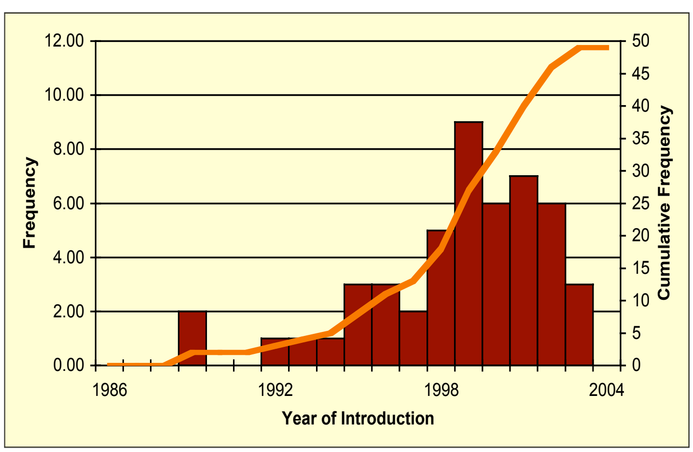


Figure II-8. Histogram of the years institutions began use of digital imaging. Orange curve is cumulative frequency.

According to the slope of the cumulative frequency plot in Figure II-8, the use of digital imaging appears to have begun to considerably increase among cultural-heritage users in 1995. Since that time there has been consistent growth. The timeline illustrated in Figure II-8 is consistent with the growth of digital photography among commercial studios. In this respect, the museum community has been representative of the greater professional photographic market.

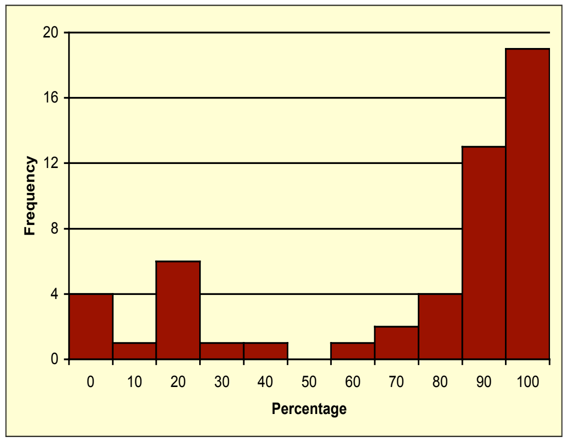


Figure II-9. Histogram of the percentage of photography performed digitally in the previous year.

When asked for the percentage of imaging performed digitally in the previous year, a median of 90% was reported, as shown in Figure II-9. The histogram in Figure II-8 shows the median year of digital introduction to have been 1999. The fact that over half of the 52 respondents took at least 90% of their photography digitally during the previous year demonstrates an extraordinary shift in an average of only five years.

Figure II-10 shows the average percentage of photography performed digitally in the previous year compared with that for the year when the digital photography program was instituted. The data show that within the first five years a majority of photographs was digitally generated. A 3% growth trend per year for digital usage was seen once digital photography was adopted.

Further documentation of the fast growth of digital photography within these institutions: 49 of the respondents, 94% of the total, reported that they were increasing their use of digital photography; 32 respondents, 62%, said their departments were investing in new equipment; 14 respondents, 27% of the survey population, described recent new staff hires to support the digital photography programs; and 21 of the organizations, 41%, applied for grants to support their transition to a digital workflow. Other indicators are reports by many of the respondents that they were buying new software, that they were receiving requests for digital images from new users within the institution, and that often these new customers came from departments not previously served by the photographic studios. Investment in staff retraining was commonly mentioned on the surveys.

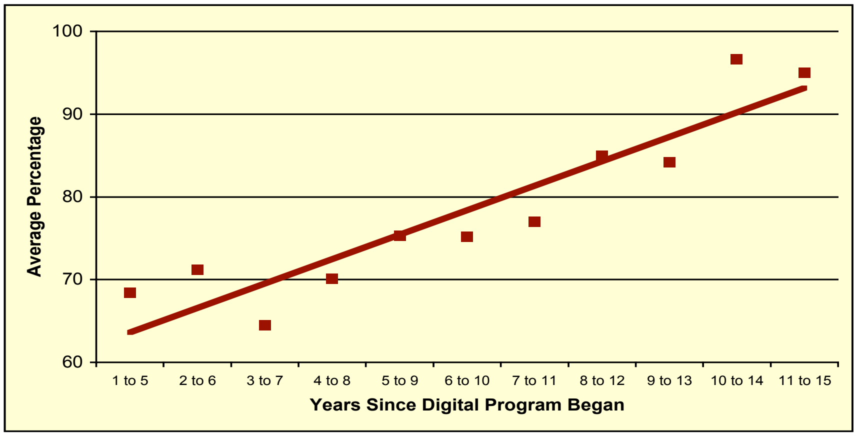


Figure II-10. Comparison of the percentage of photography performed digitally in the previous year with the percentage performed in the year in which the digital photography program was introduced. Trend line shows an average 3% growth per year.

Table II-VIII depicts who decides on the imaging technology used. In a majority of the institutions the decisions were made by the photographer or the team. This is important information since it shows who needs to be targeted to bring new equipment into an institution.

Table II-VIII. Individual(s) making decisions on imaging technology used.

Job Function	*Count*
Director	8
Yourself	29
Team	21
Outside consultant	6
Other	6

Imaging Workflow

Table II-IX summarizes the demands being met by digital photography within the museums, libraries, and archives represented in the survey population. While many of the demands fell within traditional documentation and publication workflows, it is interesting to note that the most common ones could not be accomplished without digital imaging: making collections accessible over the Internet and placing images into a collection management system. Both categories were selected by close to 90% of the institutions as reasons for their use of direct digital photography of their artwork.

Table II-IX. Reasons for taking digital images of the collection (Question 30).

Reason	*Percentage*
To protect vulnerable originals from use	67%
To produce printed reproductions	78%
To make collection accessible over the Internet	88%
To include in a collection management system	87%
To document conservation treatment	60%
Other	29%

Only 6% of the institutions placed images with a resolution greater than screen resolution on their websites. Close to a fourth of the participants produced CDs for commercial distribution of their images. Interactive kiosks and print-on-demand capabilities for museums visitors were available in less than 10% of the institutions' stores. This reveals an untapped opportunity for sales, assuming an institution owns the necessary rights.

Studio Setups and Equipment Used

In the Introduction, it was mentioned that several institutions from the target population participated in a beta survey before the final survey was published. From those early responses, it was already clear that a large variety of digital studio configurations would be found in the field. The survey provided space for five complete studio descriptions from each institution. A total of 92 digital studio configurations were described. While this is not surprising, it does create problems, especially for cross-media publishing and the creation of common image archives. The following sections describe some of the findings regarding the different studio configurations. A complete description of the workflows of four institutions can be found in Section III of this report.

After examining the studio descriptions, they were divided into three categories: *high-end*, *medium-level*, and *low-end*. Point-and-shoot systems fell into the low-end category. Systems that delivered the same or better quality than a traditional 4 x 5 studio camera were classified as high-end. All others fell into the medium-level category. Several systems were not sufficiently described. The studio system summary is shown in Table II-X.

Table II-X. Digital studio camera categories (survey section VI).

Camera category	Count
High-end camera	53
Medium-level camera	27
Low-end camera	8
Camera not sufficiently described	4

Table II-XI lists the manufacturers of the cameras found in the high-end systems. For American museum imaging departments, it appears that four manufacturers dominated the field: Better Light, Sinar, Phase One, and Leaf. Only one of these companies, Sinar, comes out of traditional photography. The other three companies have been solely digitally based since their inception. Not surprisingly, a wide variety of capture software was being used with the cameras.

Table II-XI. Dominant camera systems in high-end studios (survey section VI);
scan = linear CCD array, area = 2-dimensional CCD array.

Manufacturer	Count
Better Light (scan)	14
Sinar (area)	10
Phase One (scan)	9
Leaf (area)	7
Phase One (area)	6
Other/ambiguous	7

The small number of camera manufacturers represented on the list combined with the steady growth of museum digital studios should be seen as interesting news to those manufacturers not found on the list. For those willing to invest in the development of high-end cameras that serve this population, it is likely that there are opportunities to compete. As the museum community continues to come together and understand its requirements for camera systems, those camera systems that most closely respond to such demands probably will find the marketplace open to them.

Questions concerning the lighting setup revealed interesting facts. Twenty-seven percent of the respondents consulted a conservator when setting up the imaging systems. Besides correct handling, lighting issues such as exposure time and light source type are areas of expertise of conservators, and it was a surprising fact that only one fourth of the respondents were involving a conservator at this stage. About two thirds of the survey participants used special lighting setups and almost the same number adjusted the lighting for each artwork imaged. A majority of the latter group also measured the light levels of the system. Only a little more than 10% of the respondents had installed A/C to control the heat produced by the lights.

In many cases, a digital photography system was shared among the staff members of a department. On average three members of a department were able to operate each of the systems used. When asked to rate the comfort level of system users, a majority of respondents reported that photographers were “very comfortable” (see Figure II-11). Only 23% were seen as being neutral or below. No one was reported as being “not at all comfortable.”

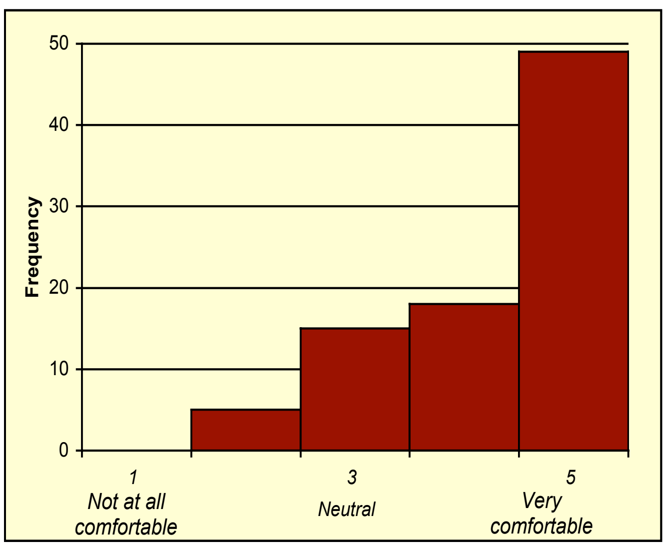


Figure II-11. Histogram of photographers’ comfort with studio digital camera systems.

The histogram in Figure II-12 shows a slightly lower comfort level when respondents were questioned about how comfortable the operators were in changing camera control software settings. Compared with the histogram in Figure II-11, 6% more operators are categorized as neutral or lower. In Figure II-12, four operators reported as being “not at all comfortable.” As with the previous question, though, more than half were in the highest, “very comfortable” category.

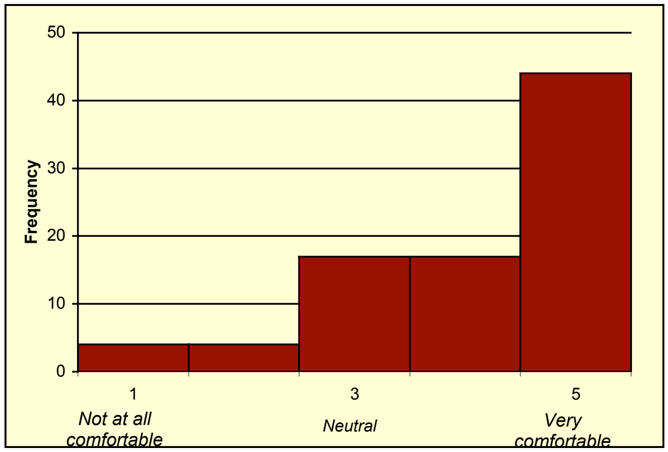


Figure II-12. Histogram of photographers' comfort with changing the software settings for controlling the studio digital cameras.

The camera calibration behavior of participants was also captured by the Section VI questions. More than 50% of the studio setups were described as following a regular calibration practice. Most indicated the use of a GretagMacbeth ColorChecker, either the traditional 24-patch target or the ColorChecker DC. Other targets popularly mentioned in survey responses included the Kodak gray scale and the Kodak Color Separation target. Calibration frequencies ranged from "several times a session" to every three to six months. Although, as already mentioned, approximately half of the studios performed calibration, 91% of the studios captured and saved targets along with their artwork. The targets saved were (in ranking order): Kodak gray scale (n=24), Kodak color separation target (n=21), GretagMacbeth ColorChecker (n=14), ColorChecker DC (n=1), and other (n=6). How these saved targets were used in the future was not investigated in the current survey. However, previous exchanges with practitioners and discussions during the case study visits showed that the usage of the targets varied widely and was often not entirely understood (Berns, 2001; Berns, 2002).

Image Editing and Color Management

Section VII and VIII of the survey included questions on any processing applied to photographs once the cameras have delivered data to the system. The vast majority of the institutions, 85%, used CRTs for image editing. A wide variety of hardware and software was used to calibrate these monitors. The calibration was performed on average every 1.5 months.

Of the 49 institutions that answered the question, 94% reported that Adobe Photoshop was one of the software applications they used for image editing. Only eight reported using any other applications; five used other applications in addition to Photoshop, and three did not use Photoshop. There was practically no commonality among the alternate applications as only DeBabelizer was mentioned twice.

Respondents were asked to describe manipulations made within their workflow. Survey question 49 sought information about ways in which images were processed; results are illustrated in Figure II-13. Types of processing were divided into the following categories: visual editing, defined as *global changes* such as contrast and color balance; retouching, defined as *local changes*; and *sharpening*. Most images produced by the survey community incurred some form of digital processing.

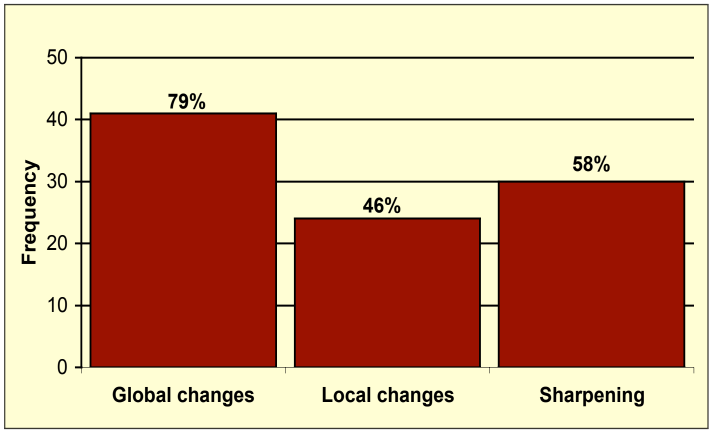


Figure II-13. Histogram of ways in which images are processed.

Of great interest to the researchers of this study was gaining understanding of the manner in which these processes were applied. Most of the tasks were performed manually. Only 20% of the institutions reported any form of automated processing. Of these, seven of the institutions had developed these timesavers by themselves. Without exception, all those using automated processing were still spending some time manually processing images as well, some for as long as 40 minutes per image on average.

Figure II-14 shows a histogram of the amount of time spent in post-processing images by all institutions. The spread is wide. More than half of the respondents spent an average of over 12 minutes per image, with one out of five of the population investing an average of half an hour or more per image for post-capture processing.

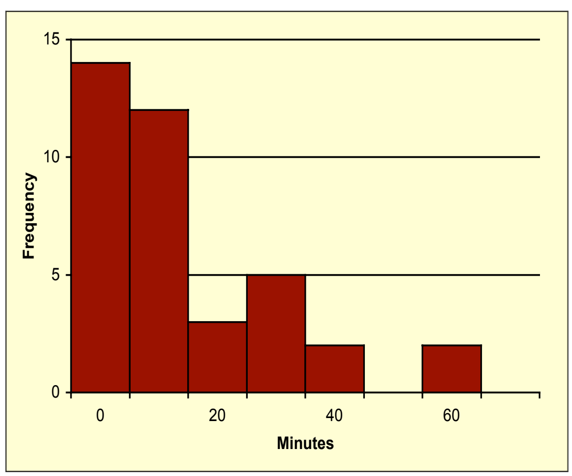


Figure II-14. Histogram of average time spent editing images.

For sharpening, those surveyed were asked where in the workflow sharpening occurred. Forty-one of the 52 respondents answered this question. Responses are summarized in Table II-

XII. Over 30% of this group sharpened either at capture or at some other point in the workflow prior to saving the highest quality digital master.

Table II-XII. Point at which sharpening is applied first in workflow (Question 49).

When Sharpening First Occurs	Percentage
At capture	7%
Before printing	34%
Highest quality image is sharpened before saving	24%
Other	29%
Do not know	2%

The survey asked how image quality was defined at the institution. Respondents could choose from the following five categories or define their own:

- Specified values for a target are matched in the digital file
- The image on the screen looks like the original
- You have an aesthetically pleasing reproduction on the display
- You have an aesthetically pleasing printed reproduction
- The measurements on the output device match the measurements on the original

A majority of the institutions defined image quality within the second category: "the image on the screen looks like the original." Table II-XIII shows the full results of this question with a comparison to the average time spent in visual editing by those who responded in each category.

Table II-XIII. Definition of image quality against average time for visual editing.

Category	Average Time Visual Editing	N
1. Specified values for a target are matched in the digital file	15.7	7
2. The image on the screen looks like the original	18.8	17
3. You have an aesthetically pleasing reproduction on the display	6.6	4
4. You have an aesthetically pleasing printed reproduction	15.3	3
5. The measurements on the output device match the measurements on the original	15.0	2
6. All (from other category)	16.0	2
7. The image on the print looks like the original (from other category)	26.0	2
8. Other (not covered above)	5.4	4

It appears that an additional 10 minutes were invested on average when going from an aesthetically-based definition of image quality (as in category 3) to a quantitative definition (as in category 1). Likewise, going from a screen-based definition (as in category 2) to a print-based definition (like category 7), an additional 10 minutes of visual editing time was used per image.

Table II-XIV looks at the same questions, but takes its data only from institutions that had at least one high-end studio as defined above (see Table II-XI). None of these institutions deal with aesthetics on the screen. The data also show the increase in time spent visually editing when image quality was judged on the basis of the print.

Table II-XIV. Definition of image quality compared to average time spent for visual editing (institutions with high-end cameras only).

Category	Average Time Visual Editing	N
1. Specified values for a target are matched in the digital file	15.7	7
2. The image on the screen looks like the original	20.3	8
3. You have an aesthetically pleasing reproduction on the display		0
4. You have an aesthetically pleasing printed reproduction	40.0	1
5. The measurements on the output device match the measurements on the original	15.0	2
6. All (from other category)		0
7. The image on the print looks like the original (from other category)	22.0	1
8. Other (not covered above)	5.4	4

Fifty-four percent of the respondents reported using color management. Of these, 80% said they built their own profiles. A wide variety of color management software packages were used for this task. Only 14 of the 28 institutions that used color management reported using color measurement instrumentation to check the validity of their profiles.

Table II-XV summarizes the rendering intents used. Twenty percent of the respondents did not know what rendering intent they were using. Participants were asked if they felt comfortable choosing a rendering intent. All the categories from 1 (not at all comfortable) to 5 (very comfortable) were chosen by about the same number of respondents. This showed that while a choice was made, the photographers were, in many cases, not sure whether they were making the right choice.

Table II-XV. Rendering intent used (question 56).

Rendering Intent	Percentage
Media/relative colorimetric	34%
ICC/absolute colorimetric	17%
Perceptual	29%
Saturation	0%
Do not know	20%

The next set of questions targeted the working color spaces used. Adobe98 was the most popular one (38%); the tabulated results for all color spaces used can be found in Table II-XVI. More than half of the respondents were “comfortable” or “very comfortable” choosing a working color space.

Table II-XVI. Working color space used (question 58).

Working Color Space	Percentage
Native camera RGB using profile	23%
Adobe98	38%
sRGB	13%
Do not know	9%
Other	17%

A histogram of responses to survey question 14, "Do you know enough about Color Management?" is found in Figure II-15. Fifty-two percent of those surveyed categorized themselves as neutral to "I do not know enough." It is worth noting that only 1% of the respondents gave themselves highest marks. This negative bias of respondents' comfort with color management deserves attention within the community. A very similar distribution could be found in response to question 62, "How knowledgeable do you feel you are about your color management workflow?"

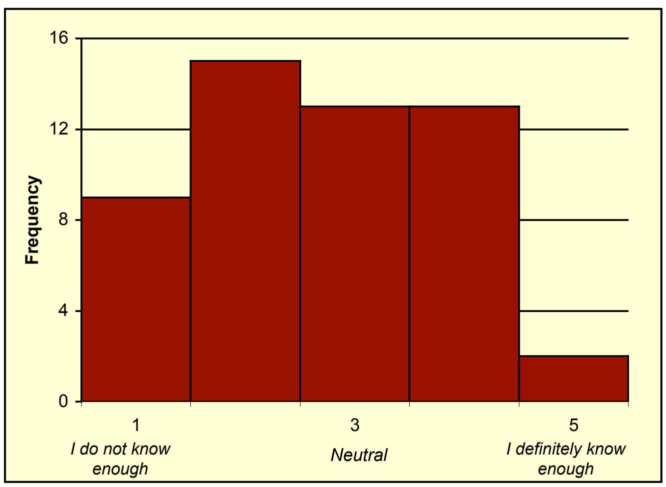


Figure II-15. Histogram of respondent self-described knowledge of color management.

A third of the participants had made changes to their workflow within the past year; 70% had made changes over the past three years. The color management workflows were designed by the respondent (53%), the photographer (6%), an outside consultant (16%) and other (25%). Almost a third of the respondents were working with consultants if they had questions on color management.

A series of questions focused on imaging for publication. Close to 80% of the survey participants produced images for publication. Half of the respondents used different workflows depending on whether they imaged for publication or for documentation. This was an interesting fact given the reality that a "rich" digital master can be repurposed for a wide variety of usages. Only 20% of the respondents produced the separations for printing, and 40% produced proofs in-house. When asked about the environment they used for viewing reproductions, 35% of the participants answered that they were using mixed illumination (such as natural daylight and office light). Close to half of the participants claimed their viewing environment was based on a standard. Light placement in the most used viewing environment was equally distributed between "ceiling," "light booth," and "other." Table II-XVII summarizes the type of lighting used in the environment to view reproductions.

The wide variety of approaches to producing files for reproductions made it clear that the quality of the resulting images varied widely among institutions.

Table II-XVII. Type of light used in reproduction viewing environment (question 68).

Type of Light	*Percentage*
Office fluorescent	28%
D65 daylight fluorescent	12%
D50 daylight fluorescent	40%
Tungsten	7%
Natural Daylight	7%
Other	7%

Digital Masters

Section IX discussed the generation and storage of digital masters. This part was not the focus of this study; however, it is important to look at the whole workflow from capture to storage, especially when keeping in mind the costs associated with capture.

Sixty-six percent of the respondents used the TIFF format for their digital masters. The next largest group (12%) used JPEG. This is somewhat surprising, since most guidelines recommend TIFF as the preferred format for digital masters. When respondents were asked if they compressed their digital masters, 14% answered yes. The compression algorithms used were evenly divided between LZW, JPEG, and other. The vast majority, 84%, of the respondents felt comfortable with their choice for compression. Close to half of the institutions were keeping the original camera raw file that was captured. No further questions were asked as to whether they regard this one as their digital master (Waibel and Dale, 2004; NISO, 2002).

Asked about backing up the digital masters, 88% of the respondents answered that they routinely backed up their files. However, this also means that 12% did not. Considering the costs associated with capture, it was quite surprising that the latter number is so high. The types of media used for backing up the files are found in Table II-XVIII. It was remarkable that close to 50% of the institutions were using media that are known to be somewhat unstable and that are not recommended for longer term storage, such as CDs and DVDs (Frey and Susstrunk, 2000). Twenty-three percent of all institutions reported that, at some point, they had lost a digital master that was unrecoverable. This shows clearly, that digital preservation is an issue that is only starting to be embraced.

Table II-XVIII: Digital master backup system (question 75).

System	Percentage
CDs	28%
Tape	21%
DVD	21%
Other	30%

At the end of the survey, participants were asked to comment on issues related to digital imaging. One of the biggest advantages mentioned when moving from analog to digital photography was the ability to instantly see results. This led to a sizeable increase in productivity. Color management and image management were mentioned on top of the list of the most difficult and time consuming aspects concerning the production of digital images.

III. Develop a Quantitative Procedure to Benchmark Image Quality and Evaluate the Procedure at Several Institutions

Introduction

For decades, museums, libraries, and other cultural-heritage institutions have used analog photography as a means for documenting their collections and producing reproductions of their artifacts. Through the years, these institutions developed best practices for the process of documentation and reproduction, which included photographing the object, storing the image, and cataloging it, so that a high quality image archive could be obtained and maintained for many years. Now that digital photography is well established and can produce images of a quality comparable to those produced by analog photography, these cultural-heritage institutions have a choice of whether to continue imaging in the traditional way or to start using digital technology.

A number of procedures for testing the quality of digital cameras have been recently established. Unfortunately, there has been no attempt to collect them into a cohesive package for the purpose of comprehensive evaluation of studio-imaging environments, particularly those used in museums for the direct digital capture of artwork. The ultimate goals of this research were twofold. It was intended to benefit the cultural-heritage community by providing guidelines for high-quality-digital imaging, and second, to benchmark four camera systems and procedures currently used for digital imaging by the cultural-heritage community. Although the saying "You get what you pay for" typically applies in the acquisition of imaging systems, there is no substitute for the careful and thorough testing and benchmarking of digital-imaging systems (Conway, 2000). Benchmarking systems help to compare different camera systems, giving better information than the manufacturers provide, and should lead to a better understanding of the whole imaging process (Kenney, 2000).

The aims of the testing procedure were to follow current digital-photography standards to the greatest extent possible and provide only objective measures of image quality by imaging test targets. The outcome of this procedure was an extensive quantitative description of the digital-image-quality parameters that characterized four museum digital cameras and procedures used for the direct-digital capture of cultural-heritage paintings.

Case Study Descriptions

The cameras and lights used in the case studies in each of the four museums were different. The four museums were not chosen as case studies for this reason; they were chosen because they were early adopters of digital imaging. Table IV-I summarizes the camera hardware and imaging setups of the four museum case studies.

Table IV-I. Case study camera and imaging setup descriptions.

Parameter	Case Study I	Case Study II	Case Study III	Case Study IV
Camera Mfg.	Leica	Phase One	Sinar	Better Light
Camera Body	Leica (integrated)	TTI 4 × 5 (on copy stand)	Horseman 4 × 5	Sinar 4 × 5
CCD Format	Tri-Linear	Tri-Linear	Area	Tri-Linear
Maximum Native Resolution	5140 × 5140	10500 × 12600	4080 × 5450	8000 × 6000
Lens	100mm f/2.8 Leica	150mm Schneider enlarging	100mm f/4 Rodenstock Apo Sironar digital HR	210mm f/5.6 MC Sinaron SE
Filter	Leica daylight balancing/IR cut-off	Phase One tungsten balancing/IR cut-off	Sinar IR cut-off	Better Light daylight balancing/IR cut-off
Illumination	4 Lowel Scandles (~5000K)	2 TTI Reflective Lighting tungsten lights, each w/ 4 OSRAM 250W Quartz Halogen photo optic bulbs (~3000K)	4 Speedotron Xenon strobe imaging lights in a 202VF light unit w/ UV correction filter over bulb (~6700K)	4 Broncolor HMI F1200 bouncing the light off of white walls and a 12' ceiling (~5000K)
Capture Software	Silver Fast Leica S (version 5.5.2)	Phase One Image Capture (version 3.5.2)	Sinar CaptureShop (version 4.0.15)	Better Light ViewFinder (version 5.3.4)
Image Area	Cropped	Cropped	Uncropped	Cropped

Case Study Testing Procedure and Cultural-Heritage Institution Workflows

The case study testing procedures were divided into two main parts. The purpose of the first part was to learn about each museum's digital-imaging workflows. The purpose of the second part was to characterize the camera systems used by the cultural-heritage institutions.

In the first part, two paintings (Figure III-1), which were painted with Gamblin Artist Oil paints, were imaged and processed through each museum's normal digital-imaging workflow.

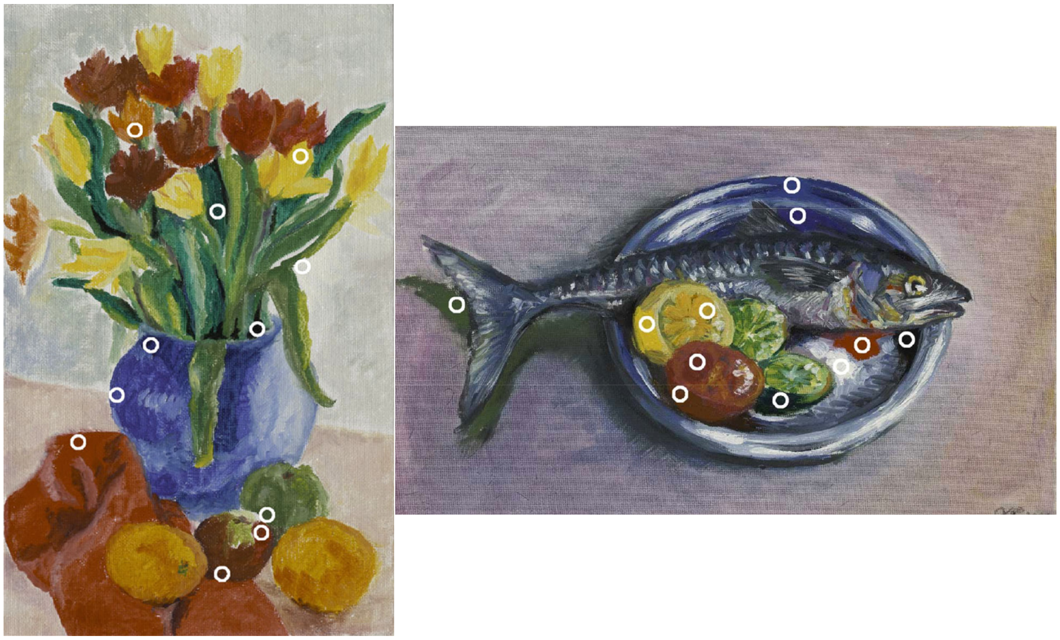


Figure III-1. Flower (left) and fish (right) paintings used for the analysis of each museum's digital-imaging workflow. Uniform areas of pigment are marked with a white circle. They were used to evaluate color accuracy.

In each case study, the photographer at each institution was asked to image the pair of paintings as he or she would routinely. This included everything from the setup of the camera and lights to the processing of the image for storage as a digital master. In Case Study I, only a digital master was created, whereas in Case Studies II – IV, the photographers created both ICC color-managed images and digital masters. Figures III-2a – III-d show the digital-imaging workflows performed in the four case studies.

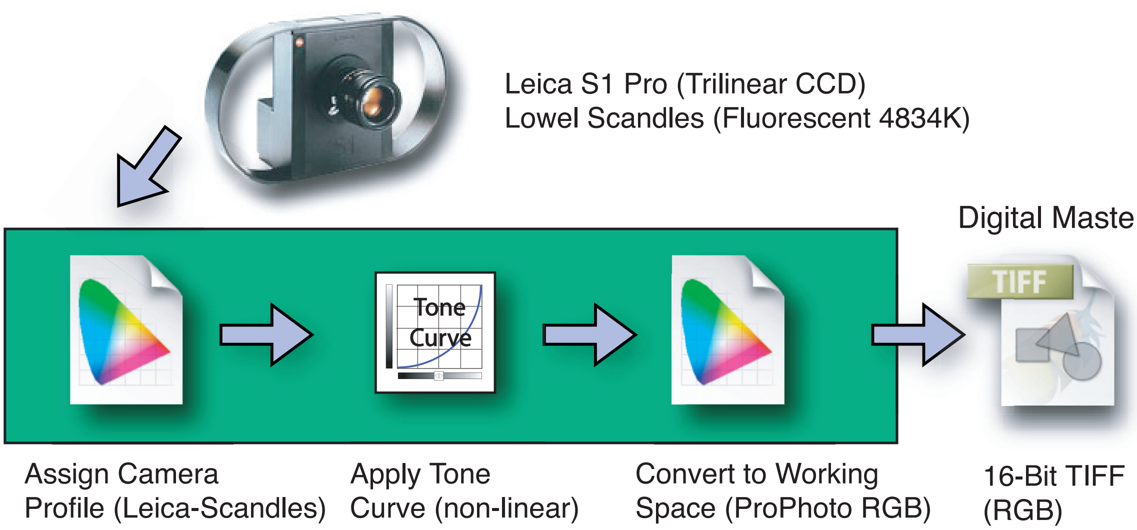


Figure III-2a. Case Study I digital-imaging workflow. A green background indicates that the action was performed in the capture software. A red background indicates that the action was performed in Adobe Photoshop.

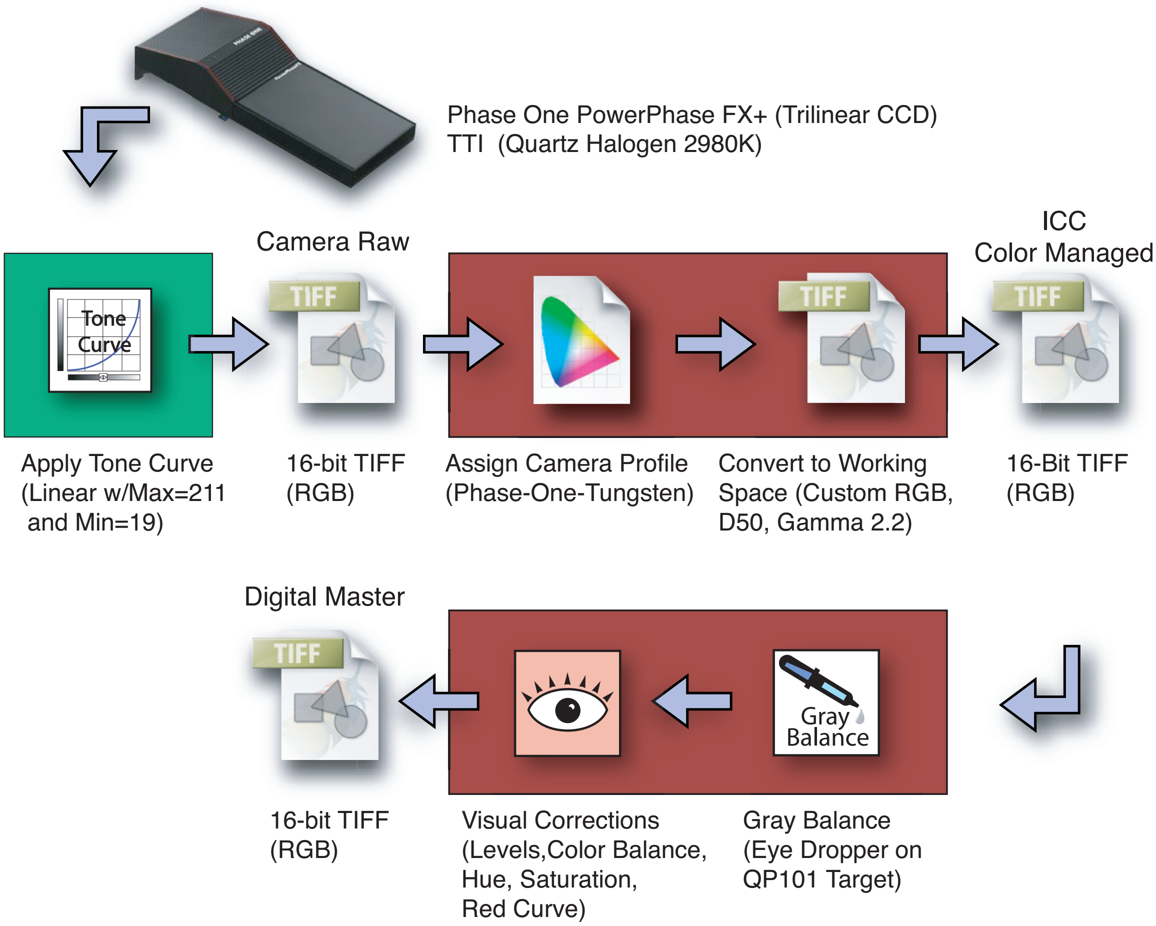


Figure III-2b. Case Study II digital-imaging workflow. A green background indicates that the action was performed in the capture software. A red background indicates that the action was performed in Adobe Photoshop.

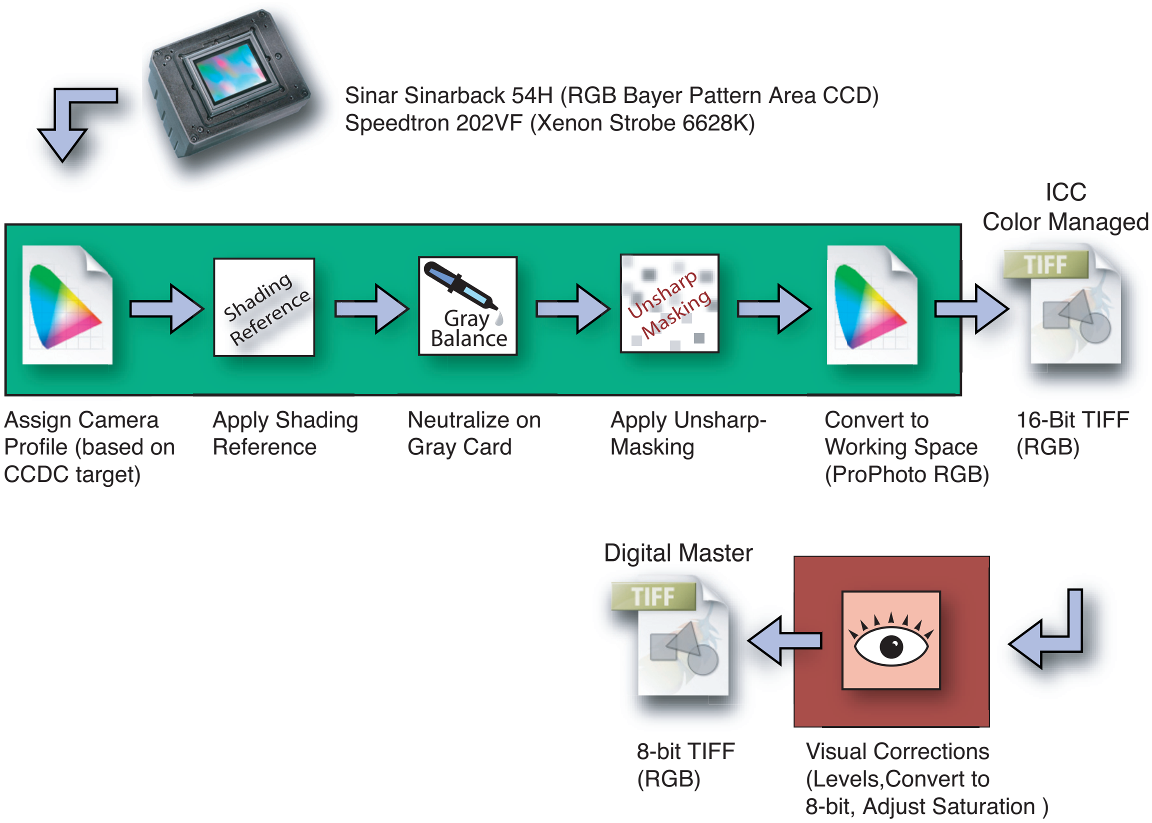


Figure III-2c. Case Study III digital-imaging workflow. A green background indicates that the action was performed in the capture software. A red background indicates that the action was performed in Adobe Photoshop.

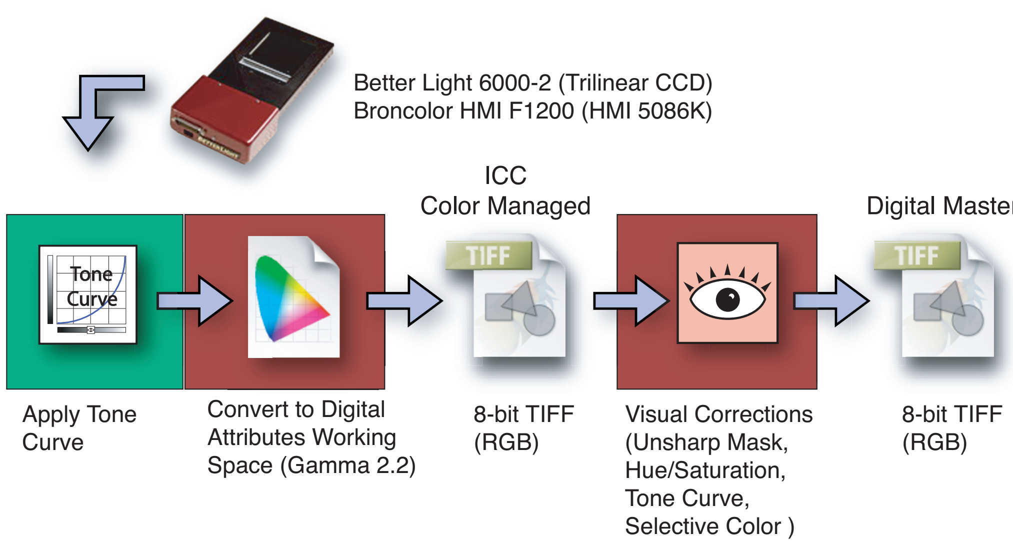
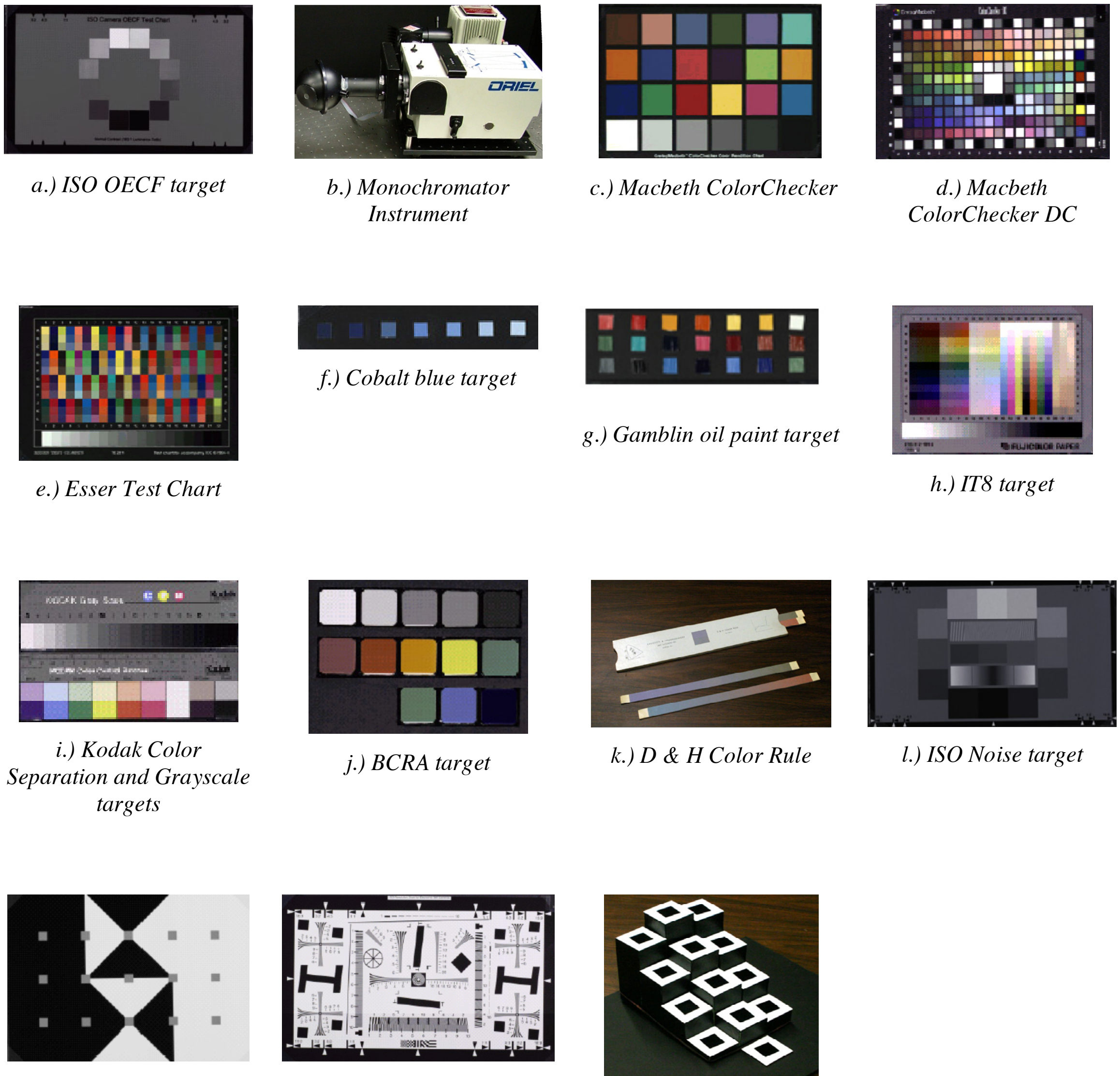


Figure III-2d. Case Study IV digital-imaging workflow. A green background indicates that the action was performed in the capture software. A red background indicates that the action was performed in Adobe Photoshop.

The colorimetric accuracy of the ICC color-managed and digital masters of the paintings were evaluated using 11 uniform areas of pigment (circled in Figure III-1) on each painting and compared across the four museums. In addition, spectroradiometric measurements, which were made from the CRT monitors in each case study of the 11 uniform areas of the digital masters, were also analyzed (Murphy, 2005).

In the second part of the case study testing procedure, nine quality parameters were tested. The first one, system spatial uniformity, which assesses the amount of uncorrected system spatial non-uniformities that can be caused by such things as uneven illumination of the scene and lens fall-off, was tested using a uniform gray-card target. The second was tone reproduction, which was tested using an International Standards Organization (ISO) standard grayscale target (Figure III-3a) and analyzed in the form of an opto-electronic conversion function, or OECF. The third was color reproduction inaccuracy, which is fundamentally caused by the inherent lack of correlation between the camera's spectral sensitivities and those of the average human observer. Spectral sensitivities were determined by imaging a monochromator instrument (Figure III-3b). Also, nine different color targets were imaged and analyzed (Figures III-3c – III-j). Observer metamerism was evaluated between the camera and photographer using a tool called the Davidson & Hemmendinger (D&H) Color Rule (Figure III-3k), unfortunately no longer manufactured. The fourth and fifth parameters were noise (image and color) and dynamic range. Image noise and dynamic range were both tested using an ISO standard noise target (Figure III-3l), imaged eight times at the same exposure level. Color noise was tested using selected patches of the Macbeth ColorChecker (Figure III-3c). The sixth image quality parameter, spatial crosstalk, commonly known as image flare, was tested using an International Electrotechnical Commission (IEC) standard target (Figure III-3m). The seventh, spatial frequency response (SFR), which is used to characterize a camera's ability to reproduce detail, and the eighth, color-channel registration, were both tested using the knife-edges of an ISO resolution target (Figure III-3n). Depth of field was tested using a novel three-dimensional target (Figure III-3o) that had a total depth of 6".

The test targets and paintings were approximately the same size, so the camera and lighting setup remained consistent throughout most of the imaging process. The imaging of the monochromator instrument and depth-of-field target were the exceptions. Although the basic imaging procedure was consistent for all four of the museum case studies, each study was unique because the photographer had the freedom to follow his or her normal imaging procedure.



a.) ISO OECF target
b.) Monochromator Instrument
c.) Macbeth ColorChecker
d.) Macbeth ColorChecker DC
e.) Esser Test Chart
f.) Cobalt blue target
g.) Gamblin oil paint target
h.) IT8 target
i.) Kodak Color Separation and Grayscale targets
j.) BCRA target
k.) D & H Color Rule
l.) ISO Noise target
m.) IEC spatial crosstalk target
n.) ISO Resolution target
o.) Depth-of-field target

Figure III-3. Test targets used in the characterization of each museum's digital camera system and imaging workflow.

Paintings Analysis

The paintings shown in Figure III-1 were imaged in each case study as if they were one painting, because they both contained the same pigments. The images were processed using each institution's normal workflow (Figures III-2a – III-2d). In Case Studies II, III, and IV, this included visual editing. The circled areas of the paintings, shown in Figure III-1, were evaluated for colorimetric accuracy by comparing the ICC color-managed and visually corrected image data to contact measurements made with a spectrophotometer. The images were converted to a common color space for visual comparisons (Figures III-4 – III-6). Figure III-4 compares the ICC color-managed images of each of the four case studies, and Figure III-5 compares the digital masters of Case Studies II, III, and IV. The differences between the colors in the ICC color-managed images of the four case studies were attributed mostly to the cameras' spectral sensitivities and the accuracy of the profiles used (Figure III-4). Furthermore, different photographers visually edited the ICC color-managed images in Case Studies II – IV, causing color differences in the digital masters (Figure III-5). Figure III-6 shows the fish painting before and after visual editing. The large differences indicate that the CRT images were poor matches to the painting, as a result of the photographers' subjective judgment, which appears to include attempts to improve color accuracy as well as to impart aesthetic preferences.

Figure III-4. ICC color-managed images of paintings for Case Study I, II, III, and IV, from left to right.

Figure III-5. Digital masters of Case Study II, III, and IV, from left to right. (These digital masters included visual editing in their workflow.)

Figure III-6. ICC color-managed (top) and visually corrected digital master (bottom) images of the fish of Case Studies II, III, and IV, from left to right.

The colorimetric differences between the measured spectral data and the ICC color-managed image or visually corrected digital master image of the fish painting are plotted in Figures III-7a – d. The left-hand plots are a*b* plots, showing chromatic differences. The color-coded filled circles are the spectrophotometric-based values. A vector is drawn from this point to the image-based values. The black lines are the ICC color-managed image values while the green lines are the visually corrected values. Vectors pointing away or towards the origin describe differences in chroma while changes in other directions describe differences in hue. The right-hand plots are $L^*C^*_{ab}$ plots, showing lightness and chroma for the same measurement data. Vectors pointing up or down describe differences in lightness while vectors moving from right to left or vice versa describe differences in chroma. Since the goal of the imaging was to create color-accurate image files, these difference vectors, in fact, are error vectors (based on the reasonable assumption that the spectrophotometer measured these paintings accurately). Ideally, the arrowhead should be coincident with the filled circles.

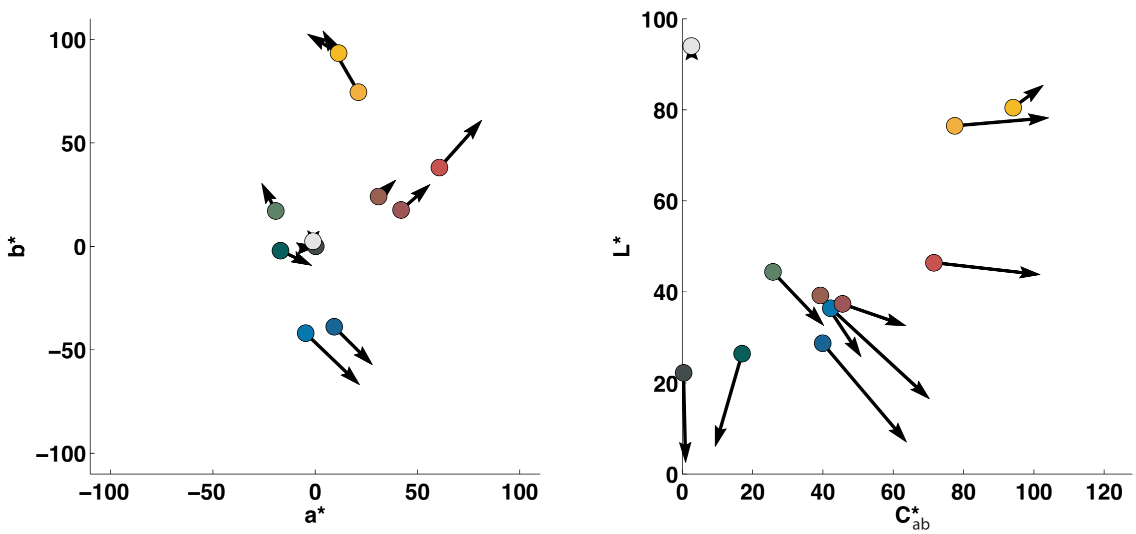


Figure III-7a. CIELAB a [green (-) to red (+)] vs. b* [blue (-) to yellow (+)] and CIELAB L* vs. C^*_{ab} error vector plots comparing the measured (dot) and the ICC color-managed image (point of black vector arrow) data or the visually corrected digital master image data (point of green vector arrow) for the Case Study I fish images.*

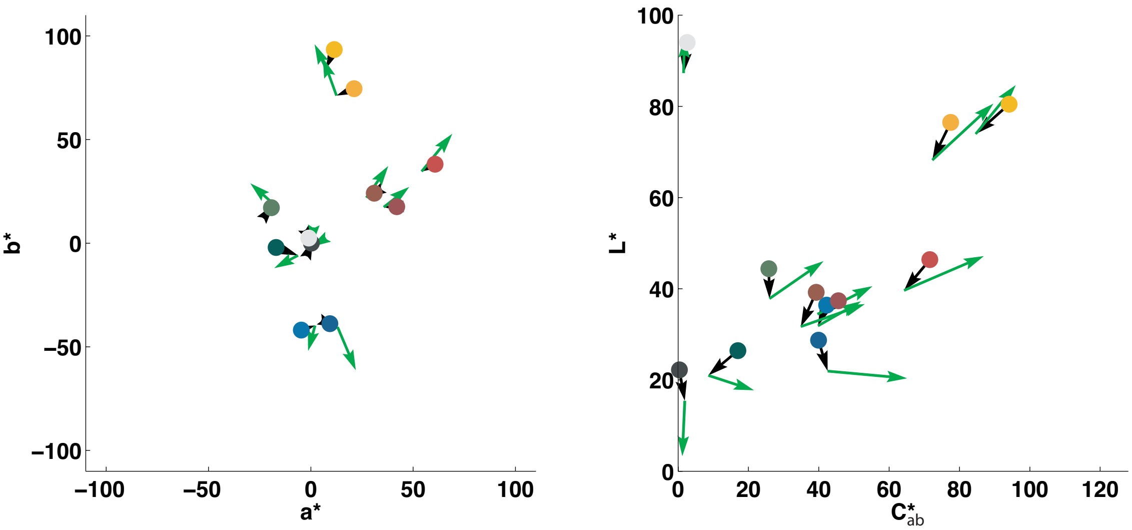


Figure III-7b. CIELAB a [green (-) to red (+)] vs. b* [blue (-) to yellow (+)] and CIELAB L* vs. C*$_{ab}$ error vector plots comparing the measured (dot) and the ICC color-managed image (point of black vector arrow) data or the visually corrected digital master image data (point of green vector arrow) for the Case Study II fish images.*

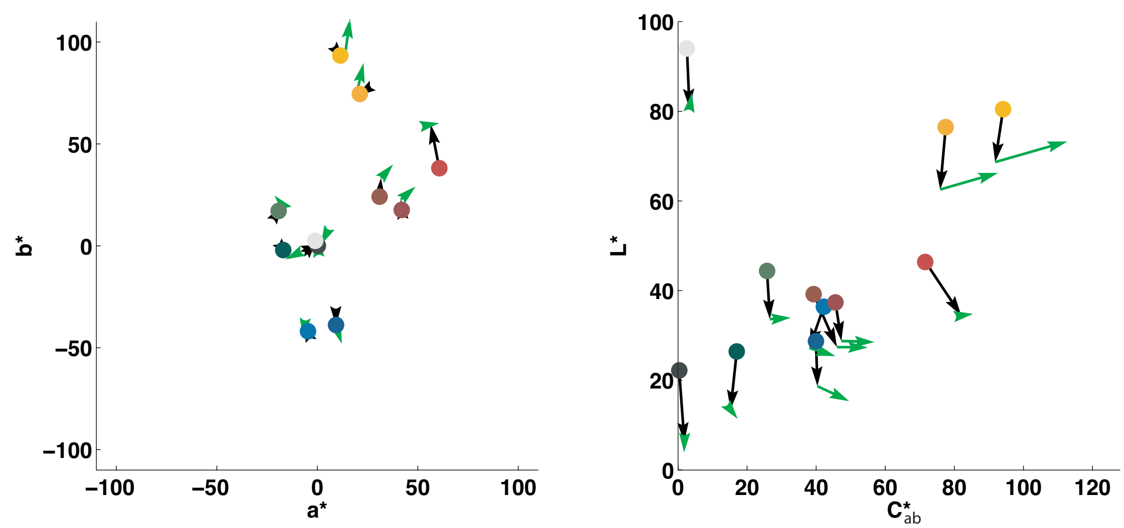


Figure III-7c. CIELAB a [green (-) to red (+)] vs. b* [blue (-) to yellow (+)] and CIELAB L* vs. C*$_{ab}$ error vector plots comparing the measured (dot) and the ICC color-managed image (point of black vector arrow) data or the visually corrected digital master image data (point of green vector arrow) for the Case Study III fish images.*

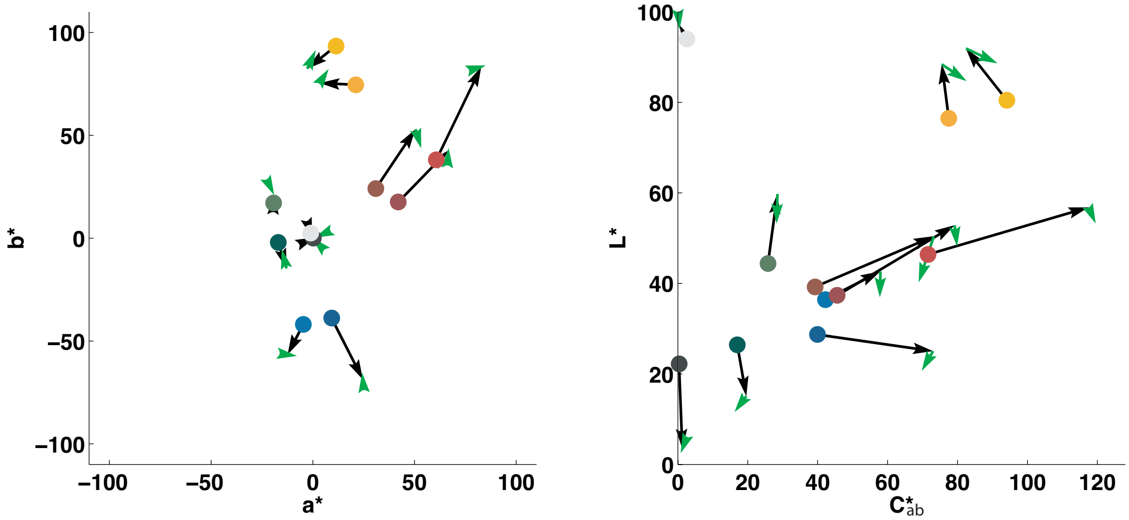


Figure III-7d. CIELAB a [green (-) to red (+)] vs. b* [blue (-) to yellow (+)] and CIELAB L* vs. C^*_{ab} error vector plots comparing the measured (dot) and the ICC color-managed image (point of black vector arrow) data or the visually corrected digital master image data (point of green vector arrow) for the Case Study IV fish images.*

The color error for Case Study I was appreciable: The image data were boosted in contrast and chroma. In the a*b* plot, vectors are pointing outward from the origin, indicating an increase in chroma. In the $L^*C^*_{ab}$ plot, the vectors are pointing downward and to the right for dark colors and upward and to the right for light colors, indicating an increase in the range of lightnesses (i.e., an increase in contrast) and an increase in chroma. This is more likely a result of the color profile than inherent design issues. The two blue colors show a large hue shift towards red. This is common with trilinear array sensors when measuring blue pigments with long-wavelength reflectance "tails," in this case, cobalt blue.

Case Study II ICC color-managed images had less error than Case Study I, revealed by shorter-length vectors. Although visual editing was expected to improve color accuracy, this did not occur. Vectors were drawn from the color-managed data to the visually corrected digital master data. Ideally, the green arrowheads should be coincident with the filled dots. This occurred for the white area on the painting. For the other colors, the visual correction boosted contrast and chroma. This phenomenon is found in many archived images and is similar to the color reproduction in conventional photography.

Trends in Case Study III were similar to those in Case Study II, except the errors were larger. The ICC color-managed image data were too dark; the visual editing did not change this appreciably. The differences between the yellow color data for the two files are interesting: Error in lightness was replaced with error in lightness and chroma.

Case Study IV was similar to Case Study I in that both had large errors. However, Case Study IV increased chroma and lightness (except for the two darkest colors that decreased in lightness) while Case Study I increased chroma and contrast. It is clear that the direction of color error has a large impact on preference. As seen in Figure III-4, the Case Study I images would be preferred over those of Case Study IV, though both have poor accuracy. The visual editing slightly improved color accuracy; the green and black arrowheads are in close proximity. This was surprising, since the most time spent on visual editing was at the Case IV institution.

Color-difference metrics are used to relate the vector length (i.e., the Euclidean distance in L*a*b*) with perceived difference in total color, that is, simultaneous differences in hue, lightness, and chroma. The CIE has recently recommended a new metric, CIEDE2000 (ΔE_{00}) (CIE 142, 2001). Table IV-II lists the mean values between the spectral measurements and the ICC color-managed image or digital masters of the flower and fish paintings. Color differences are used as a summary metric, as they measure only magnitude and not direction. Since the purpose of visually editing the ICC color-managed image was to improve its color accuracy (make it appear more like the original), it would be expected that the ΔE_{00} of the visually corrected digital master image would be much smaller than the ICC color-managed image. For Case Studies II and III, the average differences were nearly identical; errors in one direction were replaced with errors in a different direction. For Case Study IV, visual editing resulted in improvement in average color accuracy. However, this did not overcome the low color accuracy.

Table IV-II. Case study mean ΔE_{00} of the 22 image areas between the measured spectral reflectance and the CIELAB data of the ICC color-managed image or visually corrected image of the fish and flower paintings.

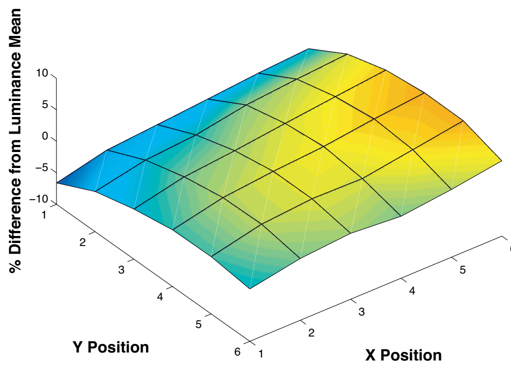
Case Study	ICC Color-Managed Image	Visually Corrected Digital Master Image
I	12.3	N/A
II	6.9	6.9
III	10.5	10.6
IV	12.7	9.7

Target-Based Analyses

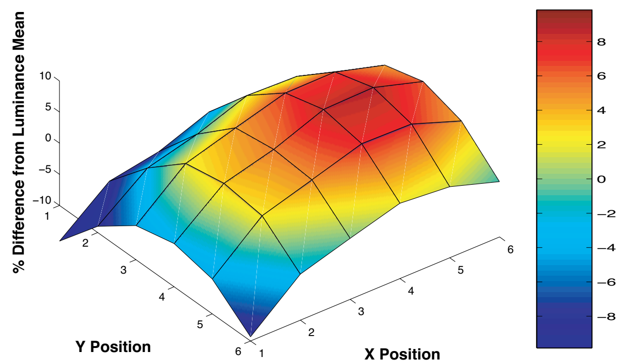
System Spatial Uniformity

An image of a uniform colored area should have image data that are identical, otherwise, non-uniformity may be associated with the artwork rather than the imaging system. Uniformity is achieved in two ways. First, the photographer may adjust the position of the taking illumination and evaluate uniformity using a light meter. Through trial and error, uniformity is achieved. However, uniform lighting is not always a goal in digital photography of artwork where one may want to accentuate surface topography. In these cases, or in cases where uniform lighting is not achievable, camera software is used that evaluates the image data of a neutral, spatially uniform material, and from that evaluation, creates a uniformity correction. For example, in Case Study III, the workflow (Figure III-2c) included applying a shading reference; this was a software correction for lighting non-uniformity.

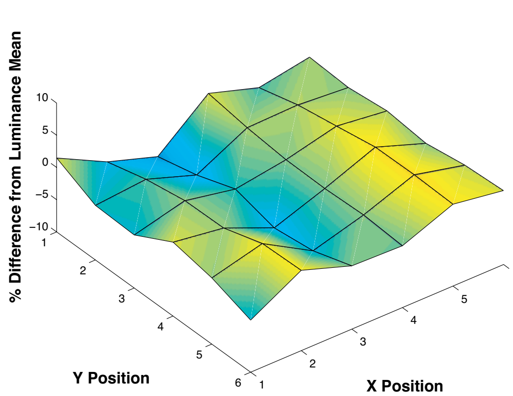
Spatial uniformity was analyzed using a 6 by 6 grid of evenly spaced patches of a target consisting of two gray cards made from Gray 6.5 Color-Aid paper, which were placed side by side. The spatial uniformity analysis was similar to that described in the IEC 61966-8 and 61966-9 standards. The average CIE tristimulus value Y over each patch, obtained from the color-managed images, was compared to the mean tristimulus Y of all 36 patches, and a percent difference was calculated between them. CIE tristimulus value Y is known as luminance factor, a measure of light (or reflectance) that relates to perceptions of brightness and lightness. Light meters measure equivalently. The system spatial uniformity results of the four case studies are plotted in Figure III-8.



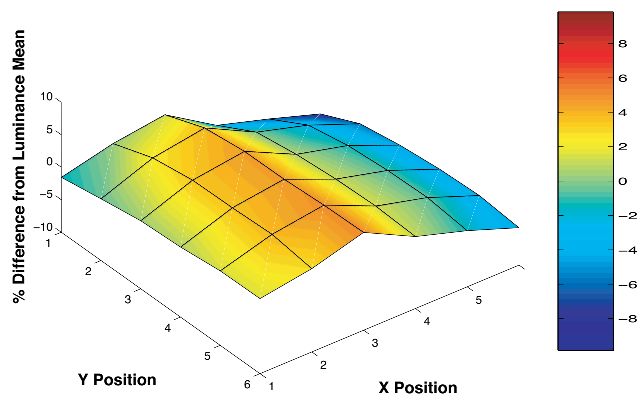
III-8a. Case Study I



III-8b. Case Study II



III-8c. Case Study III



III-8d. Case Study IV

Figure III-8. System spatial uniformity results case study comparison.

In Case Study I, light metering was performed during the imaging system setup. Figure III-8a shows that there was slightly more light on the right side of the gray-card target and slightly less light on the left and upper edges in comparison to the middle of the image. Although perfect uniformity was not achieved, this is probably typical of only using physical changes in the lighting setup in order to achieve spatial uniformity. In Case Study II, a uniformity correction was not done, so there was a hot spot of light on the right side of the image and much less light on the left and upper edges in comparison to the middle of the image. In Case Study III, the non-uniformities were corrected using the image-capture software and an image of a uniform white target, so even though the distribution of the spatial non-uniformity was slightly noisy, seen as the "crinkly" plot, the overall system spatial uniformity was adequate. This noise was caused by the image processing rather than lighting non-uniformity. In Case Study IV, the uniformity was checked in the image capture software during setup, which resulted in the left side of the gray card target being of higher luminance than the right side. From these data, it can be concluded that metering of the entire image area or doing a correction of non-uniformities using the image capture software before imaging helped to reduce system spatial non-uniformities.

Tone Reproduction

During the case studies, the ISO OECF target (ISO 14524) shown in Figure III-3a was nominally exposed, underexposed, and overexposed, so that the target patch image data over the full range of possible digital-count values were obtained. Each patch was also measured with a spectroradiometer to obtain *in situ* luminances. The average image target patch values were determined for each exposure level and rescaled to match the nominal exposure level. The OECF functions for each channel are shown in Figure III-9. The solid colored lines show a cubic interpolation of the measured values and represent each channel's OECF. These curves should be smooth and should monotonically increase until the point of clipping, where the line flattens near normalized digital counts of 1. All four case studies had this property. As a summary metric, each curve was fitted with gamma encoding, a common image-processing step in digital photography used to reduce visual artifacts such as banding and loss of shadow and highlight tonal detail caused by quantization (Berns, 2001). Some of the case studies had different OECF curves for each channel. The fitted gammas of the three channels are listed in Table IV-III for the four case studies. The OECF result from one case study was not necessarily better or worse than that of any another case study. As images are stored as 16-bit-per-channel TIFF files, the need for gamma encoding diminishes. The digital masters for each of the case studies had embedded or associated ICC profiles that contain the OECF LUT that should be used to interpret the files photometrically. When the OECF used by the system does not match the curve in the profile, errors are inevitable in future interpretations without re-characterization. Case studies I and III claimed an OECF with a gamma of 1.8 and case studies II and IV a gamma of 2.2. In all of the case studies there was some deviation from the reported values as shown in Table III-III.

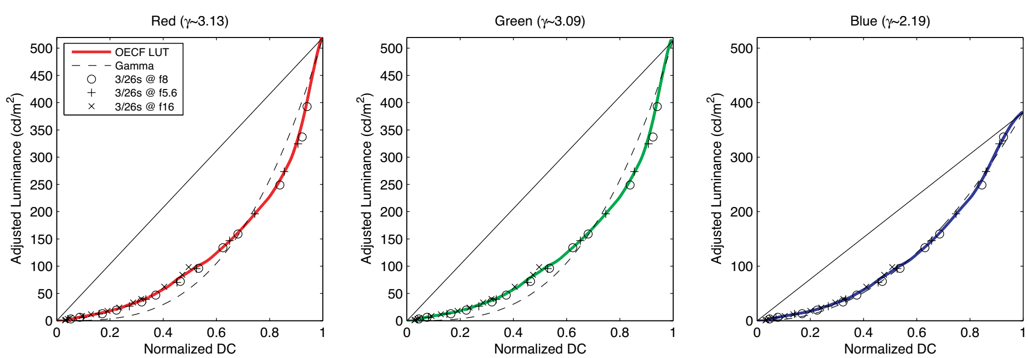


Figure III-9a. Tone reproduction OECF curves of RGB channels for Case Study I.

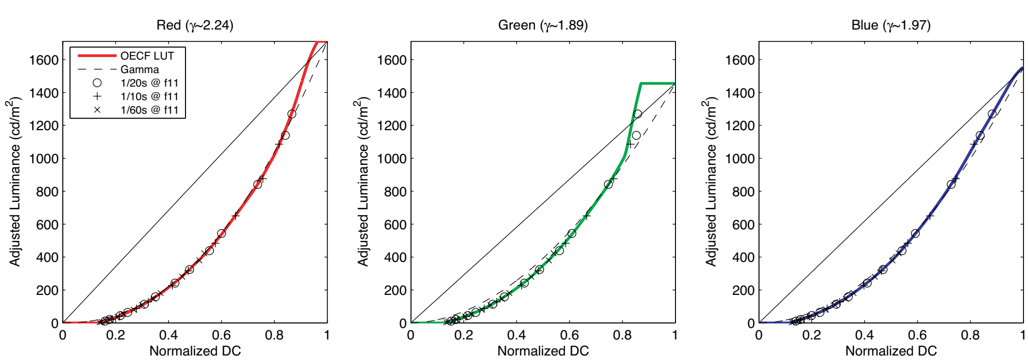


Figure III-9b. Tone reproduction OECF curves of RGB channels for Case Study II.

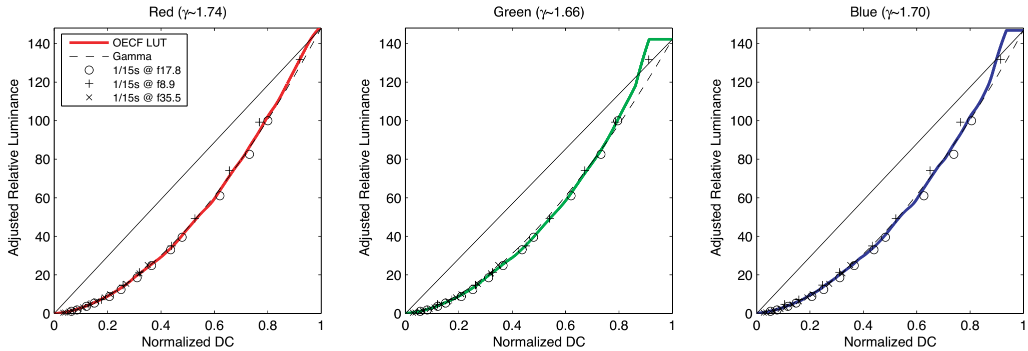


Figure III-9c. Tone reproduction OECF curves of RGB channels for Case Study III.

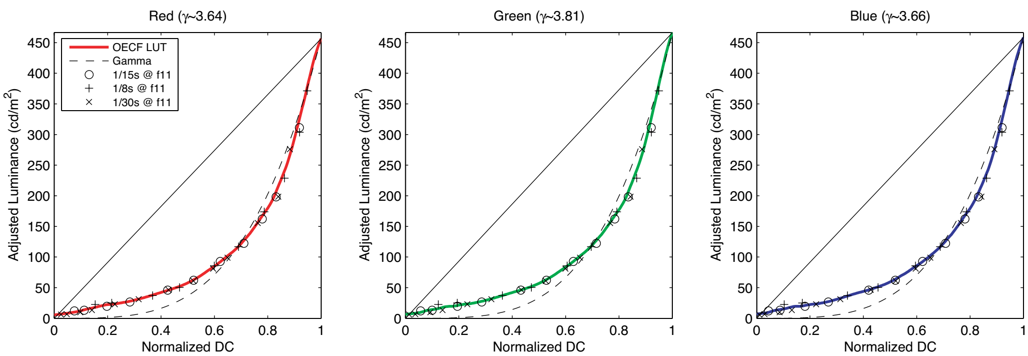


Figure III-9d. Tone reproduction OECF curves of RGB channels for Case Study IV.

Table III-III. Fitted gamma functions for each case study.

Case Study	Red	Green	Blue
I	3.13	3.09	2.19
II	2.24	1.89	1.97
III	1.74	1.66	1.70
IV	3.64	3.81	3.66

Color Reproduction Inaccuracy

Spectral sensitivity is a measurement of a sensor's sensitivity (or response) as a function of wavelength. In a digital camera, we often refer to its red, green, and blue channels, where the red, green, or blue channels have their greatest sensitivity to red, green, or blue light, respectively. It is the most fundamental description of the color properties of an imaging system. Most digital camera spectral sensitivities are not linear transformations of an average human visual system's spectral sensitivities (IEC 61966-9; Berns, 2001; ISO 17321-1). That is, through a linear mapping, the camera and a standardized observer do not "see" color identically. This is, perhaps, the main underlying reason why color inaccuracies exist in digital images. The spectral sensitivity of each case study camera system was measured using the monochromator instrument shown in Figure III-3b. Thirty-six images were captured corresponding to peak wavelengths of 380nm to 730nm in 10nm increments. Spectral radiance was measured simultaneously using a spectroradiometer. These data were used to calculate spectral sensitivity. Because a camera may have internal color processing, these sensitivities were rotated to best fit the CIE 1931 2° standard observer "sensitivities," (CIE 15.2) plotted in Figure III-10.

The lack of fit to the 2° observer can be summarized using a quality metric, μ-factor, where values range between zero and unity, conceptually equivalent to a multi-dimensional correlation coefficient (Vora and Trussell, 1993). The closer this value is to unity, the better the correlation of the camera's spectral sensitivities to the 2° observer. A value of zero signifies no correlation. The μ-factor was calculated for each case study using the CIE 1931 2° standard observer and the assumption that the taking and rendering illuminants were CIE illuminant D50. The results for the four case studies are shown in Table III-IV. For all four camera systems, the similarity to the human visual system was poor. The red, green, and blue peak sensitivities were poorly aligned with human vision. The blue and red sensitivities were shifted to longer wavelengths; the red sensitivities had too narrow a bandwidth. Cameras designed for high colorimetric accuracy have μ-factors above 0.9.

The targets shown in Figures III-3c – III-3j were used to evaluate color accuracy: the Macbeth ColorChecker (3c), Macbeth ColorChecker DC (3d), the Esser Test Chart (3e) (IEC 61966-8), a cobalt blue pigment target (3f), a Gamblin oil paint target (3g), the IT8 target (3h) (ISO 17321), the Kodak Color Separation and Grayscale targets (3i), and a target made from ceramic BCRA spectrophotometer calibration tiles (3j). Each digital master also included a white reference plaque; this plaque was used to normalize all the digital masters. This is similar to the concept of calibrating a color-measuring instrument. Bar charts comparing the average and 90th percentile ΔE_{00} color differences are shown in Figures III-11 and III-12. The 90th percentile is a better metric than the commonly reported maximum color difference, as it minimizes the influence of possible outliers. There was a considerable range of accuracy. In general, the performance order of the case studies from best to poorest was III, II, I, and IV. The targets that produced the greatest range of performance were the Gamblin oil pigments (3g) and Macbeth ColorChecker (3c). The amount of color difference errors resulting in all four case studies was mostly dependent on the spectral sensitivities of the camera system and, to a lesser extent, the camera system's color-management profile. Since the spectral sensitivities of the camera cannot be changed, except with the use of filters, the focus tends to be on improving profile performance. Therefore, profiles should be optimized using a target representing the pigments and materials being imaged with the camera.

Table III-IV. μ-factor values for the four case studies for the CIE 1931 2° standard observer and matching taking and rendering illuminants: 1.0 equals perfect correlation.

Case Study	μ *Factor*
I	0.79
II	0.82
III	0.82
IV	0.80

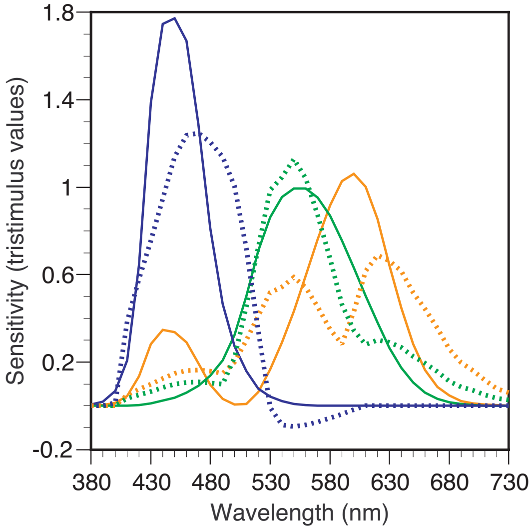


Figure III-10a. (Case Study I)

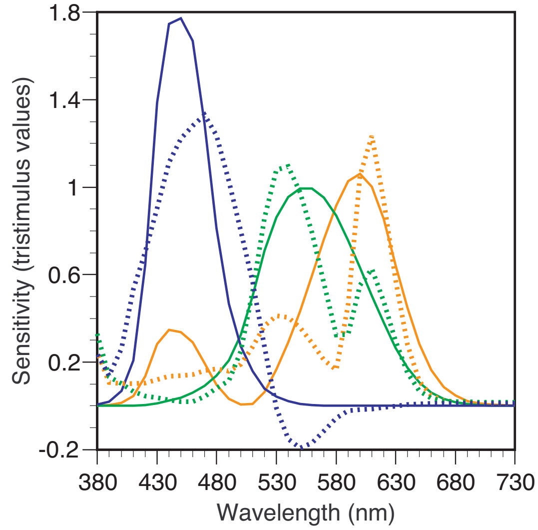


Figure III-10b. (Case Study II)

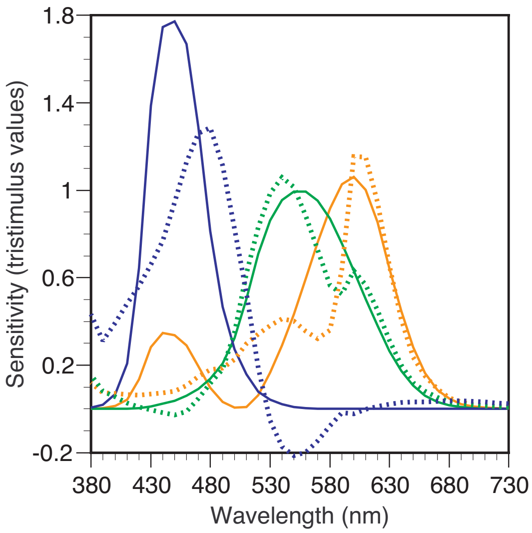


Figure III-10c. (Case Study III)

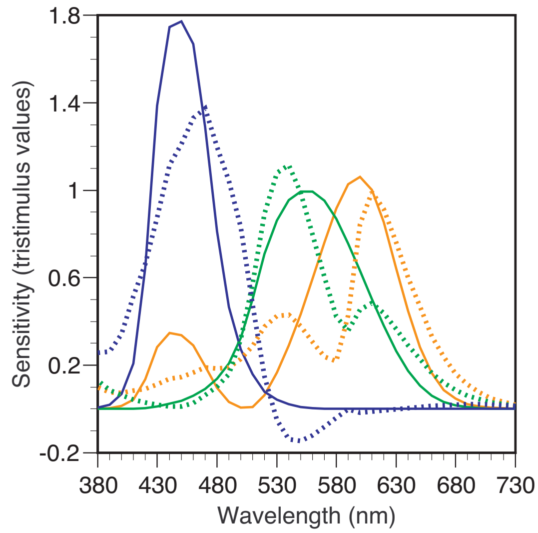


Figure III-10d. (Case Study IV)

Figure III-10. Spectral sensitivity case study comparison of relative spectral sensitivities (dotted lines) rotated to fit the CIE 1931 2° standard observer (solid lines).

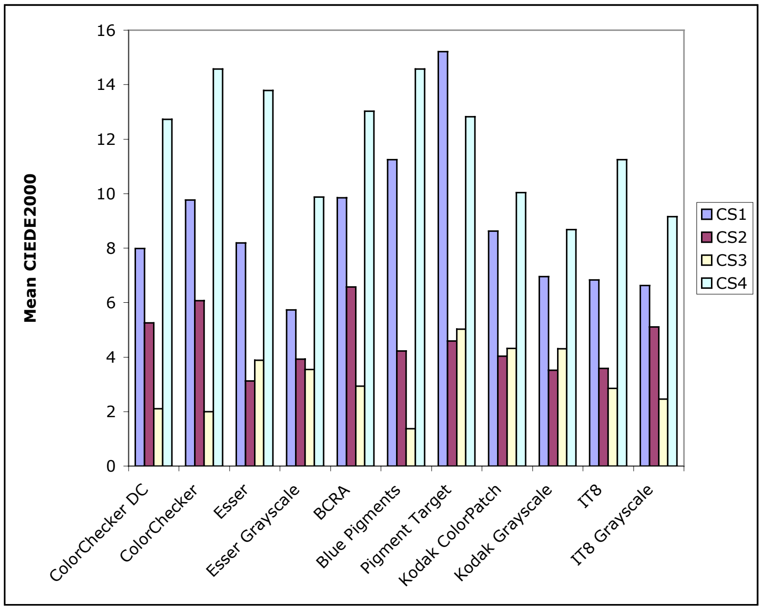


Figure III-11. Average ΔE_{00} color difference comparison of each case study where each digital master was normalized to a reference white plaque.

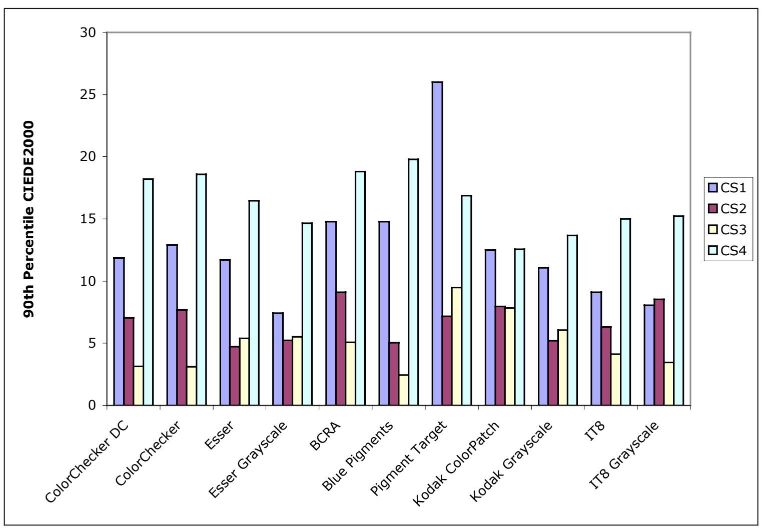


Figure III-12. Ninetieth percentile ΔE_{00} color difference comparison of each case study where each digital master was normalized to a reference white plaque.

In order to visualize the variation in color rendition amongst the case studies, each digital master of the Macbeth ColorChecker and the reference spectrophotometric measurements were converted to the sRGB color space (IEC 61966-2-1, IEC 61966-2-1-A). From these images, a composite image was created (Figure III-13). Ideally, all four surrounding patches should match the central patch for each color of the ColorChecker.

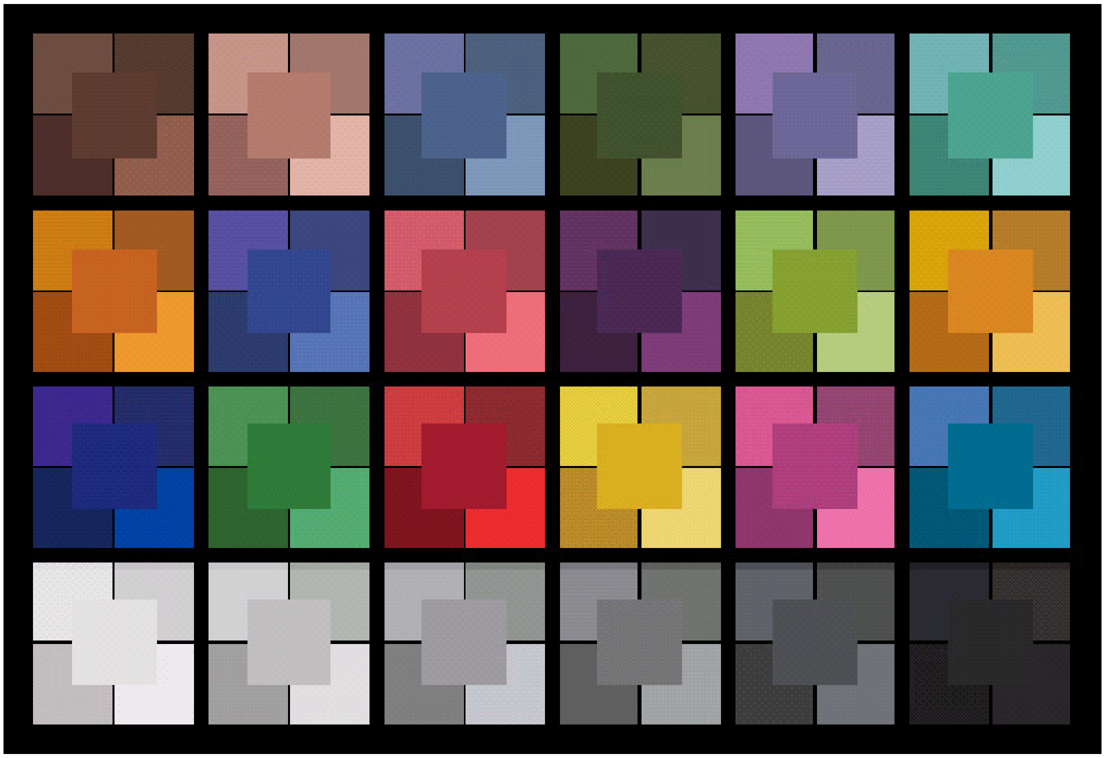


Figure III-13. Color reproduction accuracy comparison of the Macbeth ColorChecker digital masters (corners of each color) to the measured data (central square of each color) rendered using illuminant D_{50}. Case Study I (top left), Case Study II (top right), Case Study III (bottom left) and Case Study IV (bottom right).

Observer metamerism occurs when two spectrally different stimuli viewed under the same light source match to one observer, but do not match to another observer. The D&H Color Rule tool (Figure III-3k) demonstrates how closely what the photographer sees resembles what the camera sees. The Color Rule consists of two strips of metameric colors, one labeled alphabetically and one labeled numerically. When placed behind a mask with only one color of each strip showing at a time, these two color strips can be slid back and forth by an observer under a light source until the best match is made. In each case study, the photographer made a match under the illuminant used in the imaging of the targets (in Case Study III, the match was made under the fluorescent illuminant used to illuminate the paintings during the visual correction, because Xenon strobes were used as the taking illuminant). The camera's match in each case study was determined by comparing the CIELAB values between each of the patches of the alphabetic and numeric strips by calculating ΔE_{00}. The two patches (one from each strip) with the lowest ΔE_{00} value were deemed the camera match. Figure III-14 shows how the metameric camera and photographer matches differed from each other for each museum case study.

There is no "correct" metameric match that can be made using the D&H Color Rule. The match depends on the light source under which the match is made and the inherent spectral sensitivities of the detector. If the metameric matches were the same for the camera and the photographer in each case study, then this would indicate that no, or only a small amount of, visual correction would need to be made to the images after digital capture, because the images would already match visually and have CIELAB values that were the same as or similar to the original painting.

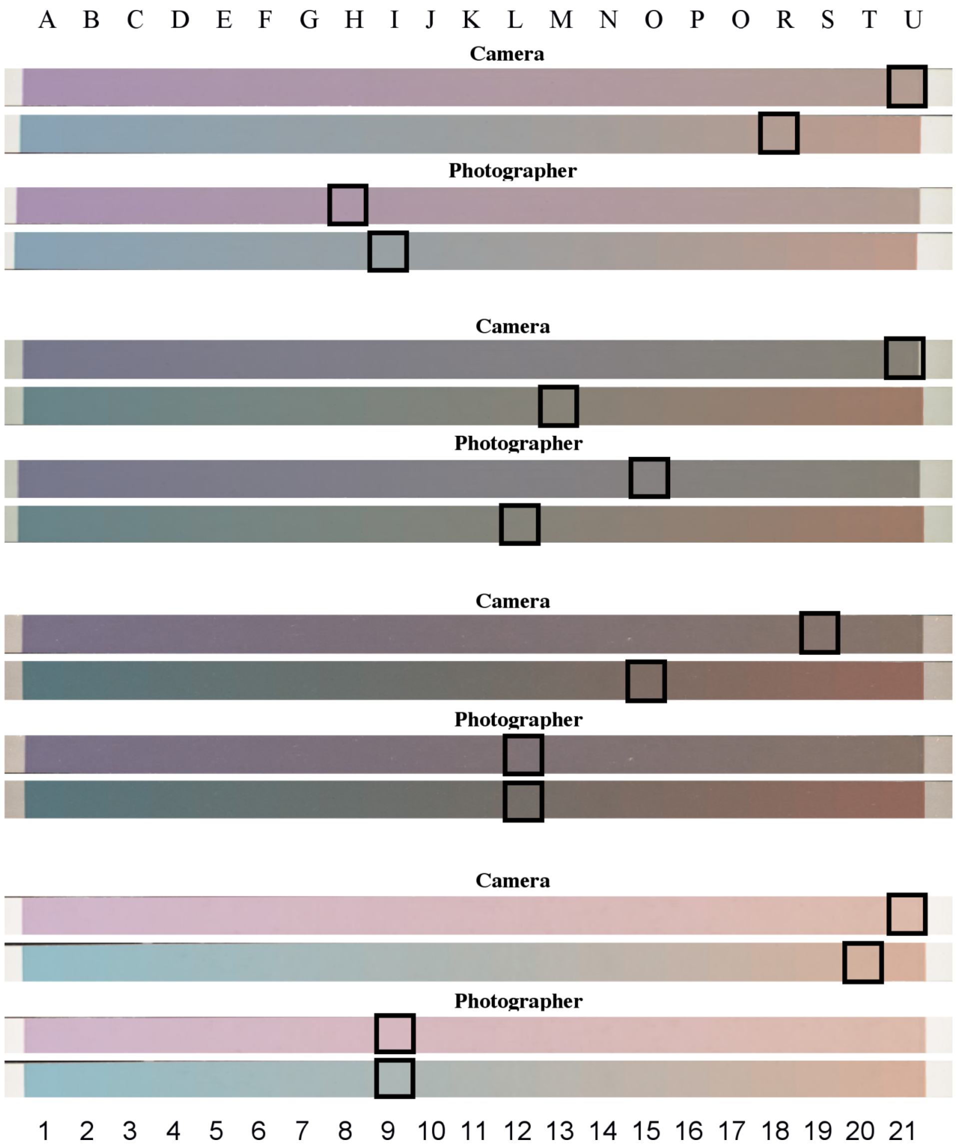


Figure III-14. D&H Color Rule metameric matches made by the photographer and camera in each of the four case studies. From top to bottom: Case Study I, Case Study II, Case Study III, Case Study IV.

Noise

The three center patches of the ISO 15739 Noise target, shown in Figure III-3l, were used to evaluate image noise. The total average noise measurements of each case study are listed in Table III-V. These values were calculated according to the ISO 15739 standard. The smaller this value, the less noise the image had. In order to produce images with a small amount of noise, at least one dark-correction image should be subtracted with the processing workflow. Also, using a low ISO and short exposure time when imaging will help in the reduction of the image-noise level.

Color noise is defined as image noise that is color-dependent. It is seen as pixel variations in an image of a uniform patch of color. The patches of the Macbeth ColorChecker (see Figure III-3c) that were used in the color-noise evaluation were red (#15), green (#14), blue (#13), yellow (#16), magenta (#17), cyan (#18), white (#19), gray (#22), and black (#24). The color noise was evaluated using a metric called the *mean color difference from the mean* (MCDM) (Berns, 2000).

First, the mean of the image-pixel data of each color patch was determined. Next, the color difference of each pixel of the patch from the mean was determined using ΔE_{00}. Then, the average was calculated from the color differences of all of the pixels, i.e., the MCDM. The mean MCDM, or MMCDM, which is the mean of all nine of the selected Macbeth ColorChecker patches, is listed in Table III-VI for each of the four case studies. The smaller the MMCDM value, the less color noise a digital camera produces.

The dynamic range, otherwise known as tonal range, of a digital camera system is the capacity of the camera to capture extreme density variations. The darkest and second darkest patches of the ISO Noise target in Figure III-3l were used to calculate the dynamic range as a luminance ratio according to ISO standard 15739. The $\log_{10}$ of this ratio was calculated to determine the dynamic range density values listed in Table III-VII for all four case studies. It is desirable to have a high dynamic range. A density of 0.3 is equal to one stop of light ($\log_{10}2$). In order to obtain the most dynamic range achievable by a digital imaging system, the amount of flare should be reduced as much as possible.

Table III-V. Total average image noise for the four case studies.

Case Study	Red Channel	Green Channel	Blue Channel
I (16-bit)	329	335	458
II (16-bit)	698	617	844
III (16-bit)	722	593	666
IV (8-bit)	3	3	3

Table III-VI. MMCDM of the Macbeth Color Checker for the four case studies.

Case Study	MMCDM (ΔE_{00})
I	0.9
II	1.0
III	0.9
IV	0.9

Table III-VII. Dynamic range measured in density for the four case studies.

Case Study	Red Channel	Green Channel	Blue Channel
I	2.85	2.87	2.86
II	2.60	2.97	2.77
III	2.53	2.68	2.71
IV	2.74	2.92	2.93

Spatial Crosstalk

Spatial crosstalk is equivalent to image flare and occurs where image data in one location affects data in another location. The target shown in Figure III-3m was imaged twice in order to evaluate spatial crosstalk (IEC 61966-8). The target was rotated 180° after the first image was taken, so that the second image would have, for example, a gray patch with a white background where the first image had a gray patch with a black background. The spatial crosstalk results listed in Table III-VIII for the four case studies are the relative maximum percent differences between the 30 gray patches in the two target image rotations. The smaller this value, the less spatial crosstalk the digital masters had. In order to reduce the amount of spatial crosstalk in a digital image, the image area surrounding the work of art should be as dark as possible.

Table III-VIII. Mean relative maximum percent difference for the four case studies.

Case Study	Red Channel	Green Channel	Blue Channel
I	4.49	3.98	9.02
II	5.63	5.40	8.54
III	5.14	4.91	9.23
IV	3.37	2.76	5.76

Spatial Frequency Response

The central and upper left corner square horizontal and vertical knife edges of the ISO Resolution target (ISO 12233) shown in Figure III-3n were used to determine the spatial frequency response (SFR) of the digital masters (ISO 12233; Burns, 2000). The best SFR curves for each case study are plotted in Figure III-15. For the scanning linear array cameras (Case Studies I, II, and IV), the SFR in the direction of the linear array itself was better than the SFR in the direction of the linear array's scanning. The higher the SFR curves are across the frequency range, the better the preservation of detail at each frequency of the object being imaged. Differences in the SFR curves between the channels were caused by color misregistration in the image or a difference in the image processing that was performed on each channel. Half sampling, at a frequency of 0.5 cycles/pixel, is the Nyquist frequency, where aliasing starts to occur in an image.

Because un-sharp masking was performed on the digital master in Case Study III, the SFR curve exceeds a value of unity. However, sharpening increases image noise: The SFR curve for Case Study III was noisier than those of the other case studies; the SNR was very low for Case Study III. The SFR results of the case studies were affected by the precision with which the camera was focused. In Case Study I, the photographer focused by looking through the camera's view-finder. In the other three case studies, a magnification or frequency-focusing tool in the image-capture software was used to focus the images. Using the image data to focus is preferred as it ensures that the focal plane inside the camera is at the sensor.

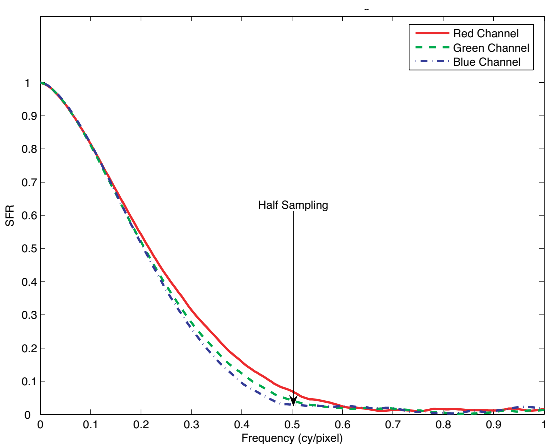


Figure III-15a. Case Study I (center vertical edge)

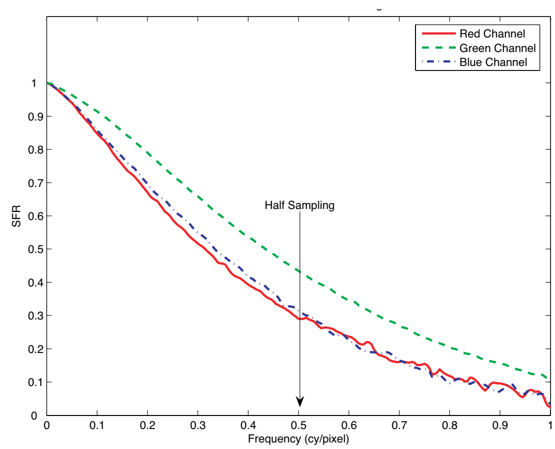


Figure III-15b. Case Study II (center horizontal edge)

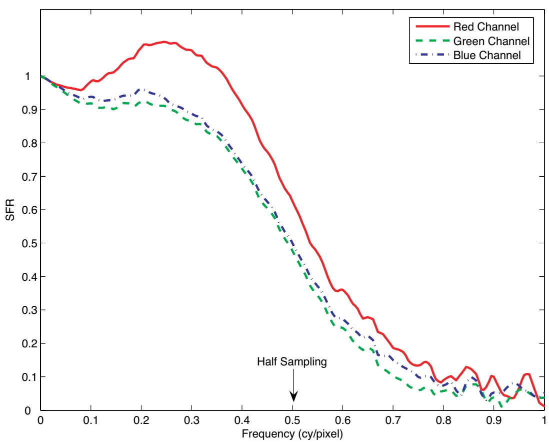


Figure III-15c. Case Study III (center horizontal edge)

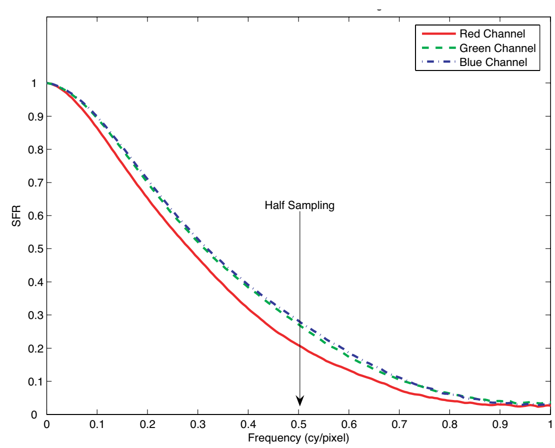


Figure III-15d. Case Study IV (center horizontal edge)

Figure III-15. SFR plots of center edges of each case study. The horizontal or vertical edges that had the best SFR for each case study are plotted.

Color Channel Registration

The color channel registration was evaluated (Burns, 1999) using the same four knife-edges as in the SFR analysis. The mean amounts of color channel misregistration of all three color channels across the four knife-edges are listed in Table III-IX. Misregistration in images from both scanback and area array cameras can be caused by such things as chromatic aberration of the lens or color filter array lenslets. All four case studies had good registration.

Table III-IX. Mean registration shift of the three color channels (RGB) and across all four edges evaluated.

Case Study	Shift (pixels)
I	0.130
II	0.136
III	0.035
IV	0.027

Depth of Field

Depth of field is the range of distance for which the subject is rendered acceptably sharp in an image. It increases as the lens is closed down (f-stop increases) and for a given lens, increases with the subject distance. A digital-imaging system should take depth of field into account when it is used to image even two-dimensional cultural heritage since works such as paintings and drawings may not lie flat and often contain topographic features like impasto. The center column of the depth-of-field target shown in Figure III-3o was used as a point of focus when the image of this target was captured. The SFR of the knife-edge of the square on top of each of the 13 columns was determined. The same edges (horizontal or vertical) plotted in Figure III-15 were used.

Figure III-16 shows the depth-of-field results of the four case studies as plots of the areas under the SFR curves from frequencies of 0.0 to 0.5 cycles/pixel vs. distance on the target. Steep curves on each side of the peak indicate a small depth of field; Case Study II exemplifies this. The Case Study III curves indicate a long depth of field, since the curves are flat with respect to distance. Also, if the peaks are shifted with respect to the focus aim point, as seen in the Case Study I curves, then the focusing tool was inaccurate.

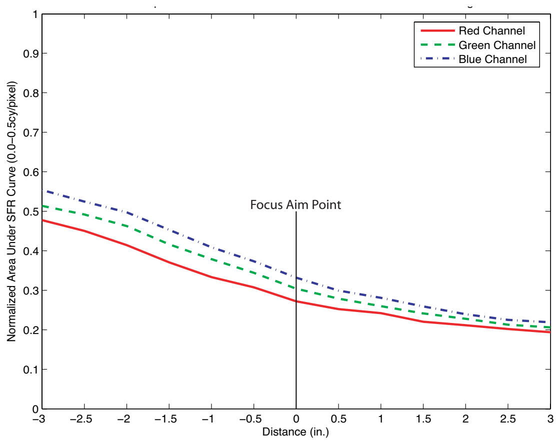


Figure III-16a. Case Study I

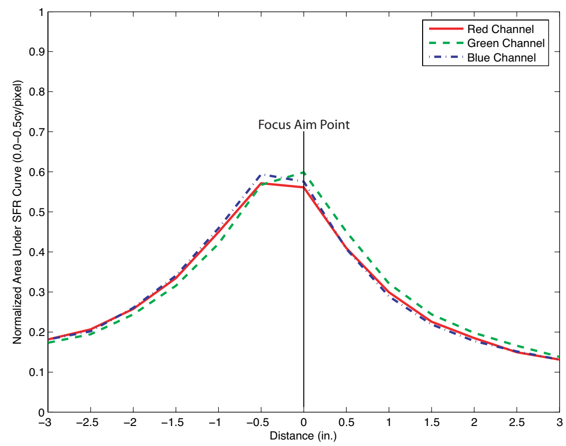


Figure III-16b. Case Study II

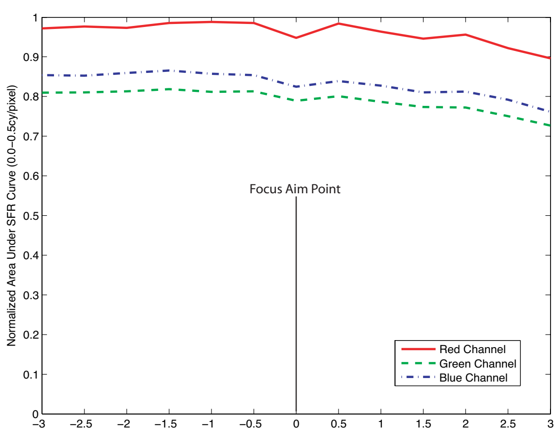


Figure III-16c. Case Study III

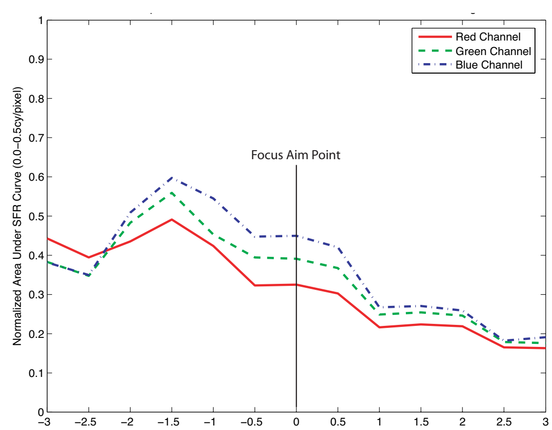


Figure III-16d. Case Study IV

Figure III-16. Depth-of-field results comparison of the case studies.

Summary of Analyses

The color and image-quality mononumeric metric values of nine of the quality parameters discussed in the characterization analysis of the four case studies are summarized in Table III-X. The data listed in this table were obtained from 16-bit digital masters in Case Studies I, II, and III and 8-bit digital masters in Case Study IV.

Table III-X. Case study characterization results of nine of the quality parameters and their aim values.

Quality Parameter	***Ideal Value***	***Case Study I*** (16-bit)	***Case Study II*** ***(16-bit)***	***Case Study III*** (16-bit)	***Case Study IV*** (8-bit)
Tone Reproduction (Mean gamma)	1.80 (*I, III*) 2.20 (*II,IV*)	2.80	2.03	1.70	3.70
Spectral Sensitivity (μ-factor)	1.00	0.68	0.79	0.81	0.80
Target-based Color Reproduction Inaccuracy (Mean ΔE_{00} 90^{th} percentile of 9 targets)	0.0	12.7	6.7	5.1	16.3
Image Noise (Mean total average noise of RGB channels, digital counts)	1 (8 bit) 255 (16 bit)	374	720	660	3
Color Noise (MMCDM)	0.0	0.9	1.0	0.9	0.9
Dynamic Range (Density)	2.41 (8 bit) 3.61 (12 bit)	2.86	2.81	2.65	2.87
Spatial Crosstalk (Mean relative maximum % difference of RGB channels)	0.00	5.83	6.52	6.43	3.97
Spatial Frequency Response (Mean area under the RGB curves across all four edges from frequencies of 0.0 to 0.5 cycles/pixel)	1.000	0.484	0.616	0.862	0.592
Color Channel Registration (Mean registration shift of RGB channels and across four edges)	0.000	0.130	0.136	0.035	0.027

The digital masters from each case study were encoded in a defined RGB working space. The working space used in Case Study I and Case Study III, ProPhoto RGB (see Figures 2a and 2c), had a gamma encoding of 1.80 for all three channels. The working space used in Case Study II, Custom-RGB-D_{50}-2.2gamma-7-01 (see Figure III-2b), had a gamma encoding of 2.20 for all three channels. The working space used in Case Study IV, Digital Attributes_22_Space (see Figure III-2d), had a gamma encoding of 2.20 for all three channels. The gamma values derived by fitting each system's OECF were quite different than the expected gamma values for Case Studies I, II, and IV. These differences contributed to color inaccuracies. For Case Study III, the value of 1.7 was similar to the expected encoding of 1.8.

The spectral sensitivity μ-factor values listed in Table III-X incorporated each system's actual light source as the taking illuminant and D50 as the rendering illuminant. This had a dramatic impact on Case Study I with a μ-factor of 0.68 compared with 0.79 (Table III-IV) when taking and rendering illuminants were assumed to be equal. For the other cases, the choice of illuminants had a small impact. The target-based color reproduction inaccuracy ΔE_{00} 90th percentile values were correlated with the color differences seen visually in the Macbeth ColorChecker composite image shown in Figure III-13. Case Studies II and III performed well in comparison to Case Studies I and IV. The inaccuracy of Case I was likely a result of the fluorescent simulated daylight taking illuminant and a poor color-management profile (exemplified by the poor gamma match). For Case IV, poor color management was the likely source of the large color error.

The image noise total average noise values exceeded their aim values in all four case studies. The noise performance of Case Studies I and IV was much better than the noise performance of Case Studies II and III. The noise performance of Case Study III was affected by the inclusion of an un-sharp masking tool in the processing workflow. The color noise MMCDMs of the four museum case studies were small and very similar to each other. The color noise results were not correlated with the image noise results.

The ideal dynamic range density values were theoretical and calculated based on the number of bits in the image and assumed linear encoding (i.e. gamma of unity). These values are only used as a reference point, so the dynamic range of the imaging system can be higher or lower than this value. An upper limit of 12 bits was used even though Case Studies I, II, and III used 16-bit encoding. Charged-couple devise (CCD) sensors typically have a well capacity equivalent to 12-bits of linear encoding. All four case studies had a dynamic range between 9 bits (dynamic range of 2.71) and 10 bits (dynamic range of 3.01). Although Case Study IV had 8-bit digital masters, the non-linear encoding (gamma of 3.70) increased dynamic range.

Case Studies II and III had the highest spatial crosstalk mean relative maximum percent difference of the RGB channels, and Case Study IV had the lowest. The SFR areas correlate with what can be seen from the curves in Figure III-15. Case Study III had the highest SFR, which was mostly caused by the applied un-sharp masking as part of the workflow. Case Study I had the lowest SFR of the four case studies. This might be attributed to the use of a view-finder for focusing, whereas in Case Studies II, III, and IV, a magnification or frequency-focusing software tool was used to focus the images. The misregistration errors in all four case studies were low. The results show that Case Study IV had the least amount of misregistration error as would be expected with an area array, and that Case Study II had the most.

Further Details

This section summarizes the quantitative analyses of the four case studies. Greater details are found in the form of a Master's thesis (Murphy, 2005), which contains a review of standards, a detailed description of how each case study was performed, a detailed description of how the data were analyzed, the results of each case study, and a comparison of the four case studies.

IV. Benchmarking Conference

Rochester Institute of Technology (RIT) hosted the *American Museums Digital Imaging Conference* from September 21 – 23, 2004. The first two days were a mix of formal presentations, panel discussions, and open discussions. There was also ample time to tour the Munsell Color Science Laboratory at RIT and the George Eastman House International Museum of Photography and Film, and to exchange ideas. Approximately 150 people came to the conference from around the world. The third day was optional and hosted by the Image Permanence Institute at RIT. About 50 conference attendees stayed for the third day program.

The final program schedule is shown in Figure IV-1. Photographs taken at the conference are shown in Figures IV-2a – IV-2d.

FINAL PROGRAM SCHEDULE

	Tuesday, September 21, 2004		Wednesday, September 22, 2004		Thursday, September 23, 2004
8:00 am	Registration Coffee, Continential Breakfast, CIMS, Rm. 2210	8:00am	Coffee, Continential Breakfast, CIMS, Rm. 2210	8:00am	Coffee, Continential Breakfast, CIMS, Rm. 2210
8:30	Welcome *Ian Gatley, Dean, College of Science* *Joan Stone, Dean, Imaging Arts & Sciences* Principal Investigators' Introduction *Roy S. Berns and Franziska S. Frey*	8:30	Invited Talk: Digital Cameras: What Is Happening In the Research Labs?, *Ricardo Motta*, Pixim Inc.	8:30	RIT Image Permanence Institute - I P I *Storage Environments for Archival Media* Talk held in CIMS, Rm. 2240
9:00	Introduction of the Benchmarking Project and Other Related Projects at MCSL, *Roy S. Berns*	9:15	Evaluation of Case Study Imaging Systems, *Erin P. Murphy and Lawrence A. Taplin*	12:00 pm	Lunch, CIMS, Rm. 2210
10:15	Coffee Break	10:15	Coffee Break	1:30	Image Permanence Institute Tour
10:45	Analysis of the Survey and Case Studies, *Mitchell R. Rosen*	10:45	Invited Talk: Criteria for Camera Development, *Peter Burns and Don Williams*, Eastman Kodak Co.	3:00	Adjourn
		11:15	Open Forum: *Camera User Needs*		
12:00 pm	Lunch at CIMS, Rm. 2210 and Patio	12:00 pm	Lunch and Tour, Munsell Color Science Laboratory, Color Science Bldg, 18		
1:30 pm	Panel Discussion: *Museum of Modern Art, NY* *Metropolitan Museum of Art, NY* *Harvard University Libraries, Cambridge* *Harvard University Art Museums, Cambridge* *Art Institute of Chicago*	2:00	Invited Talk: Metadata, *Günter Waibel*, RLG		
		2:30	Invited Talk: Future of Imaging in the Cultural Heritage Arena, *Alan Newman*, National Gallery of Art		
3:15	Afternoon Break, Rm. 2210	3:30	Post-Conference Get Together, Rm. 2210		
3:45	Invited Talk: Imaging in Conservation, *Francesca Casadio*, Art Institute of Chicago	4:30	Adjourn		
4:15	Digital Preservation, *Franziska S. Frey*				
5:00	Adjourn				
5:15	Bus Pick-up at CIMS (front main door) leaving to George Eastman House				
6:00pm	Dinner Reception and Tour Begins George Eastman House - Driving directions (from RIT) are located at the registration desk.				
8:30	Bus Begins Return Rides Bus will drop off at CIMS, Park Plaza and RIT's Inn and Conference Center.		*Evening is on own for participants registering for day three.*		

Figure IV-1. Benchmark Conference program schedule.

The American Museums Digital Imaging Conference had invited speakers including Francesca Casadio of the Art Institute of Chicago (*The Use of Imaging in Conservation Science*), Ricardo Motta from Pixim Inc. (*Emerging Technologies*), Peter Burns and Don Williams from the Eastman Kodak Co. (*Criteria for Camera Development*), Günter Waibel from the Research Libraries Group (*Metadata Standards*), and Alan Newman from the National Gallery of Art in Washington, DC (*The Future of Museum Imaging*).

Panelists included Erik Landsberg from the New York Museum of Modern Art, Barbara Bridgers from the Metropolitan Museum of Art, David Remington from the Harvard University Libraries, Andrew Gunther from the Harvard University Art Museums, and Christopher Gallagher from the Art Institute of Chicago. The panel discussion was designed to help conference participants learn more about the imaging practices in each institution, the institutions' digital archiving philosophies, their successes and obstacles, and their needs for future improvement.

Figure IV-2a. Co-investigator Franziska Frey introducing a speaker.

Figure IV-2b. Panel discussion.

Figure IV-2c. Open laboratory session showing the differences in each institution's rendering of the oil paintings.

Figure IV-2d. Open laboratory session where co-investigator Roy Berns is showing the test targets used for the objective measurements.

Figure IV-2. Images taken during the conference (photographs taken by Natalie Russo).

Panel Discussion Summary

The purpose of the panel discussion was to have representatives from the case study institutions present an overview of their imaging practices. This was followed by questions and answers. Because this report is keeping the case study institutions anonymous, this write-up will consist of quotes and paraphrased comments.

- For several institutions, digital photography began using an outsourced consulting company. This has been replaced with in-house personnel. The role of consultants at each institution was not entirely clear, though several consultants participated in the conference.

- Image quality was defined by file size in most cases. As camera technology has evolved, so has file size. File size was used as a metric of quality.

• There was a variety of “raw” files. Institutions have different definitions of a raw file.

• Each institution had a different definition of a digital master. This varied from a true raw file (digitized sensor data) to sharpened, color-corrected, visually edited, and working-space encoded files.

• The imaging goal, in theory, was to shoot a work of art once. However, this concept was viewed as naïve because with significant technological advances, re-imaging may be desirable.

• Digital archiving ranged from CD to centralized file servers. All agreed that data storage was often a hidden cost, not considered in the initial move from analog to digital imaging.

• “We want the image to look like the work of art.” (More about this below.)

• “Photographers are color separators.” This comment reinforced that much of digital photography was driven by catalog and print, not archiving collections digitally.

• The move from analog to digital was evolutionary. Digital imaging had to be shown to be equivalent in quality to analog. Small digital projects begat larger projects. In some institutions, only digital imaging was used.

• Both RGB and CMYK files were sent for printing. Thus color separation becomes the domain of the imaging department.

• At one institution, a digital color target (image file) was included along with files sent for printing as an aid for color separation. At other institutions, the preference was to image a color target along with the work of art. The target aided printing and provided image calibration. The target was cropped out of the final image.

• There was a lengthy discussion about how to evaluate cameras being considered for purchase. Subjective evaluation of the camera system was of greater importance than objective measures. The key subjective criteria included ease of use, feel, software, reputation of the vendor, technical support, compatibility with existing lenses and camera bodies, and “allowing photographers to be photographers.”

• The number of pixels and file size were the main objective criteria in camera selection. This was the main justification of using scanbacks over area arrays.

• Vendors with proprietary color management, file formats, and so forth were not seen as desirable or advantageous. There was a desire for open and standardized procedures and a move towards industry-wide compatibility.

• Scanners were evaluated more objectively than cameras.

• Photographers have become information-technology (IT) personnel. In many institutions, they were the only people worrying about data storage, backup, etc. There was a clear lack of expertise, and IT experts were not being hired to service imaging departments. Institutions where IT issues have been resolved are part of larger computer-driven entities such as research universities.

• There was a lengthy discussion about the required skill set for future hires in imaging departments. Commercial photographers, graphic designers, and computer scientists were not desirable despite their familiarity with the technology. A background in art history was considered to be very important; this enables the photographer to understand the needs of the curators. For the leading institutions, 10-15 years of fine-art photography experience was necessary; this could be acquired at a museum or auction house. The successful photographer had a “visceral understanding” of the art; “aesthetic judgment is critical.”

• “Aesthetic judgment” in photographing works of art was discussed. The main issue was the difficulty in lighting. Because the current practice was to create two-dimensional images of three-dimensional objects (even paintings), subjective decisions were required to either accentuate or de-accentuate topographic details. An understanding of how the object is understood as a work of art aided photographeres in making proper lighting decisions. This was one of the main reasons for wanting photographers with a background in art history.

• Digital photography was considered advantageous over analog photography when aesthetic changes were required. One aspect was the ease of changing tone and color reproduction characteristics.

• The pervasiveness of slide libraries in the curatorial and art historian communities was at odds with the move to digital. In some cases, imaging departments were using a digital film recorder to generate 35mm slides. There was a feeling that this was a top-down issue; that is, if museum directors moved to digital approaches and the use of software such as Microsoft Powerpoint, curators would follow. One limitation that remained was the use of dual projectors. Adjacent images in Powerpoint do not have the same quality as two projected slides filling two screens. Quality expectations and prejudices seemed a function of experience. Without question, there is a large range of computer-projector quality (as there is with slide projectors).

Open Discussion on User Needs

There was an open discussion about user needs, with topics ranging from the philosophical to the practical.

A number of practical needs were voiced. They are listed below:

• Automatic recording of metadata through capture software

• Lens development for improved capture of large objects

• Off-axis color improvement

• Detector development for improved capture of large objects

• Automated creation of derivative images, that is, from an archival image (synthesis-independent), creation of images for different applications such as catalog and the web

• Appropriate targets and calibration data for imaging cultural heritage

• Universal file format for “raw” files

• Definition of “raw” and what amount of processing by the camera is appropriate for a raw file

• Better understanding of color management

• Integration of color-profiling software for color management incorporated into camera capture software

• Spectral imaging for conservation

After this list of specific, practical needs was compiled, there was a discussion about how images are used by art historians. One aspect was that, ideally, the digital image should be a true surrogate for the object. We should be able to view it from different angles, to see its surface properties, to look at it in magnified form, to see it rendered for different lighting, etc. Clearly, this was a manifesto for future research in imaging cultural heritage that includes spectral and topographic measurements. This will require a significant effort of color, imaging, and computer sciences.

Philosophically, there was a dichotomy between libraries and museums. Library-initiated imaging seemed to be oriented towards archiving; that is, the end product is the digital archive. Museum-initiated imaging was production-oriented, with the end product often a printed catalog. This two-world scenario does make sense when taking into account the users of the images and the way the highest-quality images are presented to the users: websites in the case of the libraries, books and catalogs in the case of museums. The role of the curators and the publishing department in the museums has to be taken into account as well. They are the ones making the ultimate quality call.

A second philosophical topic concerned the problem museums have in encouraging manufacturers to design and produce specialized products for their applications. Certainly most of the high-resolution digital cameras are sold for advertising photography. Nonetheless, the museum and library communities represent a reasonable number of camera purchases. In addition, museum photography could be used advantageously for marketing purposes. Perhaps to underscore the lack of leverage exerted by the musum and library communities, we were unable to convince representatives from the major camera vendors, Betterlight, Sinar, and Phase I, to participate in the conference. Suggestions for leverage included the medical imaging community and other biological applications. However, these applications, while requiring high spatial and color quality, do not require the high resolution that is needed for cultural-heritage applications.

V. Key Findings

The time period over which this project occurred was part of a transitional period in professional photography. It was a transition from analog (chemical) to digital photography. Accordingly, workflows optimized for analog-based input systems required a complete overhaul. The challenges faced by photographers in cultural-heritage institutions were the same as those facing photographers in other fields with the additional challenge of a consistent lack of funding for long-term support (i.e., hardware and software upgrading, data storage). In addition, expectations for quality were very high. Lastly, images produced in the studios of cultural-heritage institutions could be used as a scientific tool; e.g., studies in conservation science, placing even more stringent demands on quality. The following is a summary of the key findings of this project.

Strong Move Towards Digital

Over half of the survey respondents took at least 90% of their photographs digitally in 2003. This was a remarkable number, and will approach 100% in the near future. The majority of the institutions invested or planned to invest in new equipment and staff to support the move to digital. A variety of grant applications were pursued to support the implementation of fully digital workflows. This was all happening despite a perceived lack of knowledge about digital imaging by the practitioners. However, they all felt very comfortable with the "digital direction" their institutions were taking. All case study institutions reported a large increase in productivity with the move to digital. This was based mainly on a change in workflow, which gave the immediate availability of the images taken. A majority of the institutions used high-end cameras capable of delivering quality similar to or better than traditional large-format studio cameras.

Museum Imaging was Output Driven

Historically, the key driving force behind many of the imaging projects in cultural-heritage institutions has been publishing. The publishing department, in conjunction with the curators made decisions on the selection of objects to be imaged and on various aspects of image capture and processing, such as lighting, cropping, and color reproduction. This means that most of the imaging in these institutions was driven more "by content than by color physics." Until a few years ago, publishing meant printing books and other forms of reproductions such as posters and postcards. The increasing importance of the Internet for marketing and research purposes added another output medium, the computer display. The top three surveyed reasons for imaging were to make collections accessible over the Internet, to include digital images in a collection management system, and to produce printed reproductions. Increasingly, cultural-heritage institutions will face the challenges of cross-media publishing and the associated difficulty in producing derivative images for different devices that result in consistent color and spatial quality. Many of the institutions worked with a variety of printers, many quite distant such as Asia. One of the case-study institutions went back to using printers in the US and Europe for book production, a result of poor communication and color management with more-distant printers. Future cross-media publishing workflows will benefit greatly from a use-neutral digital master. This is where output-driven imaging and color physics will meet.

Selection Criteria for Digital Camera Systems

It was interesting to note, but not surprising, that quantitative metrics for color and spatial quality often were not the primary selection criteria for the purchase of a camera system. Subjective criteria, word-of-mouth and technical support were viewed as more important. This research project showed that it is possible to develop a single experimental procedure to evaluate the objective quality of a camera system. While it is possible, it must be noted that the procedure developed was complex and is not yet ready to be used in a practitioner's environment. It is also important to keep in mind that the cultural-heritage field does not have sufficient leverage to effect advances or changes in imaging technology.

The cultural-heritage field has a clear sense of who the ideal operator of the camera system is: the ideal photographer has extensive expertise in photographing cultural heritage and in-depth knowledge in information technology and art history.

Workflows

The workflows encountered in the different imaging departments varied widely. About every possible combination was found including cameras, light sources, viewing environment, color management, visual editing, spatial image processing, file format and encoding, and digital preservation of the image files. The lack of a common (or even a small range of) workflow meant that image databases from different institutions should not be combined without additional calibration. However, current practices and equipment severely limit the viability of calibration or defining a single workflow used throughout the cultural-heritage field.

Documentation of Procedures

One of the case study findings was that almost none of the institutions had written documentation of procedures and workflows used. In one instance, documentation was produced because the head of the imaging department was leaving and one of his goals was to create documentation for the person taking over. The lack of procedural documentation created communication problems and considerably different results from operator to operator. While this was understandable when looking at image capture as an aesthetic act in which the photographer-as-artist was the focal point, it created challenges when consistency of digital masters was desired. This challenge was consistent with workflow issues described above.

Color Management

Significant differences in color quality were found among the tested institutions. There were two main reasons behind this fact: different color sensitivity (i.e., spectral sensitivity) of the systems used, and different approaches to color management. While nothing could be done about the intrinsic color quality of the cameras used [without significant hardware and software changes as demonstrated in RIT's spectral imaging research program (Berns, 2005)], improving color management routines could improve color quality to a certain degree. The majority of the survey participants categorized themselves within a range from "neutral" to "I do not know enough about color management." This showed clearly that implementing digital workflows including color management was a challenge for most cultural-heritage institutions. It should also be noted that workflows were oftentimes implemented while the pressure was "on" to produce a certain number of images.

Lighting

Since the aesthetic value of the images taken was of high importance, it was obvious that the photographers, often in conjunction with the curators, made decisions on lighting an object. The case studies showed a variety of approaches to lighting owing to different aesthetics and equipment. The image files of the two reference oil paintings had a range of topographical interpretation (i.e., gloss and impasto) at each institution. It was unclear if lighting choices were based on aesthetics only or also included scientific and standardization considerations.

Visual Editing

Most museums included some visual editing and other forms of image processing in their workflows. The visual editing step added a considerable amount of time to the entire workflow. Twenty percent of the responding institutions spent half an hour or more for post-capture processing. When investigated closely, it was found that visual editing decreased color accuracy in all cases. The libraries that took part in the survey rarely included visual editing on a monitor as part of their workflow. This makes sense, since library imaging was not driven by higher-end reproduction, but rather by access to the materials for patrons and researchers. In addition to visual editing, many images also incurred retouching and sharpening steps. The fact that many of the participants sharpened the images either at capture or before the digital master was saved raised the question of whether the implications of the choices made were well understood. Most of the image processing carried out was not automated; automation represents a possibility for improvement in setting up consistent, reproducible workflows.

Digital Master

This project showed clearly that there is a need to discuss and clarify what a digital master is and how it is created. While close to half of the institutions kept the camera raw files, they did not keep characterization metadata critical to processing images at a later stage. Ideally, a raw digital image should be captured and stored as a digital master along with the characterization metadata of the digital-imaging system. This will preserve information about how the raw data was formed and facilitate its retrieval and processing for final output and use. Currently produced digital masters incorporate spatial image processing, color management, visual editing, and encoding. While this is fine for certain applications and is supported by many current workflow tools, it is not what current and future digital photography and digital imaging technology have the potential to deliver. There is still considerable work to be done to get from here to there, starting with camera manufacturers who will need to build the necessary systems, and ending with the education of the field about the full potential of digital imaging. Conservators and conservation scientists as well as curators and art historians are just beginning to learn how to make use of the rich potential of digital-imaging techniques. The future holds many more possibilities as a well-defined digital master can be used to create derivative images optimized for each constituency.

Digital Preservation

Sixty-six percent of the survey respondents used the TIFF format for their digital masters. The next largest group (12%) used JPEG. This was somewhat surprising since most published imaging guidelines recommend TIFF as the preferred format for master files. When respondents were asked if they compress their digital master files, 14% answered “yes.” This number was high as well, when considering the implications that compression could have on the future readability of a file. Close to half of the institutions kept the original camera raw file. However, as mentioned earlier, they were not keeping camera characterization data along with the file. When asked about backing up their master files, 88% of the respondents answered that they routinely backed up their files. In view of the costs associated with capture, it was quite surprising that 12% did not. Media used for backups included: CDs (28%), tape (21%), DVDs (21%), and other (30%). It was remarkable that close to 50% of the institutions used media not recommended for longer-term storage such as CDs and DVDs. Twenty-three percent of all institutions reported that, at some point, they lost a digital master that was unrecoverable.

In conclusion it should be mentioned that, while there is room for improvement in the way cultural institutions were imaging paintings and sculpture, the dedication of the people working on these projects was remarkable. This will make it much easier to implement better workflows that take full advantage of what digital photography has to offer.

VI. Future Research

This research project points to a number of paths forward for future research, services, conferences, and related activities.

Establish a User Group Devoted to Imaging, Archiving, and Reproducing Cultural Heritage

Obtaining information relating to museum imaging comes from many disparate avenues. Camera manufacturers such as Sinar, Phase One, and Better Light host user forums and mailing lists for their customers to share their experiences and ask each other questions There are the Museum Computing Network (http://www.mcn.edu), Digital Libraries Federation (http://www.diglib.org), and similar digital networks. Standards can be accessed as listed in the standards review written during this project, but they are often difficult to understand, and implementing the described procedures is often cumbersome. Photography and imaging textbooks tend to be on general imaging or specific software. Conferences including sessions on museum imaging tend to be research-oriented; in some cases, there are not published proceedings (e.g., American Institute of Conservation). Museum photographers would benefit from a user group devoted to imaging, archiving, and reproducing cultural heritage.

Hold Periodic Conferences

We have received a number of requests asking when the next RIT conference will be held. Clearly, there is a need for museum imaging professionals, managers, researchers, and vendors to come together on a periodic basis. A more informal structure than society-sponsored conferences would be the most effective. The conference would be for gathering and sharing practical information and would not focus on scholarly research. Publications should be encouraged, of course.

Develop a Practical Characterization Test Method

The objective test method developed for this program was complex. Since this was the first time museum imaging systems were studied in such detail, we used many recommended standard targets as well as targets used in research laboratories. We sought to be comprehensive. There was some redundancy in these targets. Several of the tests generated data of lesser interest since they were developed for camera systems of lower quality. There are opportunities to consolidate the characterization procedure by reducing the number of targets that must be imaged. It would also be worthwhile to explore developing new targets that are optimized for the direct digital capture of cultural heritage. (For example, some of the targets that were used were developed for scanners.)

The data processing was performed within the context of graduate-level research. There were a number of different types of software used including Photoshop and Matlab, a high-level programming environment. This processing required considerable expertise. An application to guide a novice user through the testing procedure would be very useful. This should include instructions for capture of the test images and automatic processing of the image data. In addition, it can be difficult for non-experts to interpret the results. It would be useful to create a “metrics report” (see Establishing a Testing Service, below).

Incorporate Characterization Data into a Metadata Structure

Characterization is the process of determining an imaging system's performance at some point in time. Characterization data may enable calibration, where an image is related to a set of standard conditions. It may be possible to combine image archives from different collections and different institutions, reducing well-known visual disparities in image databases used for scholarly activities. Characterization data can also be used to determine a system's repeatability and reproducibility. Ideally, these data can help relate the archived image to the actual object, although the accuracy and generality will be constrained by the particular imaging system. Including the characterization data in an image's metadata structure ensures that an image will not be separated from the imaging system characteristics. Integrating characterization data into a metadata structure would require the integration of the practical characterization test method with metadata standards activities.

Develop and Test a System Calibration Protocol

A museum imaging system has many components including lighting, camera setup (exposure time, dynamic range, depth of field, magnification, etc.), color management, file format and encoding, metadata, and workflow. As the case studies revealed, each institution had a unique system. This was true for each subsystem as well. For example, the differences in lighting geometry were striking. The very large differences in rendition of the two small oil paintings exemplified these differences in a tangible fashion. There is a critical need to develop a calibration procedure. Calibration is the process of adjusting the system so the image archive conforms to a set of standard conditions. A calibration procedure would reduce the large variability between institutions. Unlike calibrating a measurement device such as an altimeter, ruler, or spectrophotometer, there is not a reference for what constitutes a standard image. This is because it is impossible to standardize aesthetics. Cultural heritage is imaged predominantly with the goal of capturing aesthetic intent and semantic content, not physical attributes. During the Benchmarking Conference, the ideal photographer was discussed. A key qualification was knowledge of art history, an obvious link to aesthetics. One of the most important roles of the photographer is to work within the limitations of the imaging system to capture images that faithfully reproduce the original. Their knowledge provides an interface between the curator's world of aesthetics and human perception and the digital one of technical experts such as printers, publishers, and information technologists. It is naïve to think that one can capture a piece of artwork in a single two-dimensional digital image it in such a way that consensus is achieved on aesthetic interpretation. (This goal may be attainable in the future with new imaging systems capable of topographic recording.) Lighting is the main tool the photographer uses to adjust the appearance of the captured image. Standardization for this subsystem is therefore unlikely. However, research to develop and test system calibration procedures for the other subsystems could be carried out at representative institutions.

Define Quality Criteria Based on Objective and Subjective Metrics

The benchmarking research resulted in objective tests that characterized system performance. The experience of the researchers allowed them to judge the quality of the images and form conclusions such as, "this system has unacceptable color accuracy for the purpose of image archiving," and so forth. It would be of great value to the community to be able to use the objective measurements of the systems to come to similar conclusions. Unfortunately, many of the objective metrics could not be judged other than rank ordering the performance of the four case studies. We did not attempt to derive a single figure of merit. Such a metric would be extremely useful, particularly in improving the quality of future commercial products. This requires visual experiments where subjective judgments and objective measurements are correlated. The observers for such experiments should include conservators, art historians, curators, etc. It is likely that different criteria will be required for different constituencies. However, if the imaging system meets the most stringent criteria for each observer group, a single archive can be used for many purposes. This same experimental approach can be used to better understand aesthetic requirements by having psychophysics performed where, for example, the experimental parameter is lighting geometry.

Establish a Testing Service

During the 1970s, there was a testing service for color instrumentation, the Color and Color-Difference Collaborative Reference Program (CRP) of the U.S. Manufacturer's Council on Color and Appearance (MCCA.) The CRP sent colored materials to industry. Following color measurement in a prescribed fashion, data were returned and forwarded to an independent color consultant with expertise in color measurement and statistics. Data were analyzed and a written report sent to the members. This provided an important tool for industry to gauge their measurement quality compared with each other and with standard instrumentation. These data were also used for education and, in limited cases, as leverage for improvements in commercial instrumentation. Having defined methods of system characterization and calibration and psychophysical-based quality criteria, one can envision a testing service similar to the CRP where test targets and art objects are used.

Establish an Informal Imaging Inter-Institution Comparison

Many of the above topics require multi-year research and development programs. A more modest exercise would be to develop a simple inter-institution comparison "round robin." Such a program would involve the passing of particular art objects and test targets between institutions where each would be imaged under best conditions. The results would be shared and informal comparisons made, both aesthetic and objective. A round robin of this sort can be expedient and yet powerful in creating a large amount of information that can be generated and shared without too much time or effort.

Research and Develop New Imaging Systems

The case study imaging systems were limited in two ways. First, they all had low color accuracy. We found that for three of the four institutions, we could improve accuracy by more informed color management (Murphy, 2005). This supports the need for system characterization and calibration. However, even following color management, and in some cases, visual editing, the inherent color accuracy was still low. The solution is to improve the spectral sensitivities of digital cameras. Recall that spectral sensitivity is the fundamental property of a camera affecting inherent color accuracy. Improvement can be achieved by increasing the number of colored sensors, or other multi-filter techniques such as those developed at Rochester Institute of Technology's Art Spectral Imaging research initiative (Berns, 2005).

The second limitation relates to collecting images with a single lighting geometry. Nearly all of cultural heritage, including paintings and drawings, have three-dimensional properties. For paintings, surface roughness (i.e., gloss) and impasto have a dramatic effect on appearance. This information is captured implicitly when a photographer determines lighting, both its placement and geometric distribution (i.e., collimated or diffuse). Limiting the image archive to a single geometry is the underlying reason for having photographers with backgrounds in art history. This also underscores the aesthetic nature of imaging cultural heritage. The next generation imaging system should include both spectral and topographic measurements. There are a number of different research paths that would enable a more comprehensive image archive where optical properties are defined as a function of spatial location and geometry. Such an archive would truly enable a calibrated system. Different lighting aesthetics would be a matter of re-rendering the object with a desired virtual lighting setup. This system would use spectral-based computer graphics rendering techniques. The opportunities for studying an object interactively when the original is not available, because it is, for example, in a remote location or because it is fragile or light-sensitive, would be tremendous.

VII. Publications and Presentations

The following lists publications, technical reports, and presentations given during this research program.

Publications

Berns, R. S. et al. (2005). High-accuracy digital imaging of cultural heritage without visual editing. *Proc. IS&T 2005 Archiving Conference*. 91-95.

Frey, F. (2005). Direct digital capture of cultural heritage: Benchmarking American museum practices and defining future needs, *AIC News*. *30*: *3.* 1 and 14-15.

Murphy, E. P. (2005). *A testing procedure to characterize color and spatial quality of digital cameras used to image cultural heritage.* Unpublished master's thesis, Rochester Institute of Technology, Rochester, NY.

Rosen, M. R. (2004). The RIT American museums digital imaging benchmark survey, *Proc. Digital Archives Conference on Workflows & Quality Management*. 2-5.

Rosen, M. R., & Frey, F. S. (2005). RIT American museums survey on digital imaging for direct capture of artwork, *Proc. IS&T 2005 Archiving Conference*. 79-84.

Smoyer, E. P. M., Taplin, L. A., & Berns, R. S. (2005). Experimental evaluation of museum case study digital camera systems, *Proc. IS&T 2005 Archiving Conference*. 85-90.

Downloadable Technical Reports

Project-related documents are available at http://www.cis.rit.edu/museumsurvey/ and http://art-si.org/.

Berns, R. S., et al. (2005, April). *Direct digital capture of cultural heritage — Benchmarking American museum practices and defining future needs project report*.

Murphy, E. P. (2004). *A Review of Standards Defining Testing Procedures for Characterizing the Color and Spatial Quality of Digital Cameras Used to Image Cultural Heritage*. Munsell Color Science Laboratory Technical Report.

Murphy, E. P. (2005, February). *A testing procedure to characterize color and spatial quality of digital cameras used to image cultural heritage.* Unpublished masters thesis.

Rosen, M. R., et al. (2004, September) *American museums digital imaging survey benchmarking conference program*.

Rosen, M. R., & Frey, F. S. (2005, April). *Survey analysis report.*

Presentations

Berns, R. S. (2005, April). High-accuracy digital imaging of cultural heritage without visual editing. At IS&T 2005 Archiving Conference.

Berns, R. S. (2004, September). Introduction of the Benchmarking Project and other related projects at MCSL. At American Museums Digital Imaging Survey Benchmarking Conference.

Frey, F. S. (2004, September). Digital preservation. At American Museums Digital Imaging Survey Benchmarking Conference.

Frey, F. S. (2005, April). Direct digital capture. Mini-workshop at Museums and the Web.

Frey, F. S., & Rosen, M. R. (2005, November). Direct digital image capture of cultural heritage in American institutions. Interactive session at Museum Computer Network.

Rosen, M. R. (2004, September). Analysis of the case survey and case studies. At American Museums Digital Imaging Survey Benchmarking Conference.

Rosen, M. R. (2005, April). RIT American museums survey on digital imaging for direct capture of artwork. At IS&T 2005 Archiving Conference.

Rosen, M. R. (2004, December). The RIT American museums digital imaging benchmark survey. Invited keynote at the Digital Archives Conference on Workflows & Quality Management.

Smoyer, E. P. (2004, September). Evaluation of case study imaging systems. At American Museums Digital Imaging Survey Benchmarking Conference.

Smoyer, E. P. (2004, May). Experimental evaluation of museum case study digital camera systems. At Council for Optical Radiation 2004 Annual Meeting.

Smoyer, E. P. (2004, May). Experimental evaluation of museum case study digital camera systems. At RIT Center for Imaging Science Annual Industrial Associates Meeting.

Smoyer, E. P. (2005, April). Experimental evaluation of museum case study digital camera systems. At IS&T 2005 Archiving Conference.

VIII. Personnel

Roy S. Berns
R. S. Hunter Professor in Color Science, Appearance, and Technology
Munsell Color Science Laboratory
Chester F. Carlson Center for Imaging Science
Color Science Building 18
54 Lomb Memorial Drive
Rochester, NY 14623
(585) 475-2230
berns@cis.rit.edu
http://www.cis.rit.edu/people/faculty/berns/

Dr. Roy S. Berns is the Richard S. Hunter Professor in Color Science, Appearance, and Technology at the Munsell Color Science Laboratory and Graduate Coordinator of the Color Science master's degree program within the Center for Imaging Science at Rochester Institute of Technology. He received B.S. and M.S. degrees in textile science from the University of California at Davis and a Ph.D. degree in chemistry with an emphasis in color science from Rensselaer Polytechnic Institute. His research includes spectral-based imaging, archiving, and reproduction of cultural heritage; algorithm development for multi-ink printing; the use of color and imaging sciences for art conservation science, and colorimetry. He is active in the International Commission on Illumination, the Council for Optical Radiation Measurements, the Inter-Society Color Council, and the Society for Imaging Science and Technology. He has authored over 150 publications including the third edition of Billmeyer and Saltzman's Principles of Color Technology. During the 1999-2000 academic year, he was on sabbatical at the National Gallery of Art, Washington, DC as a Senior Fellow in Conservation Science. Since 2000, Dr. Berns is a member of the Technical Advisory Group of the Star-Spangled Banner Preservation Project. He is currently involved in a joint research program in museum imaging with the National Gallery of Art, Washington, DC and the Museum of Modern Art, New York. He is also collaborating with the Art Institute of Chicago and the Van Gogh Museum in digitally rejuvenating paintings that have undergone undesirable color changes.

Franziska S. Frey
Assistant Professor
School of Print Media
College of Imaging Arts and Sciences
Rochester Institute of Technology
69 Lomb Memorial Drive
Rochester, NY 14623-5603
Phone (585) 475-2712
fsfpph@rit.edu

Dr. Franziska S. Frey is an Assistant Professor at the School of Print Media at Rochester Institute of Technology. She teaches courses in materials and processes for printing, image database design, and digital asset management, and is involved in research projects in the Sloan Printing Industry Center at RIT, and the Munsell Color Science Laboratory. Dr. Frey is also on faculty at the "Mellon Advanced Residency Program in Photograph Conservation" at the George Eastman House, International Museum of Photography. She received her Ph.D. degree in Natural Sciences (Concentration: Imaging Science) from the Swiss Federal Institute of Technology in Zurich, Switzerland in 1994. Before joining the faculty of the School of Print Media, Dr. Frey has worked as a research scientist at the Image Permanence Institute at RIT. Her work has primarily focused on establishing guidelines for viewing, scanning, quality control, and archiving digital images. She publishes, consults, and teaches in the US and around the world on various issues related to establishing digital image databases and digital libraries and is also involved in several international standards groups. Dr. Frey serves as a vice president on the board of the Society of Imaging Science and Technology and is active in organizing international conferences on archiving.

Mitchell R. Rosen
Research Assistant Professor
Munsell Color Science Laboratory
Chester F. Carlson Center for Imaging Science
Color Science Building 18
54 Lomb Memorial Drive
Rochester, NY 14623
(585) 475-7691
rosen@cis.rit.edu
http://www.cis.rit.edu/rosen

Dr. Mitchell R. Rosen is a member of the Munsell Color Science Laboratory and the Visual Perception Laboratory, both of the Center for Imaging Science at RIT. His research is in the areas of color management, spectral imaging systems, museum imaging and eye movement analysis. He teaches graduate courses on color systems and tutorials on color management and color reproduction. He joined the Munsell Color Science Laboratory in 1998 as a Senior Color Scientist and was recently appointed Assistant Professor. Previously, Dr. Rosen spent a decade in the research laboratories of Polaroid working on design and support of digital cameras, scanners, printers and color management systems. He is the Color Imaging editor of the Journal of Imaging Science and Technology and active in organizing international conferences on spectral imaging.

Lawrence A. Taplin
Color Scientist
Munsell Color Science Laboratory
Chester F. Carlson Center for Imaging Science
Color Science Building 18
54 Lomb Memorial Drive
Rochester, NY 14623
taplin@cis.rit.edu

Lawrence A. Taplin is a scientist with the Munsell Color Science Laboratory at the Rochester Institute of Technology where he received a M. S. degree in Color Science. He also holds a B. S. in Computer Science from the University of Delaware. His research is focused on spectral imaging of museum artwork for digital archiving and reproduction.

Erin P. M. Smoyer
M.S. Color Science Graduate, 2005
Rochester Institute of Technology
Currently employed at Texas Instruments
esmoyer@ti.com

Erin P. M. Smoyer received her B.S. degree in Imaging and Photographic Technology from the Rochester Institute of Technology in 2002 and her M.S. degree in Color Science in 2005 at the Munsell Color Science Laboratory, also at the Rochester Institute of Technology. She is currently a Color Scientist at Texas Instruments in Plano, TX working on DLP™ products research.

IX. References

Berns, R. S. (2000). *Billmeyer and Saltzman's principles of color technology.* (3rd ed.) New York: John Wiley & Sons.

Berns, R. S. (2001). The science of digitizing paintings for color-accurate image archives: A review. *J. Imaging Sci. Technol.* 45, 373-383.

Berns, R. S. (2002). Sneaking scientific validity into imaging tools for the masses. *Proc. IS&T First European Conference on Color in Graphics, Imaging, and Vision*. 1-2.

Berns, R. S. (2005). Color-accurate image archives using spectral imaging. National Academy of Science. In press.

Burns, P. (2000). Slanted-edge MTF for digital camera and scanner analysis. *Proc. IS&T PICS, 2000*. 135-138.

Burns, P., & Williams, D. (1999). Using slanted-edge analysis for color registration measurement. *Proc. IS&T PICS, 1999*. 51-53.

CIE 15.2: (1986). *Colorimetry* (2nd ed.) (CIE Publication No. 15.2). Vienna: CIE Central Bureau.

CIE 142: *Improvement to industrial colour-difference evaluation* (2001). (CIE Publication No. 142-2001). Vienna: CIE Central Bureau.

Conway, P. (2000). Overview: Rationale for digitization and preservation. In *Handbook for digital projects: A management tool for preservation and access*; (Ch. 2). Andover, MA: Northeast Document Conservation Center.

Frey, F. S., & Reilly, J. M. (1999) *Digital imaging for photographic collections: Foundations for technical standards*. Rochester, NY: Image Permanence Institute.

Frey, F. S., & Susstrunk, S. (2000). Digital photography—how long will it last? *Proc. of IEEE ISACAS*. V-113.

ISO 17321-1: *Graphic technology and photography – Colour characterisation of digital still cameras (DSCs) – Part 1: Stimuli, metrology, and test procedures.* (ISO 17321-1: 2003). Working draft.

IEC 61966-2-1: *Multimedia systems and equipment – Colour measurement and management – Part 2-1: Colour management – Default RGB colour space – sRGB* (1999). (IEC 61966-2-1: 1999). Geneva, Switzerland: International Electrotechnical Commission.

IEC 61966-2-1-A: *Multimedia systems and equipment – Colour measurement and management – Part 2-1: Colour management – Default RGB colour space – sRGB* (2003). (IEC 61966-2-1 Amendment 1: 2003). Geneva, Switzerland: International Electrotechnical Commission.

IEC 61966-8: *Multimedia systems and equipment – Colour measurement and management – Part 8: Multimedia colour scanners* (2001). (IEC 61966-8: 2001). Geneva, Switzerland: International Electrotechnical Commission.

IEC 61966-9: *Multimedia systems and equipment - Colour measurement and management - Part 9: Digital cameras* (2000). (IEC 61966-9: 2000). Geneva, Switzerland: International Electrotechnical Commission.

ISO 12233: *Photography – Electronic still-picture cameras – Resolution measurements* (2000). (ISO 12233: 2000). Geneva, Switzerland: International Organization for Standardization.

ISO 14524: *Photography – Electronic still-picture cameras – Methods for measuring opto-electronic conversion functions (OECFs)* (1999). (ISO 14524: 1999). Geneva, Switzerland: International Organization for Standardization.

ISO 15739: *Photography – Electronic still-picture imaging – Noise measurements* (2003). (ISO 15739: 2003). Geneva, Switzerland: International Organization for Standardization.

ISO 17321: *Graphic technology – Color reflection target for input scanner calibration* (1993). (ANSI IT8.7/2: 1993). New York: American National Standards Institute.

Kenney, A. (2000). *Digital benchmarking for conversion and access. In Moving theory into practice: Digital imaging for libraries and archives* (pp. 24-60). Mountain View, CA: Research Libraries Group.

Klijn, E., & de Lusenet, Y. (2000). *In the picture; preservation and digitisation of European photographic collections*.
Retrieved July 10, 2005 from http://www.knaw.nl/ecpa/PUBL/pdf/885.pdf

Murphy, E. P. (2005). *A testing procedure to characterize color and spatial quality of digital cameras used to image cultural heritage*. Unpublished master's thesis, Rochester Institute of Technology, Rochester, NY.

NISO: *Data dictionary—Technical metadata for digital still images* (2002). NISO Z39.87-2002; AIIM 20-2002.
Retrieved July 10, 2005 from http://www.niso.org/standards/resources/Z39_87_trial_use.pdf.

Rieger, O. (2004). Implementing a digital imaging and archiving program: Technology meets reality. *Proc. IS&T 2004 Archiving Conference*. 191-194.

Sitts, M. (2000). *Handbook for digital projects: a management tool for preservation and access*. Andover, MA: Northeast Document Conservation Center.

Vora, P. L., & Trussell, H. J. (1993). Measure of goodness of a set of color scanning filters, *J. Opt. Soc. Am. A.* 10, 8-23.

Waibel, G., & Dale, R. (2004). Automatic exposure: Capturing technical metadata for digital still images. *Proc. 2004 IS&T Archiving Conference*. 260-265.

Supported by a grant from

The Andrew W. Mellon Foundation

with additional support from

Rochester Institute of Technology