Tracking Color Shift in Ballpoint Pen Ink Using Photoshop Assisted Spectroscopy: A Nondestructive Technique Developed to Rehouse a Nobel Laureate's Manuscript

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ABSTRACT

Many historically and culturally significant documents from the mid-to-late twentieth century were written in ballpoint pen inks, which contain light-sensitive dyes that present problems for collection custodians and paper conservators. The conservation staff at the National Library of Medicine (NLM), National Institutes of Health, conducted a multiphase project on the chemistry and aging of ballpoint pen ink that culminated in the development of a new method to detect aging of ballpoint pen ink while examining a variety of storage environments. NLM staff determined that ballpoint pen ink color shift can be detected noninvasively using image editing software. Instructions are provided on how to detect color shift in digitized materials using a technique developed specifically for this project—Photoshop Assisted Spectroscopy.[1] The study results offer collection custodians storage options for historic documents containing ballpoint pen ink.

KEY WORDS

Ink, Fading, Ballpoint pen, Shifting, Anoxia, Oxygen-free, Low oxygen, Photoshop, RGB, Colorants, Lightfast, Skillcraft, Photoshop Assisted Spectroscopy, Nirenberg, Lebby, Natural aging

The National Library of Medicine (NLM) conservation staff developed Photoshop Assisted Spectroscopy as part of a project focused on the study of storage requirements for documents with sensitive components like ballpoint pen ink. The first part of this multiphase ballpoint pen ink study dealt with the destructive analysis of ballpoint pen ink using traditional analytical methods on weeded documents. The second phase moved toward digital methodologies using Photoshop software as an analytical tool. The third and final phase used Photoshop Assisted Spectroscopy to track color shift in Skilcraft brand ballpoint pen inks stored under a variety of environmental conditions.

Literature Review

Most research involving the use of Photoshop[2] software for document analysis has been done in the forensics field. The applications for forensics research are generally intended to discriminate inks by age for legal needs rather than to detect color shift for preservation purposes, but in many ways the forensics research is valuable to conservation.[3]

Additionally, forensic science offers a wealth of research on some of the aging properties of modern ballpoint pen inks which has guided the NLM conservators with this ink study and analysis. For example, forensics experts have studied the degradation of certain ballpoint ink dyes in the dark. Variation in degradation of the inks is related to several factors including temperature, relative humidity, paper type, and analysis methods.[4] Forensic scientist Jan Andrasko has found that alkaline inks darken and become dull with time, and blue inks, which are commonly alkaline, are particularly susceptible to degradation as a result of exposure to light. Some combination of crystal violet and methyl violet, both of which have poor light-fastness, has been found in every blue ballpoint ink in his studies.[5]

In the archival and library sciences, however, research on ballpoint pen ink is in its early stages. Many storage recommendations for paper-based objects focus primarily on the paper type. This often leads to storage in a dark, buffered environment.[6] However, with forensic studies indicating shift even in environments that preservation professionals generally consider appropriate, further study appears necessary. How can the effects of storage environment on ballpoint pen inks be assessed?

Phase 1: Traditional Analytical Testing

The initial goal of this project was to determine the chemistry of ballpoint ink and to define accurate but simple methods to identify, house, and conserve ballpoint pen ink. In 2005, the best practice for determining the nature of the ink was using spot tests from fixatives, which is subjective due to the nature of visual assessment through the fixatives and leaves a lot of room for error.[7] This phase focused on analysis of the ballpoint pen ink chemistry as it exists on historic paper documents with the intention to corroborate the spot testing using chemical analysis and testing. For this testing, ballpoint ink from weeded historic documents was extracted into a fifty-fifty solution of pyridine and deionized water. Several analytical tests including ultraviolet-visible microspectrophotometry, Fourier-transform infrared spectroscopy, and gas chromatography/mass spectrometry[8] were performed on the extractions. The goal was to compile the resulting data and not only gauge the accuracy of the spot tests but also compare the historic ink data to similar tests performed on modern inks. The methodology proved to be time consuming, and extracting ink in large enough quantities from historic samples while minimizing factors such as paper type and extraneous ink interaction caused many samples to be unusable. Additionally, destructive analysis of this type would not be performed as part of a treatment procedure. These factors led the project team to seek out a more streamlined and nondestructive method.

Phase 2: The Development of Photoshop Assisted Spectroscopy

The project transitioned from the use of traditional scientific analytical methods to an all-digital analysis, creating a way to assess the level of degradation in ballpoint pen ink without the analytical equipment explored in phase one. Visual inspection of artwork and documents created in ballpoint ink reveals that the color in different pens, even different batches of the same pen type, can shift differently while stored in the same environments. Some of the observed color shift, such as on ballpoint pen artwork by Larry Lebby, occurred while the art was stored in a dark, cool, alkaline environment—that is, "proper" storage.

Project Goal

The driving force behind continuing the research was to determine the proper storage for the Marshall Nirenberg Genetic Code Charts—a series of important documents in scientific history. The six charts in the Images and Archives collections of the National Library of Medicine's History of Medicine Division contain original data from experiments that determined how the sequence of precursor ribonucleic acids (RNAs) dictates protein sequence. As a

FIGURE 1. This portrait of Rutledge Osborne by prominent ballpoint pen artist Larry Lebby originally contained only one color of ink, but required multiple pens for its creation. Though it was stored in a proper environment, both the curator and artist confirmed that the color has shifted visibly. Image courtesy of McKissick Museum, University of South Carolina.

result of the work recorded on the charts, Dr. Nirenberg was awarded the 1968 Nobel Prize in Physiology or Medicine.

The charts consist of multiple sheets of 1950s Addison-Wesley lined paper joined with pressure-sensitive tape to create an area large enough to record the data. The tape is in an oxidized state, but is an important part of the chart because Dr. Nirenberg wrote information on top of the tape carrier.[9]

In 2011, the charts were scanned at 500 ppi using a Cruse Synchron Light Scanner to create high-quality facsimiles. NLM conservators chose to use these

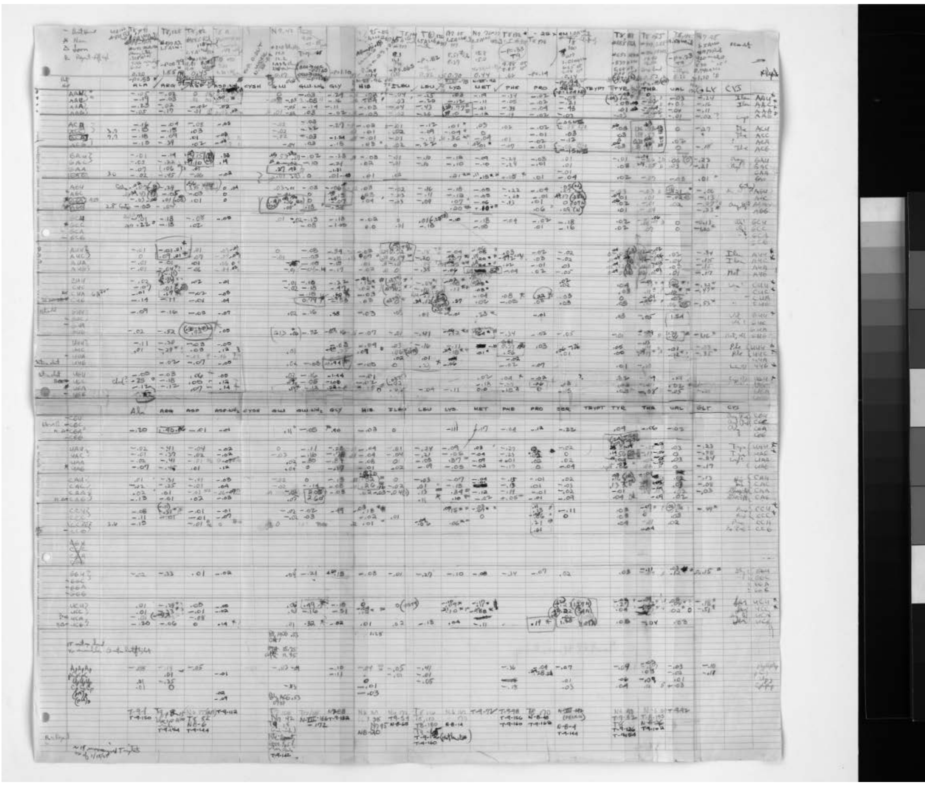

FIGURE 2. This is one of several charts created by Dr. Marshall Nirenberg and his lab during the research on RNA sequencing. Image courtesy of the U.S. National Library of Medicine.

scans for a secondary purpose—to attempt analysis of color shift in ink using the newly developed Photoshop Assisted Spectroscopy technique.

The goal of this analysis was to determine the optimal storage and display environments for the charts. A comparison of the different charts from the same period, all on the same paper type, was one step in this process. The charts were examined to determine what storage and environmental conditions may have affected the color shift. Prior to their accession by the NLM in 2011, most of the charts were stored without enclosures in Dr. Nirenberg's lab, office, or home. One chart, the working copy, considered by some scientists to be the "Rosetta Stone" of modern science, is housed in a buffered matboard enclosure inside a cloth-covered clamshell box. It has been stored in this enclosure and kept at approximately 60 degrees Fahrenheit and 40% relative humidity since the mid-1990s.

NLM staff are fortunate to have consulted with two of the original technicians who worked with Dr. Nirenberg on the charts, Norma Zabriskie Heaton and Theresa Caryk. They provided essential information to the project team regarding materials and practices used during the period of the charts' creation.

Additionally, they recently cross-analyzed data from the chart with data in their lab notebooks and linked that information to journal publications to provide data validation.

Application of Nondestructive Analysis

Many different nondestructive analytical techniques are available for color shift, a term conservators use to describe color change of pigments or dyes, usually attributed to environmental factors or chemical interactions. Some of these are multispectral imaging, X-ray fluorescence, near-infrared and infrared imaging, UV analysis, microfadeometry, and polarization optical microscopy.[10] Photoshop Assisted Spectroscopy is one option for broad spectrum analysis of color shift. The technique can be performed using a scanner and a program that allows the user to monitor red, green, and blue (RGB) values on a pixel-by-pixel basis. NLM conservators found Photoshop software to be optimal for this purpose.

Many different factors, like light, temperature, oxygen, and humidity, affect color shift. However, the unique nature of the design and function of ballpoint ink creates other factors. Ink components added during the manufacturing process to make writing easier include a variety of lubricants, resins, dyes, pigments, binders, and solvents that can also contribute to color shift.[11] During writing, friction is created between the pen's ball, paper, and outside casing—which generates heat, thus changing the ink chemistry further.[12]

Some early ballpoint ink components can be identified based on the year the pen was manufactured. The ink formulae started out relatively simple,[13] but have become more complicated as the industry has grown.[14] The need to facilitate smooth lines, to provide quick-drying ink, and to ensure the pen writes easily when first applied to paper are just some of the reasons that lubricants, resins, solvents, and binders change regularly. These factors, combined with the need to keep costs down, result in ballpoint pen ink chemistry that is constantly changing.[15] Therefore, a broad range of components might be present in any given ink. The National Institutes of Health has been supplying its employees with the same type of pen since 1955—a Skilcraft ballpoint pen that, according to the Skilcraft company,[16] has had no ink formula changes, a rarity in an industry focused on constantly improving writability while keeping costs down to meet consumer demands. Multispectral imaging analysis of both historic and modern samples of Skilcraft and other ballpoint pen brands shows differences between the Skilcraft ink and the other brands but consistency within the Skilcraft brand, providing one constant in the project.

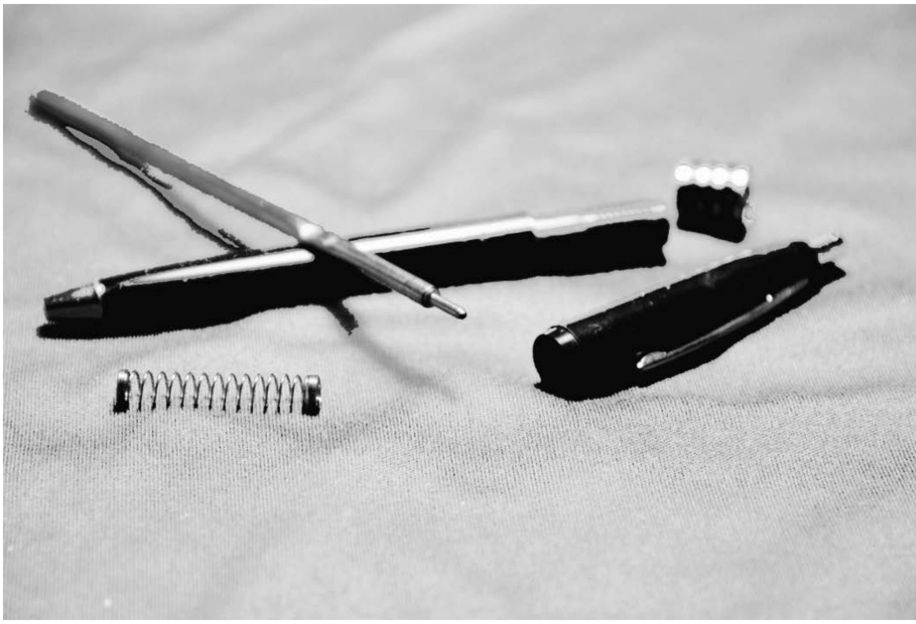

FIGURE 3. The key to a ballpoint pen is the ball, around which ink flows during the writing process. This Skilcraft ballpoint pen has been taken apart to reveal the main components of the pen. Image by NLM staff.

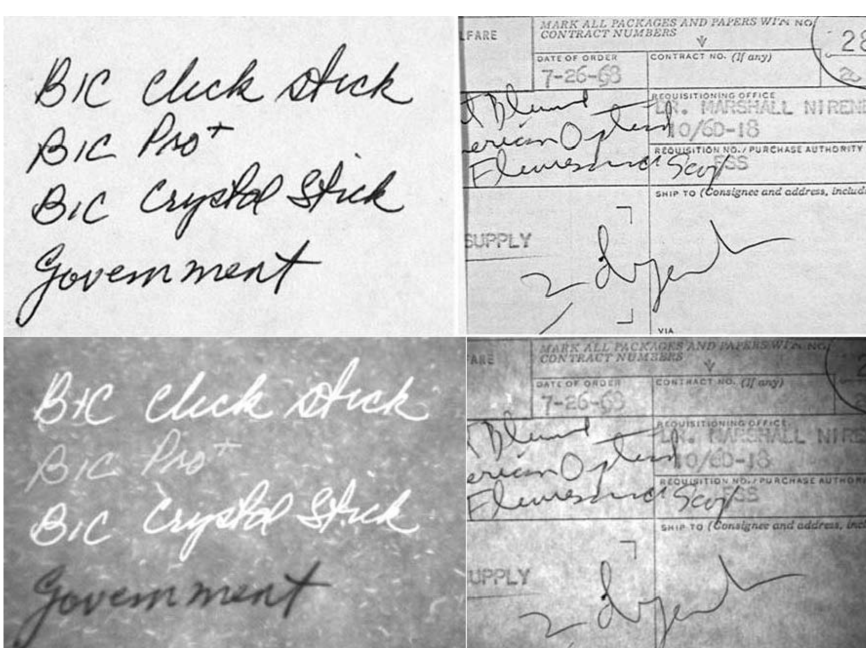

FIGURE 4. Imaging done with a VSC 6000 shows similarities between modern and historic Skilcraft ink, supporting statements made by the company that the formula remains unchanged. Image by NLM staff.

While NLM only addressed Skilcraft in this study, it is important for archivists to be aware that ballpoint ink components vary widely. As a result, a "one-size-fits-all" approach to storage of documents containing ballpoint ink may not emerge.

Summary of Photoshop Assisted Spectroscopy

Examination of ink using various types of light interactions, such as spectroscopy or scanning, can provide useful information regarding the ink's components. Photoshop Assisted Spectroscopy helps specifically with analysis of the chromophores—the ink components that determine color. Generally, when a chromophore in ballpoint ink is exposed to light, it enters an excited state that is especially prone to reaction with oxygen, starting a deterioration process, called oxidation, that results in color shift.[17] Chromophore oxidation often begins with the initial ink application and continues throughout the life of the document.

Photoshop Assisted Spectroscopy is an analysis technique using numbers to represent color. The method allows the observer to pinpoint the location of each RGB triplet group on the object. The numbers are plotted on a 3-D graph to show the degree of color shift in the ink. The project team used 3-D graphing software[18] that enables plotted data points to be viewed from any angle. The third dimension allows the viewer to understand the direction in which the color is moving on the graph since the RGB values correspond easily to an XYZ axis. All axes were set with 0 as a minimum and 255 as a maximum to correspond to RGB values. Additionally, to increase readability, the x axis was set to display in red, the y in green, and the z in blue. As a result, color shift can be viewed in relation to the direction the ink is shifting based on the axis color it approaches (or moves away from). Because color is directly linked to chemical properties, these numbers do have meaning. With further study, it should be possible to link the RGB values to the chemical properties each value represents.

Initial Technique Testing

To achieve accuracy across the board while using this technique, a properly calibrated scanner that can accurately represent the colors in the object is imperative. NLM conservation staff determined that monitor calibration and computer hardware are largely irrelevant for analysis, though accurate monitor calibration does assist the user in visual distinction of color. Photoshop software relies on the RGB values, and these do not inherently change even if the image file is opened on different computers.

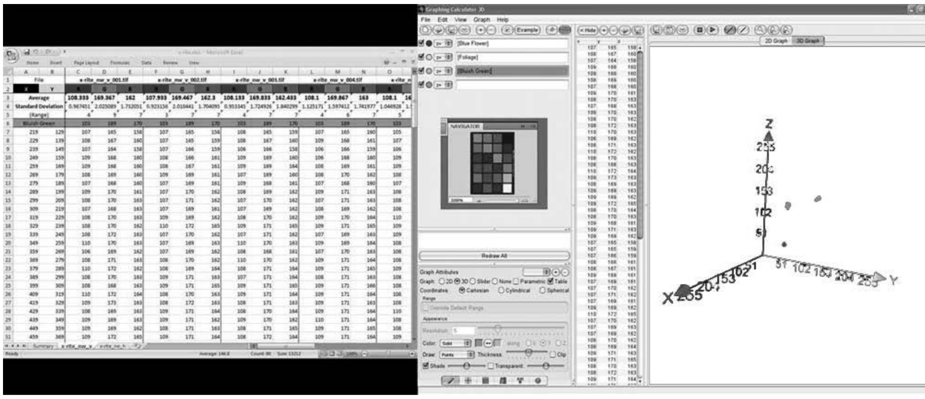

FIGURE 5. This screenshot of the analysis of the color-checker card (middle) shows, on the left side, the Excel file used for data collection. The right side shows the points graphed on a 3-D axis. Note the cluster shape of the graphed data points. Screenshot by NLM staff.

In the initial test, a color-checker card, intended for color accuracy in photography, was scanned repeatedly in four different positions on a scanner and then analyzed in Photoshop software to answer several questions:

1. How much variation is present from pixel to pixel in the scanner (keeping in mind that the color should be even throughout)?
2. How much variation is present from a "cold" scanner bulb to a "hot" scanner bulb?
3. How much variation is present when different scanner quadrants are used?

After scanning, the RGB values were recorded for the same pixels across a series of images. The average of the pixel variation was compared to the standard RGB values provided by the color-checker card vendor. The degree of variation from pixel to pixel within the same scan was also recorded in a spreadsheet. The scanner portrayed the image accurately in all quadrants and under both hot and cold bulb conditions.

Next, the team focused on analyzing an ink line. Two lines of Skilcraft ink in blue and black were drawn on a weeded scrap of 1960s Addison-Wesley paper. The sample was scanned then artificially aged under UV light for 72 hours. Data was collected from both the initial and final scans and graphed on a 3-D axis.

When the color-checker card RGB values are graphed on a 3-D axis, the graphed points appear as clusters. This is due to the evenness of color application and the lack of variation from pixel to pixel. Hand-applied ink graphs show a linear pattern that differs from the color-checker card clusters. This difference can be attributed to the variations in both ballpoint ink components and the thickness of the ink on the paper.

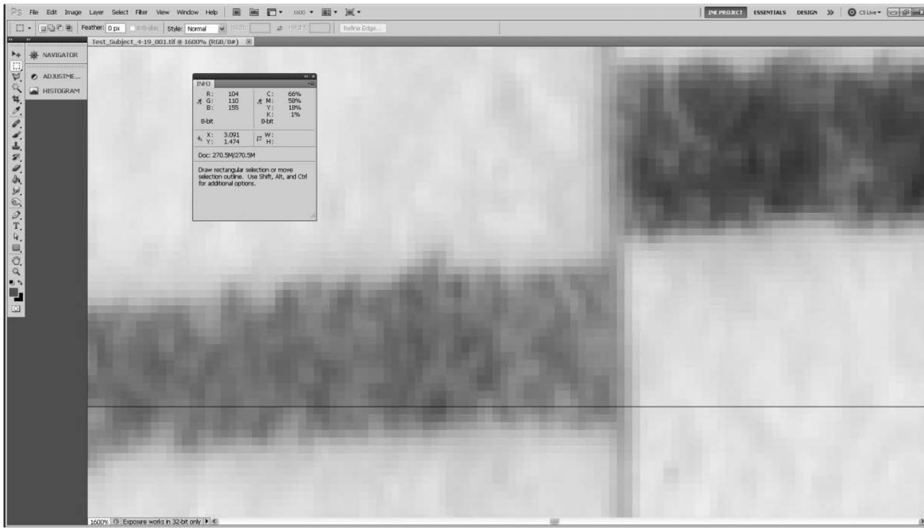

FIGURE 6. This is the first "real" ink line examined using Photoshop Assisted Spectroscopy. The right side shows the control sample, and the left side the sample after 72 hours of UV exposure. NLM staff created this screenshot of the image in Adobe Photoshop.

As a result of these tests, the NLM team determined that it is possible to track color shift using Photoshop software. However, tracking this process on an item in a more realistic environment presents additional variables and was addressed in phase 3 of the project.

Phase 3: Application for Evaluation of Storage Environments

The goal during this phase was to determine appropriate storage environments for ballpoint pen ink using the Photoshop Assisted Spectroscopy technique. To start, the project team decided to expand the 72-hour test to include a series of different sample types naturally aged in a variety of ambient environmental conditions.

Samples were created using different types of paper, ballpoint inks, and enclosure options. Each sample set was exposed to an assigned type of lighting for a period of time and evaluated using Photoshop Assisted Spectroscopy. The samples were scanned before exposure and rescanned at intervals throughout the project. Analysis of the scanned images revealed the relative degree of color shift based on the different environmental conditions. Environmental conditions were recorded for the tests.[19] Based upon this data, ideal storage conditions were determined for the charts, and valuable information collected regarding enclosure considerations for other ballpoint ink documents.

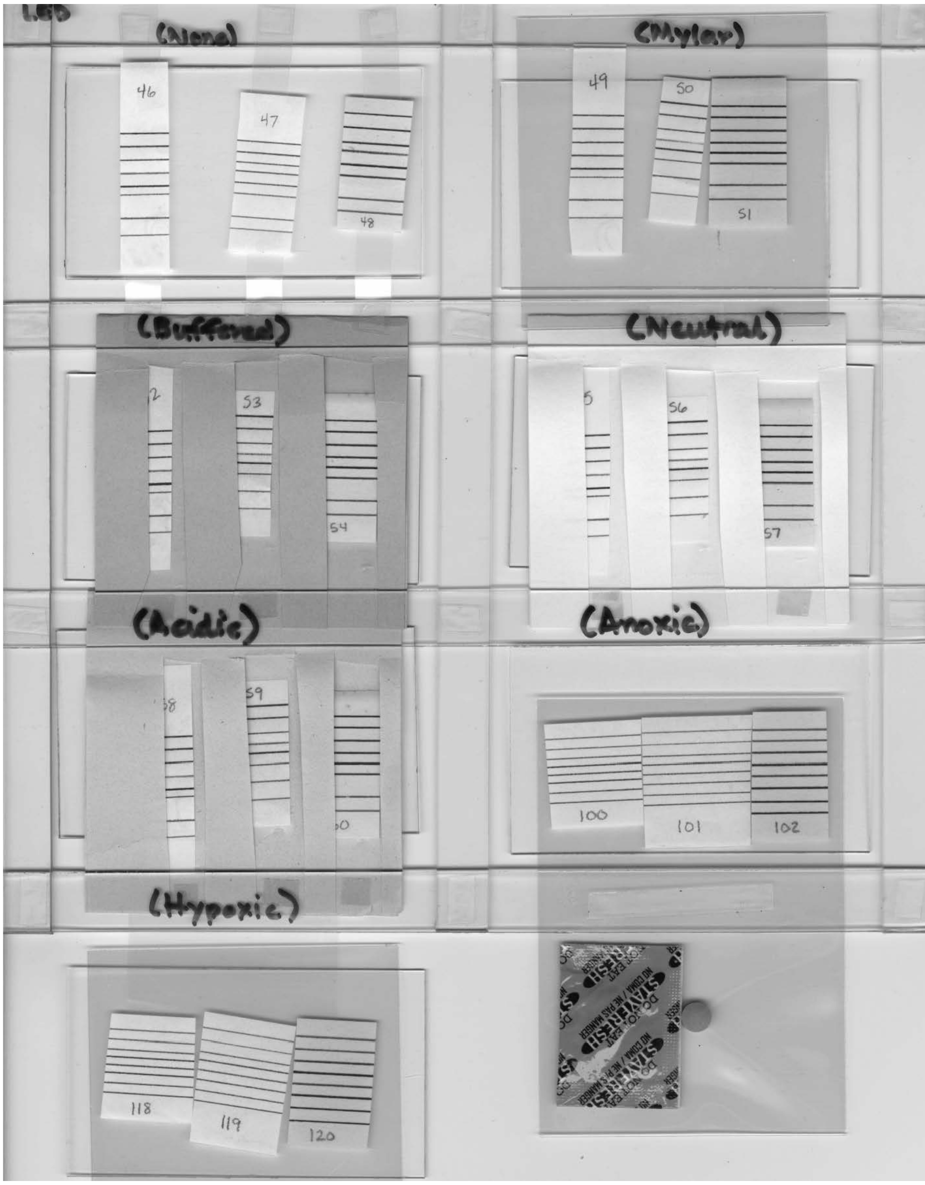

FIGURE 7. Samples were created using selected papers and enclosures then exposed to different lighting conditions. Image of test sample created by NLM staff.

Six distinct sample sets were created for exposure under the following lighting conditions: south-facing window; fluorescent; incandescent; light-emitting diode (LED); dark; and one week's exposure in the window then storage in the dark (light/dark).[20]

Each sample set contained 7 distinct enclosure types: no enclosure; polyester film encapsulation; acidic paper enclosure (pH 5.5); neutral paper enclosure (pH 7.0); buffered paper enclosure (pH 8.5); hypoxic polyester film enclosure; and anoxic polyester film enclosure.

Each enclosure type contained 3 paper types: acidic, neutral, and buffered. Each paper type contained 8 different ballpoint inks applied as described below.[21] Of the 8 inks, 3 are discussed in this paper: Skilcraft ballpoint inks in black, blue, and red.[22]

To create the samples, a continuous line was drawn on strips of paper using the selected pen types. The strips were then cut into sections and numbered. Each group was placed in a different environment. Six sample sets were created using all of the listed enclosure types. Each set was put in an inert, rigid plastic support to ensure that each sample was positioned in the same place on the scanner platen for each scan.

An initial scan at 1200 dpi on an Epson 10000 XL scanner was made of each sample set. All files were saved in the TIF format. Each set was then exposed under the assigned lighting environment and scanned weekly for a total exposure period of 2 months. Samples were placed in the same quadrant of the scanner with the same orientation for all scans.

Methodology for Data Collection

The scanned images were opened in Photoshop CS5 software for data collection. No editing was done to the files. Using the "Info" window, set to display RGB values and *xy* coordinates, the displayed data were collected along each ink line intended for analysis. Data were recorded from the middle of the ink line, moving 10 pixels along the *x* axis between each point. Data were stored in a spreadsheet. The scans remain available and are unaltered, so additional data may be collected.

The collected data points were plotted on a 3-D axis as described in phase 2. To demonstrate the degree of color shift, the data points from the initial scan were plotted on the graph with the data points from the final scan. For convenience, the graphed color corresponds roughly to the original ink color, while the other data points, representing the shifted ink, are displayed in gray.

After all of the sample data were plotted on 3-D graphs, the color shift for each ink line was evaluated and measured. Color shift was rated minor, moderate, or major based on visual assessment by team members. The results were subsequently compiled and compared. Ink colors were examined separately from one another and evaluated in the following categories: lighting type, paper type, and enclosure type. In addition to visual analysis, Delta-E calculations for color change were done using the Cie94 analysis formula.[23] In most instances, the Delta-E calculations corroborated the results of the visual analysis.

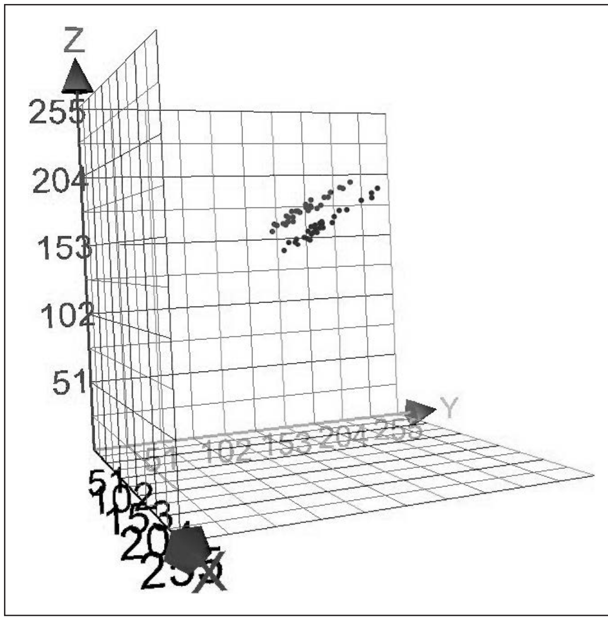

FIGURE 8. The bright blue line displays the gathered data for the initial, unexposed ink. The gray line shows the data for the shifted ink. The graph can be rotated on a computer screen so it can be viewed at different angles. Image created by NLM staff using graphing software.

Phase 3 Results

Results of average color shift in different environmental conditions were as follows:

Lighting types:

Black ink
- Least shift in the dark and the light/dark combination
- Minor shift in LED lighting conditions
- Most shift in window and fluorescent samples
- Moderate shift in incandescent samples

Blue ink
- Least shift in LED light
- Minor shift in dark and light/dark samples
- Most shift in fluorescent samples
- Moderate shift in window and incandescent samples

Red ink
- Least shift in the light/dark combination, LED, and window samples
- Moderate shift in fluorescent, incandescent, and dark samples

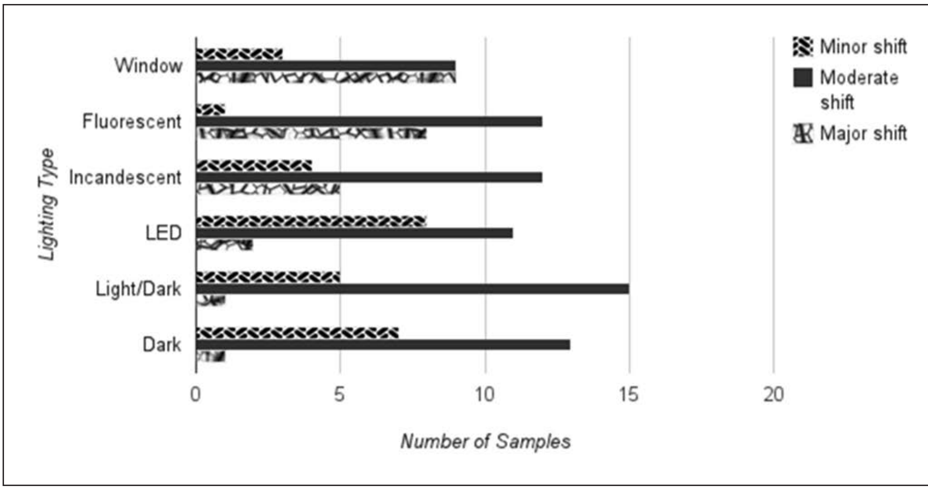

FIGURE 9. This graph shows black ink shift by lighting type.

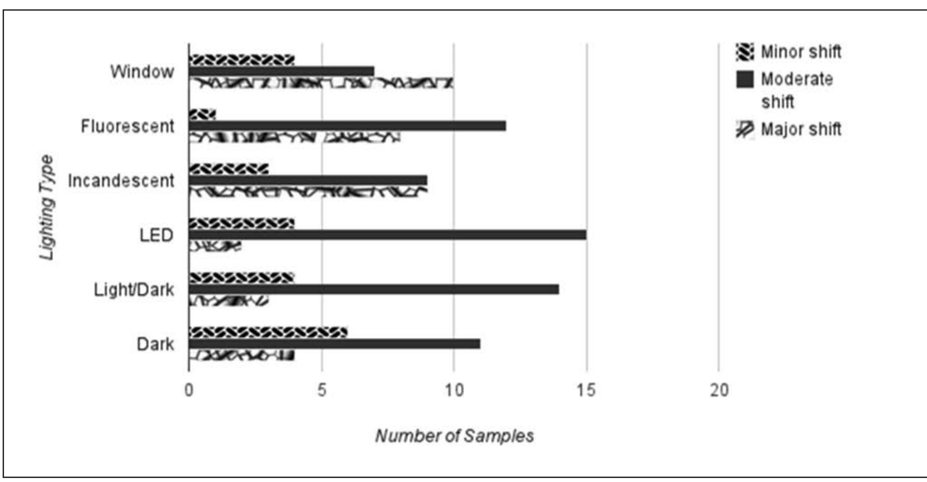

FIGURE 10. This graph shows blue ink shift by lighting type.

- Degree of shift for red inks does not vary nearly as widely under different lighting as it does for blue and black inks.

Paper types:

Black ink
- Least shift on acidic paper
- Equal shift on buffered and neutral paper

Blue ink
- Least shift on acidic paper
- Most shift on neutral paper

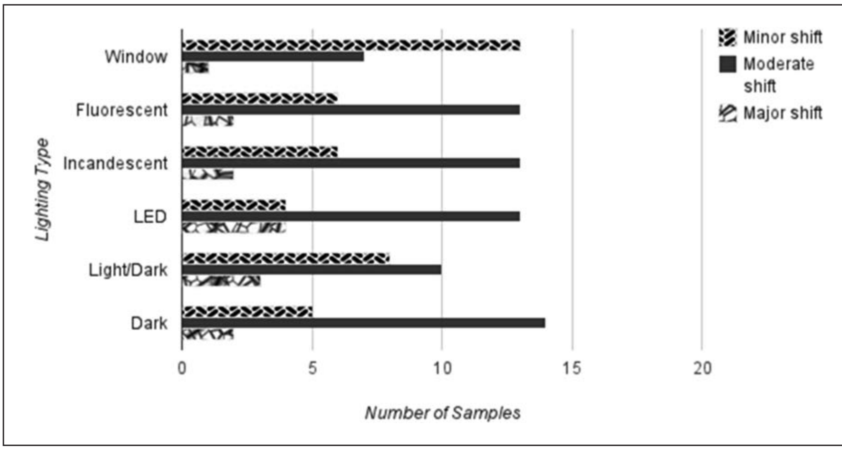

FIGURE 11. This graph shows red ink shift by lighting type.

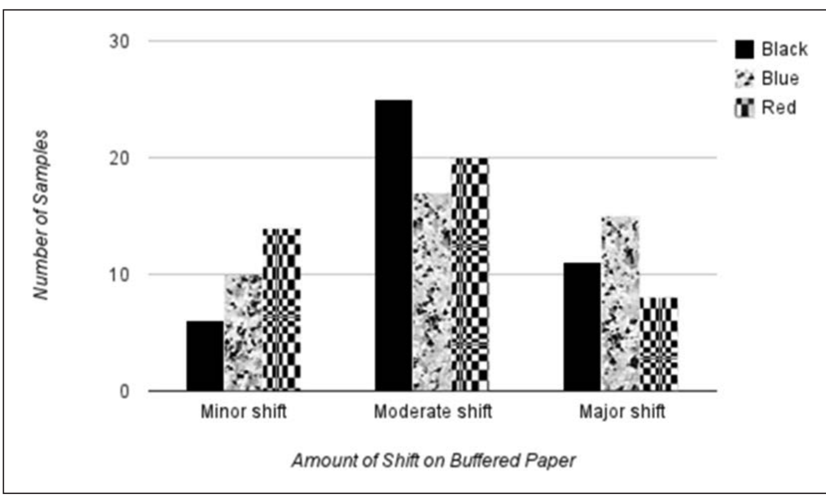

FIGURE 12. This graph shows the amount of shift on buffered paper.

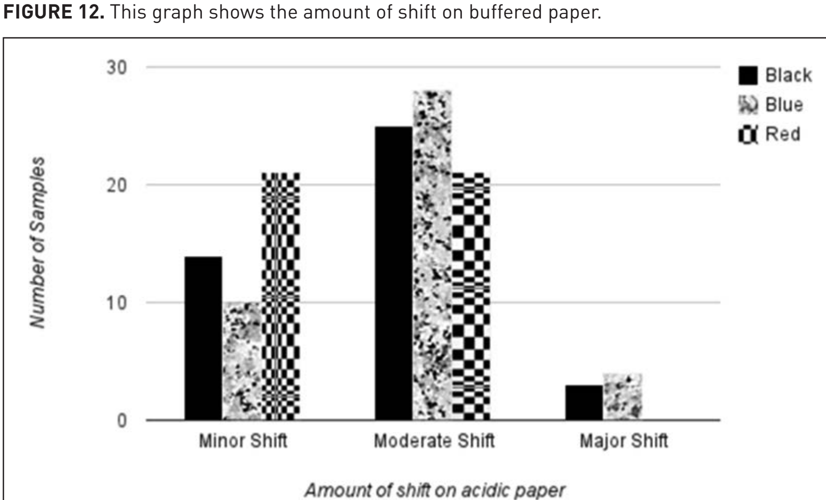

FIGURE 13. This graph shows the amount of shift on acidic paper.

Red ink

- Least shift on acidic paper
- Most shift on buffered paper

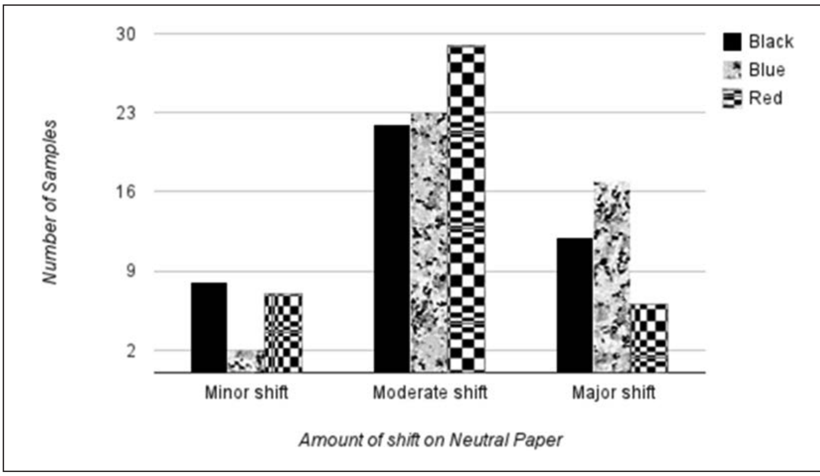

FIGURE 14. This graph shows the amount of shift on neutral paper.

Enclosure types:

Black ink

- Least shift in anoxic and hypoxic enclosures
- Most shift in neutral and acidic enclosures
- Moderate shift in buffered, polyester film, and no enclosures

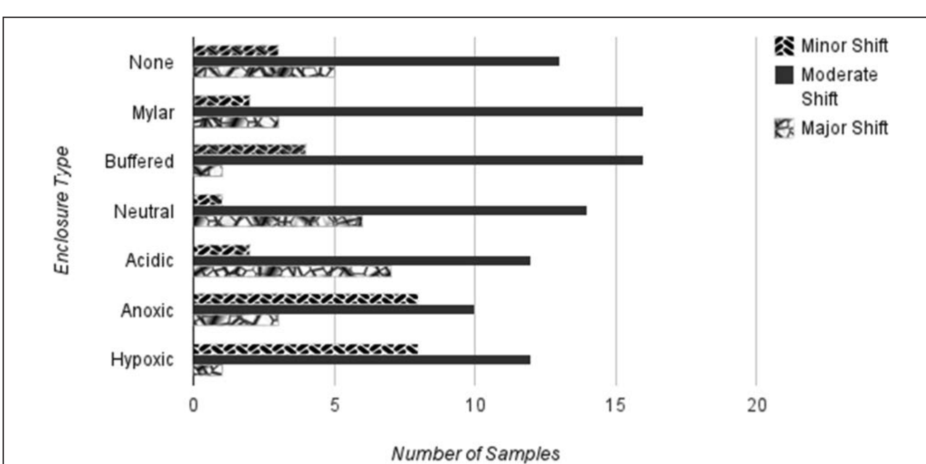

FIGURE 15. This graph shows black ink shift by enclosure type.

Blue ink

- Least shift in anoxic and hypoxic enclosures
- Most shift in polyester film, neutral, and acidic enclosures
- Moderate shift in buffered and no enclosures

Red ink

- Least shift in anoxic and hypoxic enclosures
- Most shift in neutral and no enclosures
- Moderate shift in acidic, buffered, and polyester film enclosures

As expected, ideal lighting conditions are in line with the current standard practice of storing items in the dark and using LED lighting for exhibition.[24] The red Skilcraft ink displayed greater stability than the blue or black Skilcraft

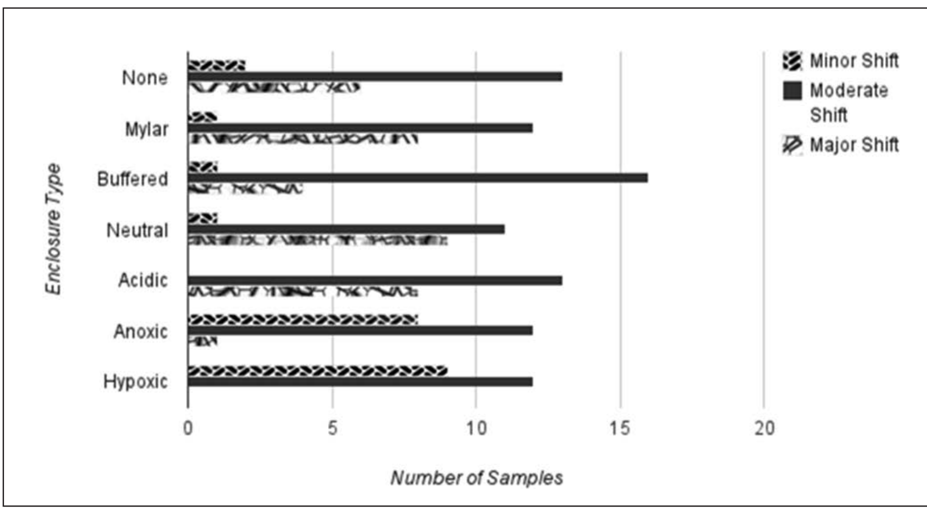

FIGURE 16. This graph shows blue ink shift by enclosure type.

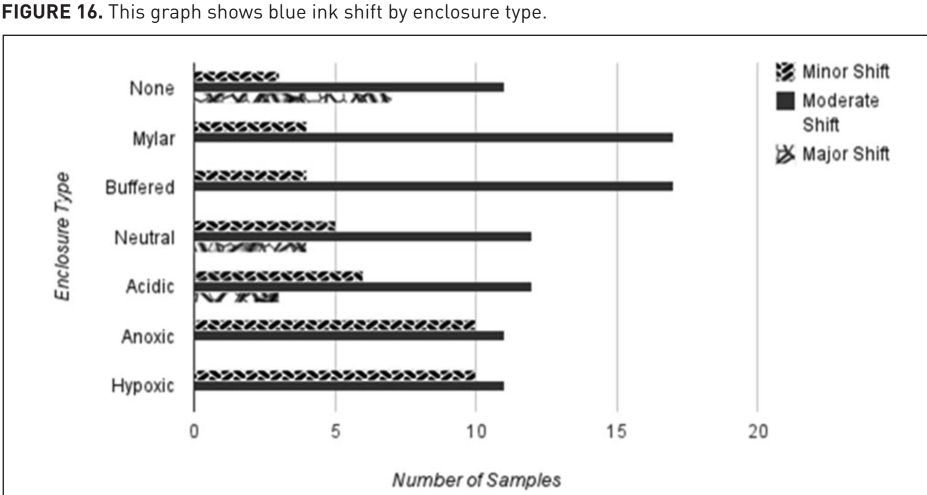

FIGURE 17. This graph shows red ink shift by enclosure type.

inks. It is possible that this is related to the presence of highly light sensitive triarylmethane dyes such as methyl violet commonly found in both the black and blue inks.[25]

In contrast to the lighting results, the observation that all 3 inks displayed the least shift on acidic paper may be counterintuitive. However, in the early stages of ink formulation, basic dyes were considered less permanent than acidic dyes. For the most satisfactory writing results with ballpoint ink, a paper with pH 4 or 5 was recommended.[26] While this is interesting to note, over the life of a document, the paper degradation processes would certainly outweigh any perceived short-term benefit provided by acidic paper. This result may also be related to differences in paper sizing between the samples chosen for the study.

Comparing the enclosure results shows that all 3 inks displayed the least shift in anoxic or hypoxic environments. This supports evidence previously presented in both the forensics and conservation fields that color shifts in many dyes are slowed when oxygen is removed from or severely reduced in the storage environment.[27]

Storage for ballpoint pen ink documents should be evaluated on a case-by-case basis. Because of the variations in ink formulae, even within the same manufacturers, further research needs to be done on ideal storage environments for these items. For now, the authors cannot definitively offer an "across-the-board" solution.

Conclusions and Further Study

Image-editing software is more affordable than traditional analytical equipment and can have multiple applications in an institutional setting. While scanning specifications must be maintained, the methodology is easy to learn and replicate. We recommend that scanning details be kept in the metadata to ensure that the initial settings are stored for comparison in the future.

Ballpoint pen ink displays in a linear manner when the test results are plotted on a 3-D graph. NLM conservators noticed that the color shift for ballpoint pen ink will sometimes parallel the original graphed ink line, but other times will shift at an angle to the original ink line. While this project does not assess the reasons for this difference in shift pattern, it is an interesting observation that could be studied further in the future. Linking RGB values displayed in Photoshop software to distinct ink components also requires further study and validation.

Opportunity exists for the creation of a Photoshop software plug-in to streamline the data collection for larger sample sets. With such a plug-in, the data collection process would be more automated for the tracking of color shift on a larger scale over time. While the staff at NLM has become aware of the existence of software that may automate color shift tracking, we have not yet evaluated it for this purpose.

Photoshop Assisted Spectroscopy has applications outside of this project including use as a monitoring tool. Collection custodians may use this tool to monitor color shift using previously scanned digital collections as long as the previous scanning conditions, including calibration, match. For example, when collections are initially scanned, this technique could be used on any subsequent scans to assess the condition of the colors. The technique could be applied to inks other than ballpoint as it relies purely on color shift rather than on the specific chemistry of the ink.

For this project, Photoshop Assisted Spectroscopy was used to assess the suitability of select enclosures specifically for the ballpoint ink on the Nirenberg Genetic Code Charts. The 3 phases of this study reveal that Skilcraft ballpoint inks benefit from storage in either anoxic or hypoxic enclosures and in the dark. When placed on exhibit, LED lighting is most desirable. As a result of the testing, the conservation staff have recommended that the Nirenberg Genetic Code Charts be stored in custom-built anoxic frames.

Notes

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1 Photoshop Assisted Spectroscopy is not authorized, endorsed, or sponsored by Adobe Systems Incorporated, publisher of Adobe Photoshop.

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[8] Readers desiring information on the use of these analytical techniques may wish to consult the following sources: A. Casoli, G. Palla, and J. Tavlaridis, "Gas-Chromatography/Mass-Spectrometry of Works of Art: Characterization of Binding Media in Post-Byzantine Icons," *Studies in Conservation* 43, no. 3 (1998): 150–58; Stephen L. Morgan, Alexander A. Nieuwland, Christopher R. Mubarak, James E. Hendrix, Elizabeth M. Enlow, Bryan J. Vasser, and Edward G. Bartick, "Forensic Discrimination of Dyed Textile Fibers Using UV-VIS and Fluorescence Microspectrophotometry," in *Proceedings of the European Fibres Group* (Prague, Czechoslovakia: 2004); Jaap van der Weerd, Annelies van Loon, and Jaap J. Boon, "FTIR [Fourier-Transform Infrared Spectroscopy] Studies of the Effects of Pigments on the Aging of Oil," *Studies in Conservation* 50, no. 1 (2005): 3–22.

[9] The tape carrier is backing material that holds the pressure-sensitive adhesive and can be made from paper, plastic, metal, cloth, or another substance.

[10] Readers desiring information on the use of nondestructive techniques mentioned here may wish to consult the following sources: Antonino Consentino, "Identification of Pigments by Multispectral Imaging; A Flowchart Method," *Heritage Science* 2, no. 8 (March 17, 2014); Kristin DeGhetaldi and Brian Baade, "X-Ray Fluorescence," University of Delaware College of Arts and Sciences, http://www.artcons.udel.edu/about/kress/examination-techniques-and-scientific-terms/x-ray-fluorescence; The Getty Conservation Institute, "Museum Lighting Research: Microfadeometry," http://www.getty.edu/conservation/our_projects/science/lighting/microfade.html; Walter C. McCrone, "Polarized Light Microscopy in Conservation: A Personal Perspective," *Journal of the American Institute for Conservation* 33, no. 2 (1994): 101–14; Smithsonian Museum Conservation Institute Imaging Studio, "Infrared and Ultraviolet Imaging," http://www.si.edu/MCIImagingStudio/IR_UV.

[11] Weyermann, "Mass Spectrometric Investigation," 17–27.

[12] Peter Gabriele, interview, National Library of Medicine, Bethesda, Md., 2011.

[13] Wilmer Souder, "Composition, Properties and Behavior of Ball Pens and Inks," *Journal of Criminal Law and Criminology* 45, no. 6 (1955): 744.

[14] Weyermann, "Mass Spectrometric Investigation," 17–20.

[15] Gabriele, interview.

[16] Gabriele, interview.

[17] Jacob L. Thomas, "Evaluation of Reduced Oxygen Display and Storage of Watercolours" (PhD diss., University College London, 2012), 36–37; Weyermann, "Mass Spectrometric Investigation," 20–24.

[18] "Graphing Calculator 3D," 2014, Runiter Company, http://www.runiter.com/graphing-calculator.

[19] Average lighting conditions: Window—30 UV, 7800 Lux; Fluorescent—90 UV, 6590 Lux; Incandescent—45 UV, 5500 Lux; LED—0 UV, 1200 Lux; Dark—0 UV, 0 Lux. Temperature ranges: Window: 60—90 F; Fluorescent: 69—75 F; Incandescent: 65—92 F; LED: 66—68 F; Dark: 61—65 F. Relative humidity ranges: Window: 15—45%; Fluorescent: 29—54%; Incandescent: 16—35%; LED: 31—38%; Dark: 35—48%.

[20] This sixth sample is intended to mimic potential conditions for an item moving from a poor preservation environment to an ideal one.

[21] All 8 inks are Skilcraft black (3 different pen housing types); Pilot black; Uniball black; Skilcraft blue; Skilcraft red; Uniball fade-proof red. Though only the 3 Skilcraft inks are included in these results, the scans would allow evaluation of any of the 8 inks at some point in the future.

[22] Skilcraft black (Lot # 03-2A9-12-11032102), blue (Lot # 01-11-07-12-21011008), and red (Lot # 02-11-08-12-11021401).

[23] "Cie94 Delta-E Calculator," ColorMine.org, http://colormine.org/delta-e-calculator/cie94.

[24] British Standards Institution, comp., *Specification for Environmental Conditions for Cultural Collections*, Publicly Available Specification, 2011.

[25] Gabriele, interview; Celine Weyermann et al., "Photofading of Ballpoint Dyes Studied on Paper by LDI and MALDI MS," *Journal of American Society for Mass Spectrometry* 17, no. 3 (2006): 297–98.

[26] Souder, "Composition, Properties and Behavior," 744.

[27] Thomas, "Evaluation of Reduced Oxygen," 245–47.

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