COLOR REPRODUCTION

7

Producing images and reproductions of artwork is indispensable for the creators, conservators, and connoisseurs of works of art. Artists often keep records of their work, and they may want to make signed prints or posters from an original. Conservators, for their part, need to document condition and any treatments they undertake. Images created using a variety of technologies have become an important tool in the technical examination of art. Connoisseurs often use reproductions as surrogates for the actual object.

The availability of art images in digital format seems boundless. Often, unfortunately, the range of colors of these images is also boundless, as an image search quickly reveals. Different imaging systems produce different colors because of inherent differences in cameras and lighting. Many images are not color managed, and as a result our computers misinterpret their RGB data. Printing can also distort color. In some cases the color gamut achievable for a specific set of inks and paper type is too small to reproduce a painting's vivid colors. A final possibility is that an author or publisher may have wanted the printed image to have a certain aesthetic; the intention may not have been to reproduce colors accurately.

Many printing technologies use four inks—cyan, magenta, yellow, and black (CMYK). Here these are visible in the form of magnified dots in a detail of Renoir's *Albert Cahen d'Anvers*. Modulating the size of the dot within a fixed pattern produces full color (detail, fig. 7.2f).

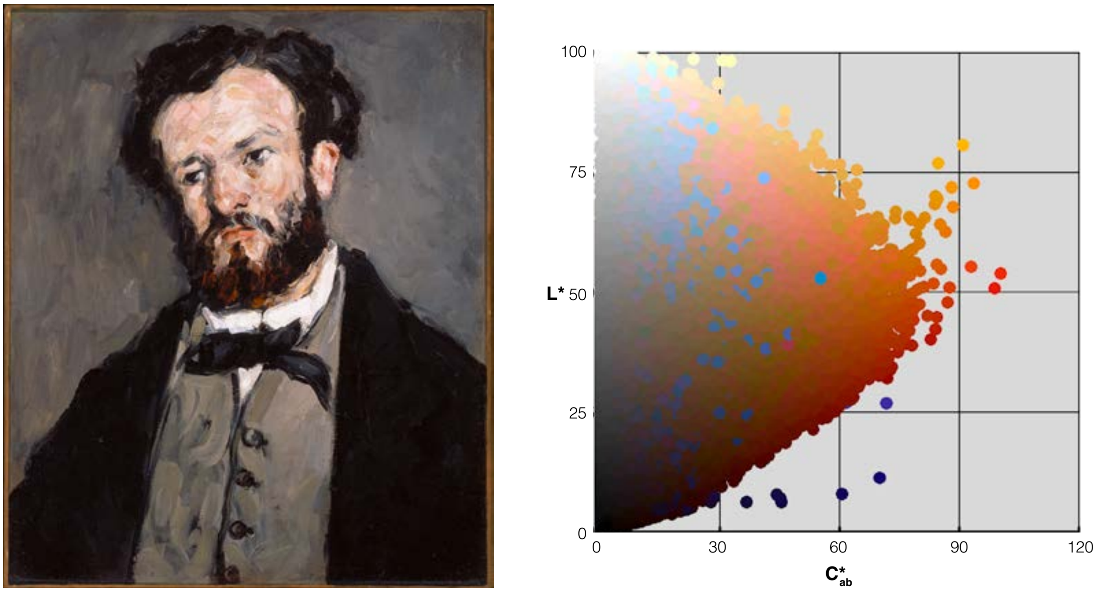
Goals of Color Reproduction

Three color-reproduction goals are relevant to artwork reproduction: preferred, spectral, and, colorimetric. Chemical photography is an excellent example of preferred color reproduction. As color photography evolved, it became clear that consumers did not want a color-accurate recording of an event; rather, they wanted a picture that was both beautiful and matched their memory of the event, achieved by increasing the chroma of familiar objects, such as green grass and blue sky, and increasing overall lightness contrast (Newhall, Burnham, and Clark 1957; Hunt, Pitt, and Winter 1974). Preferred color reproduction was well understood by the middle of the twentieth century (Evans 1959; Hunt 1970), and as digital photography evolved, image processing was used to mimic chemical photography. This still occurs today, from mobile devices to medium-format studio cameras.

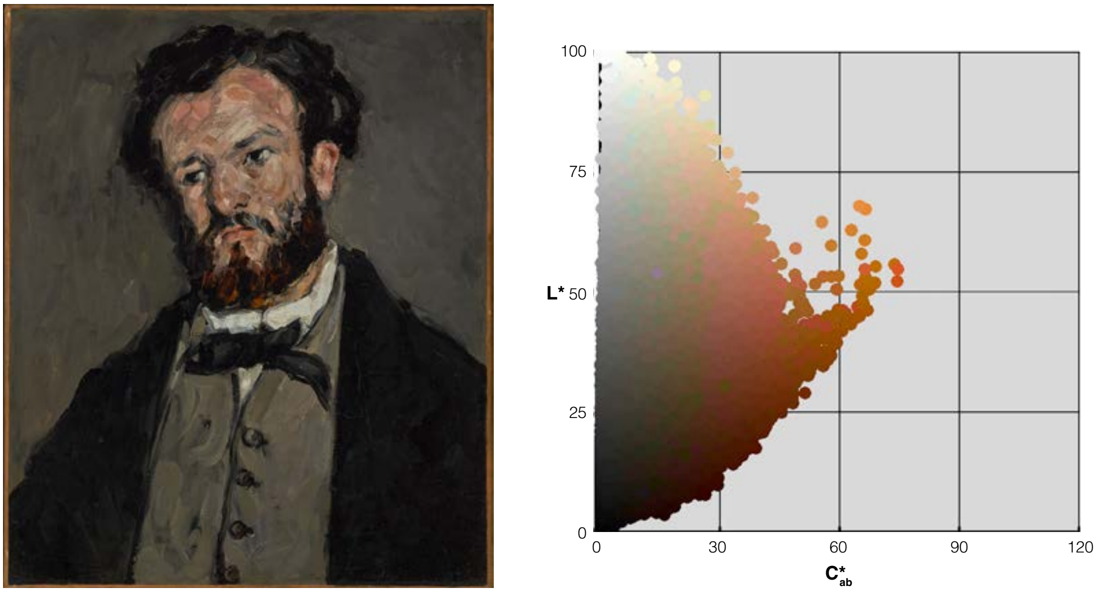
The goal of spectral color reproduction is to match the spectral reflectance properties of the artwork. This requires a multi- or hyperspectral camera and a printing system whose ink and paper can match the artwork's spectral properties. Spectral color reproduction has two advantages. First, the reproduction matches the original under any lighting condition and when viewed by any observer. The print will match the painting both in the imaging studio and in the gallery. Second, the painting and the print will have the same color inconstancy. By taking the print outdoors, we can see how the painting appeared to a *plein air* painter. The spectral match is also a colorimetric match, with CIELAB coordinates for both the painting and the print that are identical for all observers and all lighting conditions.

The vast majority of digital cameras are RGB; that is, they have three channels to record a painting's colors. With just three channels, it is possible to match XYZ tristimulus values or CIELAB coordinates for only a single observer and a single type of lighting. This is known as colorimetric color reproduction.

To create figure 7.1, two different systems—preferred and colorimetric—were used to image Paul Cézanne's *Portrait of Anthony Valabrègue*. The preferred system used a scanner to digitize a photographic transparency, resulting in high lightness and color contrast, appearing as if overcleaned. The colorimetric image is a more accurate record of the painting's colors, which are typical of a mid-nineteenth-century painting with a natural varnish about thirty years old.



A



B

FIGURE 7.1. Paul Cézanne (French, 1839–1906), *Portrait of Anthony Valabrègue*, ca. 1870. Oil on canvas, 60 × 50.2 cm (23⅝ × 19¾ in.). Los Angeles, J. Paul Getty Museum, 85.PA.45. Principles of either (A) preferred or (B) colorimetric color reproduction are used to make each image, with its colors plotted in CIELAB to the right. The green and blue colors correspond to image noise, observable only at high magnification.

The Image

The properties of a digital image include dimensions, resolution, bit depth, file type, color mode, and color encoding (color management). We can think of a digital image as a piece of graph paper. Each square is called a pixel (a shortened form of "picture element"), and the number of squares on the sheet of paper defines the resolution. Digital cameras are marketed according to their total number of pixels. A 24-megapixel (mpixel or MP or M) camera has 24 million pixels, usually arranged as 6,000 pixels in one direction and 4,000 pixels in the other direction: 6,000 x 4,000 = 24,000,000. As consumers, we have been trained to equate the number of pixels with image quality. But there is a more critical dimension: the size of the sensor. From the number of pixels and the sensor size, the size of each pixel can be determined. Larger pixels have better noise properties. This is why studio cameras have larger sensors than consumer cameras. A small-megapixel camera can easily outperform one with many more pixels if it has superior optics and a sensor area that is the same size or larger. As these factors are more important than the total number of pixels, the images will be sharper and lower in noise. Note also that using Adobe Photoshop to increase resolution does not improve image quality, just file size.[1]

Our numerical system is the decimal system, based on powers of 10 organized in ascending columns from right to left. Each column has ten unique values: 0, 1, 2, . . ., 9. Images use the binary system, based on powers of 2. Each position has two unique values: 0 and 1. Each column is called a bit. Most commonly, images use 8-bit encoding with values ranging from 00000000 to 11111111. There are 256 unique values, 0 to 255. The number of bits, called bit depth, determines numerical precision. Previously, most imaging hardware and software was limited to 8 bits; this precision was just adequate if best practices were followed, particularly during image capture and visual editing. Recently, digital cameras have advanced to the point where their precision exceeds 12 bits, and improvements continue to be made. An 8-bit-per-channel image (24 total bits for RGB) will negate such improvement, and 16- and 32-bit precisions are now used. If an image is a legacy 8-bit-per-channel image or if a digital camera stores only 8-bit-per-channel images, changing the bit depth to 16 or 32 will not improve image quality, just increase its file size.[2]

Two common file types are TIFF (image.tif or image.tiff) and JPEG (image.jpg). TIFF files contain complete data, whereas JPEG files have reduced data that does not degrade image quality for many viewing applications. This type of data reduction is known as visually lossless file compression. Most amateur photographers store images in JPEG format, whereas professionals store images in TIFF format or a raw image format that is specific to the camera manufacturer. JPEG image compression should not be used for scientific imaging or for archiving artwork.

The color mode defines the number of channels. Modes include grayscale (one channel), RGB (three channels: red, green, and blue), CMYK (four channels: cyan, magenta, yellow, and black),[3] and Lab (three channels: L*, a*, and b*). A color mode is underspecified until the color coordinates are related to a set of reference conditions. This process, called color encoding, is the domain of color management. The exception is a Lab image. When an image is assigned as a Lab image, it is encoded as CIELAB L*, a*, and b* for CIE illuminant D50 and the 1931 standard observer.

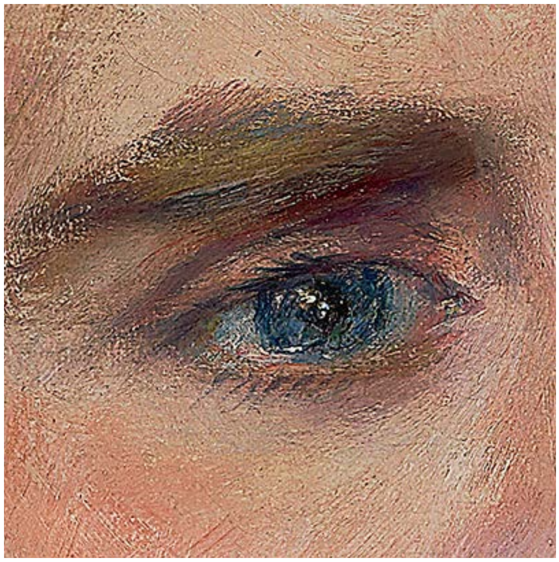
Image Quality

Producing a color image can be as simple as pointing a mobile phone at the artwork or as complicated as the practices of a museum's imaging department (Berns, Frey, et al. 2005; Frey and Farnard 2011). How do we determine quality requirements? How is quality even defined? A good place to start is to look at images with different kinds of image-quality limitations.

Quality is separated into spatial and color quality, visualized in figures 7.2 and 7.3. Spatial quality, explored in figure 7.2 with a detail of an eye from Renoir's *Albert Cahen d'Anvers,* can be evaluated visually by looking at images at full resolution on screen ("100% magnification" in Photoshop). A silkscreened or paint-by-numbers appearance may come from insufficient bit depth (fig. 7.2b). The problem can also arise when an underexposed image is rescaled ("levels adjustment" in Photoshop). Limitations in the optical properties of lenses, the need to have a shallow depth of field sometimes, or an inability to focus can result in image blur (fig. 7.2c). This can be corrected to a large extent by sharpening, which involves amplifying the high spatial frequencies, but there is the danger of oversharpening, with unnatural edge contrast as a result (fig. 7.2d). Another problem with quality stems from the uncertainty that is part of all processes. In imaging, uncertainty takes the form of a random variability called image noise, which gives a speckled appearance (fig. 7.2e). Depending on the cause of the noise, the speckle may appear chromatic or achromatic

FIGURE 7.2. (A) Detail of Renoir's *Albert Cahen d'Anvers*, with examples of (B) insufficient number of levels, (C) blurring, (D) oversharpening, (E) excessive random noise, and (F) systematic pattern noise.

A



D

B

C

E

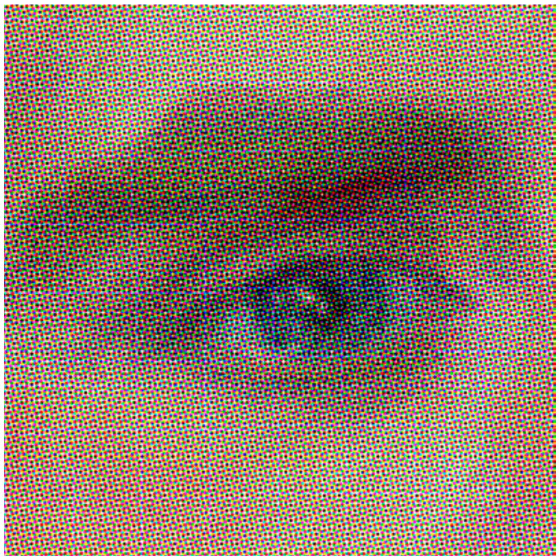


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FIGURE 7.3. (A) Detail of Renoir's *Albert Cahen d'Anvers,* with examples of (B) color balance errors, (C) lightness (tone reproduction) errors, and (D) chroma errors.

A

C

B

D

and is often observable in dark colors. Finally, there may be a spatial pattern, as in the case of low-quality printing (fig. 7.2f). The visibility of spatial image-quality limitations depends on the particular spatial image content of the painting, the viewing distance, and the image magnification.

Color quality, explored in figure 7.3 with a larger detail from Renoir's painting, is first evaluated by looking at color balance. Consumer imaging attempts to mimic our chromatic adaptation, including incomplete adaptation: think of the warm color balance of the candlelit dinner. When artwork is imaged, adaptation is assumed to be complete, and any lighting-based color cast should be removed (fig. 7.3b). Next, lightness accuracy is evaluated; this is often called tone reproduction. The most common error is a mismatch in the middle tones (fig. 7.3c): the values for white and black are correct, but everything in between is not. Chroma errors occur when the image is boosted using Photoshop's levels, contrast, saturation, and vibrance adjustment tools (fig. 7.3d). When increases in chroma are too extreme, the image appears unnatural (Yendrikhovskij, Blommaert, and de Ridder 1999), though this can be difficult to judge when viewing images of artwork. Hue errors can also occur. In this case, only specific colors have incorrect hue, not the entire image. The main causes of color errors of all kinds are poor color management, inappropriate visual editing, and fundamental limitations in the color engineering of imaging devices.

Color Management

Before digital imaging was ubiquitous, color reproduction was the domain of professionals using specialized equipment. We sent our rolls of film out for processing and received either transparencies or prints. Photographs and text were sent to printers, and books were sent back. In the 1980s, developments in desktop computers, color displays, color scanners, digital cameras, color printers, and WYSIWYG ("what you see is what you get") software launched digital color imaging and a new approach to color reproduction—desktop publishing. Chemical photography was no longer required to produce colored images. Images could be viewed on a display as well as in the form of prints. Changes in the printing industry were even more dramatic. Suddenly, many of the functions performed by highly trained specialists, using expensive technology such as analog scanning and color separation, could be performed digitally using equipment that was much lower in cost.

After the initial excitement of being able to create, view, and print colored images had worn off, many users became dissatisfied with inconsistent color and, often, low color quality. The solution was to manage color through reference color-imaging systems: one for desktop publishing and, several years later, one for consumer imaging. The consumer reference system was a color cathode ray tube (CRT) driven by a computer running Microsoft's operating system, that is, a PC. Based on measurements of PCs in office settings and existing television and computer-controlled display standards, a reference display was defined—sRGB, the "s" being an abbreviation for "standard" (IEC 1999). Cameras and scanners would define images using sRGB. These images would appear reasonable when displayed directly on a PC. Printers became sRGB devices where internal hardware and software transformed RGB data into CMYK signals that controlled the printer. sRGB cameras could be plugged directly into sRGB printers. The sRGB workflow was very effective in improving color consistency, and when image processing was optimized for preferred color reproduction, the resulting images met most consumer expectations.

Desktop publishing required a reference color-imaging system with a much larger color gamut than a CRT display. Imaging scientists and engineers also recognized that defining images using a device's native internal data would improve spatial image quality for cameras, scanners, and displays by reducing effects caused by insufficient bit depth and would be better suited for printing systems like offset printing that defined colors only by CMYK. Rather than working through a standards organization such as the CIE, in 1993 the leading imaging companies of the day formed the International Color Consortium, ICC (Green 2010).[4] This consortium standardized a reference system and protocol for translating native data into and out of the reference system.

The basic workflow for the ICC's color-management system is shown in figure 7.4. Each imaging device has its own native digital color signals. The profile converts native device data to data controlling the reference color-imaging system. The profile is assigned to an image as a component of non-image data called metadata. Device data can be thought of as forming a color space: RGB is a three-dimensional space, and CMYK is four-dimensional. Using this terminology, the reference-imaging-system data form what is called the profile connection space (PCS), so called because the reference imaging system connects different imaging

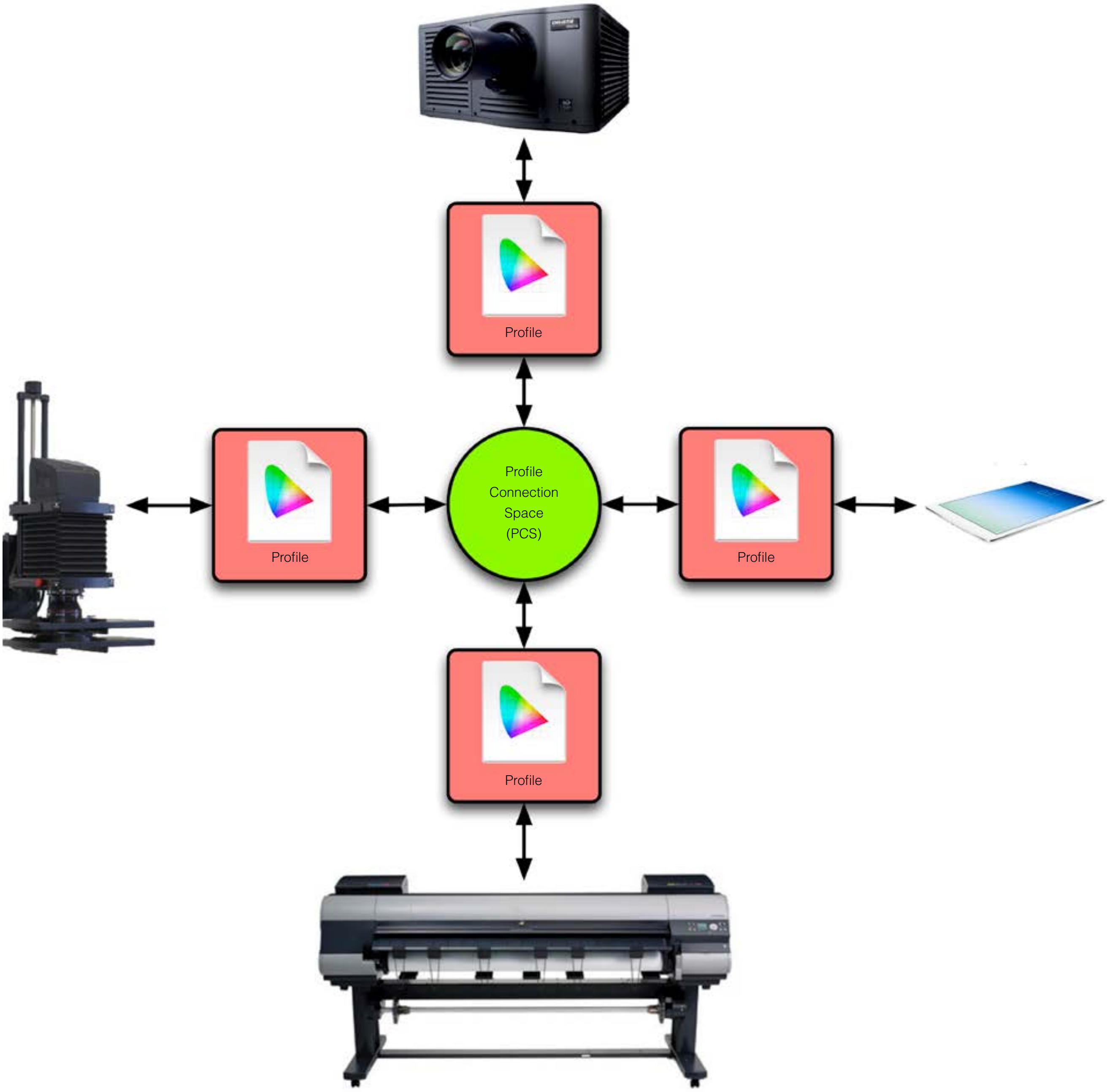


FIGURE 7.4. ICC color-management workflow diagram. Profiles are specific to each device. If each device produces the same PCS coordinates, the colors match.

devices. The PCS defines the digital signals that control an ideal printer, with paper that reflects 100% of the incident light and colorants that produce an extremely large color gamut.[5] This ideal print is illuminated by CIE illuminant D50 and viewed by the CIE 1931 standard observer. This reference imaging system is further abstracted to a colorimetric specification, either XYZ or Lab, leading back to the tenets of colorimetry and colorimetric color reproduction: two colors (or images) that have the same colorimetry match each other for a specific illuminant and specific observer.

Software known as the color engine or color-management module (CMM) is used to convert between devices and the PCS. In practice, profiles are concatenated, and there is a direct conversion between imaging devices: an RGB image is converted to CMYK. The most common software to implement ICC-based color management is Adobe Photoshop. In fact, Adobe was one of the founding members of the ICC. Today, Adobe products control their colors using ICC conventions.

Accurate profiles are the key to effective color management. If a profile is created for bright-white paper and printed on brownish yellow newsprint, the resulting colors will not look correct. A profile created for newsprint will compensate for the paper color. Every imaging device has one or more default profiles: cameras, scanners, and displays have a single profile while printers have multiple profiles, one for each kind of paper. It is also possible to create and optimize profiles using independent software and hardware. The most effective profiling systems use measurement instrumentation—for example, a spectrophotometer when profiling a printer and a spectroradiometer when profiling a display. This way, we are assured that the profile corresponds to the actual conditions.

Most consumer cameras encode using sRGB even though CRT technology is nearly obsolete. If an image does not have a profile, it is safest to assume sRGB encoding. However, if there is a profile and the viewing software does not recognize it—as occurs in some web browsers—and assumes sRGB encoding, severe color errors like those shown in figure 7.5 can result.

Professional camera systems use a variety of encoding spaces. The most common are sRGB, Adobe RGB (1998), eciRGB v2, and ProPhoto RGB. The particular choice depends on bit depth, existing standards and recommendations, the use of visual editing software, and the scene colors. For museum imaging, ProPhoto RGB with 16-bit depth is a good choice

FIGURE 7.5.
(A) ProPhoto RGB image of Renoir's *Albert Cahen d'Anvers,* (B) rendered under the assumption that the image encoding is sRGB.

A

because artist paints are within its color-rendering gamut;[6] with their smaller rendering gamuts, all the other spaces produce encoding errors (Berns 2014a; Berns and Derhak 2014). The problem is demonstrated in figure 7.6 for mixtures of twenty-one artist acrylic dispersion paints with a glossy picture varnish.[7] Many of the colors cannot be encoded accurately for sRGB and Adobe RGB (1998), encoding spaces often used in museums.

Printers also contain profiles. Instead of residing within the metadata, the profiles are a component of the software used to set up and control the printer. It is up to the user to choose the correct profile for each paper type.

B

Once all the necessary profiles are in place, the user converts to a profile—the process of implementing color management, performed by the color engine. Suppose the image is very chromatic and many of the colors cannot be printed accurately. Rather than the paper remaining blank in those places, these colors are changed to fit within the printing system's color gamut. The opposite can also occur: an image with lackluster colors might be printed to take advantage of a system's color capabilities. There are many approaches to changes of this kind, which are known as color-gamut mapping (Morovic 2008). The ICC has defined four general categories, called color-rendering intents: perceptual, saturation, media-relative colorimetric, and ICC-absolute colorimetric.[8]

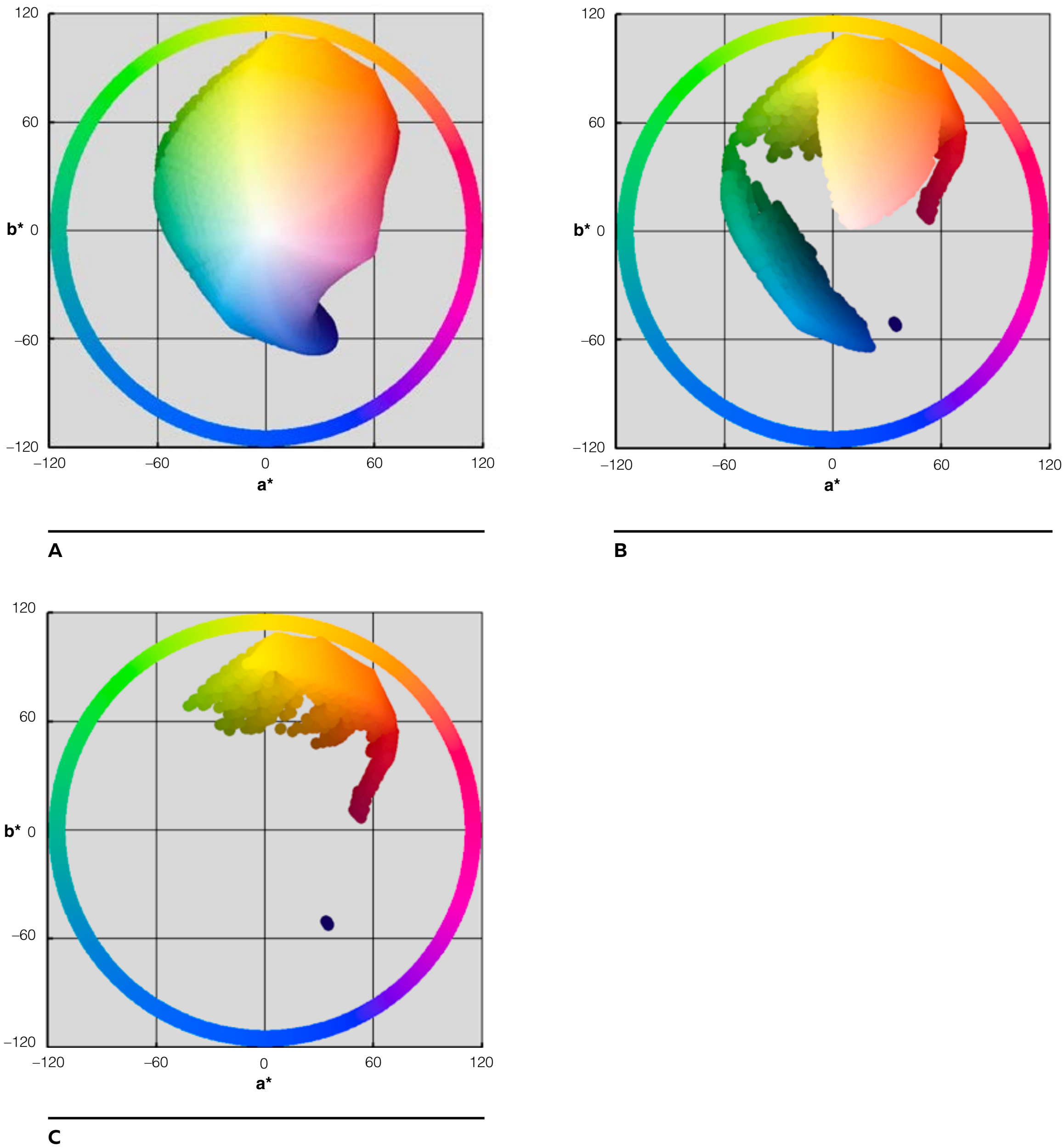


FIGURE 7.6.
(A) CIELAB coordinates of mixtures of twenty-one artist acrylic dispersion paints with a glossy picture varnish. Colors that cannot be encoded accurately—that is, out-of-gamut colors—are shown for (B) sRGB and (C) Adobe RGB (1998) encoding spaces.

Perceptual mapping mimics chemical photographic systems based on principles of preferred color reproduction. Such mapping also has the option of "black-point compensation," in which the black of the input is remapped to the black of the output. (Saturation and media-relative colorimetric also have the black-point compensation option.) Perceptual rendering can produce large errors in color and is not recommended for artwork reproduction.

Saturation mapping distorts colors to fully utilize a device's color gamut and should also not be used for artwork reproduction.

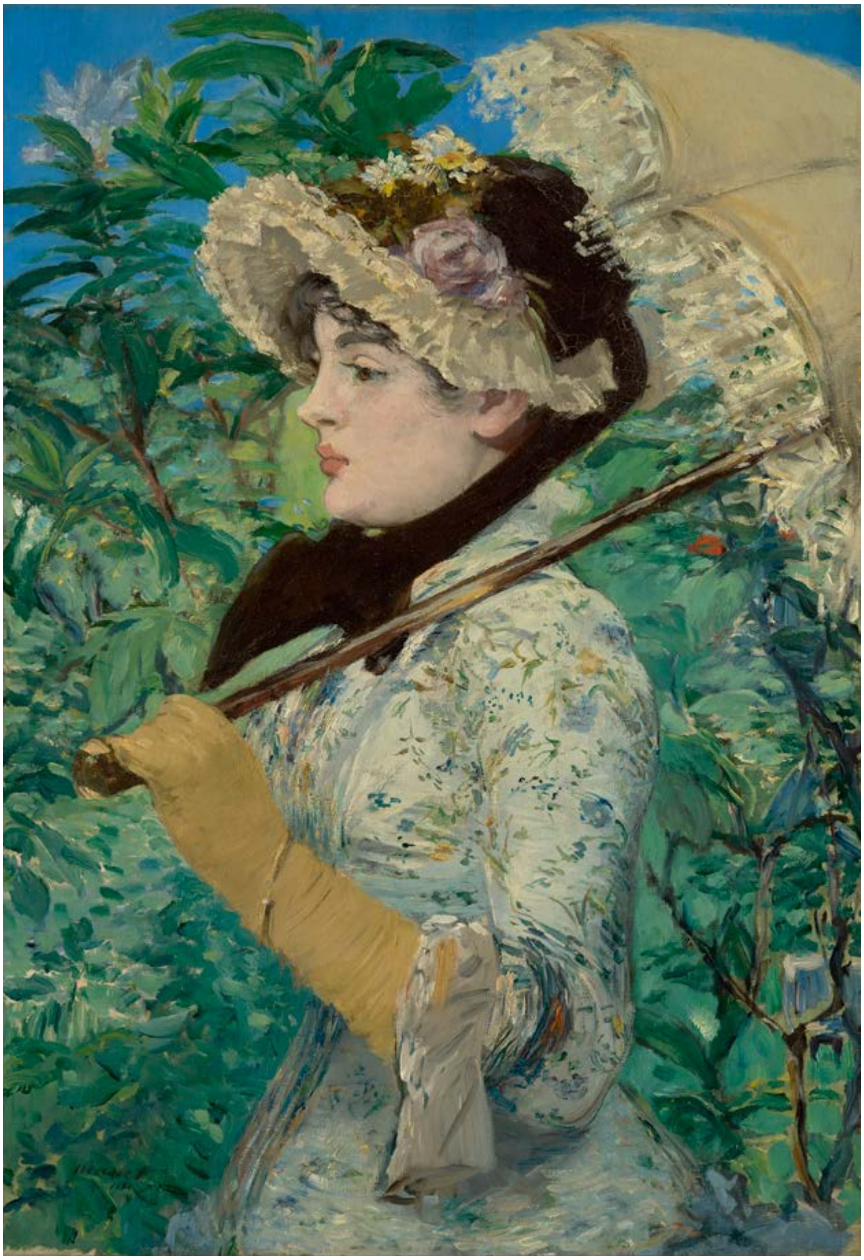
The media-relative colorimetric rendering, including black-point compensation, produces a color match on the assumption that each device's white defines the observer's state of chromatic adaptation. Because of the rescaling of the white points, the amount of clipping caused by differences in color gamut is greatly reduced. The same is true when rescaling the black points. Thus, media-relative colorimetric rendering intent with black-point compensation can be effective for artwork reproduction.

The ICC-absolute colorimetric mapping also produces a match for colors within the output device's color gamut and will clip any colors outside of the color gamut. Because it is not remapping the image white, this rendering intent can be effective for artwork with a slightly colored substrate, such as many early photographic prints.

Choosing between media-relative and ICC-absolute rendering intents when printing depends on the application. When a duplicate of the same size is being made, ICC-absolute rendering should be used. When the image is in a book where unprinted paper is visible around the image, this rendering can have an excessive color cast, and media-relative rendering may be a better choice. The two are compared in figure 7.7 for a painting by Édouard Manet.

Print profiles include all four rendering intents. It may be prudent to evaluate each one, with and without black-point compensation, by printing a digital target — as shown in figure 7.8 — with known CIELAB values, measuring each sample with a spectrophotometer and calculating CIELAB, and then determining the best profile for a given usage based on the colorimetric data.

FIGURE 7.7. Édouard Manet (French, 1832–1883), *Le Printemps (Jeanne Demarsy)*, 1881. Oil on canvas, 74 × 51.4 cm (29⅛ × 20¼ in.). Los Angeles, J. Paul Getty Museum, 2014.62. The Adobe RGB (1998) encoded image is rendered according to (A) media relative colorimetric intent, which compensates for the color of both the viewing illuminant and the paper, and (B) the ICC-absolute colorimetric intent, which preserves the encoded white point, resulting, in this instance, in a bluish color balance.



A

B

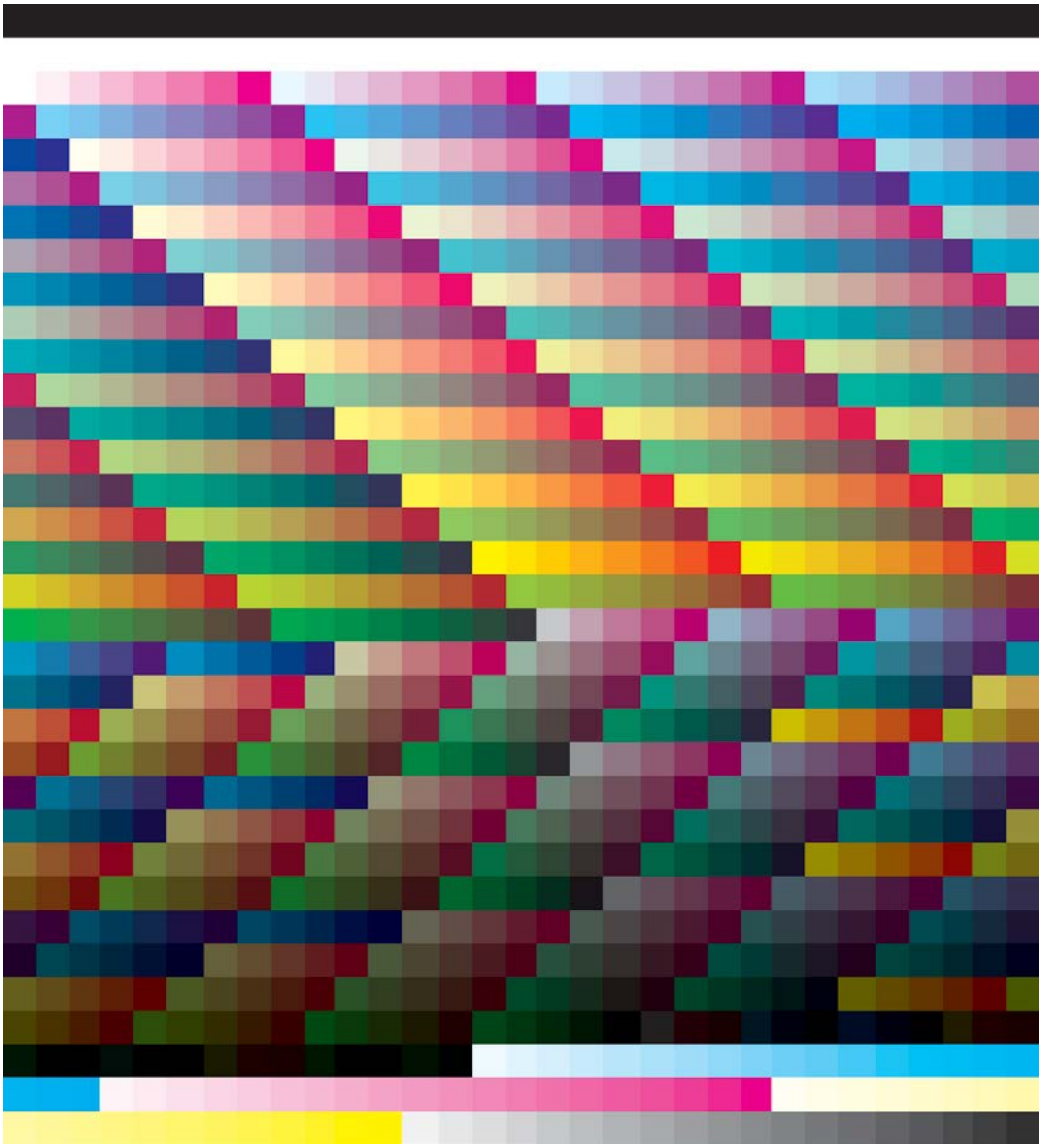


FIGURE 7.8. CMYK (cyan, magenta, yellow, and black) printer target used to create an ICC profile.

Why Reproducing Artwork Is Difficult

Achieving a high-quality reproduction or image archive is difficult. No matter who is doing the work and what their level of expertise, there are fundamental limitations preventing perfection, which in any case remains to be defined.

Consider an artwork imaging workflow consisting of a painting, its digitization, and its reproduction in print. The first decisions concern lighting. Should the print match the painting under gallery conditions, under the conditions experienced by the artist, in the photographic studio, or in the curator's office? Lighting dramatically affects the appearance of artwork because of color inconstancy. Suppose the painting is light sensitive and is exhibited under incandescent illumination at 2200 K below 50 lx. Under such conditions, the painting has a warm and slightly blurry appearance. Outside the exhibition is a point-of-sale kiosk lit by 5000 K natural daylight at an illuminance above 500 lx. If the gallery experience is reproduced for the kiosk lighting condition, the printed image will be yellowish, dark, and a bit blurry. Although the viewing experience is matched, the image has poor color and spatial image quality. A better approach might be to produce a print that matches the painting for the specific gallery lighting condition. That is, the print will match the painting when viewed adjacent to it. Certainly the exhibition curator will be pleased, knowing that the print matches the painting in the gallery. This is not common practice, however. Instead, following graphic arts practices, the painting and the print are viewed under standardized 5000 K daylight (CIE D50) at either 500 lx for practical appraisal or 2000 lx for critical appraisal (ISO 2009). Many museum imaging departments have such lighting conditions using high color-rendering daylight simulators to validate their color-management accuracy visually, and photographers will encourage curatorial and publications staff to approve any color decisions under these conditions. The photographic lighting should be similar in spectral properties to the defined reference illumination in order to reduce problems related to metamerism. Xenon flash lamps are recommended; other effective choices might be ceramic high-intensity discharge lamps, high-color-rendering solid-state lights with a 5000 K CCT (Berns 2014b), and incandescent lights with bluish filters.

The choice of camera is extremely important. Lens quality and sensor size play a larger role than the number of pixels in determining spatial image quality, as mentioned above.[9] The most important sensor property for color accuracy is its spectral sensitivity—the response of each color channel as a function of wavelength. Ideally, a color sensor should have spectral sensitivities that are equivalent to the eye's L, M, and S responses, plotted in figure 7.9.[10] The sensor will respond to incident light as our cone receptors do, and after processing, the images will be color accurate. This ideal is rarely met, however, because of manufacturing constraints and because color accuracy is only one of many design criteria. In particular, there is a tradeoff between color accuracy and image noise, and cameras designed for a wide range of lighting conditions may sacrifice color accuracy for spatial image quality (Kuniba and Berns 2009).

The inherent limitations in spectral sensitivity and the differences between the reference and camera-taking lighting are mitigated to some extent through color management. When a camera is "profiled," a reference target containing dozens or hundreds of color patches is imaged. Three such targets are shown in figure 7.10. Prior to imaging, the selected target is measured using a spectrophotometer, and reference CIELAB coordinates are calculated for the reference illuminant and observer. Software is used to create a camera ICC profile that minimizes color differences between the reference and camera CIELAB coordinates.[11] Profiles are most effective when the limitations in spectral sensitivity are not too severe, when the spectral properties of the target are similar to the work of art, and when the target's range of colors—its color gamut—exceeds that of the work of art.

The Digital ColorChecker SG target was used to create profiles for cameras having the spectral sensitivities plotted in figure 7.9. A xenon flash was used with the color-filter-array (CFA) camera, while tungsten halogen was used with the scanning camera. The Artist Paint Target was used to evaluate performance.[12] The results appear in figure 7.11. Both of the imaging systems had excellent lightness accuracy; the last row of neutrals matches the actual target well. The CFA system was much more accurate than the scanning system. Because the scanning system's red channel peaks at 630 nm and a tungsten halogen source was used, samples with appreciable reflectance at long wavelengths have color error, such as cobalt blue (row 2, column 2), pyrrole red (row 3, column 1), and quinacridone magenta (row 4, column 1). Cobalt blue becoming purplish has always been an acute problem with scanning cameras. The green samples were reduced in chroma. By comparison, the CFA system had much better color accuracy; only the reduction in chroma for the pyrrole red sample (row 3, column 1) is visible.

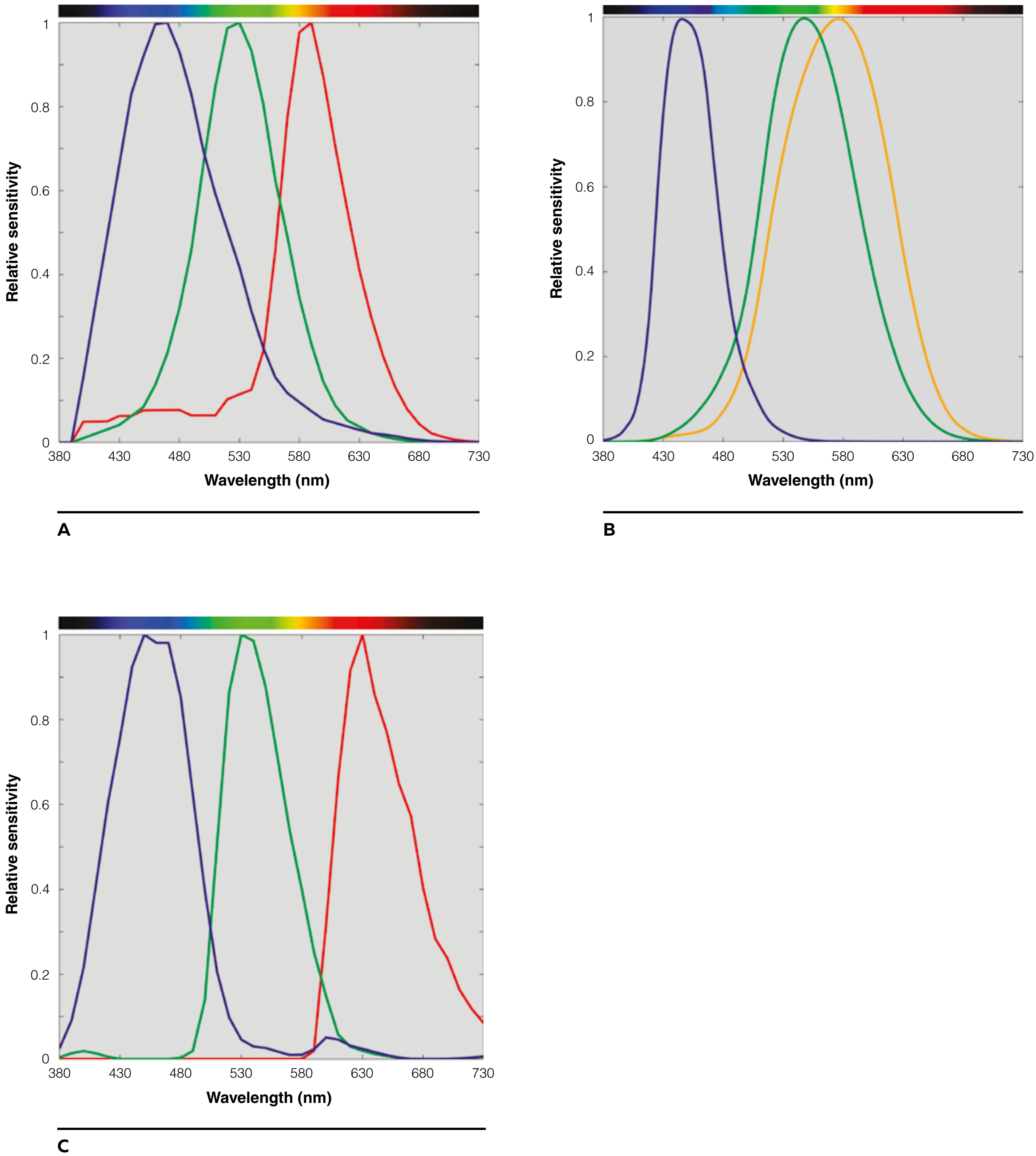
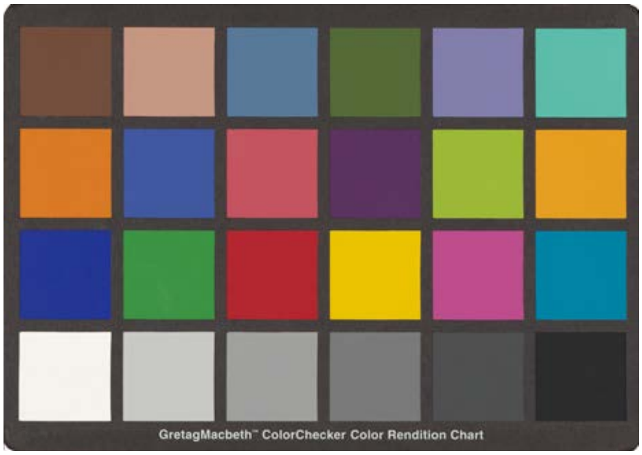


FIGURE 7.9. Relative spectral sensitivities of (A) a color-filter-array (CFA) camera system, (B) the human visual system, and (C) a scanning camera.

FIGURE 7.10. Typical targets used to create and evaluate camera profiles: (A) X-Rite Digital ColorChecker SG (20.5 × 28.8cm), (B) X-Rite ColorChecker Classic (20.5 × 28.8 cm), and (C) Artist Paint Target (6.4 × 8.6 cm).

A



B

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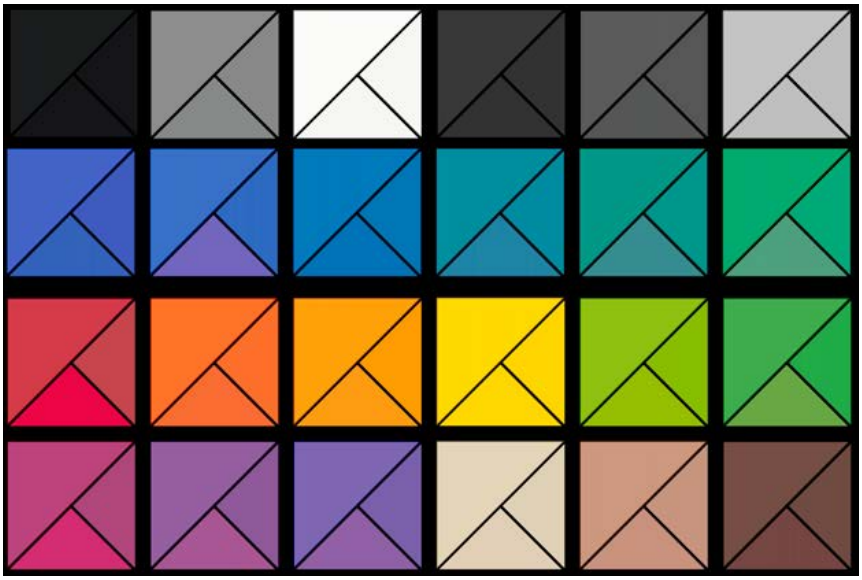
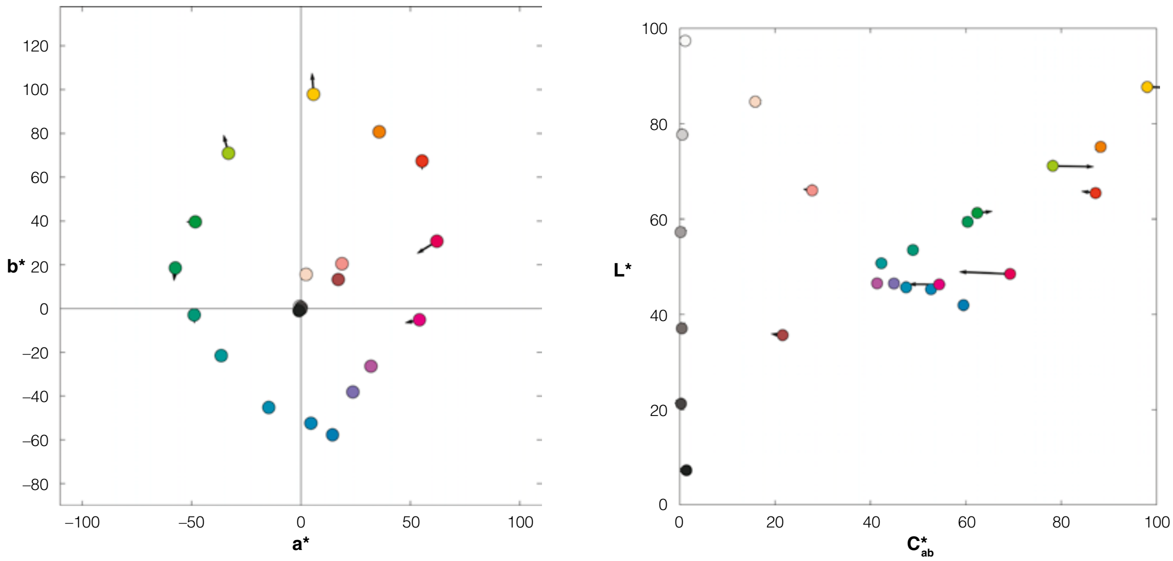
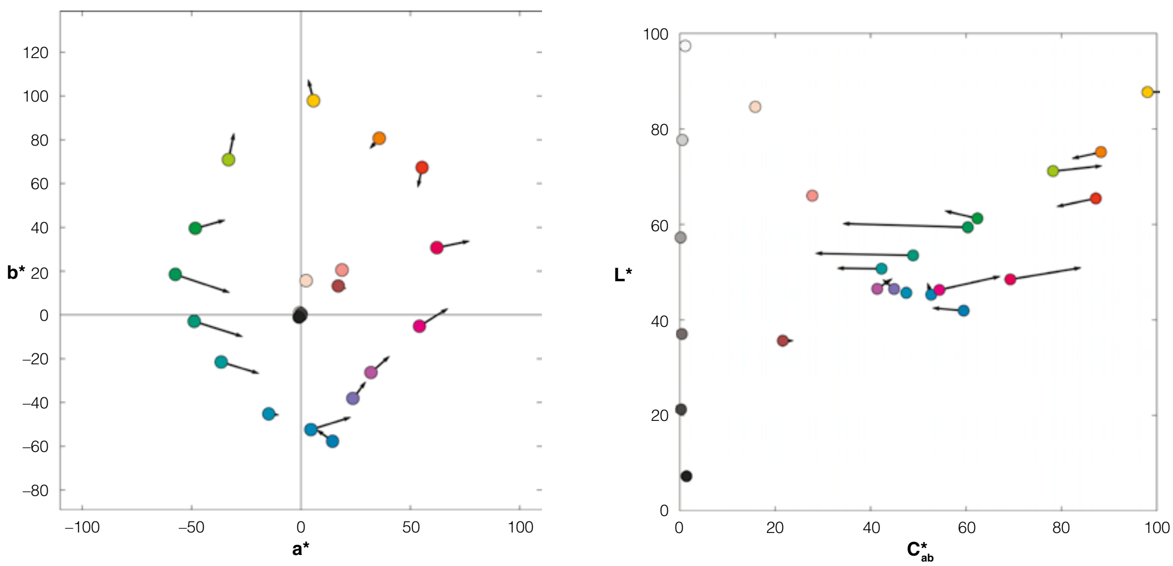


FIGURE 7.11. The Artist Paint Target (top left triangle) is compared with imaging using a color-managed CFA camera and xenon strobe lighting (right triangle) or a color-managed scanning camera and tungsten halogen lighting (bottom triangle).

Visual assessment, although very effective for qualitative evaluation, lacks precision for quantitative evaluation. In the latter case, it is more effective to calculate color differences and plot colors in CIELAB, as shown in figure 7.12. These "vector" plots point to the image colors of a color reproduction system. The color-coded dots indicate the location of the reference values, in this case based on direct spectrophotometry of the target. Ideally, the arrowheads and the colored dots are coincident. For both systems, the neutrals were imaged with high accuracy, which is the goal for color-managed camera systems used for artwork imaging (that is, colorimetric color reproduction). The CFA system had errors for three colors, mainly in chroma. The scanning system had large errors in both hue and chroma for most of the colors. Hue errors are indicated on the a*b* projection where the arrows point in directions other than toward or away from the origin (a* = b* = 0). Chroma errors are indicated by the length of the arrows in the $C^*_{ab}L^*$ plot. For the CFA system, the average and maximum color differences were 1.1 and 3.0 ΔE_{00} (2.8 and 10.7 ΔE^*_{ab}), respectively, while for the scanning system, they were 4.2 and 15.0 ΔE_{00} (9.0 and 26.0 ΔE^*_{ab}).[13] Only this CFA system has sufficient accuracy for imaging artwork (FADGI 2010; Dormolen 2012).



A



B

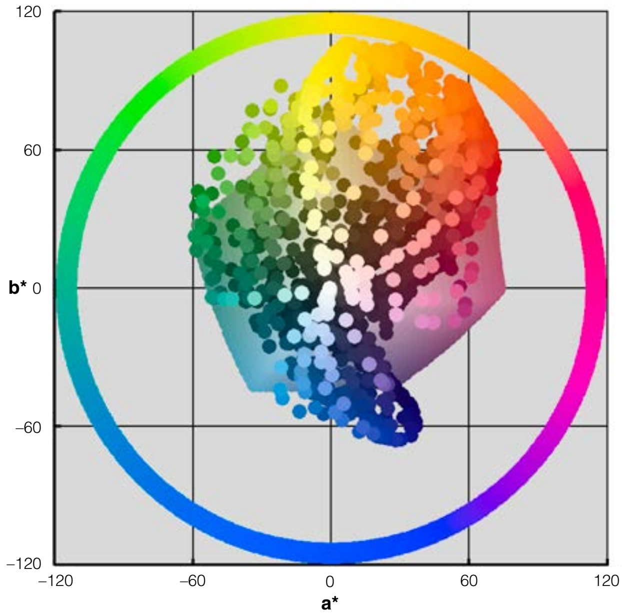
FIGURE 7.12. Color reproduction vector plots indicating the color accuracy of (A) CFA and (B) scanning camera systems when evaluating the Artist Paint Target. The colored dot defines the coordinates of the reference color, while the arrowhead defines the coordinates of the image-based colors.

Museum imaging professionals are quick to point out that reasonable performance for targets does not guarantee reasonable performance for paintings; as a consequence, image data are often manipulated in Photoshop in an effort to improve color accuracy through visual comparisons between the artwork and its rendering on a color-managed computer display. Unfortunately, this rarely does improve color accuracy (Berns et al. 2005; Frey and Farnand 2011). Because of mismatches in viewing conditions (the display is often dimmer than the illuminated painting), differences in image size, the need to look back and forth between the painting and display, and the tendency for preferred color reproduction, visually adjusted images often have increased chroma and lightness contrast compared with the painting (Newhall, Burnham, and Clark 1957; Hunt, Pitt, and Winter 1974; Nezamabadi, Berns, and Montag 2007). There will be instances in which a critical color is clearly wrong, necessitating visual correction. This should be done only for a well-profiled display with a white point and maximum luminance that match the painting's illumination.

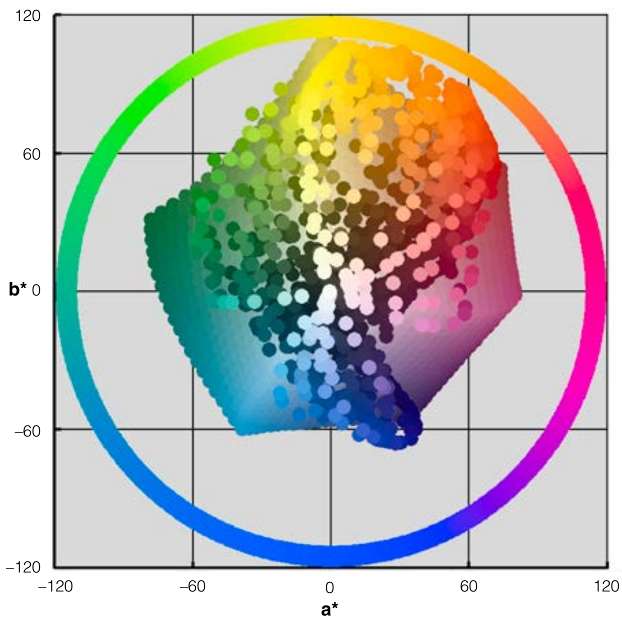
The final step in this example is to produce a printed reproduction. There are two common approaches to profiling printing systems. One is to print a test target of known ink area coverages, measure each color patch with a spectrophotometer and record CIELAB values, and build a profile that relates CIELAB and area coverages. The profile is specific to the printer, paper, inks, color separation, and halftoning. This approach is most common with inkjet printers using ICC-based color management. The other approach is to calibrate a printing system to reproduce a standardized printing process[14] and to use standardized profiles (such as Uncoated FOGRA29 and U.S. Web Coated SWOP v2). In offset printing, this approach is used both for generating proofs and for the actual printing, facilitating the use of color management within a conventional printing environment.

A well-profiled or well-calibrated printer does not guarantee excellent results. There are inherent limitations with most printing systems. When the palette of the twenty-one artist paints is compared with offset printing that uses cyan, magenta, yellow, and black inks on smooth uncoated paper,[15] the differences in color gamut—shown in figure 7.13—are quite dramatic.[16] An offset-printed art book using these inks and paper cannot reproduce a modern artist's palette, particularly when a picture varnish is applied. On-demand inkjet printing is now used by museums to produce large reproductions, with the printer located in the museum

FIGURE 7.13. Sparsely sampled CIELAB coordinates of mixtures of twenty-one artist acrylic dispersion paints with a glossy picture varnish overlaid on (A) a CMYK offset print on smooth uncoated paper or (B) a CMYK inkjet print on high-quality inkjet paper. (The colors of the printer gamuts have been dulled.)



A



B

store. The color gamut for a four-color inkjet printer using high-quality paper with a small amount of optical brightener produces a gamut that encompasses many more of these colors, though not all of them. Printers with additional inks (such as red, green, blue, and orange) should produce color gamuts capable of reproducing most artwork.

The next limitation — metamerism — is the leading cause of acrimony between curators or artists and imaging professionals. The principles demonstrated in chapter 4 apply here as well. Pairs of matching colors produced from different colorants will mismatch if either the illumination or the observer changes. Since few, if any, artists paint with only cyan, magenta, yellow, black, and white paints, any print will be metameric to the artwork.

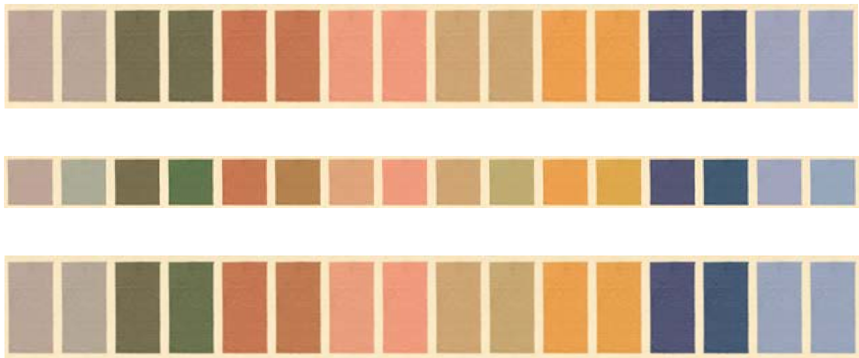
The difficulty is maintaining a color match when the artwork and print are viewed under a nonreference condition, as shown in figure 7.14. The metamer target introduced in chapter 4 was reproduced using a seven-ink inkjet printer.[17] Two prints were made, one using only cyan, magenta, and yellow and the other using all seven inks: cyan, magenta, yellow, black, red, green, and blue. For the three-ink print, ink amounts were calculated to result in a colorimetric match for CIE illuminant D50 and the CIE 1931 standard observer — the reference condition. For the seven-ink print, ink amounts were first calculated to give each sample the best spectral match, and then the amounts were adjusted slightly to produce a colorimetric match for the reference condition. By design, both prints matched all of the paint samples for the reference condition (fig. 7.14a).

Changing the illumination from D50 to 2200 K gallery lighting (fig. 7.14b) resulted in two kinds of mismatches, both examples of illuminant metamerism. First, the pairs of paint samples are metameric and, as a result, mismatch when illuminated by gallery lighting, as explained in chapter 4. Second, the three- and seven-ink prints are metameric compared with each painted sample. Both prints resulted in large errors. An interesting result was that only one sample of each pair was a poor match. In all cases, the paint sample contained pyrrole orange. If the multi-ink printer had contained an orange ink, the seven-ink prints would have matched both paint samples of each pair.

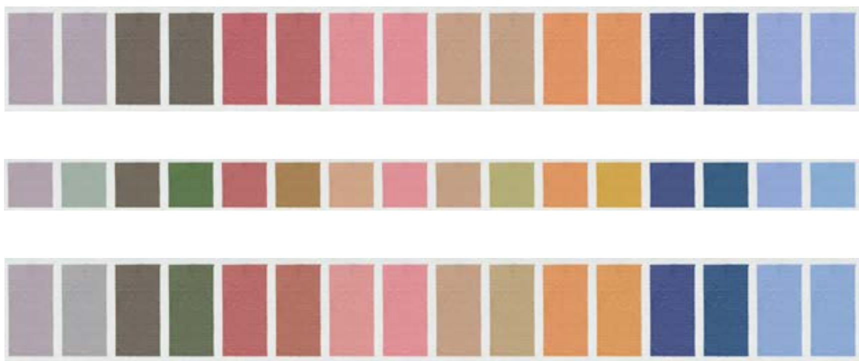
Changing the observer from the 1931 standard observer to the uncommon observer introduced in chapter 4 and illuminating with D50 also changes the reference condition. The resulting mismatches, similar in

FIGURE 7.14. The effect of changing the reference condition from (A) CIE illuminant D50 and the 1931 standard observer, to (B) 2000 K gallery lighting and the 1931 standard observer, or to (C) D50 and the uncommon observer. For each condition, the three-color print is shown in the top row, the paint samples in the middle, and the seven-color print at the bottom.

A



B



C

magnitude to those caused by changing the lighting, exemplify observer metamerism. Viewing the painting and proof in the imaging studio under reference lighting does not guarantee a match because a specific individual may have color vision that differs from that of the 1931 standard observer. As noted in chapter 4, the magnitude of color mismatch for any color-normal observer will vary between none—the standard observer—and that of the uncommon observer.

An additional problem, color inconstancy, is most apparent in the second paint sample in figure 7.14. Changing either the lighting or the observer altered its appearance from neutral gray to a low-chroma green. The sample was made using ultramarine blue, phthalocyanine green, pyrrole orange, and titanium white. As shown in figure 7.15, its reflectance spectrum is quite complex, leading to the significant color inconstancy (Berns, Billmeyer, and Sacher 1985). The three-color print's spectrum is also complex, though almost a mirror image of the paint sample; it, too, is color inconstant, but rather than becoming green, it turned to a low-chroma purple.

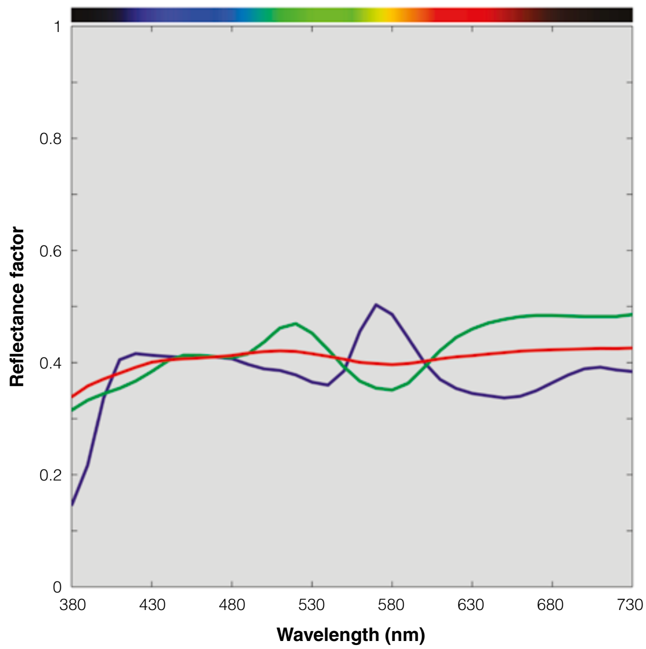


FIGURE 7.15. Reflectance spectra of the painted gray sample (blue line), three-ink print (green line), and seven-ink print (red line).

The seven-color print's spectrum is the least complex and, as a result, it is the least color inconstant, retaining a neutral appearance with changes in both lighting and observer. The best print might be the one that is least color inconstant rather than least metameric, particularly since printed reproductions such as catalogues, books, and posters are usually viewed without the original painting available for comparison (Chen et al. 2008).

Spectral Color Reproduction

Spectral color reproduction has many advantages compared with colorimetric color reproduction. A spectrally matching print is not metameric. A painting and print will match for all lighting conditions and all observers. The print can be used to evaluate how the painting will look under different lighting conditions, which is useful for scholarship and lighting design. A spectral imaging system would eliminate all the limitations of colorimetric color reproduction.

Despite these significant advantages, spectral reproduction is not available commercially. There are two reasons. First, ICC color management, which is universally used, is fundamentally three-dimensional with a colorimetric profile connection space. This is an insufficient amount of data to produce a nonmetameric print.[18] Second, there has not been a commercial demand for it.

The situation will soon change. Since 2014, the ICC has been developing an extension to PCS-based color management called iccMAX.[19] The PCS is replaced by a PCC, a profile connection condition, which facilitates spectral processing. This will enable multi- and hyperspectral cameras to connect directly with multi-ink printers and multi-primary displays. The advantages of spectral reproduction have already been demonstrated in the laboratory (Tsutsumi, Rosen, and Berns 2007, 2008; Berns, Taplin, et al. 2008; Urban, Rosen, and Berns 2008; Derhak and Berns 2010). An ICC spectral workflow will lead to dramatic improvements in color quality for imaging services. It will enable conservators and conservation scientists to analyze images from different imaging modalities without requiring computer-programming expertise, as iccMAX will include an image calculator. Images can also be defined as pigment maps, which will be useful for inpainting and studying an artist's working method.

Summary

Our ability to reproduce artwork on display and in print is a result of the trichromatic nature of vision, where hundreds of wavelengths are reduced to three color signals, defined using colorimetry. Assuming sufficient resolution, an original and a reproduction will match if the signals match for every pixel. Because display and printing systems use colorants that are rarely used by artists, these matches are metameric and it is necessary to standardize — in essence, restrict — the viewing conditions so that a calculated match actually matches for many observers. Departures from standardized conditions, such as viewing a printed reproduction in an incandescent-lit gallery adjacent to the artwork, often results in a severe mismatch.

Even when viewing is limited to standardized conditions, achieving color matches is still difficult because of limitations in camera design, printing inks, differences in color gamut, and observer metamerism. The proper use of color management mitigates these limitations to a great extent, though not completely. Spectral color reproduction holds great promise, eliminating many of the limitations of colorimetric color reproduction and providing new opportunities for the technical examination of art.

Notes

1. The image is being resampled using nearby pixels to approximate a higher-resolution sensor. As a mathematical approximation, it can never equal an optical equivalent.
2. This is the same reasoning as increasing resolution.
3. In graphic arts, the variable K is used for black ink. The origin of the K designation seems to be lost, but one possibility — the more likely one — is that K stood for “key.” (In this interpretation, the other color separations were aligned with the “key” image, black, because it was the most visible.) Another possibility — the less likely one — is that K was chosen because it is the last letter of “black,” and B was already being used to represent blue. (In the past, printers called their inks red, yellow, blue, and black.)
4. Information about the history of the ICC can be found at www.color.org.
5. When the color gamut is defined using CIELAB, L* ranges from 0 to 100 and a* and b* ranges from −127 to 128. When the color gamut is defined using XYZ, each tristimulus value ranges from 0 to the illuminant’s tristimulus value.
6. The term “color-rendering gamut” is used, rather than color gamut, because an encoding space is not a device that produces colors (Berns 2007).

7. Mixtures of the following Golden Artist Colors "Heavy Body" acrylic dispersion paints were produced computationally using optical data of each paint (Berns and Mohammadi 2007): cadmium yellow primrose (PY 35), bismuth vanadate yellow (PY 184), hansa (arylide) yellow opaque (PY 74), diarylide yellow (PY 83), cadmium orange (PO 20), pyrrole orange (PO 73), cadmium red light (PR 108), pyrrole red (PR 254), quinacridone red (PV 19), quinacridone magenta (PR 122), dioxazine purple (PV 23), ultramarine blue (PB 29), cobalt blue (PB 28), cerulean blue, chromium (PB 36:1), phthalo blue (red shade) (PB 15:1), phthalo blue (green shade) (PB 15:4), phthalo green (blue shade) (PG 7), phthalo green (yellow shade) (PG 36), ivory black (PBk 7), and titanium white (PW 6). A high-gloss varnish was applied, also computationally (Abed, Berns, and Masaoka 2013).
8. Photoshop refers to these as perceptual, saturation, relative colorimetric, and absolute colorimetric.
9. For book reproduction, 300 pixels per inch (ppi) is generally sufficient for pictorial images (Hunt 2004). For line art and text, 600 ppi is a better choice. For this book, both pictorial images and graphs were 600 ppi and encoded as ProPhoto RGB 16-bit TIFF files. The increased image resolution led to more flexibility in layout design.
10. The term "equivalent" was used deliberately. Equivalent spectral sensitivities are sensitivities that, following a linear transformation, are identical to LMS responses, known as the Ives or Luther-Ives criterion (Berns 2001).
11. Each company that offers software to build color profiles uses its own approach and in some cases its own targets. As a consequence, color accuracy varies, even for identical cameras.
12. This is known as independent data, that is, data not used to build the profile. Quite often, color accuracy is reported based on the profiling target. It is important to evaluate independent data.
13. Both camera systems were computational: the spectral data for the ColorChecker SG and Artist Paint Target were used to calculate camera signals given each device's spectral sensitivities and taking-illuminant spectral radiance. Because there was no image noise, the color error is smaller than in real imaging experiments (Berns and Smith 2012).
14. Standards exist for many different printing technologies, defined by the International Organization for Standardization (ISO) Technical Committee on Graphic Technology, TC 130.
15. The color gamut of smooth uncoated paper printed with an offset press was calculated using spectral measurements of each ink and the paper of *Billmeyer and Saltzman's Principles of Color Technology* (Berns 2000).
16. When a significant amount of color gamut mapping is required, the customer (e.g., artist, curator, etc.) may want to perform the mapping rather than use the embedded mapping in the printer profile or relying on the printer when performing color separation. Using

Photoshop's proofing feature and the print profile, the image is adjusted until colors are within the print color gamut. However, soft proofing has limited accuracy, and for very color-critical requirements, printed proofs should be produced.

17. The printer was an HP Designjet Z3100 with HP semigloss proofing paper.
18. There is one exception. If the painting was produced using only three chromatic paints plus white, and a three-color print was produced using inks with the identical spectral properties to the paints, a colorimetric match would also be a spectral match.
19. More information can be found at www.color.org.

References

Abed, F. M., R. S. Berns, and K. Masaoka. 2013. "Geometry-Independent Target-Based Camera Colorimetric Characterization." *Journal of Imaging Science and Technology* 57: 50503-1–50503-15.

Berns, R. S. 2000. *Billmeyer and Saltzman's Principles of Color Technology*. 3rd ed. New York: Wiley Interscience.

———. 2001. "The Science of Digitizing Paintings for Color-Accurate Image Archives: A Review." *Journal of Imaging Science and Technology* 45: 373–83.

———. 2007. "Let's Call It 'Color-Gamut Rendering.'" *Color Research and Application 32:* 334–35.

———. 2014a. "Camera Encoding Evaluation for Image Archiving of Cultural Heritage." Technical report, Studio for Scientific Imaging and Archiving of Cultural Heritage, Rochester Institute of Technology. http://www.rit-mcsl.org/Mellon/PDFs/CameraEncoding_TR_May_2014.pdf.

———. 2014b. "Evaluating Solid State and Tungsten-Halogen Lighting for Imaging Artwork via Computer Simulation." Technical report, Studio for Scientific Imaging and Archiving of Cultural Heritage, Rochester Institute of Technology. http://www.rit-mcsl.org/Mellon/PDFs/Evaluating_Solid_State_Lighting_TR_Jan_2014.pdf.

Berns, R. S., J. F. W. Billmeyer, and R. S. Sacher. 1985. "Methods for Generating Spectral Reflectance Functions Leading to Color-Constant Properties." *Color Research and Application* 10: 73–83.

Berns, R. S., and M. Derhak. 2014. "A New Encoding System for Image Archiving of Cultural Heritage: ETRGB." In *Archiving 2015,* 74–77. Los Angeles: Society for Imaging Science and Technology.

Berns, R. S., F. S. Frey, M. R. Rosen, E. P. Smoyer, and L. A. Taplin. 2005. *Direct Digital Capture of Cultural Heritage: Benchmarking American Museum Practices and Defining Future Needs Final Report*. Rochester: Rochester Institute of Technology. http://www.art-si.org/PDFs/Metric/Benchmark_Report_April.pdf.

Berns, R. S., and M. Mohammadi. 2007. "Evaluating Single- and Two-Constant Kubelka-Munk Turbid Media Theory for Instrumental-Based Inpainting." *Studies in Conservation* 52: 299–314.

Berns, R. S., and S. Smith. 2012. "Analysis of Color Management Default Camera Profiles for Museum Imaging Applications." In *Archiving 2012,* 111–15. Copenhagen: Society for Imaging Science and Technology.

Berns, R. S., L. A. Taplin, P. Urban, and Y. Zhao. 2008. "Spectral Color Reproduction of Paintings." In *CGIV 2008 — Fourth European Conference on Colour in Graphics, Imaging, and MCS/08 Vision 10th International Symposium on Multispectral Colour Science,* 484–88. Barcelona: Society for Imaging Science and Technology.

Chen, Y., R. S. Berns, L. A. Taplin, and F. H. Imai. 2008. "A Multi-Ink Color-Separation Algorithm Improving Image Quality." *Journal of Imaging Science and Technology* 52: 20604-1–20604-9.

Derhak, M. W., and R. S. Berns. 2010. "Comparing LABPQR and the Spectral Gamut Mapping Framework." In *Eighteenth Color and Imaging Conference: Color Science and Engineering Systems, Technologies, and Applications,* 206–12. San Antonio: Society for Imaging Science and Technology.

Dormolen, H. van. 2012. *Metamorfoze Preservation Imaging Guidelines: Image Quality, Version 1.0, January 2012*. The Hague: National Library of the Netherlands.

Evans, R. M. 1959. *Eye, Film, and Camera in Color Photography*. New York: Wiley.

FADGI (Federal Agencies Digitization Initiative, Still Image Working Group). 2010. *Technical Guidelines for Digitizing Cultural Heritage Materials: Creation of Raster Image Master Files*. Washington, DC: U.S. National Archives and Records Administration.

Frey, F. S., and S. Farnand. 2011. *Benchmarking Art Image Interchange Cycles*. Rochester: Rochester Institute of Technology, http://www.rit-mcsl.org/Mellon/PDFs/benchmarking_art_image_interchange_cycles.pdf.

Green, P. 2010. *Color Management: Understanding and Using ICC Profiles*. Chichester, UK: Wiley.

Hunt, R. W. G. 1970. "Objectives in Colour Reproduction." *Journal of Photographic Science* 18: 205–15.

——. 2004. *The Reproduction of Colour*. 6th ed. Chichester, UK: Wiley.

Hunt, R. W. G., I. T. Pitt, and L. M. Winter. 1974. "The Preferred Reproduction of Blue Sky, Green Grass and Caucasian Skin in Colour Photography." *Journal of Photographic Science 22: 144–50.*

IEC. *1999. Multimedia Systems and Equipment: Colour Measurement and Management. Part 2-1: Colour Management — Default RGB Colour Space — sRGB (61966-2-1 ed1.0)*. Geneva: International Electrotechnical Commission.

ISO. 2009. *Graphic Technology and Photography: Viewing Condition (3664:2009)*. Geneva: International Organization for Standardization.

Kuniba, H., and R. S. Berns. 2009. "Spectral Sensitivity Optimization of Color Image Sensors Considering Photon Shot Noise." *Journal of Electronic Imaging* 18: 023002-1–023002-14.

Morovic, J. 2008. *Color Gamut Mapping, Wiley-IS&T Series in Imaging Science and Technology*. New York: Wiley.

Newhall, S. M., R. W. Burnham, and J. R. Clark. 1957. "Successive and Simultaneous Color Matching." *Journal of the Optical Society of America* 47: 43–56.

Nezamabadi, M., R. S. Berns, and E. D. Montag. 2007. "An Investigation of the Effect of Image Size on the Color Appearance of Softcopy Reproductions Using a Contrast Matching Technique." In *Color Imaging XII: Processing, Hardcopy, and Applications,* 649309. San Jose: SPIE.

Tsutsumi, S., M. R. Rosen, and R. S. Berns. 2007. "Spectral Gamut Mapping Using LabPQR." *Journal of Imaging Science and Technology* 51: 473–85.

———. 2008. "Spectral Color Management Using Interim Connections Spaces Based on Spectral Decomposition." *Color Research and Application* 33: 282–99.

Urban, P., M. Rosen, and R. S. Berns. 2008. "Spectral Gamut Mapping Framework Based on Human Color Vision." In *CGIV 2008—Fourth European Conference on Colour in Graphics, Imaging, and MCS/08 Vision 10th International Symposium on Multispectral Colour Science,* 548–53. Barcelona: Society for Imaging Science and Technology.

Yendrikhovskij, S. N., F. J. J. Blommaert, and H. de Ridder. 1999. "Color Reproduction and the Naturalness Constraint." *Color Research and Application* 24: 52–67.