COLOR SCIENCE FOR IMAGING SYSTEMS

Knowledge of the production, measurement and perception of color stimuli is essential for analyzing and optimizing complex photographic and electronic color-imaging systems.

LeRoy E. DeMarsh and Edward J. Giorgianni

Artists and artisans in all eras and civilizations have produced color images for aesthetic and informational purposes. The desire to produce images that record visual experiences and to share those images with others seems intrinsic to human nature. Color is an important aspect of the visual experience. It is only natural that we attempt to understand it so that we may have control over the way we use it in drawings, paintings, photographs and electronic images.

Color has been successfully incorporated into photographic and electronic imaging products for many years. The color-reproduction characteristics of some of the earlier products were relatively simple to analyze, and an empirical approach was often adequate for their design. By contrast, state-of-the-art photographic and electronic color-imaging products are extremely complex, and they are often part of much larger color-imaging *systems* having many sources of images and multiple modes of display. For an understanding of these complex color-imaging products and systems, a knowledge of the principles of color science, which will be discussed in this article, is essential.

The design and optimization of a color-imaging system require knowledge of the factors used to produce and control color, and this knowledge must be derived, in part, from measurements of the physical properties of that system. But how can *color* be measured? Vision begins with radiant energy reaching our eyes, so it is reasonable to begin the measurement of a given color by measuring the spectral distribution of that energy. A color stimulus can be specified by relating the measurement of its radiant energy to the calculated response of a defined observer.

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Such techniques form the basis of colorimetry, the measurement and specification of color stimuli. Colorimetry is the foundation of color science.

Color itself is a *perceptual* response, however, and colorimetry does not measure color perception. The visual process begins with physics, but it is in the mind that the stimuli produced from radiant energy are organized and interpreted to form meaningful perceptions, including the perception of color. This process is a complicated one, and understanding it calls for a knowledge of physics, chemistry, physiology and psychology. Color perceptions such as hue, saturation and lightness do not have fixed relationships to the physical world, and the perception of a given color has no unique relation to a particular color stimulus. A comprehensive color science must therefore deal with more than the measurement and specification of color stimuli. Color science is the study of the production, control, colorimetric specification and visual perception of color stimuli.

In this article we will show how color science can be used in the design, analysis and optimization of color-imaging systems. We will assume that the purpose of these systems is to make reproductions that match in appearance the original scene or image as far as possible. Our aim then is to define the objective conditions required to achieve this subjective goal. We will begin with an explanation of the uses and limitations of colorimetry. We will then discuss some of the factors that affect the relationship between colorimetry and color perception. Finally, we will analyze some specific examples of simple and complex color-imaging systems.

Human vision and colorimetry

Our color sensations derive from the responses of three types of photoreceptors in the retina with different broadband spectral sensitivities.[1,2] Human vision is there-

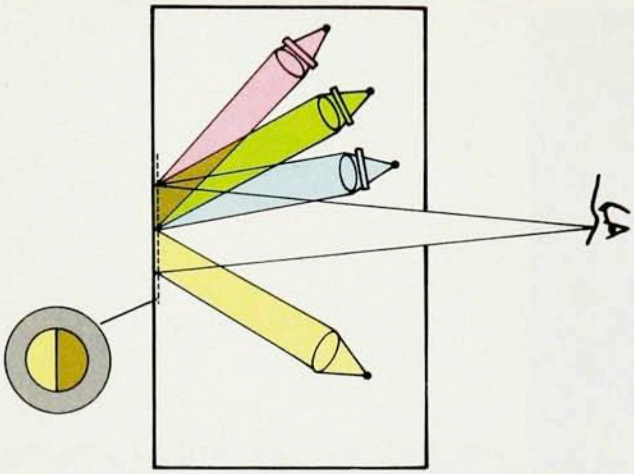
Chemical signal processing. The picture above is from a print obtained by simulating a photographic film whose image dyes have unusually large unwanted spectral absorptions. The picture on the right is from a similar simulation but with beneficial interlayer chemical interactions added.

fore trichromatic, not spectral, in nature. This is not to say that we can see only three colors, but that all color stimuli are analyzed by the retina into only three types of responses. Stimulation of the three types of photoreceptors to various levels and in various ratios can give rise to millions of distinguishable color sensations.

It is quite possible that two color stimuli with very different spectral distributions will produce equivalent stimulations of the broadband photoreceptors. This is what makes color-imaging systems practical. An original color stimulus can be reproduced by forming a visual equivalent of that stimulus. It is not necessary, and generally not technically feasible, to reproduce the spectral distribution of the original stimulus. The techniques of colorimetry, which are based on color matching, permit one to specify whether spectrally different stimuli are equivalent in their potential for stimulating the photoreceptors of a specified observer.

One direct way of studying the visual equivalence of spectrally different stimuli is additive color mixing. In classical color-matching studies, an observer views a small circular field that is split into two halves (see the upper figure on page 46).[1–4] Light of a particular test color, which may be monochromatic light, is used to illuminate one half of the circle. The other half is simultaneously illuminated by three independent light sources of different color (usually red, green and blue), called primaries, providing a visual stimulus that is the sum of the three independent stimuli. The observer adjusts the intensities of the three primaries until the two halves of the circle match. The intensities of the primaries required to produce the match are called tristimulus values of the test color for that set of primaries. The set of three curves obtained when the experiment is performed for each visible wavelength are called the color-matching functions for the primaries used. The lower figure on page 46 shows an example of a set of color-matching functions. The color-matching functions will be different for different sets of primaries and will also depend on the observer.

When the experiment is performed for monochromat-



Color-matching experiment. An observer views a small circular field that is split into two halves. The test color illuminates one half of the circle, while the other half is illuminated by superposed red, green and blue lights, called primaries. The observer adjusts the intensities of the three primaries until the two halves of the circle match.

ic test colors, it is found that some wavelengths cannot be matched by any combination of the three primaries. In these cases, a match is achieved by adding light from one or more of the primaries to the light from the test color. The amount of any primary added to the test color is recorded as a negative tristimulus value (as in the red curve in the figure below). All physically realizable sets of primaries will result in color-matching functions with some negative values.

While the number of possible sets of color-matching functions is unlimited, it can be shown by Grassmann's laws[3] that all sets are simple linear transformations of one another. In the following example, the set of color-matching functions represented by $\bar{r}'_\lambda$, $\bar{g}'_\lambda$, and $\bar{b}'_\lambda$ is derived from the set of color-matching functions, represented by $\bar{r}_\lambda$, $\bar{g}_\lambda$ and $\bar{b}_\lambda$ using the three-by-three matrix A:

$$\begin{bmatrix} \bar{r}'_\lambda \\ \bar{g}'_\lambda \\ \bar{b}'_\lambda \end{bmatrix} = \mathrm{A}^* \begin{bmatrix} \bar{r}_\lambda \\ \bar{g}_\lambda \\ \bar{b}_\lambda \end{bmatrix}$$

In 1931 the Commission Internationale de l'Eclairage (International Commission on Illumination) adopted one set of color-matching functions to define a standard observer, whose color-matching characteristics are representative of those of the human population having normal color vision.[5] These color-matching functions are used in the calculation of the CIE tristimulus values, X, Y and Z, which quantify the trichromatic stimulus characteristics of a color stimulus with a specified spectral distribution.

The X, Y and Z tristimulus values for a given object (characterized by its spectral reflectance or transmittance curve) that is illuminated by a light source (characterized by its spectral power distribution curve) can be calculated for the CIE standard observer (characterized by color-matching functions) by summing the products of these curves over the wavelength range 380–780 nanometers (usually at 5-nanometer intervals):

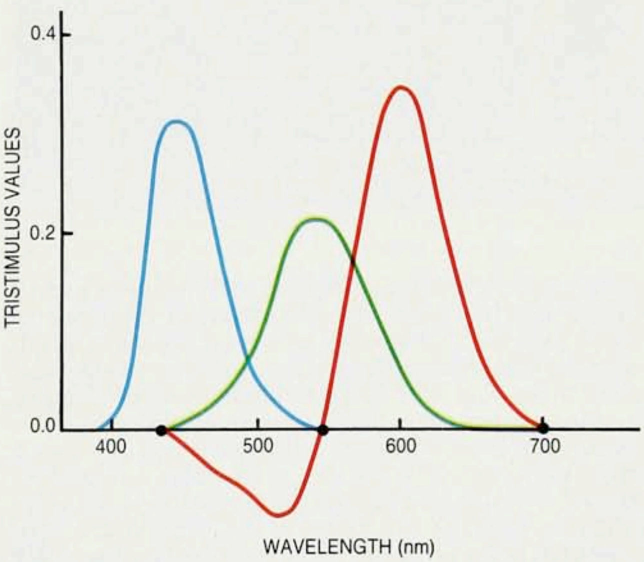
$$X = k \sum_{\lambda=380}^{780} P_\lambda R_\lambda \bar{x}_\lambda$$

$$Y = k \sum_{\lambda=380}^{780} P_\lambda R_\lambda \bar{y}_\lambda$$

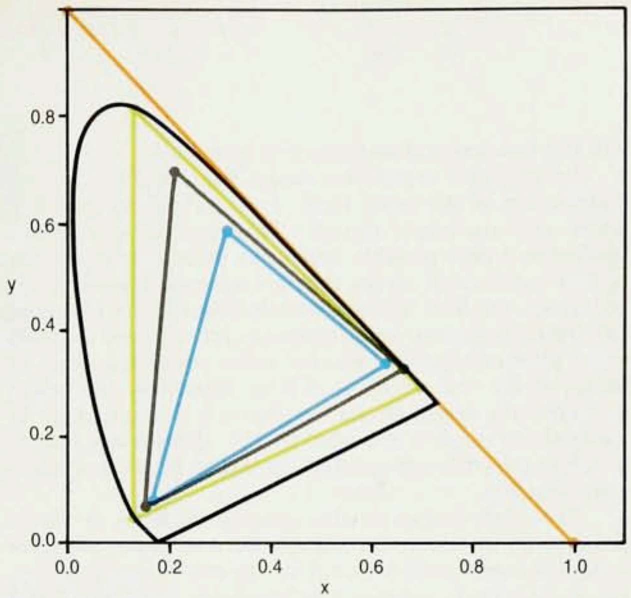
$$Z = k \sum_{\lambda=380}^{780} P_\lambda R_\lambda \bar{z}_\lambda$$

where P_λ is the spectral power of the illuminant at each wavelength λ; R_λ is the spectral reflectance or transmittance of the object; $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$ are the color-matching functions of the CIE standard observer, and k is a normalizing factor. By convention, k is determined such that $Y = 100$ when the object is a perfect, nonfluorescent, white-reflecting diffuser or a perfect transmitter of light at each wavelength.

Primarily for computational convenience, the color-matching functions for the CIE standard observer were designed so that they have no negative values. This was accomplished by defining an imaginary set of primaries that themselves must contain negative amounts of energy at some wavelengths. Another operational convenience of the CIE color-matching functions is that the Y tristimulus value corresponds to the measurement of luminance, which is related to the perception of brightness. Although the X and Z tristimulus values have no direct perceptual correlations, the CIE has defined a chromaticity diagram—a two-dimensional map of tristimulus ratios called chromaticity coordinates. The chromaticity coordinates, x and y, describe the qualities of a color stimulus other than



Color-matching functions represent tristimulus values, or the intensities of the primaries needed to match a specified intensity of light at each spectral wavelength. The matching functions shown here are for monochromatic primaries of wavelengths of 700.0 (red), 546.1 (green) and 435.8 (blue) nanometers.



Chromaticity diagram for four sets of reference primaries. The chromaticity coordinates x and y describe the qualities of a color stimulus other than its luminance. To a first approximation, the larger the range of chromaticity coordinates for a set of primaries, the larger the gamut of color stimuli that primary set can represent.

its luminance, and they are derived from the tristimulus values as follows:

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

The figure at right, which will be used in our discussion of system primaries, is a chromaticity diagram. The horseshoe-shaped outline is the spectrum locus, the line connecting the points representing the chromaticities of monochromatic color stimuli.

The CIE has also recommended the use of other coordinate systems derived from XYZ, such as the 1976 CIE $u'v'$ uniform-chromaticity-scale diagram and the 1976 CIE $L^*a^*b^*$ and 1976 CIE $L^*u^*v^*$ spaces.[2,5,6] These systems are quite useful for specifying small color *differences* between color stimuli; like the XYZ tristimulus values, however, they quantify characteristics of a color stimulus but do not specify the *appearance* of that stimulus. This fact is often misunderstood, and these coordinate systems are frequently misused and misinterpreted as color *appearance* spaces.

How can colorimetry be properly applied to the design and analysis of a color-imaging system? The color-matching experiments show that two stimuli with the same XYZ tristimulus values, regardless of their actual spectral compositions, will be visually indistinguishable to the standard observer if they are viewed under identical conditions. If the two stimuli have the same XYZ tristimulus values but are spectrally different, they are known as metamers. It might seem that a logical objective for a color-imaging system would be to match the original color stimuli with metamers produced by the color-imaging system. This colorimetric matching is not usually appropriate, however. When a reproduced stimulus is viewed under conditions that differ from those of the original, a number of other factors must also be considered.

Adaptation

To successfully reproduce the appearance of original colors, one needs to consider factors that affect the relationship between colorimetry and color appearance. Adaptation is the process by which the visual mechanism adjusts to the conditions under which the eyes are exposed to radiant energy. The relationship between the physical characteristics of a color stimulus and the perception of that color is strongly influenced by effects resulting from various adaptation phenomena.

While there is no standardized system of "appearance colorimetry," considerable research is available on visual adaptation. By using controlled conditions of illumination and observation, it has been possible to characterize color shifts due to adaptation effects and to express them in terms of shifts in XYZ tristimulus values. Properly applied, this information can be used to determine the colorimetric conditions required to achieve a color appearance match for a particular imaging application.

Two adaptation effects are of primary importance in the design and analysis of a color-imaging system: lateral adaptation and chromatic adaptation. The illustration on page 49 demonstrates one manifestation of lateral adaptation. Two identical series of gray squares are shown, one series surrounded by white, the other by black. The gray squares surrounded by black appear lighter than the identical gray squares surrounded by white. The effect is stronger for the dark grays and weaker for the light grays, so the apparent contrast of the dark-surround series of grays is lower than that of the light-surround series. Similarly, this surround effect reduces the apparent luminance contrast of an image displayed in a dark surround (as in a motion-picture theater) or a dim surround (as in typical home television viewing). Proper design of a color-imaging system must include a correction for this adaptation phenomenon.

Chromatic adaptation refers primarily to the adjustments of the visual mechanism in response to the overall color of the stimulus to which the eyes are exposed. For example, when our eyes are exposed sufficiently long to a reddish-yellow stimulus, such as a tungsten light, the long-wavelength sensitive receptors become somewhat desensitized and the short-wavelength sensitive receptors become relatively more sensitive. Chromatic adaptation must be considered in the design of a color-imaging system if the chromaticities of the illuminant used to display the reproduced image differ from those of the illuminant used to record the original. We will discuss these adaptation phenomena in greater detail in the sections of this article dealing with the analysis of more complex systems.

Color-imaging diagram

In designing and optimizing of a color-imaging system one needs to perform colorimetric analysis and properly apply adaptation transforms to determine the colorimetric conditions required to achieve an appearance match for the particular imaging application. A flow diagram of the color-imaging system is helpful for this analysis.

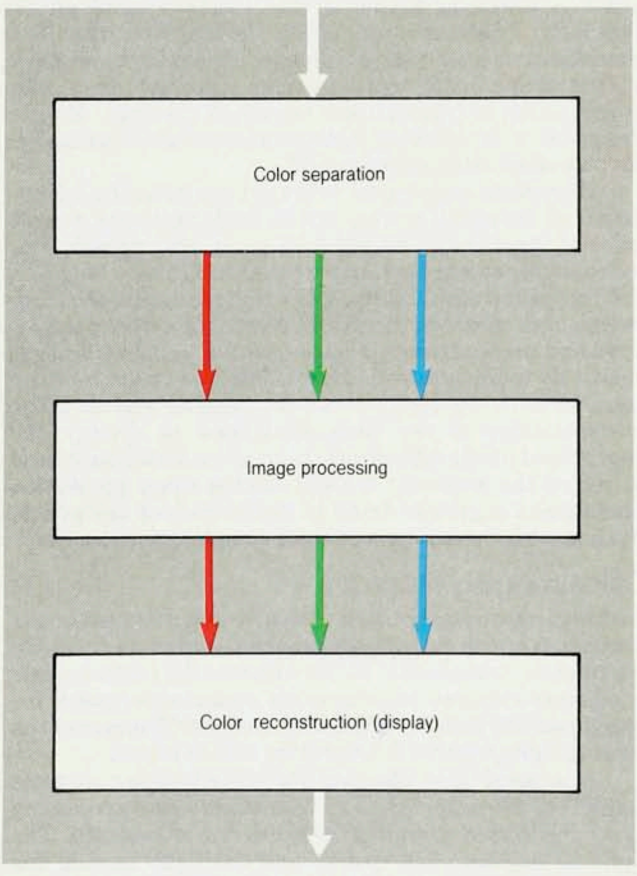
A general flow diagram for color-imaging systems consists of three stages: color separation, signal processing and color reconstruction (see the diagram on page 48). The light coming into the system and the light leaving the system are each characterized by spectral distributions for each picture element of the image. Only in very few cases will the two spectral distributions be equal.

In the color separation stage, the complex spectral distribution of the input light is separated and stored as three color records or signals. This separation is accomplished in a photographic system by three overlaid, light-sensitive emulsion layers that are spectrally sensitive to red, green and blue light, respectively (see figure a on page 51). In an electronic color-imaging system based on solid-state photoconductive sensors, color separation can be achieved by red, green and blue filters on individual elements of a single sensor (see figure b on page 51) or by using three sensors preceded by the appropriate optical arrangement of beam splitters and color filters (see figure c on page 51).

The second step of the general diagram is signal processing, in which the signals derived from the color separation are made suitable for the color-reconstruction stage. Included in signal processing are amplification of the three color signals, which may be linear and nonlinear, as well as interactions among the signals. The processing may be chemical, as in photography, or a combination of analog and digital signal processing, as in an electronic color-imaging system.

The final step of the general diagram is color reconstruction. Here the reproduced color is formed by subtractive or additive methods. In this stage, the processed signals from the second stage adjust the amounts of the color-forming elements of the image-display medium used to produce the color image. A photographic system uses cyan, magenta and yellow image dyes to modulate, by absorption or subtraction, the transmitted or reflected light (red, green and blue light, respectively) of the viewing illuminant. An electronic system might use a three-phosphor cathode-ray tube or a three-beam projector to combine modulated intensities of red, green and blue light to form the output spectral distribution.

This general system diagram is used in the analysis of simple color-imaging systems, which consist of a single input source and a single display mode. More complex color-imaging systems can be described as multiple simple systems (or parts thereof) arranged in parallel or in series.



A color-imaging diagram.

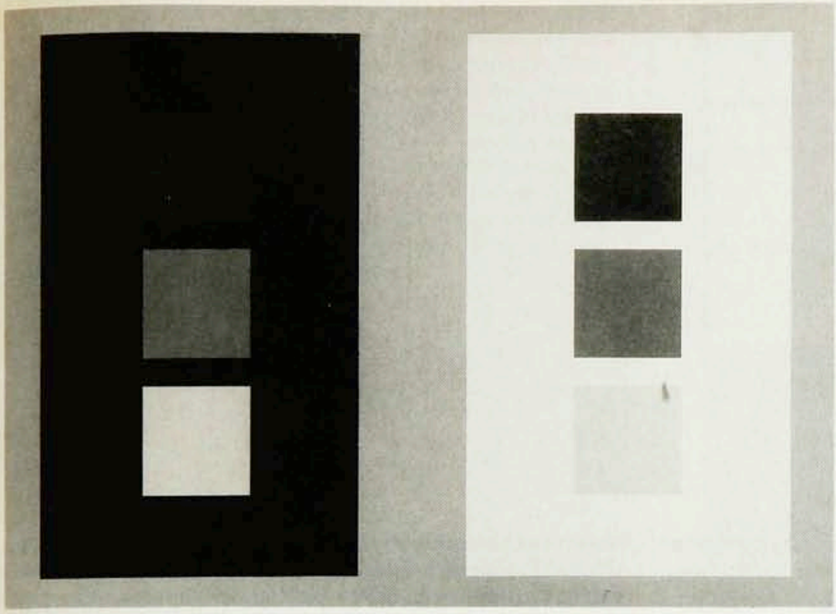
A simple imaging system

Colorimetry and the general system diagram can be readily applied to the design and optimization of simple color-imaging systems. A special case of photographic imaging can serve as an example: copying a photographic transparency by printing it onto another photographic transparency film. This example is quite straightforward because the copy is of the same form as the original and can be viewed under the same conditions. The adaptation factors are therefore constants.

In a color photographic film, all three elements described in the general diagram are incorporated in the film structure. As previously described, three-color separation is accomplished by three overlaid photographic emulsions, spectrally sensitized to red, green and blue light, respectively (again, refer to the figure on page 51). Both image processing and color reconstruction take place during photographic development whereby the latent image produced by the exposure of the film is chemically amplified. (See the article by Tadaaki Tani on page 36.) Image dyes are then formed in amounts determined by the exposure each layer received and by the effects of chemical amplification.

In the example we are discussing, the first transparency film was used to photograph an original scene (or, more properly, the film recorded the light modulated by the objects in that original scene). The light used to expose the second transparency film is modulated by the cyan, magenta and yellow image dyes of the first transparency. The block diagram of this system would consist of two general diagrams in series, with the output of the first (the original transparency) serving as the input to the second (the copy transparency). Assuming that the viewing conditions for the two transparencies will be the same and that the goal is to have the copy transparency match the appearance of the original transparency, the design criterion for the second transparency film is clear: The CIE XYZ tristimulus values for each picture element of the copy transparency should be equal to those of the corresponding picture elements of the original transparency. In this case, where the viewing conditions for the images are identical, a colorimetric match (equal tristimulus values) is also an appearance match.

One can therefore optimize a color transparency film designed specifically for copying photographic transparencies by adjusting the chemistry of each imaging layer and by adjusting layer-to-layer chemical interactions to achieve a colorimetric match to the original transparency. This match can be achieved with a high degree of



Surround effect. The three gray squares surrounded by white are identical to the three gray squares surrounded by black, but the contrast of the black-surround series appears lower than that of the white-surround series.

accuracy. Note that if the spectral absorption characteristics of the cyan, magenta and yellow image dyes of the copy transparency are identical to those of the original transparency, the colorimetric match is also a spectral match—that is, the spectral transmissions of each picture element are identical to those of the original transparency. This spectral match is an invariant match, in that it holds for any viewing illuminant, and the copy is appropriately called a duplicate. If the spectral characteristics of the image dyes of the copy transparency are different from those of the original transparency, the colorimetric match is metameric and conditional—the spectral transmissions of each picture element are different from those of the original transparency, although the *XYZ* tristimulus values are the same. The match is conditional in that it holds only for the defined viewing illuminant(s).

Television

Current broadcast television might at first seem to be a relatively simple system to analyze. The display mode is essentially limited to a CRT-based receiver, and the red, green and blue primaries—the light emitted by the phosphors used in the CRT—are reasonably standardized. Colorimetric theory allows one to calculate the color-matching functions for these primaries, and additive color theory shows that these color-matching functions specify the spectral sensitivities for the system. In practice, it is assumed that the chromaticities of the scene illuminant are equal to those of the video monitor reference white, eliminating the need to correct for chromatic adaptation.

Two factors complicate this system, however, and make the analysis somewhat more difficult. First, the color-matching functions for the primaries of the CRT (and, as previouly stated, for *all* sets of physically realizable primaries) will contain negative values, corresponding to areas of negative spectral sensitivity. In practice, responses equivalent to those with negative sensitivities can be approximated in the signal-processing stage by linear transformations of the color signals produced by the actual photosensors of the video camera. The second complication of this system is that television is normally viewed in a dim-surround viewing environment—that is, the average luminance level of the surround is somewhat lower than the average luminance level of the displayed image. The effect of this dim surround is to lower the apparent luminance contrast of the image, so that a colorimetric match of a color stimulus displayed on the CRT will *not* be an appearance match to the original color stimulus viewed in a normal surround. The tristimulus values must be modified for the reproduction to match the appearance of the original.

To calculate the tristimulus values required to achieve an appearance match one first determines the luminance factor for the original color stimulus. The luminance factor is the ratio of the Y tristimulus value of the stimulus to the Y tristimulus value of a reference white. The luminance factor for the reproduced stimulus can then be calculated from an experimentally determined exponential transform, as a positive power of the luminance factor of the original stimulus. The power, called the surround correction, is approximately 1.20 for dim-surrounding viewing.[7] In practice, this transformation is achieved by adjusting the electro-optical transfer characteristics of video cameras for typical video displays. Compensations for stray light entering the camera lens and in the viewing environment are often also included in these adjustments.

The Y tristimulus value for the reproduction can be determined from the transformed luminance factor, and a good appearance match to the original stimulus can be achieved by adjusting the original X and Z tristimulus values such that the chromaticity values (x and y) remain equal to those of the original stimulus.[8]

Photography

Another example of a more complex color-imaging system is one that uses a photographic transparency film to record an original scene. The analysis in this case, like in the previous example, is complicated by the surround effect. But chromatic adaptation effects also play a part. The general diagram is useful in this analysis because it provides the framework for constructing a mathematical model of the system.

In the first stage of the model, color separation is achieved by the red, green and blue-light-sensitive layers of the film. The relative exposures for each layer can be calculated for a given scene element and light source using equations similar to those used for calculating tristimulus values.

The signal-processing stage for the photographic transparency film can be separated into two parts: first, the formation of the gray scale, and second, the interlayer chemical reactions. The gray scale characterizes the relationship of the reproduced relative luminance ratios to the relative luminance ratios of the original scene. Gray-scale characteristic curves describe the amounts of cyan, magenta and yellow dye that form as a function of exposures from neutrals of various luminance levels. These curves usually plot the dye amount versus the logarithm of the exposure. When the original to be reproduced is a scene, rather than another transparency, many factors must be taken into account in optimizing the gray-scale characteristic of a film used to record that scene. These factors include stray light in the camera, stray light in the viewing environment and surround effects.[7,9]

The second form of signal processing used to optimize the color reproduction of a photographic film involves interlayer chemical reactions. These reactions are used to correct for the unwanted spectral absorptions of the image-forming dyes, and they also compensate for differences between the actual film spectral sensitivities and color-matching functions. The chemistry of the film can be designed such that each layer produces the correct amount of enhancement or inhibition of the silver development or the dye formation in each of the other image-forming layers. These interlayer relationships can be modeled based on a knowledge of the mechanisms involved and on direct measurements on processed film.

One can model color reconstruction by calculating the spectral transmittance cuve that will result from a given triad of red, green and blue exposures. One computes this curve from the spectral absorption characteristics of each of the image dyes and from the amounts of these dyes determined previously in the signal-processing stage. The CIE *XYZ* tristimulus values can then be determined from the resulting spectral transmittance curve, the spectral power distribution of the viewing illuminant and the color-matching functions of the CIE standard observer.

The analysis, however, is complicated by chromatic adaptation effects. Whenever the chromaticities of the display illuminant (assumed here to be a tungsten projection lamp) differ from those of the original scene illuminant (assumed here to be daylight), a reproduced color will not appear to be correctly rendered even if the film is built such that reproduced chromaticities of that color are equal to those in the original scene. One can correct for chromatic adaptation[10] by determining corresponding chromaticities, that is, chromaticities for an observer chromatically adapted to tungsten illumination that will appear equal to chromaticities for an observer chromatically adapted to daylight. The corresponding chromaticities, together with the *Y* tristimulus values determined from the gray-scale considerations, allow the calculation of the corresponding *XYZ* tristimulus values for each color stimulus that is to be reproduced. Again, these tristimulus values will not be numerically equal to the tristimulus values in the original scene. The photographic transparency film can be optimized by adjusting its signal processing such that the tristimulus values of an array of color stimuli in an original scene are reproduced at their corresponding tristimulus values.

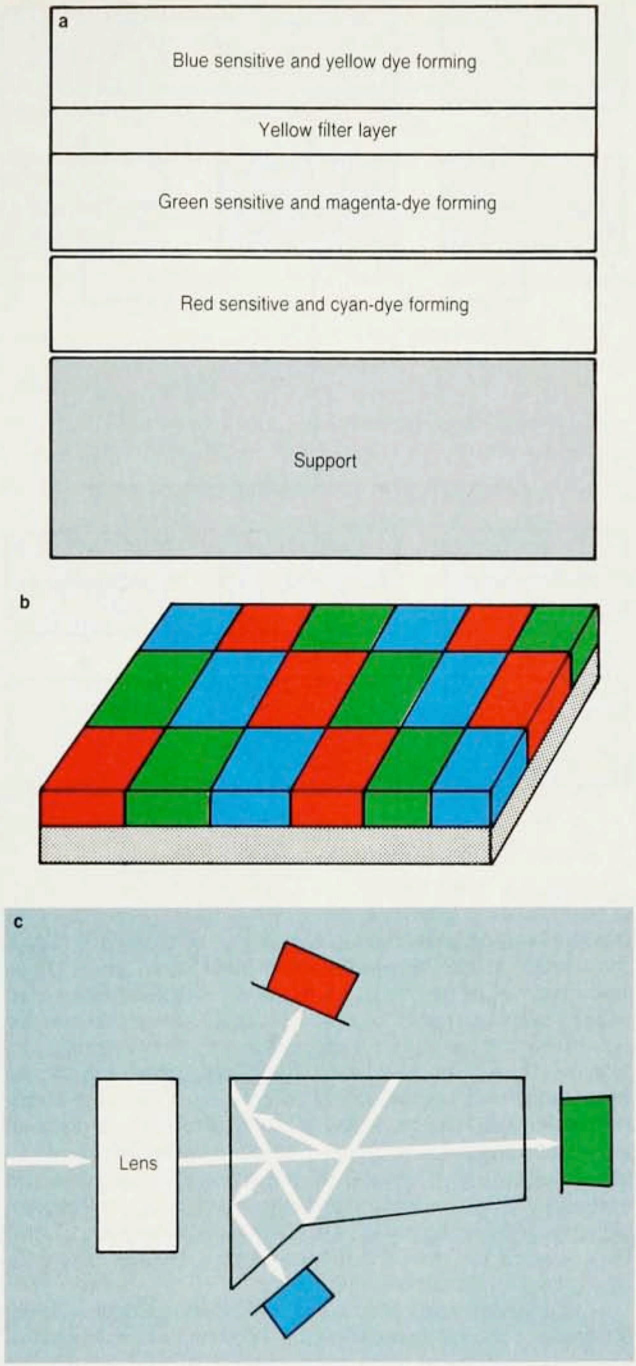
Hybrid systems

Modern color-imaging systems are often hybrids: They contain both silver halide-based and electronic imaging elements. Properly designed systems can enhance the advantages of each technology. For example, combining the superior imaging characteristics of large-format photographic film with the flexibility of electronic image editing, including real-time video display, can provide a powerful photocomposition system. The versatility of hybrid imaging is also useful in the motion picture and television industries, particularly in postproduction and special-effects applications. One hybrid system of considerable current interest is high-definition television.

The hypothetical hybrid system shown in the figure on page 52 has several sources of input images, which could include photographic film, various types of electronic cameras and computer-generated graphics. There are also multiple display modes, some of which might be considerably different from conventional CRT-based devices. (When designing such systems one should preferably plan to accommodate input and display devices that have not yet been invented!) The multiple inputs and display modes make the problems of dealing with the relationships between the physical world and visual perception considerably more difficult. The proper application of color science is critical for the successful design and optimization of such a system.

The fundamental difference between this system and the others we have discussed is that this one includes *separate* signal processing for each input and output device. Proper processing of the signal from each input device ensures that its output will conform to a defined signal format that is used to interface the input and output devices. The signal processing for each input device includes curve shaping (used to match the gray-scale transfer characteristics of the device to the signal format),

Color separation may be achieved by color photographic film (**a**), by color filters on separate areas of a single sensor (**b**) or by a dichroic beam splitter preceding three separate sensors, each of which records one primary color (**c**). Each layer in the photographic film is inherently sensitive to blue light, but the yellow-filter layer prevents blue light from reaching the underlying layers. Appropriate spectral sensitizers are used in the green-sensitive and red-sensitive layers.



color matrixing operations (used to match the color separation of the device to the signal format) and data compression (as well as any other signal processing required to conform to the defined signal format). Each display device is accompanied by the appropriate signal processing as well, such that it can use the signals of the defined format. The signal processing includes decoding of the compressed signals, color matrixing (related to the specific image-reconstruction characteristics of the device, corrected for chromatic adaptation effects) and curve shaping (dependent on the gray-scale transfer characteristics of the device, corrected for viewing conditions).

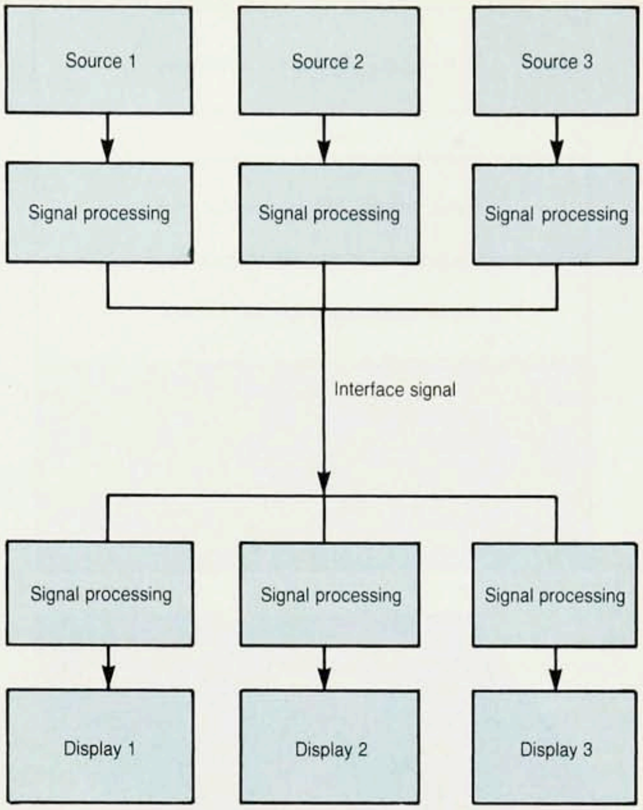
An important specification for this system is the set of the red, green and blue reference primaries chosen for the colorimetric specification of the interface signal. These primaries do not have to correspond to the primaries of any actual display device, or even to any physically realizable primaries (they may instead be purely mathematical functions). But the reference primaries must be specified to give a rigorous colorimetric definition to the system. Even in all of this complexity there is still a need for classical colorimetry.

One criterion for selecting the reference primaries is the gamut of colors those primaries can reproduce. To a first approximation, this gamut is indicated by the area of the chromaticity diagram that is included in the triangle formed by connecting the points corresponding to the chromaticity coordinates of each of the three primaries. (This is only an approximation because the actual gamut is three dimensional, and the two-dimensional projections will differ at different relative luminance levels.) The red, green and blue chromaticities for some possible sets of reference primaries are plotted in the CIE x,y chromaticity diagram shown in the figure on page 47. The blue triangle is representative of current television CRT phosphor characteristics. A hybrid system based on these primaries could, depending on the definitions of the interface signal levels, be limited to the color gamut of current television. Three other possible sets of primaries are also plotted in the figure: a "high purity" (gray), a "spectral set" using monochromatic primaries (green) and a set using the CIE XYZ primaries (yellow). In deciding which set of primaries to use one would have to balance the somewhat conflicting goals of maximizing the potential color gamut of the system while minimizing the complexity of both the hardware and the required signal processing. The gray set in the figure on page 47, for example, would represent a reasonable compromise for many applications.

Once the reference primaries are defined, the corresponding reference color-matching functions can be determined by classical colorimetric calculations. Each input device in our example would have the proper signal processing to make its effective spectral responsivities equivalent to the reference color-matching functions. In practice, some form of nonlinear signal compression would also be included at the input stage. This compression is needed for bit reduction in digital systems and for noise reduction in analog systems. While not strictly a part of color processing, this nonlinear compression needs to be completely defined so as to permit it to be reversed and the linear signals recovered by the signal processing of each display.

Practical considerations

The design and optimization of photographic, electronic and hybrid color-imaging systems is in practice considerably more complicated than what we outlined here.



A complex hybrid imaging system is outlined by this block diagram.

Modern color photographic film does not really consist of just three or four layers, for example; it is more likely to have a total of perhaps 12 or more image-forming and other special purpose layers. Similarly, actual electronic color-imaging systems are more complex than our description of them. In addition, there are other important perceptual and psychological factors, such as color memory, color preference, incomplete chromatic adaptation, effects of image sharpness and noise, and effects related to absolute luminance levels, that must be considered in the optimization of a color-imaging sytem. Compromises required by the limitations of the actual color gamut and the dynamic range of the display device are also a part of the optimization procedure.

To analyze and optimize complex photographic, electronic and hybrid color-imaging systems, manufacturers may use advanced computer modeling and nonlinear optimization techniques. Some manufacturers also include image simulation in the optimization process. Image simulaton proceeds by scanning and digitizing the photographic image, and it involves processing of the digital signals so generated. Image simulation provides test images for subjective evaluations, such as user-preference studies, where the simulations correspond in appearance to images that would be produced by a proposed color-imaging system. The illustration on page 44 shows two computer-manipulated images that demonstrate the effects of varying chemical signal processing. The picture on the left in the illustration shows the effect of increasing the unwanted spectral absorption in the image dyes of the photographic film. On the other hand, the picture on the right was obtained when beneficial interlayer interactions were added to the film to compensate for the unwanted spectral absorption. The availability of test images such as these is invaluable, because observer reactions are the final criteria in detemining how successfully a color image reproduces an original scene or image.

While the modeling and simulation techniques manufacturers use in designing and analyzing their color-imaging products are complex and sophisticated, they are built on the foundation provided by the basic color-science principles described in this article. The increasing diversity and complexity of modern color-imaging systems will challenge us to develop these techniques further and to increase our understanding of color and color science. ∎

References

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