Color Displays: The Spectral Point of View

Color is closely related to the light spectrum. Nevertheless, spectral properties are seldom discussed in the context of color displays. Here, a novel concept for a display for color-critical applications – which is designed to reproduce the light spectrum rather than just color – is presented.

by Dan Eliav and Moshe Ben-Chorin

IN RECENT YEARS, multi-primary (MP) displays using more than three primaries (R,G,B) have been discussed and demonstrated.[1,2] These displays provide significant color-gamut extension along with increased luminance efficiency. This advantage provides flexibility, which allows optimization of color and luminance attributes that fit targeted applications, including large-venue or home-theater displays with superb reproduction with a cinema look and small mobile displays with improved sunlight readability and longer battery life.[3] In this article, we will focus on a unique and important feature of MP display technology – the facilitation of spectral reproduction.

Spectral "Color" Reproduction

Color is a sensation we experience when light in the visible range excites our visual system. Because there are three types of color-sensitive cones in the human eye, color reproduction in displays tries to re-create the original sensation by presenting the eye with a spatial or temporal distribution of three stimuli – red, green, and blue (R,G,B) – which are intended to invoke cone signals similar to those generated when the original scene was observed.[4] This colorimetric match relies on models of

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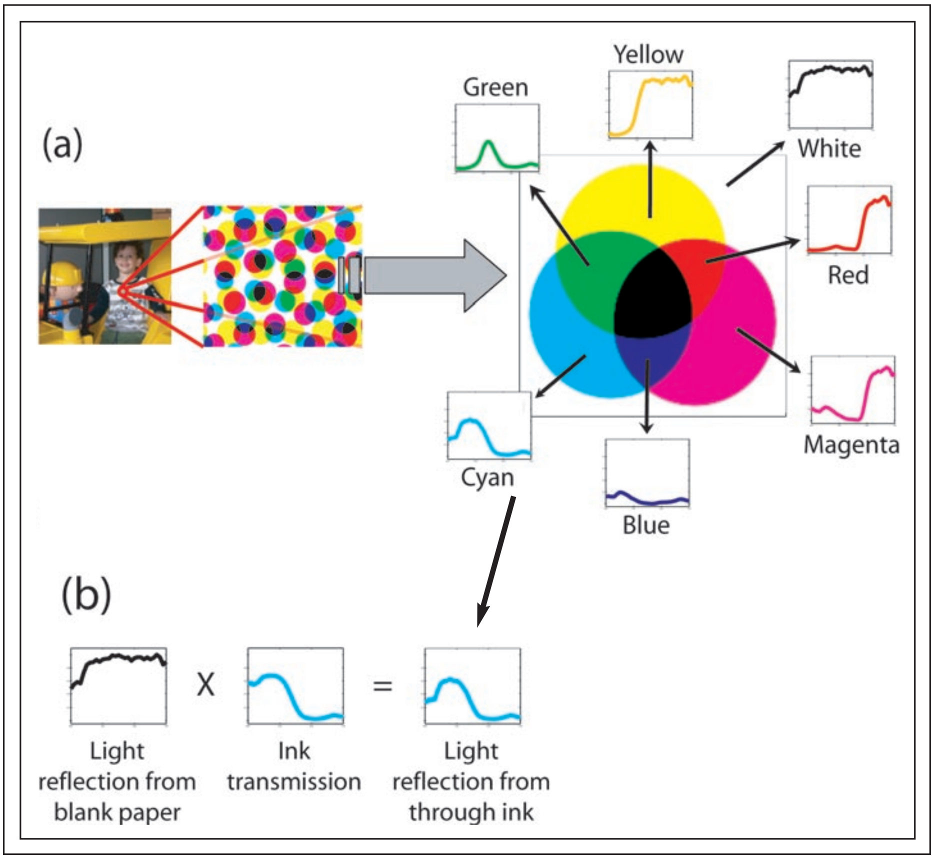

Fig. 1: (a) Enlarged section of offset-printed color image showing the printed dots and their overlaps. A blown-up printing dot and its separation into different spectra are shown on the right. When viewed from normal distance, these spectra combine additively according to the relative areas to give the local spectrum (and color). (b) The subtractive nature of print. The spectrum of light reflecting through ink (or inks overlap) is a multiplication of the spectrum of the light reflected from the blank paper with the transmission spectra of the ink (or inks overlap).

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the human visual system (HVS) which attempt to translate the physical stimuli to mathematical "color," representing the real color sensation. Multiple spectra may correspond to one color, and thus the same "mathematical sensation" may be created by different spectra in accordance with the phenomenon known as metamerism (see the article by Brill and Larimer in this issue).

Although there has been considerable progress in the understanding of the HVS, there is still much to learn. Existing models of color vision and color perception incorporate some of the phenomena observed in experiments, but not all of them. These models are based on the responses of an "average" person under strict experimental conditions, the so-called Standard Observer, which in many cases are different from those found in real scenes. Color, however, is a subjective sensation varying from one person to another. The color-matching functions vary between individuals and are known to change with age.[4,5] Therefore, colors matched by colorimetric practices may be judged to be closely matched by one observer and poorly matched by another.

This in itself is not generally problematic. Most applications do not have strict requirements for color accuracy, but rather strive to create pleasing or attractive colors. However, there are some color-critical applications in which accurate color reproduction is a requirement. In these applications – which include online procurement of color-sensitive materials and objects, remote medicine, film post-production, and print soft-proofing – colorimetric models do not provide the required level of accuracy because they rely on the interpretation of sensations rather than physical entities.

This is particularly relevant for surface colors, which are created by the reflection of light from colored surfaces and which comprise most of the colors we observe.[4,6] In colorimetric terms, surface colors change with illumination because they depend on both the reflectance spectrum of the object surface and the spectral power distribution of the impinging light. Yet, when judging color, human observers ignore the illuminant variation, a phenomenon known as illuminant discounting.[6] Thus, the important entity in the color sensation of surface colors is the physical reflectance rather than the specific mathematical representation of color.

The result of this phenomenon is that what would appear to be a faithful color reproduction under certain viewing conditions may in fact be quite different from the original when physically measured and, under different conditions or for another observer, may result in color mismatch. We can thus conclude that the perceived quality of a colorimetric reproduction is highly dependent on various conditions external to the reproduction itself, generally related to the observer and appearance issues.

The implication of this goes beyond the issue of accuracy – a prerequisite for trustworthy color communications is that one would be able to assume that "What I See Is What They See." For example, consider the need to match the color of a crown to its adjacent teeth. The lack of trustworthy color communications means that the patient (*i.e.*, "the physical system") has to physically arrive at the lab in order to perform the color match, *i.e.*, to compare the reflectance spectra of teeth and crown under the same conditions. In the digital era, where information-transfer speed is expected to be that determined by the speed of electrons, the slow process of color approval becomes a bottleneck, thus creating an urgent need for an electronic color-communications tool.

Colorimetric-based reproduction, with its underlying assumptions, is not suitable for color-critical communications. A possible approach, free of the colorimetric limitations, is to avoid the reliance on metamerism or assumptions based on our understanding of the HVS. Instead of emulating the sensation, we suggest reconstructing the spatial and spectral distribution of the light originating from the scene. This spectral reproduction differs fundamentally from the colorimetric approach. It faithfully simulates the examined physical system, as opposed to a calculated synthesis of the resultant color sensation under an assumed set of expectations. Because the physical signal is reproduced rather than emulating the sensation of color, if one observer would find the original scene and its reproduction to be identical (because the spectra reflected or emitted from both are equal), agreement is likely to be found between all other observers, including those with defective color vision, regardless of their interpretation of the sensation and the name they would give it. Therefore, by using spectral reproduction, one can provide a "color"

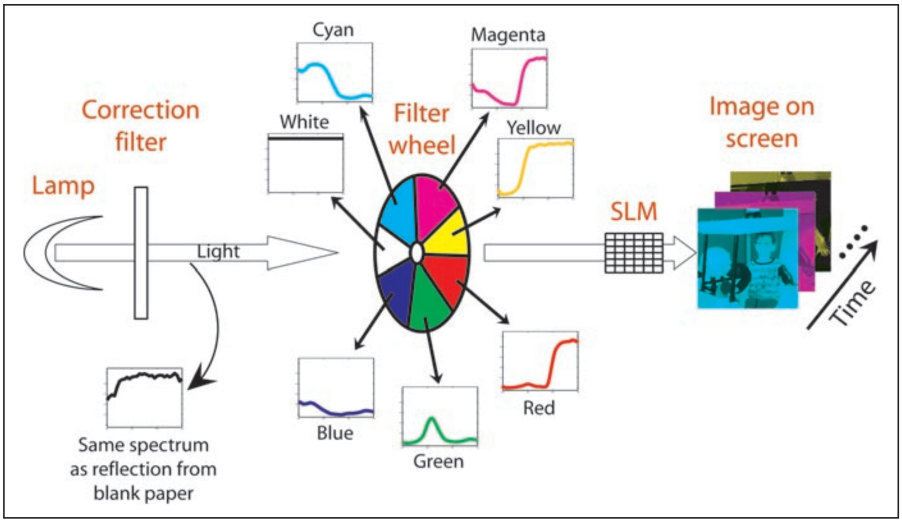

Fig. 2: *Schematic view of a sequential projector for spectral proofing. Light, identical in spectrum to that reflected from blank paper, is filtered sequentially by color filters placed on a rotating wheel, the transmission of which is identical to that of the inks and the overlaps. The resultant spectra are the multiplication of the light spectrum by the transmission spectrum of each filter, hence identical to the spectrum of light reflecting through the ink (or inks overlap). A spatial light modulator (SLM) images the spectral separations, and the temporal integration of the different spectra provides the required spectrum at each pixel.*

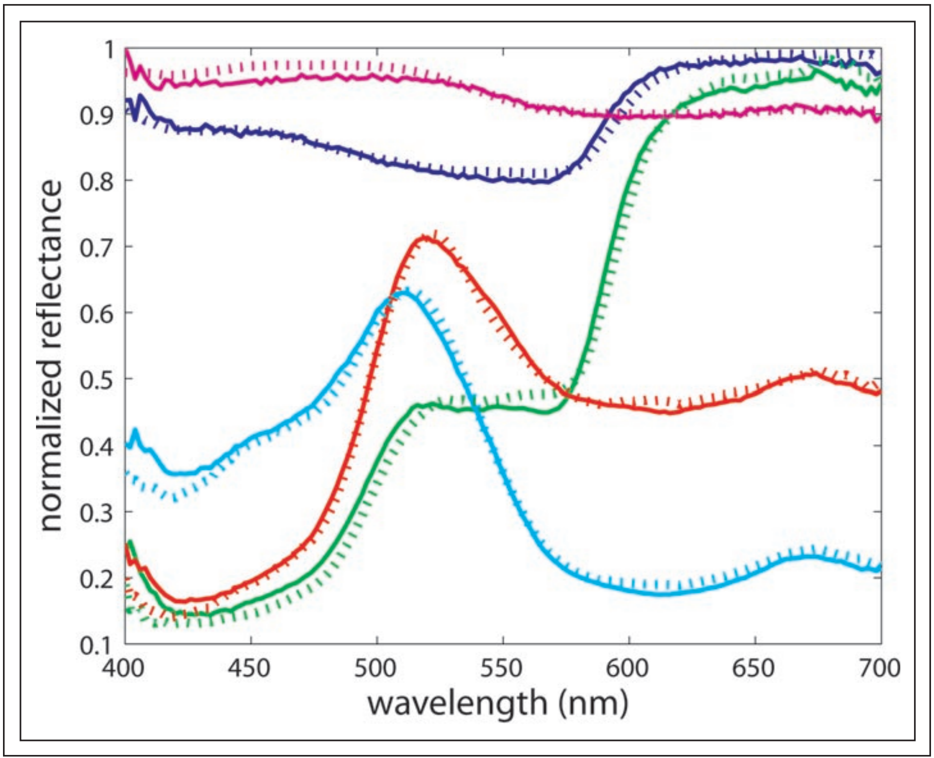

***Fig. 3:** Comparison between measured and reproduced spectra.*

communications tool whose output quality does not depend on external factors, *e.g.*, the person viewing it, and thus satisfies the above fundamental prerequisite.

Current displays rely on colorimetry and are not designed to meet the requirements of spectral reproduction. This is where MP technology may provide unique advantages. It is well known that the reflectance or transmittance spectra of most natural and artificial objects may be described by additive linear combination of only a few (in the range of 4–8) basis functions.[7-10] In a recent article,[3] we have shown that a system may be reproduced well by selecting spectra derived from the system itself as basis functions. Thus, an MP display with a small number of primaries ($4 \leq n \leq 8$) tailored to fit the basis functions may be used for spectral reproduction of natural objects by additive combination of the primaries.

Spectral Soft-Proofing

The remainder of this article describes a concept and possible MP implementation of a spectral display for soft-proofing of print. Print-proofing is a well-known color-critical application. It is a field in which colorimetric techniques have been extensively studied and applied for the past two decades, and although soft-proofing on RGB monitors has gained some ground, it has failed to replace the hard-copy work flow.

In order to fully understand the principles of this implementation, the basic mechanism of print must be briefly explained.[11] Consider Fig. 1, in which a color image printed on paper is shown. The printed image is made of four inks: cyan, magenta, yellow, and black (CMYK). These inks serve as transparent color filters that absorb some parts of the white-light spectrum impinging on the paper and allow the other parts to pass through. The part of the spectrum that passes through the ink reaches the viewer's eye and is interpreted as color. In order to create a full-color image, each "pixel" on the white paper (referred to as a printing dot) is partially covered by each of the inks according to the respective CMYK values for that printing dot. The dots of the different inks overlap each other. The enlarged examination of the print dots shows that the blank paper is covered with small areas of cyan, magenta, yellow, black, and overlaps of these inks, yielding red, green, and blue (MY, CY, and CM overlaps, respectively). For simplicity, we assume the reflectance of the black ink, its overlaps, and the black created by the CMY overlaps is zero. The light impinging on the paper is filtered by each of the inks and the overlaps to yield the different spectra shown in the small windows in Fig. 1(a). Each of these spectra is a multiplication of the light reflected by the blank paper with the transmission spectrum of the relevant ink or ink overlaps as shown in Fig. 1(b). When observed from a normal viewing distance, the dot structure is below the limit of visual acuity and, thus, the different spectra are additively integrated to create a combined spectrum.[12] Hence, to a first order, the reflected spectrum is a combination of seven spectra, identical to the spectra reflected from the blank paper, the CMY inks, and their overlaps. Within this approximation, we also neglect the contribution of the different blacks.

The Spectral-Display Concept

A spectral display that would simulate the print process should accept CMYK data as input and present a spectrum at each pixel closely resembling that originating from the printed paper. As in the printing process, it is reasonable to separate the illumination from the ink and overlap transmissions. Therefore, the display should have an independent (and preferably adjustable) light source and a color module capable of reproducing the transmission spectra.

Figure 2 describes an implementation based on a sequential rear-projection MP display. The spectrum of the light is matched by a suitable correction filter to the spectrum reflected from the blank paper. Next in the light pass is a filter wheel with seven segments, where the filter transmission spectra are identical to the normalized transmission spectra of the inks and their overlaps with respect to the blank paper. In addition, a fully transparent filter segment is included to represent the normalized blank-paper reflectance, which is unity by definition. During the rotation of the color wheel, the light transmitted through the relevant filter is identical to that reflected from the paper through the corresponding ink (or ink overlap or the blank paper). The filtered light illuminates a spatial light modulator (SLM), and each pixel is switched to the required level according to the amount of that specific spectrum needed for this pixel. The temporal stream of the different primary spectra is integrated by the HVS to create the required spectrum at each pixel.

A major advantage of this display compared to typical color displays is that the CMYK input data is not converted to RGB. Rather, the data is passed on to a spectral conversion unit which calculates the required amounts of each primary in each pixel, based on the relative coverage of the inks and overlaps. As an example, consider a pixel whose CMYK value is 50% cyan and 0% for the rest of the inks (50,0,0,0). With dot gain ignored for simplicity, such a pixel, when printed on paper, would reflect the spectrum of the blank paper from 50% of its area and the spectrum of the white light filtered through the cyan ink from the other 50%. In the described sequential projector, the spatial integration of the print halftone dot spectra is replaced by a temporal additive combination of the different primaries, meaning that each of the white and cyan spectra will occupy 50% of their respective field durations.

To test this concept, a printed color target was used, from which the spectra of the inks and their overlaps were measured. Other colors were further measured corresponding to various CMYK combinations. The CMYK data of the measured colors was then used to calculate the combination of the ink, the overlap, and the blank-paper spectra. Figure 3 demonstrates the spectral similarity between the measured and simulated spectra (normalized by reflection from white). Colorimetric assessment of 60 different colors has shown that the average color accuracy is better than a CIELAB color difference of $\Delta E = 1.95$. This color error is a result of the combined effects from two factors: (1) the accuracy of converting the CMYK data to relative coverage of the inks and overlaps and (2) the accuracy of the spectral reconstruction by a limited set of filters. We find that for the case under study, most of the color error is associated with the former.

The concept was field-tested at several prepress establishments in London. Prototype soft-proofing devices, based on a sequential projection engine (Fig. 4), were incorporated in the production of high-profile fashion magazines. With an image area of ~23 in., the devices feature an evaluation area illuminated by a standard D65 lamp. This setup was designed to compare the reproduced image with a hardcopy print or proof of the same CMYK file, in close proximity. The item shown in Fig. 5 is typical color-critical content, where even the slightest color and tonal subtleties are expected to be reproduced with high fidelity. The images reproduced on the device were reported to have the "look and feel" of printed paper and, at the end of the testing period, the system was evaluated as being capable of replacing hardcopy contract proofing.

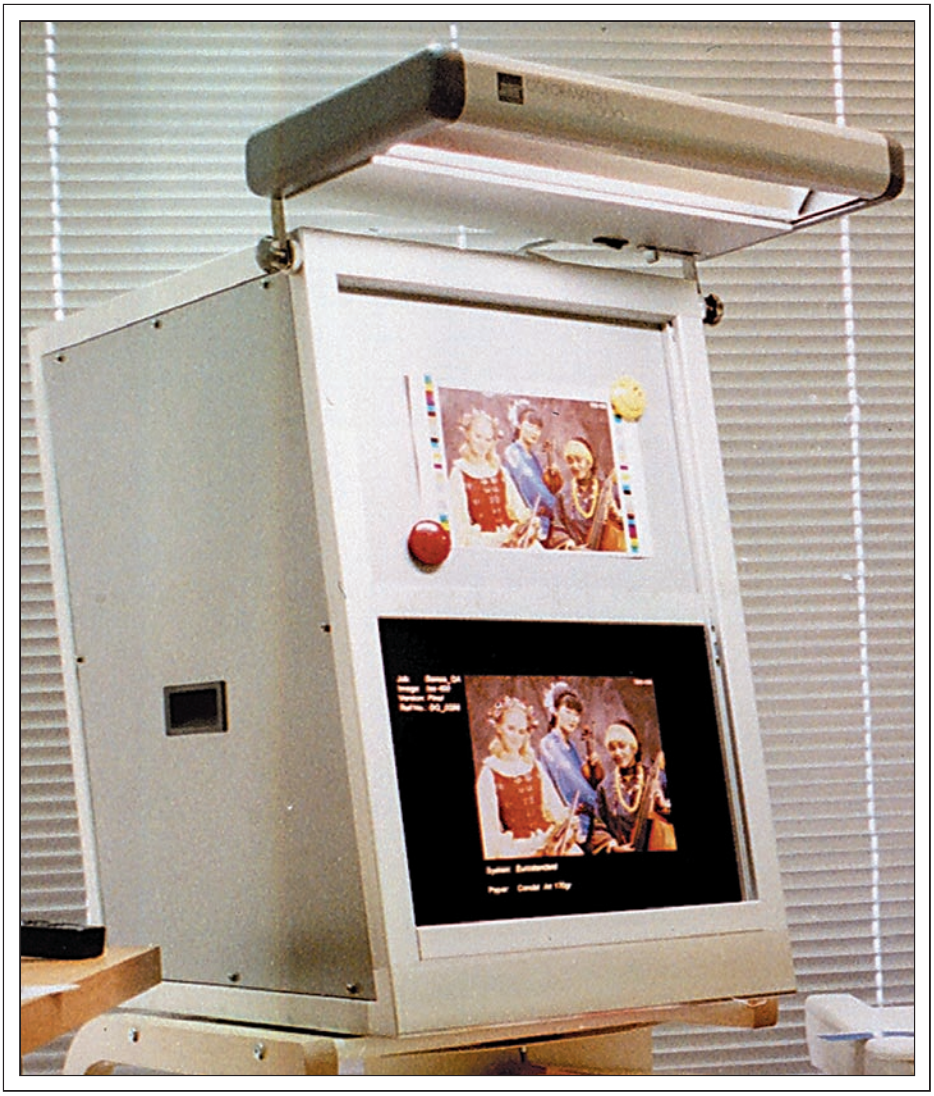

Fig. 4: *A prototype soft-proofing device, based on a sequential projection engine. The image area is ~23 in. (A4 page plus bleed margins), with an evaluation area illuminated by a standard D65 lamp. A special high-quality glass screen – a high-transmission (>50%) low-reflectance (<0.4%) gain-1 screen – coupled with the system's high brightness provides immunity to ambient light and enables the display of the image without loss of contrast. The background color of the image area can be adjusted to match that of the evaluation area in order to avoid simultaneous color and contrast biases.*

Conclusion

The spectral display concept presented here is adopted for a proofing application; however, it can be easily generalized to other fields and applications as well, including displays. This can be done by deriving a small number of basis functions to serve as color filters, which are capable of reconstructing the full spectra set of the desired system.

Fig. 5: *A scan used in a fashion magazine, with color-critical content.*

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