Challenges for Color Science in Multimedia Imaging

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Color science encompasses many technologies, one of which is multimedia. Looking at the breadth of activities and industries that define color science can provide insight into current and future problems for multimedia imaging and their solutions.

1. Introduction

Multimedia imaging requires the fundamental knowledge that constitutes such disciplines as mathematics, physics, chemistry, physiology, and psychology. We further require applied knowledge that constitutes disciplines including computer science, information processing, imaging science, and color science.

This view of multimedia imaging places color science in a subordinate position. However, it can be worthwhile to exchange the positions. That is, multimedia imaging is but one of many technologies that exemplify color science. This approach has been described previously by the author regarding educational imperatives (1) and as a pedantic vehicle for describing the relationships between user controls and resulting color for various color technologies (2). This approach will be revisited within the context of multimedia imaging.

2. Color Matching

As defined by the CIE system (3), two stimuli match when their tristimulus values are equal, i.e., a metameric match. Metameric matches are ubiquitous with multimedia imaging. CRT displays, perhaps the most prevalent multimedia device, always result in metameric matches, shown in Figure 1.

![Figure 1. Metameric match between CRT display and human skin illuminated by typical daylight.](image-url)
If the stimuli are materials, the metameric match is usually depicted as a pair of spectral reflectance factor curves. The match is defined for a particular light source, observer, and viewing condition. Figure 2 illustrates an example of such a match ("Standard" and "Metameric Match"). Also shown in Figure 2 is a sample that is not a match; its tristimulus values are different from the standard ("Simple Color Difference").

**Figure 2.** Stimuli designed to match *x*=0.27, *y*=0.33 and *Y*/*Y*ₙ=0.25 for D65 and the 10° standard observer.

The metameric matches shown in Figures 1 and 2 are similar in their spectral dissimilarities. At the long wavelength region of the visible spectrum, each metameric pair diverges significantly from one another. Accordingly, can we state that they have similar quality? Chances are that they have a similar degree of metamerism if one calculates general or special indices of metamerism (3,4).

Yet there is a large difference in quality. The CRT’s primaries are fixed. CRT developers and users have minimal if any flexibility in choosing the set of primaries. Metamerism cannot be avoided. The influence of metameric matches in multimedia imaging on color quality was recently explored by Alfvin and Fairchild (5). The variance in match equality due to observer differences was large, resulting in a dramatic reduction in quality.

In the case of materials, users often have tremendous flexibility in selecting colorants. The spectral curve shown in Figure 2 labeled “Simple Color Difference” represents a sample where the same colorants were used as those chosen to produce the “Standard”. Because of manufacturing limitations, there is still a small residual color difference. Which sample will result in higher quality, the “Metameric Match” or the “Simple Color Difference”? Clearly the latter is a better quality match. It’s small amount of color difference will be constant across changes in illumination, viewing, and observers. The metameric match will result in large differences in color with similar changes. Thus the material-based metameric pair has much lower quality than the CRT-based metameric pair. This is well known within the world of manufacturing colored materials. Only spectral matches result in high quality. In fact, metameric matches have been defined as “conditional matches” to point out these limitations (6).

### 3. Spectral Matching in Multimedia

As shown above, it is not possible to achieve a spectral match between objects and their “softcopy” CRT representations. However, in multimedia, there are tremendous possibilities...
in achieving spectral matches between original objects and their printed reproductions. Three subsystems are required: multispectral image estimation, ink selection minimizing metamerism, and spectral-based printing models including separation algorithms. This is shown in Figure 3. In addition to these subsystems, trichromatic-based multimedia imaging devices including CRT displays and desktop printers can be easily incorporated. Essentially, trichromatic-based systems are a subset of multichannel-based systems.

There is an obvious parallel to the world of color matching of materials. In the United States, many stores that sell house paint have color matching systems. These consist of a spectrophotometer, computer, and paint dispensing system. Most manufacturers including textiles, plastics, and coatings use similar systems. A standard’s spectral reflectance factor is measured using the spectrophotometer. From a data base of colorants appropriate to the particular coloration process, a subset is selected that when used to color the particular material system (e.g. paint or fabric), a match will result that is minimally metameric. The software algorithms used in these systems can be divided into two steps. The first is colorant selection. From a large database of colorants, the three or four colorant combination (the most common number of colorants used in a formulation) is selected that results in the closest spectral match (i.e. least metameric). Once the colorants are determined, their amounts, the recipe, is defined based on a color mixing model such as Kubelka-Munk turbid media theory. (Reference 2 lists references on the coloration of materials.) If an exact spectral match will result, one can combine these steps. For example, forward-selection multiple linear regression (7) can be used to order the candidate colorants in terms of their spectral matching potential. However, if an exact spectral match is not possible, there will be residual colorimetric error; accordingly, the spectral matching algorithm might be used for colorant selection followed by a colorimetric matching algorithm to insure a close match for a primary illuminant. Alternatively, iterative methods are used where every three or four colorant combination is evaluated.

The multispectral image capture is equivalent to the spectrophotometer. A set of candidate inks is equivalent to the database of appropriate colorants. The ink selection algorithm is equivalent to colorant selection minimizing metamerism. The spectral printing model and separation algorithm is equivalent to determining the final color recipe.
Figure 3. Multispectral-based multimedia flowchart. (Van Gogh image copyright of National Gallery, London.)

4. Image Capture Requirements for Multimedia

Traditional color science would argue that the requirements for building input devices are straightforward. Trichromatic systems should have spectral responsivities that are linearly transformable from color matching functions (sometimes called the Luther condition). Multispectral systems should sample the visible spectrum at constant bandpass and wavelength interval, preferably 10 nm. Interestingly, the CIE does not publish general accuracy requirements for instruments used for color measurement. A recommended metric for photometers exists (8), but not for colorimeters although a CIE technical committee has existed for some time (2-16 Characterization of the Performance of Tristimulus Colorimeters). Spectroradiometric accuracy requirements have been defined when measuring light sources (9) and CRT displays (10). Spectrophotometer accuracy requirements have not been defined. A CIE technical committee will soon be publishing techniques, but not recommended specifications (2-28 Methods of Characterizing Spectrophotometers). According to CIE Publication 15.2, tristimulus errors will not be introduced when measuring materials if a 5 nm wavelength increment and bandpass are used. This would translate to at least 60 channels. Obviously, it is necessary to reduce the number of channels.

Considerable research has been performed in determining the minimum number of channels, their spectral response, and how the multichannel information is used for spectral estimation (11-26). Issues include colorimetric accuracy, spectral accuracy, and noise propagation. For example, research at the Munsell Color Science Laboratory (11 - 14) has focused on using seven readily available filters from Melles Griot in conjunction with a typical monochrome digital camera. The system spectral sensitivities are plotted in Figure 4. The particular method of spectral estimation results in large differences on spectral reconstruction accuracy.
as shown in Figure 5. The number of available bits also has a large affect on accuracy, as shown in Figure 6. It’s clear that this is an active area of research.

**Figure 4.** The spectral sensitivity of each of the seven filter/sensor channels (14).

**Figure 5.** The spectral reconstruction using principal component analysis (PCA), modified-discrete-sine-transformation (MDST) and cubic spline interpolation, from camera signal values, for the Cyan sample from the Macbeth Color Checker chart (14).
Figure 6. Average CIELAB color difference that results from the uniform quantization of tristimulus values at 8, 10, and 12 bit encoding for neutral colors (11).

5. Image Modeling Requirements for Multimedia

Reducing metamerism between objects and their printed reproductions implies spectral matching. The color of the output device is defined by its spectral reflectance factor rather than colorimetric coordinates. In spectral-based research, it is more common to develop models rather than build \( m \times n \) dimensional look-up tables where \( m \) counts the number of measured samples and \( n \) counts the number of wavelengths. Representative models are described in references 27 - 36.

As an example Iino and Berns (31, 33) used the Yule-Nielsen modified Neugebauer equations to model process printing, shown in Eq. (1) where \( a_i \) are the effective dot areas of the 16 Neugebauer primaries for four-color printing, described in the usual manner by the Demichel equations, \( R_i \) are the reflectance factors of each \( i \)th Neugebauer primary, \( c, m, y \) and \( k \), are dot areas of each primary ink, and \( n_k \) is the Yule-Nielsen n value defined as a function of wavelength. Typical spectral model fits are shown in Figure 7.

\[
R_A = (a_c R_{\lambda,c}^{1/n_k} + a_m R_{\lambda,m}^{1/n_k} + a_y R_{\lambda,y}^{1/n_k} + a_k R_{\lambda,k}^{1/n_k})^{1/n_k} \\
+ a_r R_{\lambda,r}^{1/n_k} + a_s R_{\lambda,s}^{1/n_k} + a_g R_{\lambda,g}^{1/n_k} + a_g R_{\lambda,b}^{1/n_k} \\
+ a_{ck} R_{\lambda,ck}^{1/n_k} + a_{mk} R_{\lambda,mg}^{1/n_k} + a_{yk} R_{\lambda,yk}^{1/n_k} \\
+ a_{rk} R_{\lambda,rk}^{1/n_k} + a_{sk} R_{\lambda,sg}^{1/n_k} + a_{bk} R_{\lambda,bk}^{1/n_k} \\
+ a_{cm} R_{\lambda,cm}^{1/n_k} + a_{my} R_{\lambda,my}^{1/n_k} + a_{ck} R_{\lambda,ck}^{1/n_k} + a_{wy} R_{\lambda,wy}^{1/n_k})^{1/n_k},
\]
Figure 7 Measured spectral reflectance factor (dashed line) and predicted spectral reflectance factor (solid line) of the magenta ramp based on Eq. (1).

One difficulty often encountered in using the Demichel equations to predict the entire color gamut is a discrepancy between predicted and actual area coverage caused by optical interactions. Recognizing that the Yule-Nielsen modification is empirical, this can be removed in favor of increasing the number of Neugebauer primaries. This approach is more in line with the true optics of ink paper interactions. The number of primaries can be increased to \( i^2 \) (34,35) where \( i \) counts the number of primaries or to infinity (35,36). Alternatively, the empirical equation is used with an augmentation where the optical interactions are accounted for in the conversion between theoretical and actual area coverages (31,33,37). Iino and Berns described this using Eq. (2). Their colorimetric performance was, on average, \( \Delta E_{ab}^* \) of 2.2 with a maximum of 5 for independent colors sampling a printer color gamut represented by Matchprint III.

\[
\begin{align*}
q_c &= f_{c,m}(d_{t,m})f_{c,y}(d_{t,y})f_{c,k}(d_{t,k}) \\
q_m &= f_{m,c}(d_{t,c})f_{m,y}(d_{t,y})f_{m,k}(d_{t,k}) \\
q_y &= f_{y,c}(d_{t,c})f_{y,m}(d_{t,m})f_{y,k}(d_{t,k}) \\
q_k &= f_{k,c}(d_{t,c})f_{k,m}(d_{t,m})f_{k,y}(d_{t,y})
\end{align*}
\]

(2)

where \( q_i \) is coefficient for the overlapped ink \( i \), the function \( f_{i,j}(d_{t,j}) \) is the decreasing effective dot gain function of the secondary color (overlapped ink \( i \) by overlapping ink \( j \)), and \( d_{t,i} \) is the theoretical dot area of each overlapping primary color.

6. Multi-Ink Requirements for Multimedia

In order to fully develop a multimedia system that is analogous to the color matching of paints or textiles, a large database of inks is required. The purpose of the database is to provide sufficient spectral variability, such that one can “tune” a spectral reflectance factor, thereby matching the spectral properties of an object requiring color reproduction. This requirement is different from typical multi-ink systems, largely concerned with increasing color gamut (37-46). Published research where minimizing metamerism is the goal rather than increasing color gamut has been limited to preliminary research by the author (47). At the Munsell Color Science Laboratory, this is an active area of research.
As an example, Figure 8 is a digital representation of an acrylic painting. Using a small-aperture spectrophotometer, the spectral reflectance factor of 100 positions was measured, plotted in Figure 9. Transforming the spectral data to absorption and scattering ratios using Kubelka-Munk turbid media theory, performing principal component analysis, and rotating the significant characteristic vectors to an all-positive representation, a statistical set of pigments results, shown in Figure 10 (48). This statistical set of pigments will predict the 100 measurements to an average $\Delta E_{94}$ of 0.8 and a maximum of 1.8. The degree of metamerism (49), expressed in CIE94 units, is 0.1 on average with a maximum of 0.3. Once a printing system is defined and spectrally modeled, the optimal ink set can be determined that minimizes metamerism compared with the statistical pigment set.

Figure 8. Digital representation of an acrylic painting, by M. Gottsegen, 1989 (Kodak DC20 digital camera).

Figure 9. Measured spectral reflectance factors of 10x10 grid sampling painting.
7. Defining Quality for Multimedia

Once the spectral-based multimedia system has been developed, quality metrics are required. These should include CIE94 (50), special indices of metamerism (1,4,49,51) indices of color inconstancy (51), and indices that include the human visual system’s spatial properties (52,53).

8. Conclusions

Evaluating multimedia imaging as one of many applications of color science can result in a new paradigm for color imaging, multispectral-based imaging. However, developing multichannel multimedia systems will likely cause a dramatic increase in cost (hardware, software, personnel training, data storage, image access, etc.). If only an increase in color accuracy compared with the current state of multimedia imaging was the benefit, a cost-benefit analysis would probably not result in a favorable outcome. Fortunately, there are many additional benefits that result from spectral data bases and color printing that minimizes metamerism. Perhaps most important is the potential to define and thereby archive objects using the most fundamental definition, spectral reflectance factor. As an analogy, the U.S.’s National Institute of Standards and Technology only provides spectral definitions for their standard reference materials used for spectrophotometers. Matching spectra minimize the need for controlling lighting, viewing conditions, and observers. The benefits we take for granted when having our automobile refinished after a collision or when we purchase clothing can be applied to multimedia.

9. References

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