# Is Color Appearance Matching Necessary?

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## Abstract

An analysis of why people are willing to spend more money to buy color systems versus monochrome systems shows that the colorimetric methods used in today's color management systems are insufficient. To fulfill the user's requirements, it is necessary to preserve the appearance of color when an electronic image is reproduced. After proposing formal definitions for color perception and for color appearance, I will present two problems requiring an appearance model to solve: the color selection problem, and gamut mapping.

## 1. Introduction

The production of a hard copy color document requires a number of stages. These stages occur either for each document or are pre-computed for a given process. Yule[1] has described in detail the issues in the various production steps from the *original* art work to the hard copy reproduction in traditional printing processes. For electronic imaging the steps are almost the same:

1. Design of the original artwork by a graphic artist under such considerations as style, readability, and total production costs. The original artwork can be either a reflection copy, a transmission copy, or—in electronic imaging—a soft copy on a display monitor.
2. When the reproduction technology does not support gray levels, binarization of the artwork using a halftoning algorithm. (In electronic imaging we are mostly limited to process colors, so usually even line art or mechanicals are halftoned.)
3. To achieve a faithful tone reproduction, the tone reproduction curve (ARC) mapping tones of the original artwork to tones in the reproduction has to be linearized for all inks.
4. The visual system is particularly sensitive to neutral colors, possibly because they play a key role for color constancy. In a step known as gray balancing, it is ensured that neutral colors in the original are reproduced as neutrals.
5. To increase the gamut of colors that can be generated by a hard copy device, it is customary to incorporate a black printer. This also alleviates bleeding and similar problems in wet processes or drop-out problems in wax processes.
6. The color gamut of the device used to produce the original is often very different from the gamut of the device used for the reproduction. A gamut mapping algorithm has to be applied to make sure that all colors in the original map to colors in the hard copy gamut, i.e., are reproducible.
7. An electronic image is represented as a pixel map of digital counts. These digital counts are normalized values that are converted into voltages or currents by a device or a controller. It is necessary to define a mapping that relates the values from the device used for the original artwork to the values fed to the hard copy device for the reproduction so as to maintain color fidelity.

The last step has received much attention in the recent literature on electronic imaging. It is often considered to be the hardest—and consequently most important—problem to solve and acronyms like CMM (color matching method) and CMS (color management system) have become the main weapons for marketing color systems. Electronic images contain a very large number of data. Therefore, in practical applications table look-up methods are used. This has often led people to believe that since "it is all tables," one can focus on the last step and get the CMM right, the rest will follow automatically.

Alas, the reverse is true. The contribution to image quality decreases with the steps. Moreover, an artifact introduced in an early step cannot easily be rectified in a later step. Even if the hard copy device is perfect and optimal color fidelity can be achieved, the perfect reproduction of original artwork of poor aesthetical quality will not look pleasing to the viewer. Similarly, if the halftoning algorithm does not give sufficient detail in the shadows and highlights the reproduction will look flat, and if there is too much bleeding in the mid-tones, the reproduction will look smeary.

When a color reproduction system is implemented correctly by solving optimally each step in sequence, the contribution of each step to the quality of the final images diminishes. If one starts with a good halftoning algorithm, adjusting the TRC and balancing the grays will already deliver acceptable reproductions. A simple linear transformation to account for unwanted absorptions can often be an adequate CMM for non-critical applications. This tends to lead to a certain inertia in adopting better technologies to improve the color correction step, especially if a major cognitive effort is necessary to learn a more sophisticated technology.

For a long time densitometric methods were used in color correction. It was only with wide acceptance of client/server-based networked computing and the uncertainty due to the lack of *a priory* information inherent to an open system, that prediction of color by measuring ink quantities with a densitometer failed. Colorimetric methods have now found general acceptance and most open systems available nowadays are based on colorimetry.

A system based on colorimetry allows one to reproduce original artwork on a number of hard copy devices based on different technologies and yet to achieve good color fidelity between these various devices. It is hard to convince decision makers that even better methods are required, when the quality improvement achieved is relatively small compared to the improvement that can be achieved in the other steps.

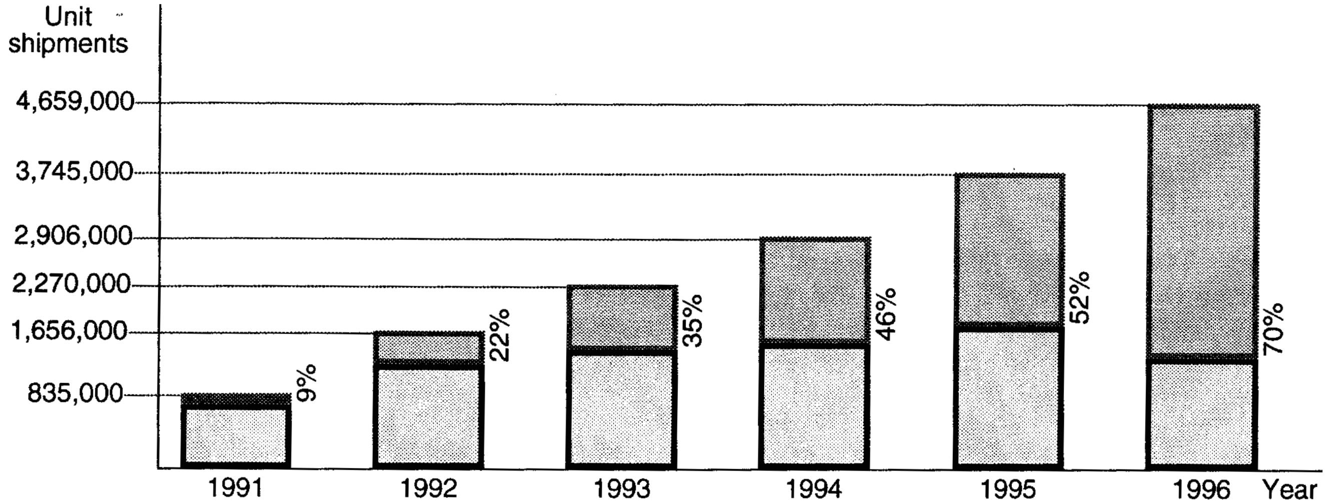


*Figure 1. Projected unit shipments of ink jet printers. The lower part of the bars refers to monochrome and the upper part refers to color ink jet printers. The percentage indicates the relative number of color units.*[2]

This paper explores the possible benefits of methods based on color appearance models.

Some color reproduction problems cannot be solved adequately with colorimetric methods. Examples are color reproduction across media, mapping colors between two very different gamuts, and the problem of building color selection tools for manipulating electronic images. These examples have been discussed widely in the literature. Our aim in this paper is to investigate the nature of problems requiring methods beyond colorimetry. To do this, we have first to identify the critical qualities of color documents and define the involved concepts. This allows us to identify solutions and evaluate them.

## 2. Color-Function

In the personal computer market, users spend typically about a fifth to a third of the computer's price for a printer. This means that the ink jet technology will probably dominate the market and therefore be the best trend indicator. Figure 1 shows that an increasing number of personal computers is configured with color ink jet printers compared to the number of monochrome systems. As for display monitors, most systems sold today are equipped with a color device. Although the incremental cost of a color computer is decreasing, for a comparable image quality a premium of several hundred dollars has to be paid. In percentage, a color computer is typically 20% to 50% more expensive than its monochrome version.

Even a 20% incremental cost cannot be explained by factors such as prestige alone. Customers tend to make purchasing decisions based on the relevance of a product for their activities. They ask themselves questions like "How much does it improve my work!" Consequently, we have to understand the function of color in documents. The function of color can be broken down into three categories, loosely reflecting the categorization common in the visual arts in orthogonal aspects of utility function, esthetic function, and informative function:

1. Color as a *compositional element.* Like fonts and delimiter characters are used to increase the readability of text, color can be used as a typographical component to assists the reader's scanning activity.
2. Color as a *decorative element*. In this use color confers style to a document to enliven or decorate it.
3. Color as an *accelerator*. Color can be used to facilitate spatial localization, grouping, and give overview; or more generally to accelerate search tasks.

A well designed document is easy to use, and a document preparation system has to facilitate this *ease of use*. Ease of use is achieved by reducing the cognitive load on the user. The most straightforward technique to reduce the cognitive load is by providing object constancy. Consequently, here we are interested only in the third use.

It is generally believed that concepts are stored in the brain in the form of "dormant" records; the search task consists in the evocation of these records. It may be that a colored version of an object is a more potent cue to memory than an uncolored one.[3] To be effective, color has to evoke such records as efficiently as possible. This means that color has to be *identified* reliably, independent of the *conditions* under which the color is presented. So the *appearance* of a color to the observer is important, not the stimulus eliciting the color.

## 3. Terminology

### 3.1. Color Sensation and Perception

It is important to have clear definitions for color sensation, perception, and appearance. *Sensation* generally refers to the mental process directly associated with stimulation. *Perception*, which in colloquial use refers to the intellectual phenomenon of being aware of the process of sensation, is harder to define.

Psychologists still debate whether perception is directly based on visual input, or is representational, i.e., constructed from stored knowledge by the act of paying attention, that is, conceptual mediation. Jules Davidoff has proposed a unifying model that takes from direct perception the notion of an external object represented unmediated at a pictorial register and from the representationalist the notion of a mediating category.[3] He calls the entity that categorizes chromatically derived surface information the *internal color space*. The categorization is the entity that maps from a continuous space of sensations to a discrete space of communicable perceptions.

Davidoff further argues that the store of knowledge about representations for sensory properties rather than the store of knowledge about functional object properties, gives more assistance in the production of an object's name. Therefore, being a representational object property, color is a likely candidate for name output facilitation. For Davidoff color thus has an interesting property: it serves as a marker for the flow of information from visual input to name output. This color identification is the key for color as an accelerator in documents.

*Color perception* can be defined in simple terms as *the awareness of a color sensation and its categorization mediated by an internal color space with the possibly ensuing facilitation of a color name*. Awareness is precognitive, i.e., refers to an unmediated representation, while the categorization refers to the discretization into a structure defined by the internal color space. The basis elements of a representation for perceptions are *percepts*, which require good correlates to facilitate the manipulation of electronic images in documents.

### 3.2. Color Appearance

Color appearance refers to the evaluation of a color stimulus with respect to a given representation. The mediation of the representation is not constant, rather it is parametrized. For example, if we take the stimulus from a fixed complexion and then change the spectral distribution of the stimulus by changing the illuminant, the perceived color will not change. This means that color perception is context-dependent. We can define color appearance as the result of a color perception together with the condition under which it occurred. More formally:

> *Color appearance* is the representation of a color sensation mediated by an internal color space, and the conditions that parametrize this representation.

The appearance of a color identifies the color and this identification can serve as a search key in a lexicon of color names. This output lexicon is not part of color appearance, and in fact an appearance match can be identified, for example, by pointing to a sample in a color atlas or by giving a forced yes/no answer in a comparison with a memory color. Figure 2 illustrates an example with the aid of a simple model.

In the introduction, we postulated that the relevant aspect for the use of color in documents is its function as an accelerator. Consequently, color identification is the crucial point, which means that in practical applications a set of reproduced colors must elicit the same representation and thus match perceptually. Most often the colors are on different media and are perceived in different modes. With color appearance we know the viewing conditions and can therefore transform the representation to allow for the changed conditions.

In this sense, for the case of desktop document preparation there is a close relation between color appearance and color perception and when two color stimuli have the same appearance, we speak of interchangeably of an *appearance match* or a *perceptual match*. Color reproduction that aims at matching appearance is called *equivalent color reproduction*, or *corresponding color reproduction* when the

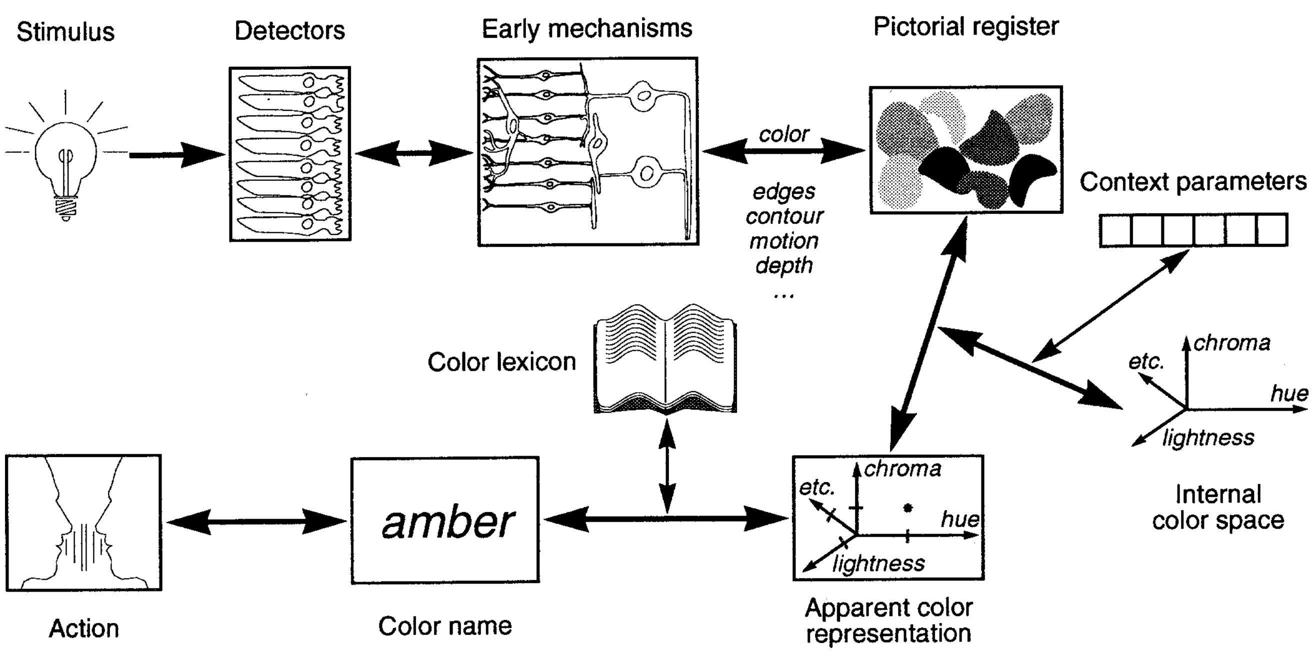


*Figure 2. Model of color appearance in the context of color vision. The radiant flux from the stimulus triggers the detectors and some processing occurs through mechanisms of "early vision." The information is presented unmediated in pictorial registers (or visual buffers) for the various visual attributes. For color, the internal color space mediates a structured representation of the color, the color appearance. The mediation process is parametrized by the context, such as the appearance mode and the surround; together, they are the aspects of the apparent color. The representation of the color can be used to look up a color name in the output lexicon, and this name can, for example, be uttered. Note the bidirectional arrows.*

luminances of the two samples are the same.[4] The formulation of algorithms to predict a perceived color under given conditions is called *color appearance modeling*.

### 3.3. Aspects of Color Appearance

Color appearance depends on a number of parameters and can be described in terms of a number of attributes. As Judd pointed out, the lack of identification and evaluation of the appearance parameters is one of the factors that prevents the tristimulus values from correlating with the color perception.[5] Examples of parameters are appearance mode, surround (or more in general, visual area), luminance level, illuminant chromaticity, chromatic adaptation, after-images, memory, and mental set. Examples of attributes are hue, colorfulness, chroma, saturation, brightness, lightness, duration, size, shape, location, texture, gloss, transparency, fluctuation, insistence, and pronouncedness.[6]

In the above definitions, the attributes are the basis elements of a representation for perceptions or *percepts*. For a given model, the *parameters* are input quantities and the *attributes* are output quantities. Models are rarely complete, they can predict some of the attributes and will require others to be input because they cannot yet be modeled. We therefore use the term *aspect* to designate collectively parameters and attributes. To apply color appearance to accelerating search tasks in desktop document preparation, the aspects in color appearance have to be identified and modeled.

A number of color appearance models was presented at the 1993 IS&T/SPIE Symposium on Electronic Imaging Science & Technology. The reader is referred to 1993's proceedings for details how an appearance match can be achieved.

## 4. Two Problems Requiring an Appearance Model to Solve

### 4.1. The Color Selection Problem

Consider the following task: figure 3 shows diagrammatically a picture of a friend in Hawaii. The image contains the following elements:

- The friend's face is the color considered, and since the picture was taken on the second day of the vacation, it sports a very noticeable sunburn.
- Hawaii's lush vegetation is represented by the green bush in front of which the friend is standing, forming the proximal field.
- The background of the whole picture is formed by the deep blue Hawaiian sea and sky.
- Finally, the image is being viewed as a hard copy in a room illuminated by incandescent lamps, which forms the surround.

The image is to be inserted into a document and should represent the friend from the best side. To fulfill this requirement it is necessary to adjust the color of the friend's face by trying to touch it up to eliminate his erythema. Typically this can be accomplished using a tool like Photoshop™ on a Macintosh® with the color picker at right.* This color tool presents a number of complexions from which the user can pick the most appropriate for the color considered. The border on the color picker symbolizes that the particular display monitor used has a correlated color temperature of $D_{93}$. When the picked color is transferred to the image, the striking green proximal field will make the picked color more vivid.

The use of a color appearance model that can account for spatial color information, makes it possible to build color selection tools that present the colors with the same name as they will have when applied to the image being manipulated. The name is preserved across media when a hard copy is produced. This is an important step towards fulfilling the average users' fuzzy desire of wanting what they ask for in color reproduction.

### 4.2. Gamut Mapping

The color gamut that can be reproduced on a printer is quite different from that reproducible on a display monitor, which in turn is different from that detectable by a scanner. In a pre-press system, for instance, the display monitor is

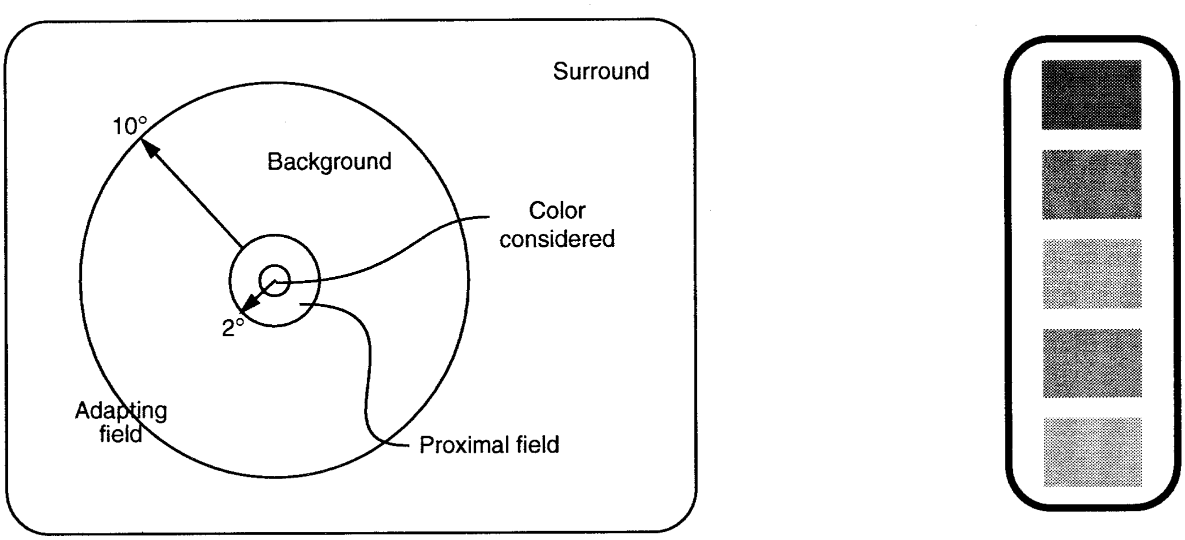


*Figure 3. A typical color editing situation. On the left side is a reflection print viewed under an incandescent light source. We wish to slightly change the color considered, whose proximal field is of the complementary color. The manipulation takes place on a display monitor with a color picker presenting a color palette. The correlated color temperature of the display monitor's white point is $D_{93}$, as is commonly the case. Source: after R.G.W. Hunt.*

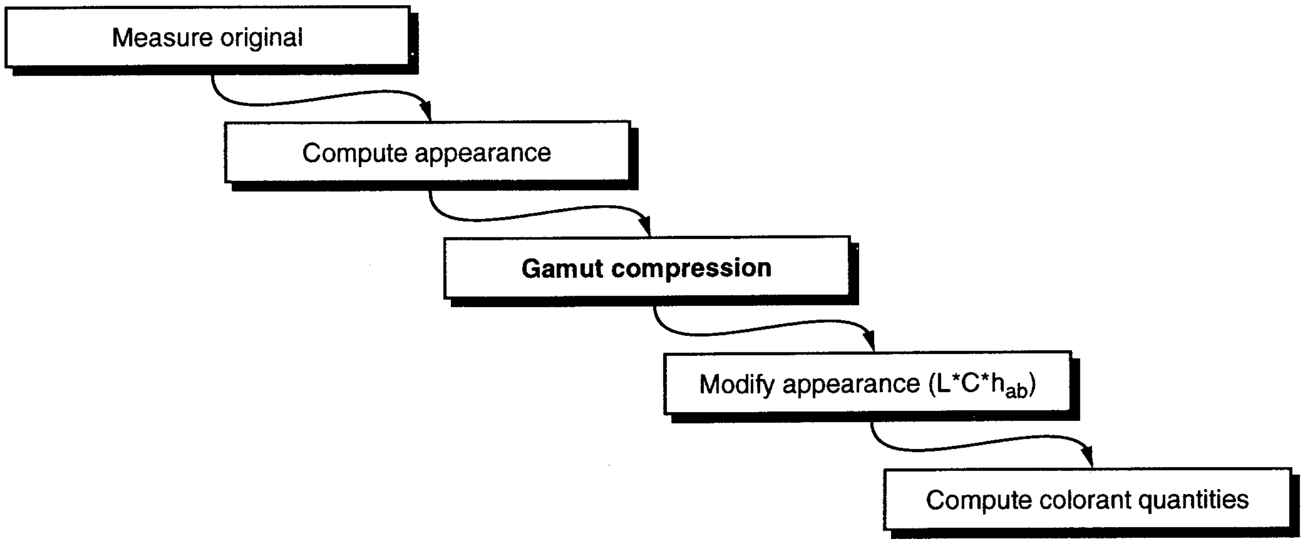


*Figure 4. The situation of gamut mapping in a color reproduction pipeline proposed by Johnson.*[7]

used only to simulate the printed image, so the monitor's color gamut can be artificially constrained to the intersection with the printer's gamut. This contrasts to the situation in a desktop publishing system, where the user expects the best image on the monitor and the best image on the printer.

Anthony Johnson has proposed[7] the pipeline shown in figure 4 to position the gamut mapping stage. As of this writing, a general gamut compression algorithm has yet to be invented. The best methods used today are empirical and follow the three rules: (1) scale lightness range linearly; (2) maintain hue; (3) scale chroma range.

As the qualifier "range" implies, gamut compression is image dependent. The best compression of lightness is known since the Fifties, and recently Stephen Viggiano and Jeffrey Wang have presented a good algorithm for the compression of in-gamut chroma in an excellent paper.[8] Fortunately, according to Tony Johnson the printing community accepts the introduction of errors up to around $\Delta E = 20$ when compressing the gamut in the chrome dimension.[†]

Maintaining the hue is the hardest problem, because the uniform color spaces typically used for this operation (e.g., CIE 1976 ($L^*a^*b^*$) color space) are not sufficiently uniform.[‡] This can be easily verified by plotting the MacAdam ellipses[10] on an $a^*b^*$ slice. As one can see especially in the direction of 315° the ellipses become quite oblong. In practice worse things happen; when the chrome is compressed sufficiently to bring out-of-gamut colors inside the gamut then colors can change their name, and empirical methods or floating models have to be used to counteract this.

When an appearance model is construeted, one of the main tasks is its verification against a database of psychophysically scaled data. These can include the MacAdam ellipses, the constant hue and saturation loci in the Munsell tree or Natural Color System space, etc. As a consequence, color appearance models may provide correlates that are more suitable for gamut mapping. Alas, one problem is that the available databases contain relativity little data for very dark colors, so that these will remain critical in algorithmic color reproduction until ulterior experimental scaling data becomes available.

## 5. Conclusions

Electronic imaging is a viable technology because color can be treated as a visual quantity; visual color is a valid *ersatz* for physical radiations. It is very hard to reproduce physical radiations. In the human visual system the infinite dimensional space of all spectral distributions is projected onto a low dimensional subspace that requires only limited processing resources. For a color reproduction system to be successful, it has to be based on the same geometric projection. In colorimetry, the projection in the human visual system is reconstructed with the aid of psychophysical experiments conducted under strictly controlled conditions.

There is more to color perception than the projection of spectral distributions onto a red-green-blue subspace with the aid of color matching functions. The human visual systems performs a discretization from an unstructured continuous space into, for example, a set of color names. This categorization has two properties: it is acquired—therefore it improves with experience or exposure—and it is an indeterminate process. This makes color appearance models much harder to build than models based on colorimetry alone.

Despite this difficulty, color appearance models take into account viewing conditions and thus can be used to predict color in reproduction across media, which is of crucial importance in electronic imaging. Furthermore, color appearance models allow for estimators of perceptual attributes like hue and saturation with higher correlation than classical perceptual correlates, allowing the construction of easier to use image manipulation tools. Together with spatial information and possibly with semantic information of images, color appearance models will allow for much improved gamut mapping algorithms.

Although color appearance models are not new, there still remains much work to be done in understanding the technological issues arising in their application to engineering. Also, some aspects are not yet well understood. For embedded video applications the temporal aspects of color vision are important, yet the issues are being crystallized only now.[11] The treatment of spatial information is hampered by the numerical complexity and robustness of the current algorithms.

* Photoshop is a trademark of Adobe Systems, Inc.; Macintosh is a registered trademark of Apple Computer, Inc.

† In research by Mike Stokes, Roy Berns and Mark Fairchild[9] the visual tolerances have been quantified for complex fields expressed in the CIE 1976 ($L^*a^*b^*$) color space. In pictorial images the lightness could be altered by a multiplicative factor of 0.93 and power of 1.1 and 0.92, the chroma by a multiplicative factor of 0.92 and powers of 1 .12 and 0.88, and hue angle offsets of +5.2° and -4.6° before 50% of the observers detected a change.

‡ There is evidence that the worst case nonuniformity might be 1:6.

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published previously in SPIE, Vol. 2171, page 220