Minimizing Color Variation

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Abstract

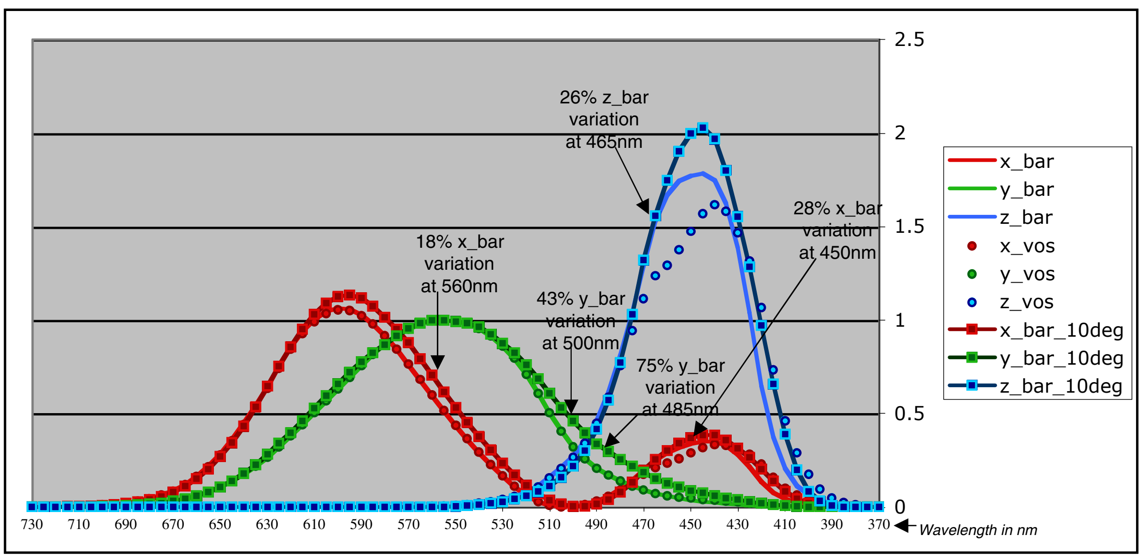
CIE 170-1:2006 provides a framework for considering variation between average viewers in cone fundamentals and corresponding color matching functions. CIE 170-1:2006 provides for variation as a function of age and angular field size for average viewers. In many situations the angular field size and average viewing age is known, and can therefore be utilized. Further, individual information with respect to color matching is not difficult to obtain. Individual information is likely to vary from the average, sometimes significantly, and even between the left and right eyes. There are various additional ways to minimize color variation, including using one or more broad spectrum emitters, such as broad-spectrum-white. If such wide-spectrum emitters are maximized, viewer variation is minimized. Numerous other methods utilizing more than three primaries can also reduce color variation, as well as sometimes offering expanded gamut. Using a variety of such readily-accessible techniques, color variation can be minimized, or at least reduced.

Overview

CIE 170-1:2006 [1] describes a workable system for cone fundamental variation as a function of age and angular field size for an average group of subjects, based originally on the Stiles and Burch 1959 color matching data [2]. However, beyond average color matching functions, there are individual variations, and often variations between the right eye and left eye. There may further be variations over time (as when adapting to a dark room when coming in from daylight). There are also variations due to light level (such as mesopic vision for common viewing such as motion picture theater presentation).

This paper describes methodologies for minimizing these variations between viewers.

Variations Shown By CIE 1931 vs. CIE 1964 and Vos 1970



Several x_bar, y_bar color matching functions showing CIE1931 x_Bar, y_bar, z_bar (2-degree), Vos 1970 version, and CIE 1964 10-degree version

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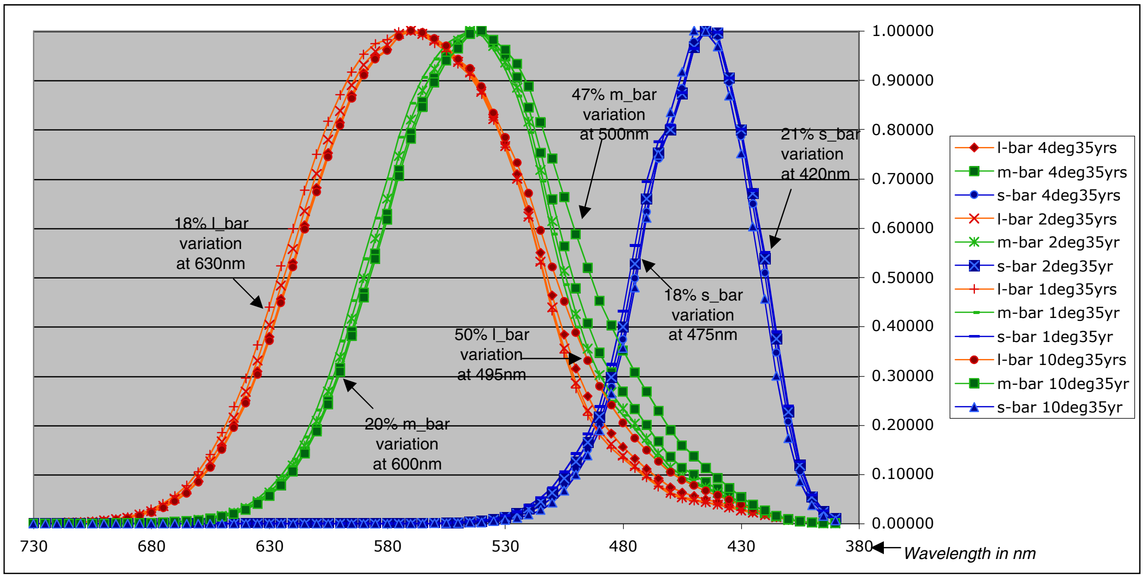
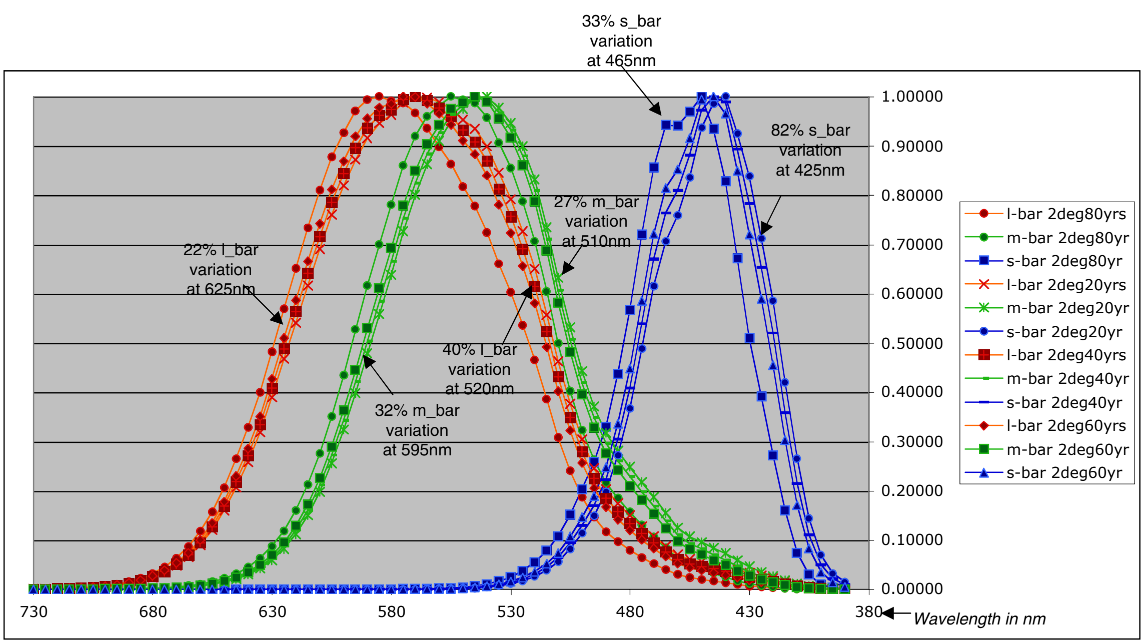
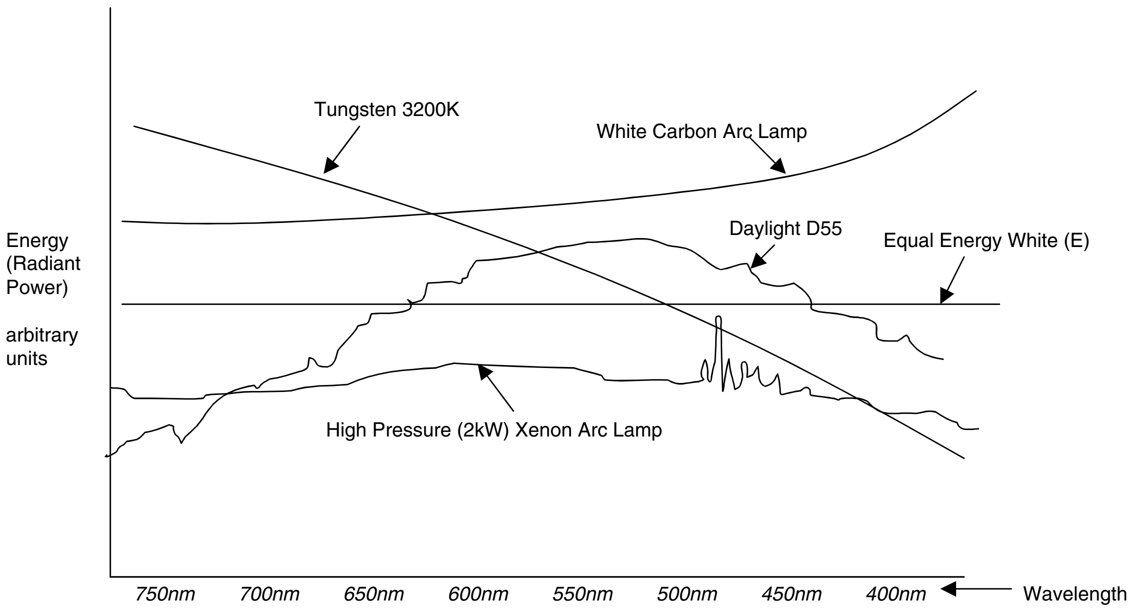
Variations Shown By CIE170-1:2006



Variation of Cone Fundamentals in CIE 170 -1:2006 as a Function of Viewing Angle (1deg, 2deg, 4deg, and 10deg) for Age 35 Years



Variation of Cone Fundamentals in CIE 170 -1:2006 as a Function of Age (20yrs, 40yrs, 40yrs, and 80yrs) for 2deg



Common Broad Spectrum (White) Radiators, Showing Tungsten, Daylight D55, White Carbon Arc, High Pressure (2kW) Xenon Arc Lamp, and Theoretical Equal Energy White (E) (Note: A Light Source's Spectrum Typically Varies With Time, e.g. as the lamp ages)

Begin With Equal Energy White

Equal energy white (called "E") is a theoretical white light that emits equal energy at all visible wavelengths (as well as, implicitly, all frequencies). While Equal Energy White does not exist in reality, it forms a useful conceptual basis with respect to minimizing color variation.

Since most color matching functions are normalized to equal (conceptually unit) area, implicitly using E, the integration of all such color matching functions will yield an identical result. Note that E, as equal energy white across the visible spectrum, should not be confused with the representation of E as chromaticity using a given set of color matching functions (such as x=0.3333 y=0.3333 representing equal area in CIE 1931 2deg or CIE 1964 10deg). In practice, E is an isomer with itself, and thus, if an image white is mastered as E, and reproduced as E, it will produce the spectrum of E as an isomer for every viewing. Further, conceptually, each color matching system will either exactly or approximately mimic this behavior, such that most color matching functions will identify E as a white which has near minimal variation between observers (and between eyes). CIE 170-1:2006 can be used to verify this. Note that E is near to D55 when considered using correlated color temperature (which uses CIE 1931 2deg color matching functions). See [2] Fig. 3(3.3.4) pg 146 at x=.3333, y=.3333.

Isomers Do Not Require Color Matching Functions

The purpose of color matching functions is to transform between one spectral representation of a color, usually trichromatic, into another spectral representation yielding the same perceived color (a metamer). However, if the spectrum of a color or a white/grey during mastering is identical to the spectrum of a color or a white/grey during presentation, there is no need for color matching functions. The color is an isomer between mastering and presentation if it is spectrally identical.

Thus, color matching functions are only needed when utilizing different spectra during presentation than were used during mastering.

The perceived color of that spectrum may vary with viewing conditions (brightness and ambient surround) [3], according to each individual, but if the viewing conditions of mastering are duplicated, then the reproduced spectrum of that color is not only an isomer with itself, but will be perceived identically to the mastering viewing conditions. The one factor that this does not consider is the variation with time (e.g. walking into a dark room from daylight). All other viewing conditions are identical.

Who Controls The Perception of the Master?

In the television or movie mastering room, the perception of the colorist and/or cinematographer, and perhaps the director and art director, may all represent the intended perceived colors. If there is one key viewer (e.g. the cinematographer) or if multiple mastering viewers are perceptually identical with respect to color matching functions, ambient viewing surround perception, and emotional viewing intent, then a knowledge of the/these mastering viewer(s) completes and embodies the intended color.

The more likely scenario is that there is variation among multiple mastering viewers. However, if there is a characterization of each such mastering viewer, then the

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multiple intended perceived presentations can all be retained and found useful in subsequent presentation.

The Real World

Of course we know that it is unlikely that we will be able to reproduce each color as an isomer, and it is further unlikely that we will reproduce the mastering viewing surround, brightness, white-point, contrast, and other key presentation attributes.

Thus, the challenge is how to convey as much as is possible of the mastered image's intended appearance.

The Spectral Bandwidth of Primaries

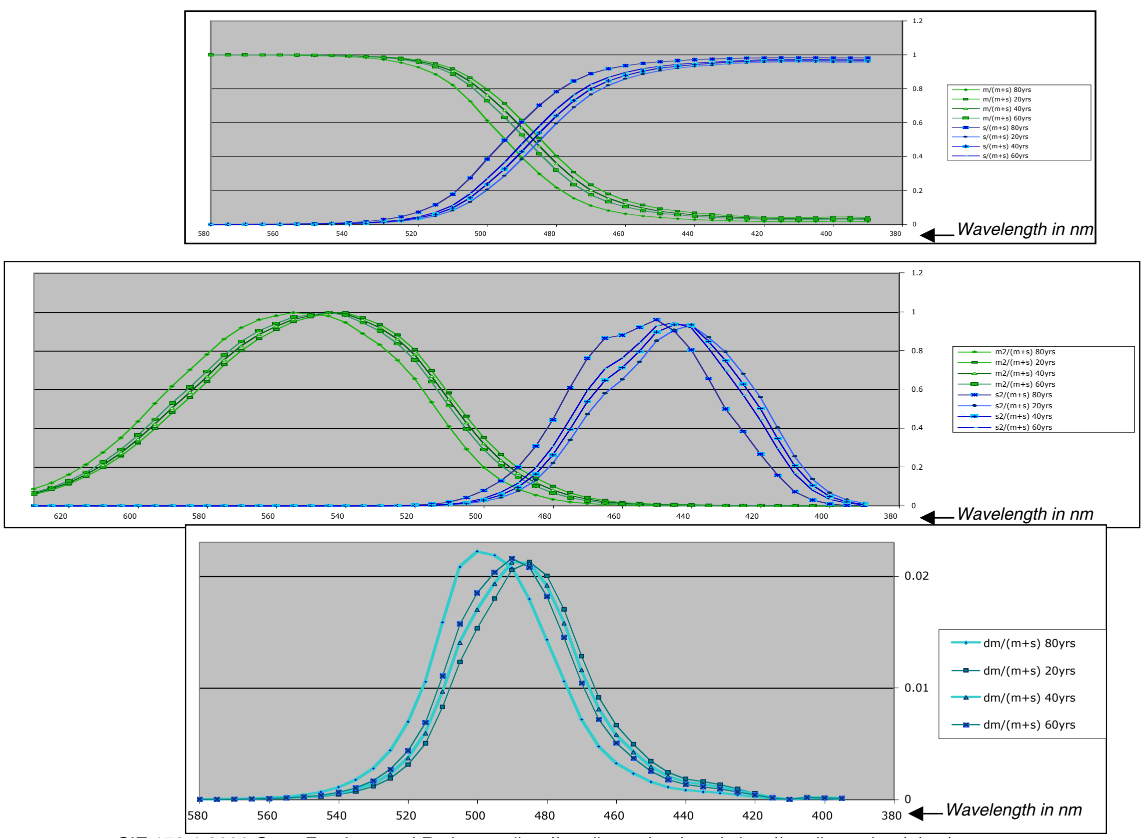
One key tool in helping to preserve mastering room intent is to attempt to minimize the variation between individuals (and between each of our two eyes). Recalling that E is likely to be relatively invariant under color matching functions, we can begin with the concept that white in the mastering room should be similar to white in every presentation, if possible. Further, that white should be as near to E as is practical. For example, a Xenon white is likely to have much less variation between individuals than a white composed of a trichromatic sum of narrow band red, green, and blue. This can be seen by integrating the spectrum of Xenon white over the variations of age and angular field size within CIE 170-1:2006, and comparing this to a similar integration with typical red, green, and blue color display or projector primaries.

The next key tool is to avoid spectral emission energy slopes at the sensitive points where the slopes of the cone fundamentals are highest. That is to say, use the broadest spectral primaries available, and avoid spectral energy spikes and other steep spectral variations.

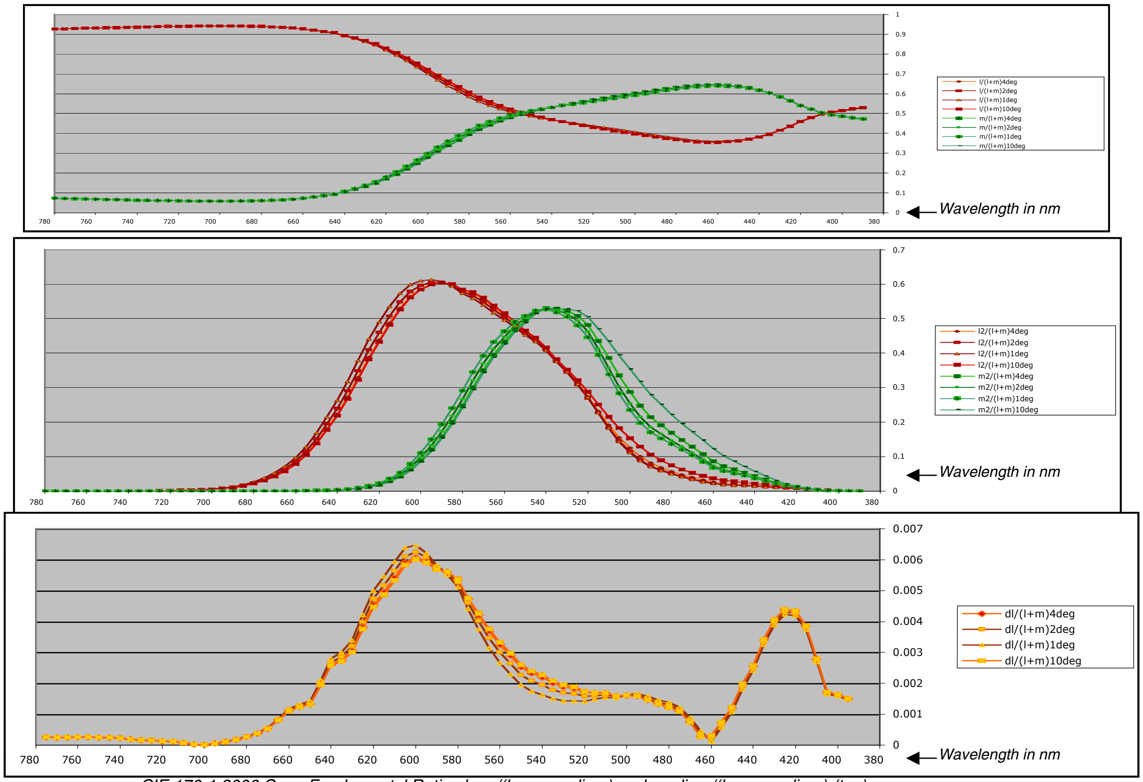
For this purpose, it is useful to consider the cone fundamental ratios long/(long+medium), medium/(long+medium), long^2/(long+medium), medium^2/(long+medium), medium/(medium+short), short/(medium+short), medium^2/(medium+short), and short^2/(medium+short). It is also useful to consider abs(delta(medium))/(medium+short) and abs(delta(long))/(long+medium). If these are each varied as a function of age and viewing angle using CIE 170-1:2006, the sensitive wavelength regions can be seen.

There are numerous sensitive regions, such as around 620nm, 570nm, 510nm, 470nm, and 430nm.

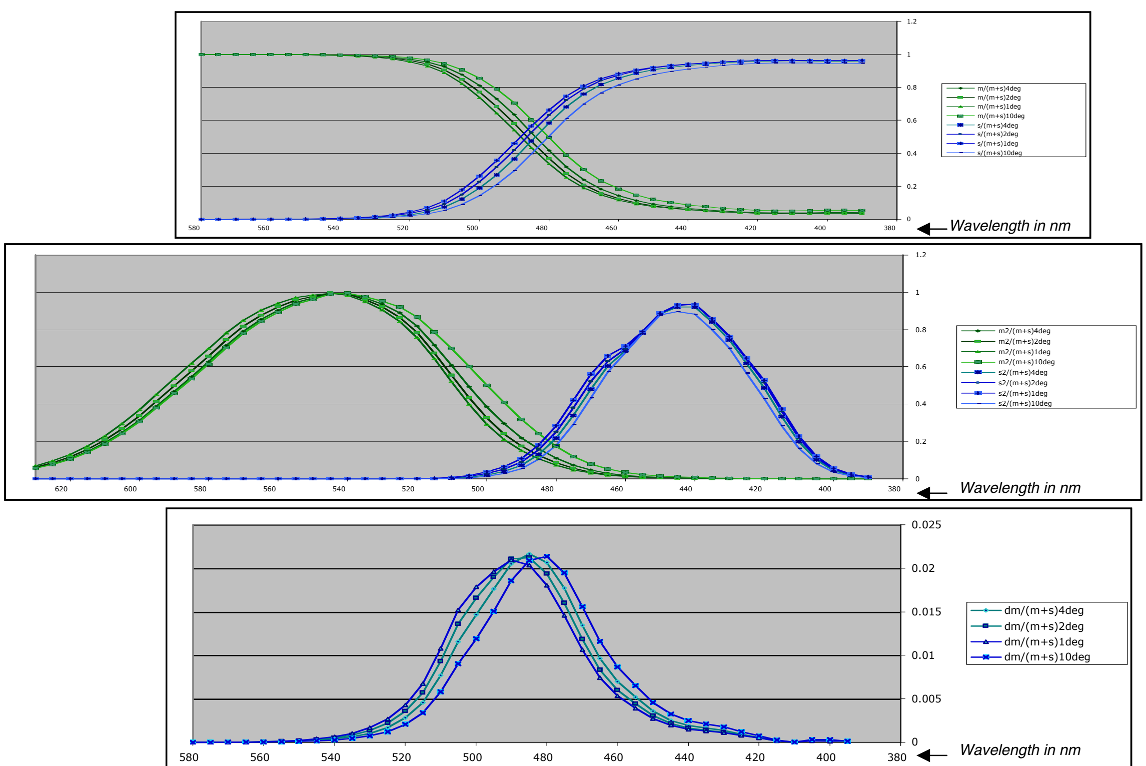
Any primaries (such as red, green, and blue) which are relatively flat as a function of spectral energy around these wavelengths will exhibit less viewer variation than primaries which have steep energy slopes or spikes around these wavelengths.



CIE 170-1:2006 Cone Fundamental Ratios medium/(medium+short) and short/(medium+short) (top) and medium^2/(medium+short) and short^2/(medium+short) (middle), and abs(delta(medium))/(medium+short) (bottom), showing variation as a function of age for 20years, 40years, 60years, and 80years for 2degrees. Note that the effect is large, since age differences are mainly due to a yellowing of the lens, thus significantly affecting medium vs. short.



CIE 170-1:2006 Cone Fundamental Ratios long/(long+medium) and medium/(long+medium) (top), and long^2/(long+medium) and medium^2/(long+medium) (middle), and abs(delta(long))/(long+medium) (bottom), showing variation as a function of angle for 1deg, 2deg, 4deg and 10deg for 35 yrs.



CIE 170-1:2006 Cone Fundamental Ratios medium/(medium+short) and short/(medium+short) (top), and medium^2/(medium+short) and short^2/(medium+short) (middle), and abs(delta(medium))/(medium+short) (bottom), showing variation as a function of angle for 1deg, 2deg, 4deg and 10deg for 35yrs. Note that the variation is large since the macular pigment is yellow, thus modulating medium vs. short.

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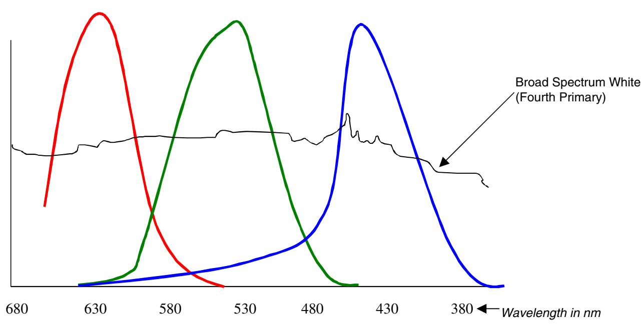
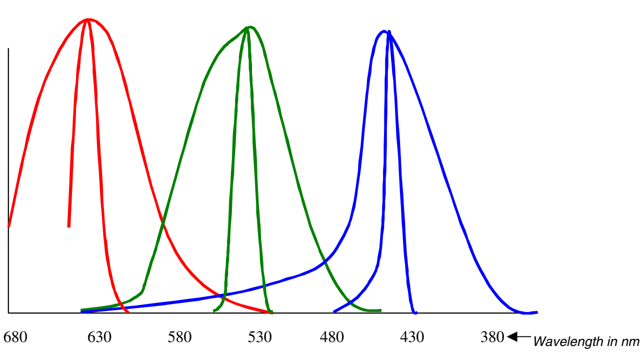
More Than Three Primaries

There are numerous ways to minimize variations when there are more than three presentation primaries. The first way is to add a fourth white primary to red, green, and blue primaries. If the fourth white primary is similar to E, then all desaturated colors can maximize E, and minimize the red, green, and blue primaries, thus minimizing variation. Remember that E has near minimum variation. Colors near the gamut edge would minimize E, but most typical desaturated colors would maximize E (or any broad-spectrum white), and thereby minimize color variation.



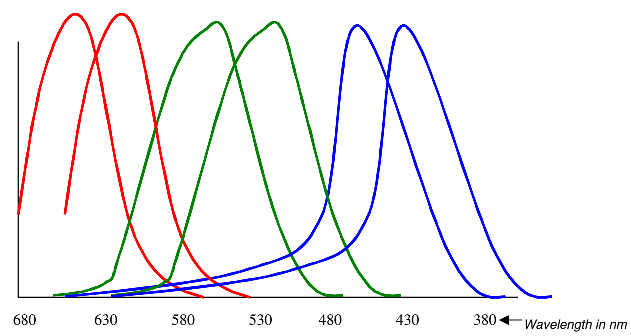
Red Green and Blue Primaries Plus a Broad Spectrum White (High Pressure 2kW Xenon Arc Lamp)

Then the next way is to have one, two, or three of the red, green, and blue primaries have wide primary versions and narrow primary versions. The narrow primaries provide the saturated colors, but all desaturated colors (most scene colors) would be made from the wider primaries. The wider primaries would preferably have minimal slope near the sensitive wavelengths.



Simultaneous Broad and Narrow Spectral Primaries, Sharing Common Peak Wavelengths

It is also possible to add wide-band yellow, green, or cyan primaries. The rule is always to maximize the wide-band primaries, and minimize the narrow-band primaries, in order to minimize variation.



Long and Short Wavelength Pairs Which Sum To Broad Red, Green, and Blue Primaries

Yet another way is to have numerous primaries, adding deep red, orange, yellow, cyan, and violet, for example. If all of these primaries yield a fairly broad spectrum white when turned on together, then such a configuration could be used to minimize variation. Further, the individual new primary colors, such as orange and yellow, need not rely on proportional sums of red and green, and thus could provide for reduced variation if such colors were also to be present in the mastering room. Also, the gamut can be extended by primaries in such intervening wavelengths, especially narrower primaries. If both wide primaries (for desaturated best match) and narrow primaries (for wider gamut) are available at one or more wavelengths, they can be optimized to always maximize the wider primaries (but yielding all narrow primaries for the most saturated colors).

Any number of configurations of multiple primaries can potentially be useful in minimizing variation, although broader primaries are best in all but the least-sensitive spectral regions.

Note that on-screen metamerism will not occur using this criterion of maximizing broad-spectrum emitters, since each color representation will utilize only one configuration of the amounts of primaries. However, the concept of on-screen metamerism is probably not useful in the context of varying color matching functions with respect to angle.

We Know More Than We Might Think

We usually know more than we might think about viewers and their individual and group spectral matching functions. For example, many movies have a clear target audience age. Some movie theaters have larger screens and less depth, and others smaller screens and longer depth, affecting the average viewing angle subtended by the whole image or by objects within the image.

As another example, it is easy to test color matches to characterize myself or my family members. It is even possible to understand the amount of yellow and the approximate location, shape, and depth function of the yellow macula lutea over the fovea. It is also a simple matter to convey an individual's information, or a small group's average information, to a computer display or a television set. Colors on a television in a retirement home could be optimized for the average viewer age and likely yield a significant improvement (the lens of the eye yellows with age).

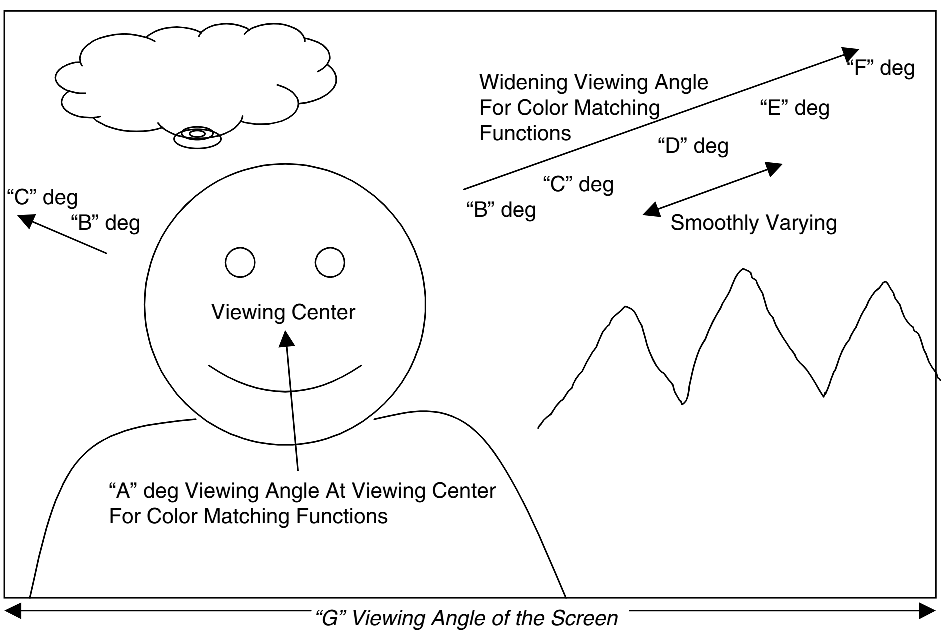
We also know, for nearly every scene, where the eye is likely to be looking, or whether the eye is expected to wander over the scene. The character who is speaking is likely to be the center of view. In this case, the angular extent of the macular yellow pigment could be utilized. Color matching functions similar to CIE 170-1:2006 set at 10deg, or CIE 1964, could be utilized to match the outer regions of the image, whereas CIE 170-1:2006 set at 1deg, or CIE 1931 would be more appropriate for the viewing center of the image (e.g. the speaking person's face).

A small amount of metadata about the viewing center, together with a simple indication of viewing location (individual or average) with respect to the screen of known size, as well as the identifying information of viewer(s) (individual or average) are quite practical to obtain and utilize.

Conclusion

Color science will continue to improve models such as CIE 170-1:2006 which allow a model of variation with age and viewing angle. Further, individual color matching information is not hard to obtain. Adding one or more additional primaries (beyond the first three) is quite feasible in both mastering and presentation. A knowledge of the mastering viewer(s) and the presentation viewer, or average of viewers, allows improved color matching. A maximization of broad-spectrum primaries, preferably including broad-spectrum white, helps minimize color variation. Lastly a knowledge of viewing conditions such as the location of a seat and the size of the screen, together with a knowledge of where a viewer is likely to be looking (or whether the eye is intended to wander the scene) can be further utilized in adapting to the affect of the yellow macular pigment.

The overall result of applying these principles could be improved color accuracy and precision, and a minimization of viewer (and left-right-eye) variation.



Viewing Angle	*G = 15 deg*	*G = 10 deg*	*G = 30 deg*	*G = 60 deg*
	A = 1.5 deg	A = 1 deg	A = 2 deg	A = 3 deg
	B = 3 deg	B = 2 deg	B = 4 deg	B = 6 deg
	C = 4 deg	C = 3 deg	C = 6.5 deg	C = 9 deg
	D = 6 deg	D = 4 deg	D = 9 deg	D = 10 deg
	E = 8 deg	E = 5.5 deg	E = 10 deg	E = 10 deg
	F = 10 deg	F = 7 deg	F = 10 deg	F = 10 deg

Example Use of Wider Viewing Angle For Color Matching Functions in Moving Away From the Viewing Center, Shown For Various Screen Sizes In the Field Of View (Viewing Angle of the Screen)

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References

[1] CIE 170-1:2006, Fundamental Chromaticity Diagram with Physiological Axes – Part 1

[2] Wyszecki and Stiles, Color Science, Concepts and Methods, Quantitative Data and Formulae, 2nd Edition, 1982, John Wiley and Sons

[3] Fairchild, Color Appearance Models, 2nd Edition, 2005 John Wiley and Sons

Author Biography

Gary Demos is the recipient of the 2005 Gordon E. Sawyer Oscar for lifetime technical achievement from the Academy of Motion Picture Arts and Sciences. He was a pioneer in the development of computer generated images for use in motion pictures, and in digital film scanning and recording. He was a founder of Digital Productions (1982-1986), Whitney-Demos Productions (1986-1988), and DemoGraFX (1988-2003). He is currently involved in digital motion picture camera technology and digital moving image compression. He is currently senior algorithm scientist for Lowry Digital. He is also CEO and founder of Image Essence LLC, which is developing wide-dynamic-range codec technology based upon a combination of wavelets, optimal filters, and flowfields.