Minimizing Color Variation

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

Several $x_{bar}$, $y_{bar}$, $z_{bar}$ color matching functions showing CIE 1931 $x_{bar}$, $y_{bar}$, $z_{bar}$ (2-degree), Vos 1970 version, and CIE 1964 10-degree version.

- $43\%$ $y_{bar}$ variation at 500nm
- $28\%$ $x_{bar}$ variation at 450nm
- $75\%$ $y_{bar}$ variation at 485nm
- $18\%$ $x_{bar}$ variation at 560nm
- $26\%$ $z_{bar}$ variation at 465nm

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The spectral map of television color systems, such as Rec709, is specified in terms of CIE 1931 x y chromaticity coordinates of the r,g,b primaries, where $x = X/(X+Y+Z)$ and $y = Y/(X+Y+Z)$.

The DCI/DC28 system for DCinema is specified in terms of X, Y, and Z. X, Y, and Z are amounts of $x_{bar}$, $y_{bar}$, $z_{bar}$.

Existing DCinema and Digital Television are defined in terms of CIE 1931. The spectral mapping in these existing color systems is via CIE 1931 $x_{bar}$, $y_{bar}$, $z_{bar}$.
Conversions from one set of color primaries to another are typically performed using a 3x3 matrix applied to linear light pixel values (gamma of 1.0).

Typical steps:

• Convert to RGB 4:4:4 if YUV and/or 4:2:2 or 4:2:0

• De-gamma (e.g. 2.22 down to 1.0) RGB values to linear light (note: “linear” is often mis-used as video gamma in post production)

• Matrix multiply pixel RGB values (requires >12bit precision, e.g. 16bits)

• Re-gamma (e.g. 1.0 to 2.22) RGB values

• Re-apply YUV and/or 4:2:2 or 4:2:0 if needed

• If DCinema, the pre-matrix or post-matrix (not both) values are XYZ, and the gamma is 2.6 (RGB only, no YUV nor 4:2:2 nor 4:2:0)
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Created via:

• Arbitrary spectral source on one side (e.g. 580nm yellow)

• Sum of narrow-band red, green, and blue on the other side (e.g. 630nm red, 540nm green, 450nm blue)

• Dial amounts of red, green, and blue for match (add to other side if needed for match, count as negative amount, e.g. red/cyan)

• Circle diameter subtends 2 degrees for CIE 1931, 10 degrees CIE 1964

• Match between 20 and 100 colors, and your color matching functions are known for a given subtended angle

Example:
yellow 580nm on left, an amount of red 630nm and green 540nm on right
CIE 1931 x_bar y_bar z_bar color matching functions:

• p_bar based upon 1923 Judd photopic luminance
  (which was flawed at that time, corrected in 1950’s by
  Judd, but still applied erroneously to CIE 1964 10deg).

• p_bar allows luminance-relative systems, such as CIE LAB,
  which have a paper reference white point, and colors
  described relative to that white point (thus not absolute
  hues independent of luminance, as provided by CIE LUV)

• p_bar not necessary for color matching, however, and is in
  many ways confusing (compared to direct use of cone
  fundamentals as color matching functions)

• x_bar, y_bar, z_bar are linearly transformable from cone
  fundamentals as inferred by 1931 r_bar, g_bar, b_bar measurements
  of Guild and Wright, based upon 7 + 10 observers, and different
  r,g,b, primaries. Flawed reconciliation of disparate primaries.
Normalization:

- CIE 1931 2deg and CIE 1964 10deg both normalized to “E”

- Chromaticity of “E” is thus 0.3333 x 0.3333 y in both CIE 1931 and CIE 1964

- Correlated color temperature (CCT), based upon CIE 1931, for “E”, is near D55

- Not necessary to normalize to “E” in order to use cone fundamentals as color matching functions. For example, older people see less blue, and thus need extra blue to match some colors, yielding higher area and higher peak for s_bar or z_bar.

- Open topic as to whether normalization to “E”, which results in equal area, should be applied or not to cone fundamentals when using them as color matching functions. Affects crossover regions.
Primary Spectra of Xenon DLP at ETC, used to master STEM (Christie)

Primary Spectra of 33” Reference HD CRT (Sony)

Primary Spectra of 60” Plasma (Panasonic)

Primary Spectra of 30” 2560x1600 LCD (Apple)

Primary Spectra of UHP-Lamp Single-Chip DMD (HP)

Primary Spectra of 55” 3840x2160 LCD (Toshiba)

Spectral Radiometry courtesy of Josh Pines, Jim Houston, Denis Leconte, Dan Sherlock, Lou Levinson, David Reisner, Ron Williams, and Jim Fancher (Using Photo Research PR650 and PR7xx Spectro-Radiometers)

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Spectral radiometry on the previous page was the work of the ASC technology committee (Adv Imaging and Display subcommittees)

Other interesting display/projector primary spectra to measure:

- SED/Spindht/Cold-Cathode/Phosphor
- White LED Backlight LCD (Sony 55” XBR8, Samsung 60”, HP 23” “Dream..”, others)
- RGB LED Backlight LCD (Sony color reference monitor prototype from last NAB, Chi-Mei prototype at SID, Brightside/Dolby prototype (white LED’s?), others)
- RGB (sequentially) LED lightsource single-chip DMD (i.e. mircomirror) retroreflective
- Grating Light Valve Projector (E&S/Sony)
- Laser Projectors/Displays (Mitsubishi retroreflective, others)
- Xenon and UHP Lamp Projectors LCOS (Sony 4k) and DILA (JVC 4k)
- Wide-gamut Plasma Displays (Panasonic 60” Prototype from last NAB, Pioneer 60” Kuro)
- Organic LED, OLED, (Sony 11”, Kodak 8”, Samsung 33” prototype at SID)
- Some LCD-type displays have a dark and a light for each primary (to simulate gamma and to increase bit depth), which may therefore yield slightly different primary spectra at different brightness levels (similar to multiple densities of paper printing inks)
CIE 170-1:2006

• Parametric as a function of subtended angle from 1deg to 10deg

• Parametric as a function of viewer age between 20yrs and 80yrs

• Based upon the 1959 Stiles and Burch 49-observer 10-deg data (which is an average over significant variations between the 49)

• Cone fundamentals only, no photopic luminance

• Cone fundamentals can be used directly as color matching functions (but do not support luminance-relative color systems such as CIE LAB, which depends upon y_bar being photopic luminance)

• Cone fundamentals not normalized to “E” (thus not equal area)

• Parametric Excel available from Mark Fairchild http://www.cis.rit.edu/fairchild/
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Variations Shown By CIE170-1:2006 As A Function Of Age

Variation of Cone Fundamentals in CIE 170-1:2006 as a Function of Age (20yrs, 40yrs, 60yrs, and 80yrs) for 2deg

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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), long\(^2\)/(long+medium) and medium\(^2\)/(long+medium) (middle), and abs(delta(long))/(long+medium) (bottom), showing variation as a function of age for 20years, 40years, 60years, and 80years for 2degrees.
CIE 170-1.2006 Cone Fundamental Ratios medium/(medium+short) and short/(medium+short) (top), and medium²/(medium+short) and short²/(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.
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.
The old paradigm:

One x_bar y_bar z_bar color matching function (CIE 1931) fits all

No provision for viewing angle subtended by the image

No provision for where a person is looking

No provision for the age of a person

No provision for variation among individuals

No provision for differences between the right and left eye

Color appearance models built upon CIE 1931 x_bar, y_bar, z_bar by making parametric adjustments, without modifying the underlying spectral map
In addition:

• There is a polymorphism of genetic components of the photopic (color) cone pigments which varies 1 or 2nm across all men and women for L and M cones.

• There are about 5% of males who are anomalous trichromats, where the L and/or M cone vary 5 or 10nm (towards each other). There will be approximately 10 males who are anomalous trichromats in an audience of 200 males.

• In low light (scotopic), our B&W brightness sensing function is a broad spectral sensor which peaks in cyan. Thus red objects appear dark brown or black in very low light. Thus, we are all tetrachromats in our sensing of low light such as movie (mesopic) viewing wherein dark parts of the image are scotopic (rods), light parts are photopic (seen in color by the cones).

• There is one documented case of a woman photopic tetrachromat, having two distinguishable L color channels.

• Your right and left eye may differ a small amount.
The yellow macular pigment varies in size, shape, and density distribution between individuals, and between the right and left eye. The yellow macular pigment is the source of 10deg (CIE 1964) vs. 2deg (CIE 1931) CMF’s, and the source of the angular subtense parameter of CIE 170-1:2006.

Wyszecki and Stiles page 90 Table 1(2.2.5) VII:

Yellow Spot (macula lutea):

“The yellow pigment permeates diffusely all layers from 4 to 9 (everything on the retina in front of the cones near the fovea). Thus pigmentation is very slight in the foveola, intense on the slopes and margin of the fovea, and gradually fades out beyond. However, it is visible in some preparations nearly up to the papilla (Polyak, 1941). The yellow spot is more extended in the horizontal than in the vertical meridian.”

Intense out to 10degrees, total outer diameter out to 17degrees
Proposed new paradigm:

• Take into account average viewer age, and the average viewing angle subtended by the image

• Take into account where the viewer is likely to be looking, or whether the eye is intended to wander the scene. Scene center of interest is often known (or can easily be determined with automatic eye tracking systems), and requires minimal metadata.

• Color matching functions can be parametric

• The parameters can be varied per frame, per viewing, or even within a frame (based upon where the viewer is likely to be looking)

• Cone fundamentals can be used directly as color matching functions

• Individual color vision information can be taken into account when known

• Can only improve color models such as CIECAM02 which are based upon CIE 1931, but perform whitepoint and other processing via simplified “bradford” matrix transform to approximate cone fundamentals (better to use actual individual and/or parametric average cone fundamentals including angle and age)
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)

<table>
<thead>
<tr>
<th>Viewing Angle</th>
<th>G = 15 deg</th>
<th>G = 10 deg</th>
<th>G = 30 deg</th>
<th>G = 60 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>A = 1.5 deg</td>
<td>A = 1 deg</td>
<td>A = 2 deg</td>
<td>A = 3 deg</td>
<td></td>
</tr>
<tr>
<td>B = 3 deg</td>
<td>B = 2 deg</td>
<td>B = 4 deg</td>
<td>B = 6 deg</td>
<td></td>
</tr>
<tr>
<td>C = 4 deg</td>
<td>C = 3 deg</td>
<td>C = 6.5 deg</td>
<td>C = 9 deg</td>
<td></td>
</tr>
<tr>
<td>D = 6 deg</td>
<td>D = 4 deg</td>
<td>D = 9 deg</td>
<td>D = 10 deg</td>
<td></td>
</tr>
<tr>
<td>E = 8 deg</td>
<td>E = 5.5 deg</td>
<td>E = 10 deg</td>
<td>E = 10 deg</td>
<td></td>
</tr>
<tr>
<td>F = 10 deg</td>
<td>F = 7 deg</td>
<td>F = 10 deg</td>
<td>F = 10 deg</td>
<td></td>
</tr>
</tbody>
</table>

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• Sufficient computing power exists in GPU’s to handle spectral processing with smooth interpolation of spectral mapping functions for each frame, and even for every region (even every pixel) within a frame. Much of the computation can be embodied within lookup tables, since the presentation primary spectra do not change, and the mastering primary spectra will not change often.

• Individual color matching functions (CMF’s) are easy to obtain and convey, thus embodying individual differences. It is a very small amount of metadata. It only need be updated infrequently (such as once per decade), once obtained. Could be carried/conveyed via a minuscule fraction of a USB stick, or via a small Bluetooth or IR card or keychain locket.

• Information about those setting color in a mastering suite can be conveyed (e.g. within the movie master’s metadata) to help in reproducing intended appearance (e.g. the Cinematographer’s and Colorist’s color matching functions).

• The three dimensional shape and density of the macular yellow pigment can be easily obtained for individuals, and applied as part of spectral conversion, applied independently or embedded within angularly-varying color matching functions. Alternatively, matching various angular sizes and shapes of patches can be used to infer macular yellow density and shape, directly yielding CMF’s for various horizontal and vertical angles.

• Wouldn’t everyone in color-critical industries such as Post-Production want to dial a few hundred rgb matches for a couple of hours every decade in order to improve the accuracy of colors being presented to them, and to improve the accuracy of colors which they prepare for presentation to others?
Linear amounts of three or more mastering primaries (e.g. R, G, and B) interpreted as weightings to the corresponding primary mastering spectra, summing to yield a mastering spectrum for every pixel.

Center of View

Angular Subtense of Screen

Age of Viewer(s)

Individual Information

Integrate spectra of presentation primaries with each Pixel's CMF

L_{presentation_{R,G,B}}, M_{presentation_{R,G,B}}, S_{presentation_{R,G,B}} (or other primary sets)

Create Transform (maximizing Broad Spectral Emitters, if more than three primaries)

Apply Transform

Amounts of Presentation Primaries (e.g. R, G, B) Having L_{source}, M_{source}, S_{source} amount of Pixel CMF

Integrate Pixel Mastered Spectrum with Pixel CMF

Determine Color Matching Functions (CMF's) for Each Pixel (as cone fundamentals)
Minimizing Color Variation Without Varying Color Matching Functions:

• When all television used RGB CRT phosphors, the similar emission spectra between displays resulted in only small adjustments being needed to adjust for spectral variation. Green and blue spectra were smooth, and only red contained a few broad spikes (typically).

• Color matching functions only become central to perceived color when emission spectra varies significantly. This is now the nature of displays and projectors, using a wide variety of spectral emission types, many with strong spectral spikes.

• Broad spectral emission color primaries result in less individual variation in the affect of applying color matching functions.
If more than three primaries:

The Equal Energy White ("E") flat emission spectrum is a white near D55 which is perceived as white by nearly everyone.

For desaturated but significant scene colors, such as face tones, the least variation is obtained if a fourth white primary similar to “E” is maximized at every pixel. Only saturated colors would minimize E.

Wide and narrow primaries can be mixed

Primaries can be shifted around the spectrum, including at yellow and cyan, to create broad spectral emission energy when the extra primaries are maximized when rendering desaturated colors.

Color matching functions can be varied with deterministic single solutions to more-than-three primary amounts by using the criteria of maximizing the breadth of energy in spectral emission composition.

These basic principles can be applied in our current situation wherein color models of human vision are continually improving.
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)
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Red Green and Blue Primaries Plus a Broad Spectrum White (High Pressure 2kW Xenon Arc Lamp)
Simultaneous Broad and Narrow Spectral Primaries, Sharing Common Peak Wavelengths
Long and Short Wavelength Pairs Which Sum To Broad Red, Green, and Blue Primaries
Long and Short Wavelength Pairs Which Sum To Broad Red, Green, and Blue Primaries

Adding Sharp Wide-Gamut Center, Between, and Beyond Primaries
Numerous Moderately Broad Primaries Across the Entire Visible Spectrum
Numerous Broad and Narrow Primaries Across the Entire Visible Spectrum
Summary:

• Two complementary and independent approaches to minimizing color variation:

  • Vary color matching functions to take into account additional viewer information during presentation (such as the angular subtense of the image, and the age of the viewer). This can be applied to existing RGB displays/projectors, as well as more than three primaries.

  • Maximize broad spectral emitters in displays and projectors (such as by adding a fourth broad spectrum white emitter similar to “E”, or by constructing wide-spectrum emission primary combinations). Arbitrary numbers of presentation and mastering primaries can be beneficially utilized.

• Do both when possible

• Significant improvement in color accuracy is possible (perhaps as much as an order of magnitude)
References:


“Physiologically-based color matching functions”, Dr Andrew Stockman, CIC16 Proceedings, pg 1, Nov 2008, Portland Oregon

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