Considerations for Evaluating Color Displays

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AAPM Annual Meeting 2021
Outline

- Defining Color
  - Pseudo vs. True Color
  - Photometry → Colorimetry
  - Chromaticity
  - Color Spaces
- Gray Tracking
  - AAPM TG270
  - AAPM TG196
- Tools, Software
- Ongoing Efforts
Color in Medical Imaging

### Pseudo Color Images
- Nuclear Medicine Fused Images
- Ultrasound Doppler Images
- MRI Elastography Images
- CT Perfusion Images

### True Color Images
- Digital Pathology Images
- Ophthalmologic Images
- Dermatologic Images

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Photometry

- Science of measuring light as it is perceived by the human visual system
- Luminosity weighting functions for radiant power as a function of wavelength
- Different weighting for different visual responses (luminance dependent)
**Colorimetry**

- Extending to colors, spectral weighting functions defined by CIE
  - 1931 Standard Colorimetric Observer
- Based on human observer studies looking at perceptible differences between colors

\[
X = \int_{\lambda} L_{x,\Omega,\lambda}(\lambda) \bar{r}(\lambda) d\lambda \\
Y = \int_{\lambda} L_{y,\Omega,\lambda}(\lambda) \bar{y}(\lambda) d\lambda \\
Z = \int_{\lambda} L_{z,\Omega,\lambda}(\lambda) \bar{z}(\lambda) d\lambda
\]

**Chromaticity**

- Separating color into brightness and chromaticity
  - "Quality" of color

\[
x = \frac{X}{X + Y + Z} \\
y = \frac{Y}{X + Y + Z} \\
z = \frac{Z}{X + Y + Z} = 1 - x - y
\]
Color Spaces

- Perceptible colors and displayable colors are not equal for most systems
- Color spaces define representable colors from all chromaticities
- RGB color models are most common
  - sRGB
  - Adobe RGB

The sRGB color space is likely the most common color space
- “Default” for most display systems
- Defined by three chromaticity coordinates (R, G, B) and a white point
- Also defined by specific luminance response and viewing conditions
  - Pseudo gamma 2.2
  - Not GSDF

<table>
<thead>
<tr>
<th>Chromaticity</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
<th>White</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>0.6400</td>
<td>0.3000</td>
<td>0.1500</td>
<td>0.3127</td>
</tr>
<tr>
<td>(y)</td>
<td>0.3300</td>
<td>0.6000</td>
<td>0.0600</td>
<td>0.3290</td>
</tr>
<tr>
<td>(Y)</td>
<td>0.2126</td>
<td>0.7152</td>
<td>0.0722</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Color Differences

- Describing the quantitative difference between colors
- CIE 1931 color diagram is not perceptually uniform
  - MacAdam ellipses
  - All colors within ellipse are indistinguishable
  - Based on human observer studies
- Efforts to transform for perceptual uniformity
  - CIE 1960 UCS
  - CIE 1976 UCS
Color Difference

- Color difference has been through many iterations
- General improvements to overall linearity for perceptual changes
- Increasingly complicated formula for higher precision
- For small differences, $\Delta(u', v')$ is relatively accurate

\[
\Delta(u', v') = \sqrt{(u'_1-u'_2)^2 + (v'_1-v'_2)^2}
\]

\[
\Delta E_{ab}^* = \sqrt{(L'_2-L'_1)^2 + (a'_2-a'_1)^2 + (b'_2-b'_1)^2}
\]

\[
\Delta E_{a^*b^*} = \sqrt{\left(\frac{\Delta L'}{K_L} + \frac{\Delta C_{a^*b^*}}{K_{C_a^*b^*}} + \frac{\Delta H_{a^*b^*}}{K_{H_{a^*b^*}}}\right)^2}
\]

\[
\Delta E_{a^*b^*c^*} = \sqrt{\left(\frac{\Delta L'}{K_L} + \frac{\Delta C_{a^*b^*}}{K_{C_a^*b^*}} + \frac{\Delta H_{a^*b^*}}{K_{H_{a^*b^*}}} + \frac{\Delta C_{a^*b^*}}{K_{C_{a^*b^*}}} + \frac{\Delta H_{a^*b^*}}{K_{H_{a^*b^*}}}\right)^2}
\]

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Gray Tracking and White Point

- Color of the light output by the display throughout the grayscale
- Evaluate by measuring the color difference
  \[ \Delta = \sqrt{(u_1' - u_2')^2 + (v_1' - v_2')^2} \]
- Compared against
  - Other display
  - Standard illuminant (e.g., D65)
  - Full brightness (TG196 methodology)

Standard Illuminants

- Standard illuminant (e.g., D65) should be used instead of correlated color temperature (CCT)
  - CCT is defined as multiple points in color space
  - The maximum difference between the points is large
Gray Tracking (TG270 Methodology)

- **Comparing two displays**
  
<table>
<thead>
<tr>
<th>Optimal Limit</th>
<th>Acceptable Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same Workstation</td>
<td>( \Delta (u', v') \leq 0.005 )</td>
</tr>
<tr>
<td>Same Image Review Chain</td>
<td>( \Delta (u', v') \leq 0.01 )</td>
</tr>
</tbody>
</table>

- **Comparing display to standard illuminant**
  
<table>
<thead>
<tr>
<th>Optimal Limit</th>
<th>Acceptable Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostic Display</td>
<td>( \Delta_{D65} (u', v') \leq 0.005 )</td>
</tr>
<tr>
<td>Modality, EHR, CS</td>
<td>( \Delta_{D65} (u', v') \leq 0.01 )</td>
</tr>
</tbody>
</table>
Gray Tracking (TG196 Methodology)

- AAPM TG196 Gray Tracking
  - Four metrics:
    \[ \tau_1, \tau_2, \tau_{1,\text{max}}, \tau_{2,\text{max}} \]
  - \( \tau_1 \) defines color difference from maximum luminance chromaticity
  - \( \tau_2 \) defines color difference from neighboring luminance chromaticity

\[
\tau_n = \frac{1}{N-1} \sum_{j=1-N}^{N} \Delta_n'(u', v')
\]
\[
\tau_{n,\text{max}} = \max(\Delta_n'(u', v')_k)
\]
\[
\Delta_1(u', v') = \sqrt{(u'_j - u'_{18})^2 + (v'_j - v'_{18})^2}
\]
\[
\Delta_2(u', v') = \sqrt{(u'_j - u'_{j-1})^2 + (v'_j - v'_{j-1})^2}
\]

Gray Tracking (TG196 Methodology)

- Good Tracking
  \[
  \tau_1 = 0.0013 \\
  \tau_{1,\text{max}} = 0.0021 \\
  \tau_2 = 0.0003 \\
  \tau_{2,\text{max}} = 0.0009
  \]

- Poor Tracking
  \[
  \tau_1 = 0.0096 \\
  \tau_{1,\text{max}} = 0.0161 \\
  \tau_2 = 0.0016 \\
  \tau_{2,\text{max}} = 0.0029
  \]
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Devices

- Colorimeters
  - Determines chromaticity by use of filters
  - May also report luminance or illuminance
- Spectroradiometers
  - Measures amplitude of light as a function of wavelength
  - Results combined with color matching functions

<table>
<thead>
<tr>
<th></th>
<th>Colorimeters</th>
<th>Spectroradiometers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output</strong></td>
<td>Chromaticity Coordinates</td>
<td>Spectral power by wavelength</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>Modest (generally a function of cost)</td>
<td>High</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Low-modest ($200-$1,000)</td>
<td>High ($5,000-$50,000+)</td>
</tr>
</tbody>
</table>
Software

- Vendors of medical displays often provide software for calibration and conformance testing
  - Color displays may allow for specified white point (based on CCT or chromaticity coordinate)
  - Significant deviation from “native” may result in other issues

Third-party software for verification and QC

pacsDisplay
- Developed at HFHS
- Calibrate displays to GSDF
- QC for displays
- Free and open source
- pacsdisplay.org
Software: pacsDisplay

- pdQC suite
  - Palette tool to “dial-in” any RGB level for evaluation
  - Meter tool to measure both luminance and chromaticity coordinates

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AAPM Efforts

- 2005 TG18 report
  - Limited to $\Delta(u',v')$ for the white point
- 2016 TG196 report
  - Defined gray tracking metrics
  - Compared accuracy between reference and field colorimeters
- 2019 TG270 report
  - Described both white point difference and TG196 metrics
  - Promoted gray tracking as part of routine QC
- TG322
  - Continuation of TG196 efforts
  - Currently stalled, may defer to ongoing IEC development

IEC Efforts

- Currently under a new work item proposal (NWIP-62635-3)
  - Part of TC 62/SC 62B/WG 51
  - Basic color accuracy evaluation methods
  - Limited scope
- Future work (62635-4?) would define more rigid limits, expectations
Conclusion

- Color displays are widely used throughout medical applications
  - Used to display both color and grayscale images
- Color display evaluation for medical applications still a work in progress
- Basic measurement of color values as part of routine QC as a first step

Thank you