Introduction

- **Color rendering** and the **color of illumination** are two key factors that support architectural lighting (e.g. retail lighting).
- However, presently accepted metrics used to describe color properties (CRI and CCT) often are not perfectly predictive of people’s assessments of illumination from a light source.
ASSIST recommends: Retail Lighting

- Guide to Light and Color in Retail Merchandising
- Recommendations for Specifying Color Properties of Light Sources for Retail Merchandising

www.lrc.rpi.edu/programs/solidstate/assist/recommends.asp

Color Rendering of Illumination
Color rendering: CRI+GAI approach

- No single metric can characterize color rendering, period.
  - Good color rendering by a light source depends on providing an optimum amount of color saturation (but without distortion; e.g., objects look like under daylight.)
  - Two-metric strategy with well established CRI plus GAI as adjunct is practical, predictive, and validated by human factors studies.

Color Appearance of Illumination
Light source color specification

- Correlated color temperature is the most used metric to specify light source color appearance
  - Based on light source chromaticity

![Graph showing light source color specification with CIE 1931 color space and blackbody locus]

![Table showing most useful light source characteristics]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Average Usefulness Rating</th>
<th>Standard Deviation</th>
<th>Number of Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color Rendering Index (CRI)</td>
<td>3.3</td>
<td>0.7</td>
<td>237</td>
</tr>
<tr>
<td>Correlated Color Temperature (CCT)</td>
<td>3.2</td>
<td>1.5</td>
<td>255</td>
</tr>
<tr>
<td>Color Saturation</td>
<td>3.2</td>
<td>1.5</td>
<td>255</td>
</tr>
<tr>
<td>Luminous Class</td>
<td>3.1</td>
<td>1.5</td>
<td>228</td>
</tr>
<tr>
<td>Color Consistency</td>
<td>3.7</td>
<td>1.5</td>
<td>228</td>
</tr>
<tr>
<td>Spectral Power Distribution (SPL)</td>
<td>2.4</td>
<td>2.2</td>
<td>236</td>
</tr>
<tr>
<td>Full Spectrum Index (FSI)</td>
<td>2.5</td>
<td>1.5</td>
<td>236</td>
</tr>
<tr>
<td>Brand Name</td>
<td>1.9</td>
<td>1.2</td>
<td>236</td>
</tr>
<tr>
<td>Emissivity Area</td>
<td>1.5</td>
<td>1.2</td>
<td>119</td>
</tr>
</tbody>
</table>

(Facing page: Lighting Research Center 8)
Goal

- To conduct a laboratory psychophysical experiment to investigate the subjective target chromaticity of white illumination from lamps of different CCTs.

Past research: Aperture mode

- Previous research has been conducted for aperture mode viewing (very small field of view, for signaling purposes).
- Past research also differs in background conditions and luminance, thus the “white points” in the literature are not applicable to illuminant mode viewing.

Experimental approach

- Illuminant mode: Viewing box with multiple light sources
  - Computer controlled to produce specific chromaticities and light levels
  - Active feedback provides temporal stability
  - Horizontal illuminance: 30 fc

- Six correlated color temperatures 2700-6500 K
- Seven chromaticities along each CCT line
- Subjective responses to four questions
  - Immediately after seeing the light source
    - Hue of light source: Green/yellow or purple/violet (hue choice)
    - Percent of hue relative to a pure white (hue %)
  - After 45 seconds adaptation
    - Hue of light source: Green/yellow or purple/violet (hue choice)
    - Percent of hue relative to a pure white (hue %)
- One viewing distance, 12-in from the opening of the box
Experimental approach

Questions:
• Hue choice
• Hue percent tint
Immediately and after 45 s adaptation

Results
Results

• For each CCT, a “white” point (i.e., a chromaticity of minimum tint) can be estimated for each of the four questions

• The four “white points” are close together for each CCT
  – White is white; does not change with time

• White points for CCT<4000 K are below the blackbody locus, and above the blackbody locus for CCT>4100 K
Iso-contours for judgments 45 sec after presentations*

- White points remain in the same place but the range -2% to +2% increases because of the chromatic adaptation that occurs over time.

- Sources appear less saturated, i.e., with less tint.


Discussion
Implications for practice:
Color appearance of the source

• Sources of the same CCT can have different hues/tints
• Change in CCT along the blackbody is not a dimension of whiteness
• Every CCT has a point of minimum tint
  – “White points” are not metamers
Implications for practice: 
Color appearance of the source

- Sources of the same CCT can have different hues/tints
- Change in CCT along the blackbody is not a dimension of whiteness
- Every CCT has a point of minimum tint
  - “White points” are not metamer
- Results can be applied in practice
  - People seem to prefer sources with less tint
- Light level matters
  - At higher light levels sources appear less tinted
  - At higher light levels, colors appear more saturated and the color of illumination closer to white

Implications for practice: 
Color rendering properties of the source

- CRI + GAI is practical and predictive
  - To ensure good color rendering, look for sources with CRI > 80 and 80 ≤ GAI ≤ 100
- Don’t just believe the numbers
  - Look at the color properties of these sources and compare to sources that are only high in CRI
Commercial Light Sources with $80 \leq \text{CRI} \leq 100$

### Table 2: Examples of light sources that meet the criteria for CRI (80) and GAI (80) and 100). (The inclusion or omission of any specific brand or product in this table is for didactic purposes only and does not constitute an endorsement by RPI or the Lighting Research Center.)

<table>
<thead>
<tr>
<th>Light source</th>
<th>Manufacturer</th>
<th>Product Model</th>
<th>CCT (K)</th>
<th>CRI</th>
<th>GAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CREE</td>
<td>D650W</td>
<td>5651</td>
<td>91</td>
<td>88</td>
</tr>
<tr>
<td>2</td>
<td>OSRAM</td>
<td>X-Rite Angel</td>
<td>4124</td>
<td>94</td>
<td>92</td>
</tr>
<tr>
<td>3</td>
<td>LGD</td>
<td>V-1010</td>
<td>5241</td>
<td>95</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>OSRAM</td>
<td>P300</td>
<td>4006</td>
<td>89</td>
<td>92</td>
</tr>
<tr>
<td>5</td>
<td>GE</td>
<td>T8O32K4125</td>
<td>4900</td>
<td>86</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Philips</td>
<td>FST600</td>
<td>4150</td>
<td>88</td>
<td>92</td>
</tr>
<tr>
<td>7</td>
<td>Philips</td>
<td>FST602</td>
<td>4150</td>
<td>88</td>
<td>92</td>
</tr>
<tr>
<td>8</td>
<td>Philips</td>
<td>FST606</td>
<td>4150</td>
<td>88</td>
<td>92</td>
</tr>
<tr>
<td>9</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>10</td>
<td>Philips</td>
<td>FST612</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>11</td>
<td>OSRAM</td>
<td>D650W</td>
<td>4006</td>
<td>89</td>
<td>92</td>
</tr>
<tr>
<td>12</td>
<td>Philips</td>
<td>Sunline P420C</td>
<td>4124</td>
<td>10</td>
<td>97</td>
</tr>
<tr>
<td>13</td>
<td>Philips</td>
<td>Sunline P420C</td>
<td>4124</td>
<td>10</td>
<td>97</td>
</tr>
<tr>
<td>14</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>15</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>16</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>17</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>18</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>19</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>20</td>
<td>Philips</td>
<td>Lumenator 1150</td>
<td>3966</td>
<td>10</td>
<td>95</td>
</tr>
</tbody>
</table>

**Implications for practice:**

**Class A light sources**

- Class A light sources
  - have a chromaticity on or near the “white” line, and
  - provide white illumination with CRI > 80 and $80 \leq \text{GAI} \leq 100$
- Hypothesis: Class A lamps will be more preferred than traditional lamps for general illumination

"The criterion of the scientific status of a theory is its falsifiability, or refutability, or testability."

— Karl Popper (1963)
Thank you!

Acknowledgements

- Sponsors of the ASSIST program for providing funding for this research

> Andrew Bierman
> John Bullough
> Mariana Figueiro
> Robert Hamner
> N. Narendran
> Martin Overington
> Howard Ohlhous
> Leora Radetsky
> Kate Sweater-Hickcox
> Rachel Taranta

---

Color rendering index (CRI)

- Measure of the degree of color shift objects undergo when illuminated by the light source as compared with the color of those same objects when illuminated by a reference source of comparable color temperature.

Gamut area index (GAI)

- In general, the larger the gamut area, the more saturated the color samples are and the easier it is to discriminate between them.