CIE Technical Committee 1-93: Calculation of self-luminous neutral scale

- Terms of Reference: To recommend a formula or computational method for an achromatic, neutral or grey scale for self-luminous (i.e. non-reflective) surfaces. (This computation complements CIE Lightness, L*, which serves a similar purpose for reflective surfaces.)
Three TC1-93 subtasks:

1. Recommend a formula or computational method.
2. Show that the formula works for calculation of self-luminous color difference.
3. Clarify the meaning of “neutral” in the self-luminous context of this TC.
CIE TC 1-93 Status Report

• January publication of CIE technical report 228:2018; Grey-scale Calculation for Self-luminous Devices (90€).

• Terms of reference have been fulfilled; all three subtasks have been successful. CIE ended the TC.

1. Whittle’s 1992 formula is recommended for grey scale (matching, thresholds, equal perceptible differences, similarity) on self-luminous devices
   a. Advantages for high contrast, high resolution and high luminance
   b. Fits classic photopic matching and threshold data, and new data relevant to surveillance or medical imagery
   c. Recommendation accounts for background luminance, and requires absolute (not device- or image-relative) luminance

2. Substitutes for L* in CIELAB, CIEDE2000; L_{OSA} in OSA-UCS
   a. Related publications by Oleari, Melgosa and others

3. The meaning of “neutral” is discussed and clarified.
   a. Annex of related terms, mostly from CIE ILV.
## Comparison of Three Photopic Self-Luminous Neutral Scales

<table>
<thead>
<tr>
<th></th>
<th>Media-relative L*</th>
<th>Whittle’s formula</th>
<th>DICOM GSDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalization</td>
<td>Peak luminance $Y_n$</td>
<td>Min(background, target) luminance</td>
<td>N/A</td>
</tr>
<tr>
<td>Independent Variables</td>
<td>Target luminance divided by $Y_n$, the “ratio principle”</td>
<td>Target &amp; background luminances</td>
<td>Target luminance</td>
</tr>
<tr>
<td>Top-end of scale</td>
<td>Corresponds to $Y_n$</td>
<td>Unlimited</td>
<td>4000 cd/m²</td>
</tr>
<tr>
<td>Expression of crispening</td>
<td>For L* = 50 in CIEDE2000</td>
<td>For any background luminance</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accounts for spatial scale</td>
<td>No</td>
</tr>
<tr>
<td>Multiple branches, one for each background</td>
<td>No</td>
<td>Yes, more shades for higher background luminances</td>
<td>No</td>
</tr>
<tr>
<td>Recognizes + versus - contrasts</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Accounts for spatial scale</td>
<td>No</td>
<td>Yes, k</td>
<td>No</td>
</tr>
<tr>
<td>Points of inflection</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
The ratio principle fails for high contrasts, achievable with self-luminous media but not with reflective media.
CIE recommends the Whittle (1992, Vision Research) Logarithmic Formula

- Endorsed by FAA Kingdom in his 2011 Vision Research review of lightness/brightness
- Whittle counted the number of Equal Perceptible Differences (nEPD) of suprathreshold grey scale (from the background) using the formula:
  \[ n_{EPD} = a \times \log_{10}(1+bW) \text{ where } W = \frac{\text{abs}(L-L_b)}{\text{minimum of } L, L_b} \]
  \( L_b = \) background luminance, \( L = \) target luminance
- nEPD between two contrasts is calculated as the difference between the contrasts’ nEPD from their respective backgrounds: \( n_{EPD_1} - n_{EPD_2} \)
- This formula is unique in its ability to model matching appearances of contrasts from different luminance backgrounds...see next two slides.
Calculating Matched Grays
From Carter and Brill, Journal of the Society for Information Display, 2014

2 experimentally matched targets, Heinemann 1961, 30’ disks in illuminated surrounds

Matching appearances imply equal Whittle nEPD from different background luminances (at least approximately).
Equal Perceptible Differences (EPD)
nEPD, 2-degree disks (k=0.055)

Disk Luminance cd*m^{-2}

Background (cd*m^{-2})

- 0
- 10
- 100
- 1000
- 10000
Heinemann’s (1972) cumulative gray-scale JND curves (Parameter on curves is log background luminance.)
Heinemann JNDs per cd*m\(^{-2}\)
“...the simplest and most precise mathematical description” of nEPD

L is target luminance, $L_b$ is background luminance

$L_{\text{min}}$ = the minimum of L or $L_b$

$\Delta L = |L - L_b|$

The number of EPD between $L_b$ and L

$n\text{EPD} = a \log(1 + bW)$, $b = 6.58$

Two cases (e.g., negative contrast case is shown in figure; i.e., L = $L_{\text{min}}$):

For negative contrast: $W = (1-k) \Delta L / (L_d + L_{\text{min}} + k \Delta L)$; $a = -7.07$

For positive contrast: $W = (1-k) \Delta L / (L_d + L_b - L_{\text{min}})$; $a = 8.22$

where $L_d = .39 \text{ cd/m}^2$ represents light perceived in darkness when adapted to photopic conditions and $k$ (0<$k$<1) represents intraocular light scattering and grows with decreasing subtense.

For $k \sim 0$ (i.e., large subtense) and $(L,L_b) >> (0,0)$, $W \sim \Delta L / L_{\text{min}}$
Explaining $0<k<1$ in the Whittle formula: **intraocular scattering** reduces image $\Delta L$ to retinal $(1-k)\Delta L$

- **Light** from a positive contrast (a target more-intense than its background) is scattered out of the target by the intraocular media:

- **Light** from the background of a negative contrast (a target less-intense than its background) is scattered into the target by the intraocular media:

Chad McKee calculated $k$ is the same for + or – contrasts of the same subtense and shape.
<table>
<thead>
<tr>
<th>Visual Subtense of Contrast</th>
<th>E with Stroke = 20% of subtense</th>
<th>Disk</th>
<th>Line with 2’ stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 mm Pupil dia.</td>
<td>5 mm</td>
<td>2.5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>2°</td>
<td><strong>k=0.0252</strong></td>
<td>0.0174</td>
<td>0.0588</td>
</tr>
<tr>
<td>1°</td>
<td>0.0419</td>
<td>0.0448</td>
<td>0.0563</td>
</tr>
<tr>
<td>30’</td>
<td>0.0667</td>
<td>0.0675</td>
<td>0.0536</td>
</tr>
<tr>
<td>15’</td>
<td>0.1182</td>
<td>0.2055</td>
<td>0.0782</td>
</tr>
<tr>
<td>7.5’</td>
<td>0.2554</td>
<td>0.3769</td>
<td>0.1469</td>
</tr>
<tr>
<td>Visual Subtense of Contrast</td>
<td>E with Stroke = 20% of subtense</td>
<td>Disk</td>
<td>Line with 2’ stroke</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------------------</td>
<td>------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Pupil diameter:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2°</td>
<td>2.5 mm</td>
<td>5 mm</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>1°</td>
<td>24.4 EPD (0-100 cd*m^-2)</td>
<td>25.2</td>
<td>22.2</td>
</tr>
<tr>
<td>30’</td>
<td>23.1</td>
<td>22.9</td>
<td>22.3</td>
</tr>
<tr>
<td>15’</td>
<td>21.8</td>
<td>21.7</td>
<td>22.4</td>
</tr>
<tr>
<td>7.5’</td>
<td>19.9</td>
<td>17.7</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>16.7</td>
<td>14.5</td>
<td>19.0</td>
</tr>
</tbody>
</table>
A surround highlight preserves retinal $\Delta L$ because it increases background and target luminances almost equally.
Haploscopic separation prevents light from scattering between left and right images; observers wore a 2 mm artificial pupil.

\[ I = 0 - 1266 \text{ cd/m}^2 \]

\[ R = 3.18 \text{ cd/m}^2 \]

Adjust \( T \) to match \( R \)

30'

9, 3, 1, 0.5, 0.166, or 0 degrees
Three subtasks:

1. Recommend a formula or computational method.

2. Show that the formula works for self-luminous color difference calculation.

3. Clarify (and perhaps standardize) the meaning of “neutral” in the self-luminous context of this TC.
Using Whittle’s formula in self-luminous color difference

• Several authors have shown that the Whittle formula fits as well as L* in CIELUV and CIELAB.
• Oleari and Melgosa showed Whittle’s formula fits full gamut of OSA-UCS.
• Melgosa showed Whittle formula fits in CIEDE2000, using many data sets.
Three subtasks:

1. Recommend a formula or computational method.

2. Show that the formula works for self-luminous color difference calculation.

3. Clarify the meaning of “neutral” in the self-luminous context of this TC.
The Meaning of Self-luminous Neutral

• Adopted Bosten, Beer and MacLeod (JOV, 2015) chromaticity coordinates for neutral.
  – Close to status-quo neutral of D65
  – Presumed, based on preponderance of evidence, to be the same for all levels of luminance.
• Adopted Fairchild’s calculation of chromatic adaptation to a self-luminous display.
• A glossary of self-luminous neutral terminology is provided in the TC1-93 report.
nEPD = \log(1 + bW) \ldots \text{What’s It Good For?}

- Derived from a self-luminous display; applies to self-luminous contrasts from background.
- Recognizes positive or negative contrasts from background.
- Produces a neutral scale with desired nEPD in any given range of luminance.
- Predicts what luminances match (on different backgrounds).
- Derivative predicts threshold \( \Delta L \) at any \( L \) and \( L_b \).
- Accounts for subtense effects (smaller is darker).
- Models crispening and black phenomena.
  - Theoretically fruitful: optimum background luminance to maximize nEPD, histogram specification to match human visual discrimination.
  - Is good for modeling discriminations during visual search.
$k = 0.0$, i.e., for contrast of practically infinite visual subtense; similar earlier graph was for $k = 0.055$, 2-degree subtense.
<table>
<thead>
<tr>
<th>k</th>
<th>Equation for optimum $L_{b}$ between 0 and $L_2$ cd/m²</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$L_{opt} = 0.4624 L^2$</td>
<td>$&gt;0.99995$</td>
</tr>
<tr>
<td>0.055</td>
<td>$L_{opt} = 1.6588 L^2^{0.5328}$</td>
<td>0.9989</td>
</tr>
<tr>
<td>0.1</td>
<td>$L_{opt} = 1.2947 L^2^{0.5244}$</td>
<td>0.9994</td>
</tr>
<tr>
<td>0.25</td>
<td>$L_{opt} = 0.7781 L^2^{0.5142}$</td>
<td>0.9998</td>
</tr>
<tr>
<td>0.4</td>
<td>$L_{opt} = 0.5269 L^2^{0.5048}$</td>
<td>$&gt;0.99995$</td>
</tr>
<tr>
<td>0.55</td>
<td>$L_{opt} = 0.3746 L^2^{0.4644}$</td>
<td>0.9985</td>
</tr>
</tbody>
</table>
Calculating Discriminability of Grays (Visual Search)

As the gray-scale difference (delta nEPD) between targets and distracters increases, frequency of eye movements fixating distracters decreases.
Limitations of Whittle’s Formula:
It models retinal & ocular processes, not cortical

• Doesn’t include (possible) source illuminant
  – Geld Effect, Adelson Illusion, meaning of “neutral”

• Doesn’t model 3D appearance
  – Shadows, veil, transparency, depth planes

• Doesn’t account for Gestalt “belongingness”
  – Benary Cross, White’s Illusion

! Many applications are 2D without an implied source of illumination.

! A later comprehensive model including “cortical” factors will need a retinal-ocular component.
Target JNDs from 3 to 111 cd/m²
Whittle Formula Applied to Bipartite Threshold Data, formerly successful with periodic and disk discriminations

Analysis and plotting by Thorstein Seim, personal communication, 2015

Avramopoulos bipartite data provided by Klaus Richter

Whittle’s formula, \( \log(W) \), see page 1502 of Whittle 1992, Vision Research for a similar plot re suprathreshold disks
Plot of independent slope estimates
78 combinations of target and background luminances (> 5 log units)

+ signifies positive contrast, else negative
Dark symbols: background < 23 cd/m²
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