New Method for Specifying Color-Rendering Properties of Light Sources Based on Feeling of Contrast

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Flow chart

Feeling on contrast

FCI method

Comparison between FCI and $R_a$

Application of FCI
Proposed method

- Feeling of contrast
  - Most important characteristic on color-rendering
  - $R_a$ method
    - Inadequate estimation
  - FCI method
    - Equal feeling of contrast on various light source
  - Using FCI together with $R_a$
    - Clarified color-rendering on light source
Visual clarity

- Affected by color-rendering of light source
- Using $R_a$ method
  - Inadequate estimation
- Closely related to feeling of contrast
  - Between object color under illumination
- Estimation of different color-rendering
  - Using four-color combination
    - Red, Yellow, Green, Blue
◆ New index FCI

- Simple transformation of gamut area
  - CIELAB space by four-color combination
- Same prediction as original on feeling of contrast
- Simple of tedious computational procedure
- White LED light source
  - Application at various light
  - Composed red, green, blue LED chips
  - High visual clarity
  - Inadequate $R_a$ method
  - Evaluated quantitatively by FCI
Summary of authors previous studies on feeling of contrast

- Summarized procedure and result
  - Based on visual clarity of object color under illumination
    - Closely related feeling of contrast for same observing condition
    - Between visual clarity and feeling of contrast
      - Using two color and four color combination under illumination
  - Effectively assessed color-rendering
    - Using four color combination
      - Highly saturated colors
  - Effect of visual clarity
    - Estimated by assessing feeling of contrast
      - Using four-color combination
– Illuminance for equal feeling of contrast
  • Under any test illuminant
  • Using gamut area
    – Component color of four-color combination
    – Summing area of two triangles
      » Consisting of red, yellow, green
      » Consisting of red, blue, green
  • Computing procedure
    – gamut area
      » Computed by area sum of two triangles
      » Reference illuminant
      » D65, 1000lx
Fig.1. The arrangement of each component color of the selected four-color combination and their Munsell notations.
– Using test illuminant instead of reference illuminant
  » Changing test illuminant
  » Corresponding gamut area by same computational procedure
– Based on computation
  » Interpolation for equality of gamut area
  » Between reference and test illuminant
– Predicted test illuminant for equal feeling of contrast
  » Test illuminant for equal gamut area
  » Equal visual clarity on same test illuminant
– Obtained illuminance ratio
  » Degree of feeling of contrast of test illuminant to reference
  » Complicated computational procedure
Present improved method

- Simplified computation for index of feeling of contrast
  - CIELAB instead of nonlinear color-appearance model
  - Gamut area under same illuminance
    - Irrespective of test and reference illuminant
  - Exception of complicated interpolation
Proposal of a simplified method for deriving a new index FCI

◆ Concept of observed index on feeling of contrast
  – Using two lamp with different color-rendering property
    • Constant Reference illuminant and reference illuminance level
    • Adjustable test illuminant and test illuminance level
    • Determined test illuminance
      – Same feeling of contrast as reference illumination
    • Illuminance ratio
      – Degree of feeling of contrast for test lamp
      – Illuminance ratio higher than unity
        » Degree of feeling of contrast for reference illuminant higher than
        test lamp
      – Illuminance ratio smaller than unity
        » Degree of feeling of contrast for reference illuminant smaller than
        test lamp
– FCI of test lamp

\[
FCI(\text{observed}) = A_c \times 100 = \left( \frac{E_r}{E_i} \right) \times 100
\]  

(1)

Where \( E_r \) is reference illuminance value, and \( E_i \) is test illuminance value for equal feeling of contrast of the test to reference.

• Given test illuminance value by observation

◆ Original prediction method of FCI

– Predicted test illuminance

\[
FCI(\text{predicted}) = \left[ \frac{E_r}{E_i(\text{predicted})} \right] \times 100
\]

(2)

• Using predicted test illuminance for equal gamut area
• Complicated computation
• Practical inability
Simplified method for deriving FCI

- Simplified method for predicting FCI value

\[
FCI(\text{new}) = \left[ \frac{G(T, E_t = 1000\text{lx})}{G(D65, E_r = 1000\text{lx})} \right]^p \times 100
\]  

Where \( G(T, E_t = 1000\text{lx}) \) corresponds to the gamut-area value on the four-color combination under the test illuminant \( T \) at illuminance \( 1000\text{lx} \), 

\( G(D65, E_r = 1000\text{lx}) \) to that for the same four-color combination under the reference illuminant \( D65 \) at reference illuminance \( 1000\text{lx} \), and 

\( p \) is an unknown contrast to be determined. It must be noted that, in the computation, the test illuminance is always kept at the same as the reference illuminance \( 1000\text{lx} \).

- Determined index FCI

\[
FCI = \left[ \frac{G(T, E_t = 1000\text{lx})}{G(D65, E_r = 1000\text{lx})} \right]^{1.5} \times 100
\]
– Calculated by computational procedure

**Step 1**: Selection of four-color combination

### Table 1. Spectral reflectance data of each component color (red, yellow, green, blue) of the four-color combination in Fig.1.

<table>
<thead>
<tr>
<th>Wavenumber (nm)</th>
<th>Red</th>
<th>Yellow</th>
<th>Green</th>
<th>Blue</th>
<th>Red</th>
<th>Yellow</th>
<th>Green</th>
<th>Blue</th>
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<td>0.750</td>
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</table>
• Step 2 : Calculation of tristimulus values of each component color of the four-color combination under test light source
  – Calculation of tristimulus in test illuminant
    » Spectral distribution data of test illuminant
    » Spectral reflectance data of each component color

• Step 3 : Determination of the tristimulus values of the corresponding colors under reflectance illuminant D65
  – Using CIE chromatic adaptation transform
  – 1000lx of value of test illminance
  – 20 of luminance factor and reflectance
• Step 4 : calculation of gamut area \( G(T, E_t =1000lx) \) for test illuminant (T)
  – Tristimulus value of corresponding color
    » Converted component color into CIELAB
  – Gamut area \( G \)
    » Computed by area sum of two triangles

• Step 5 : calculation of gamut area \( G(D65, E_r =1000lx) \) for reference illuminant D65
  – Tristimulus value of each component color
    » Calculated spectral distribution data and spectral reflectance data
    » Converting tristimulus into CIELAB
  – Gamut area \( G \)
    » Computed by area sum of two triangles
Fig.2. The gamut area in the three-dimensional space, consisting of CIELAB coordinates \((L^*, a^*, b^*)\) of each component color \((R, Y, G, B)\) of the four-color combination under illumination.
• Step 6 : calculation of FCI
  – Based on $G(T, E_t = 1000\text{lx})$ and $G(D65, E_r = 1000\text{lx})$

Fig. 3. Relationship between the value of FCI by Eq.(4) and that of FCI (observed) by Eq.(1) for 20 lamps.
Comparison between FCI and general color-rendering index $R_a$

Table 2: correlated color temperatures (K), general color rendering indices ($R_a$), and FCI by Eq. (4) for 20 kinds of lamps.

<table>
<thead>
<tr>
<th>No.</th>
<th>Lamp</th>
<th>$K$</th>
<th>$R_a$</th>
<th>FCI Eq. (4)</th>
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Fig. 4. Relationship between $R_a$ and that of FCI by Eq. (4) for each of 20 lamps.
◆ Difference in use between FCI and $R_a$

- Index $R_a$
  - Changing from reference to test illuminant
    - No information about direction of color shift on any color
      » Object color of test lamp more saturated or not

- Index FCI
  - Giving effect of feeling of contrast
    - Becoming high FCI value of test lamp
      » Increasing perceived chroma of object color under illumination
– Artificial light source
  • Classified based on rank of $R_a$ value
    – Acceptable above 60 and preferable above 80
  • Violation with above rank rule on $R_a$
    – Requiring displayed object color more colorful and attractive
    – Increasing illumination
Related topics

◆ Application of FCI to white LED light source
  – White LED light source
    • Composed of red, green, blue LED chips
    • High visual clarity or high FCI value
    • Measuring spectral power distribution (SPD) of various LED
      – Obtained SPDs data
      – Same chromaticity with correlated color temperature (5000K)
    • Impossibility of appropriate estimation
      – Using $R_a$ value
      – Using new index FCI together
Fig. 5. Two kinds of spectral power distributions of three-chip white LED light sources with the same correlated color temperature (5000K).
Use of CIECAM02 for FCI

- CIECAM02
  - Similarly computed FCI
  - Color appearance space \((J, a_c, b_c)\) in CIECAM02
  - Using instead of CIELAB color space
  - CIE chromatic adaptation transform

\[
FCl(CAM02) = \left[ \frac{G_{Jab}(T)}{G_{Jab}(D65)} \right]^{1.5} \times 100
\]

Where \(G_{Jab}(T)\) corresponds to the gamut-area value on the four-color combination under the test (T), and \(G_{Jab}(D65)\) to that for the same four-color combination under the reference illuminant (D65) in color space \((J, a_c, b_c)\)
**Fig. 6.** Relationship between FCI by Eq. (4) and FCI (CAM02) by Eq. 5 for 22 lamps.
◆ Relationships between feeling of contrast and each of other corresponding assessing methods
  – Several terms
    • Corresponding to visual clarity of test illuminant
    • Brightness sensation, feeling of contrast, preference, feeling of pleasantness
– Definition about several terms

• Visual clarity of test lamp
  – Meaning between various object color under illuminant
  – Higher feeling of clear distinction between object colors

• Corresponding feeling of contrast object color
  – High feeling of clear distinction between object color
    » High feeling of contrast

• Increasing brightness sensation
  – Raising saturation of any object color
  – High visual clarity of various object color
    » Increasing saturation of object color
• High feeling of pleasantness of various object color
  – Increasing saturation
    » Especially red and green hue

– Assessing method of color-rendering method
  • Made between CIE $R_a$ method and FCI
  • Nice observation
Summary article

- Proposed New index FCI
  - Estimating effect of feeling of contrast under any light source
  - Illuminance ratio
    - Equal feeling of contrast on various light source
- Derived FCI
  - Using simple transformation of gamut area
  - Constituted by four combination in CIELAB color space
– Concept of FCI and $R_a$
  • Completely different from each other
  • Using FCI with $R_a$
    – clarified color rendering capability of light source

– White LED light source
  • High FCI value
  • Using FCI with $R_a$
    – Improved estimation

– Represented FCI
  • Using CIECAM02 instead of CIELAB