Light Emitting Diode

Color Rendering Evaluation for LEDs for General Lighting

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1. Overview

When purchasing luminaires, various aspects are considered, such as color, brightness, power consumption, running cost based on the life of the luminaire, etc. One aspect that has received more attention recently is "color rendering".

Color rendering is a measure of how faithfully the colors of objects can be reproduced; the higher the color rendering properties of a light source are, the more accurately the light source can reproduce the colors. In the past, LEDs were said to have low color rendering; however, in recent years, due to technical improvements such as development of better phosphors there are now many LEDs that have high color rendering. An increasing number of houses and shops are using luminaires with LEDs that have high color rendering or special rendering[1] to make food look delicious, make skin look beautiful, etc. It is important to select luminaires with color rendering properties that are appropriate for the intended application in order to use the lighting effectively.

Nichia offers LEDs with a wide variety of color rendering options to meet the needs of our customers. This application note provides information on Nichia's lighting LEDs and their color rendering properties.

2. Color rendering

People recognize colors by receiving the light reflected on an object surface with the eye (i.e. retina). This means that how a color looks depends on the light that illuminates the object.

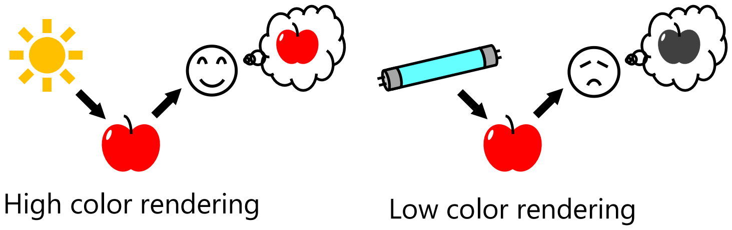


Figure 1. How color rendering affects how an object

"Color rendering" is a measure of how faithfully the true colors of an object can be reproduced when it is illuminated by a luminaire. The true color is the color of an object when it is illuminated by a reference light source (i.e. a light source whose light has properties similar to those of sunlight) defined by a standard. The higher the color rendering of that light source is, the more faithfully the true colors are reproduced. However, when a light source with low color rendering has poor color fidelity it presents colors that are quite different from the true colors. The phenomenon of colors appearing differently under indoor lighting and sunlight can be attributed in part to the low color rendering properties of the luminaires.

There are several measures to evaluate color rendering and they are specified in international standards. Among those, the color rendering index (CRI) defined by the International Commission on Illumination (CIE) is currently the most commonly used standard and is used by many lighting-related companies to describe the color rendering of luminaires. In Japan, a Japanese Industrial Standard JIS Z8726 was established based on the CIE standard. Recently, the Illuminating Engineering Society (IES) established the IES-TM-30 standard in 2015 as a new evaluation method for color rendering. The details of those standards are provided in Sections 4 and 5.

Note:

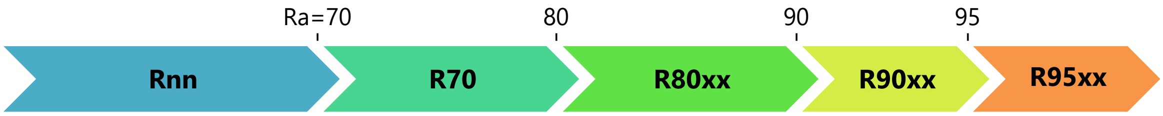
[1] The LEDs with special color rendering may not have high color rendering; those products were developed to make particular colors look better. For information on Nichia's LEDs with special color rendering, refer to the following page.

3. The color rendering ranks of Nichia's LEDs

In addition to sorting the LEDs for color and luminous flux, Nichia also sorts some LEDs by their color rendering index (CRI). Nichia uses the average color rendering index (Ra) and the special color rendering index (Ri) values of the CRI to describe the color rendering properties of those LEDs (See section 4). Figure 2 shows the typical color rendering ranks of Nichia's LEDs[2].

For most LEDs, the ratio of the light in the red and blue wavelength bands need to be increased in order to improve the color rendering properties. Since the human eye has low spectral sensitivity to those wavelengths, those LEDs tend to look dimmer (i.e. lower luminous flux). That means there is a tradeoff between the color rendering and the brightness. When selecting LEDs, it is not necessarily the case that those with the highest color rendering properties are the best. Instead, they should be used according to the color rendering performance required for the chosen luminaire and application.

Since different phosphors are used for different color rendering ranks, the appearance of LEDs from the same series and with the same color rank may look different when they have different color rendering ranks (i.e. different colored encapsulating resin).



- Rnn

  No rank specified. Low color rendering and high efficacy.
- R70

  Ra≥70.
- R80xx

  Ra≥80. The ”xx” is the minimum CRI R9 value, which corresponds to the red test color sample[3].
- R90xx

  Ra≥90. The "xx" is the minimum CRI R9 value, which corresponds to the red test color sample[3].
- R95xx

  Ra≥95. The "xx" is the minimum CRI R9 value, which corresponds to the red test color sample[3].

Figure 2. Color rendering ranks of Nichia's LEDs

Note:

[2] Not all Nichia LEDs have a color rendering rank. For information on which Nichia LEDs have color rendering ranks, contact a local Nichia sales representative.

[3] Example 1: R8000→Ra≧80, R9≧00

Example 2: R9050→Ra≧90, R9≧50

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Reference: Special CRI ranks: Rfx00 & Rfx0f (Optisolis™)

With Nichia's original phosphor technology, the LEDs with these ranks have a wavelength that is as close to that of a reference light source as possible. They have high CRI values not only for the Ra test color samples but for all the CRI test color samples, and they can reproduce the colors of objects accurately. For further information, contact a local Nichia sales representative.

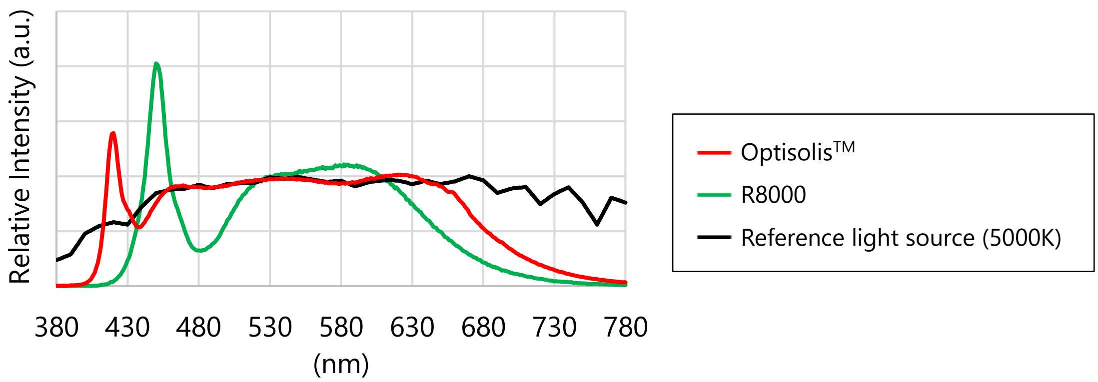

Figure 3. Example wavelength of the Optisolis™ LED[4]

Table 1. Example CRI values of the Optisolis™ LED[4]

Rank	Min. Value							
	Ra	R9	R10	R11	R12	R13	R14	R15
Rfc00 (sm50)	95	85	85	90	85	90	90	90

Reference: Special CRI ranks Rs020, Rs030, Rs075

The LEDs with these ranks may not have a high CRI Ra or Ri value. They have special color rendering properties to make particular colors look better (e.g. the reds in meat, greens in vegetables, white of clothing, etc.). For further information, see the application note "SP-QR-C2-210310 : Design Considerations for COB LED-Based Spotlights".

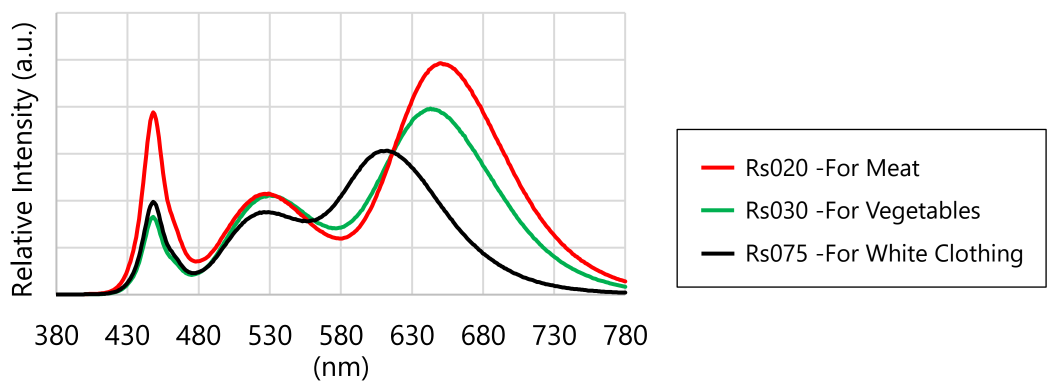

Figure 4. Example wavelengths for the special CRI ranks[5]

Note:

[4] These are the typical values of a part number NF2W757G-F1 (Optisolis™) LED at a color temperature of 5000K.

[5] These are the typical values of part number NJCWS024Z-V1 LEDs in these special CRI ranks in color temperatures between 3000-3500K.

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4. CIE13.3 Color rendering index (CRI)

4.1. Standards

CRI was defined by CIE in "CIE13.3-1995 Method of Measuring and Specifying Color Rendering Properties of Light Sources" and is currently the most commonly used standard. Many lighting-related companies use the CRI values obtained with this standard to advertise the color rendering performance of their products. Some standards that were established for specific luminaire applications specify CRI values as a requirement. In Japan, JIS Z 8726 "Evaluation method for the color rendering of light sources" was established based on the CIE standard[6]. This JIS standard is basically the same as the CIE CRI except that in addition to the R1 to R14 test color samples, it has R15 (Asian skin color).

4.2. CRI

In the CRI standard, the average color rendering index (Ra) and the special color rendering index (Ri) values are calculated from the color difference between the test color samples when viewed under the reference light source and the test light source. These values are used to describe the color rendering performance of a light source. For the evaluation method, see Section 4.4.

4.2.1. Average color rendering index (Ra)

Ra is a commonly used index in the lighting industry to describe the color fidelity of the general colors of objects. The better the color rendering performance of a light source is, the higher the value will be, with 100 as the highest Ra value possible. If the Ra of a test light source is 100, that means the source has the same wavelength as that of the reference source.

4.2.2. Special color rendering index (Ri)

Ri is the index used to describe the color fidelity of the particular colors of objects. Each i corresponds to the test color samples R1-14 (15). As with the Ra, the better the color fidelity of a light source is, the higher the value will be, with 100 as the highest Ri value possible. For the corresponding test color samples, see Section 4.3.

The CRI Ri can be a negative value; for typical white light, a negative value does not always mean the color reproduction accuracy is significantly low. The CRI values may not always correspond to human perception. For example, people may not recognize which color difference is bigger when comparing two luminaires with a CRI difference of 40 to another set of two luminaires with a CRI difference of 80. When evaluating how the colors look under a light source, it is recommended to perform a sensory evaluation with the chosen luminaires in addition to a quantitative evaluation using the CRI values.

Note:

[6] The JIS standard is based on the CIE13.2, the 2nd edition of the CIE standard.

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4.3. The CRI test color samples

To determine the CRI Ra and Ri values, the 14 (15 in the JIS standard) different test color samples shown in Table 2 are used to represent various colors of objects. These samples have been defined based on the spectral radiance factors.

The test color samples i=1-8 are used to determine the general color rendering performance. The average of the R1-R8 makes the Ra value. The samples R1-R8 represent dull (i.e. low saturation) colors and may not be appropriate to evaluate vivid (i.e. high saturation) colors.

The test color samples i=9-14 (15) are used to describe the color fidelity of each sample as an Ri value. In particular, the samples i=9-12 represent higher saturation colors that are difficult to evaluate with the Ra. Since the strong red color represented by the R9 test color is especially difficult for typical white LEDs for general lighting to reproduce, the R9 value is often used with the Ra value to advertise the color rendering performance of a light source.

Table 2. CRI Test color

i	Munsell Notation[7]	Color Appearance
1	7.5R 6/4	Light greyish red
2	5Y 6/4	Dark greyish yellow
3	5GY 6/8	Strong yellow green
4	2.5G 6/6	Moderate yellowish green
5	10BG 6/4	Light bluish green
6	5PB 6/8	Light blue
7	2.5P 6/8	Light violet
8	10P 6/8	Light reddish purple
9	4.5R 4/13	Strong red
10	5Y 8/10	Strong yellow
11	4.5G 5/8	Strong Green
12	3PB 3/11	Strong blue
13	5YR 8/4	Light yellowish pink(skin)
14	5GY 4/4	Moderate olive green(leaf)
(15)	1YR 6/4	Asian skin

Note:

[7] For the Munsell color notation, each color is comprised of three color attributes: hue (the color itself), value (lightness/darkness), and chroma (color saturation or brilliance).

4.4. How to determine Ra and Ri values

Figure 5 shows how to determine an Ra and Ri value. For detailed information, see the applicable standards.

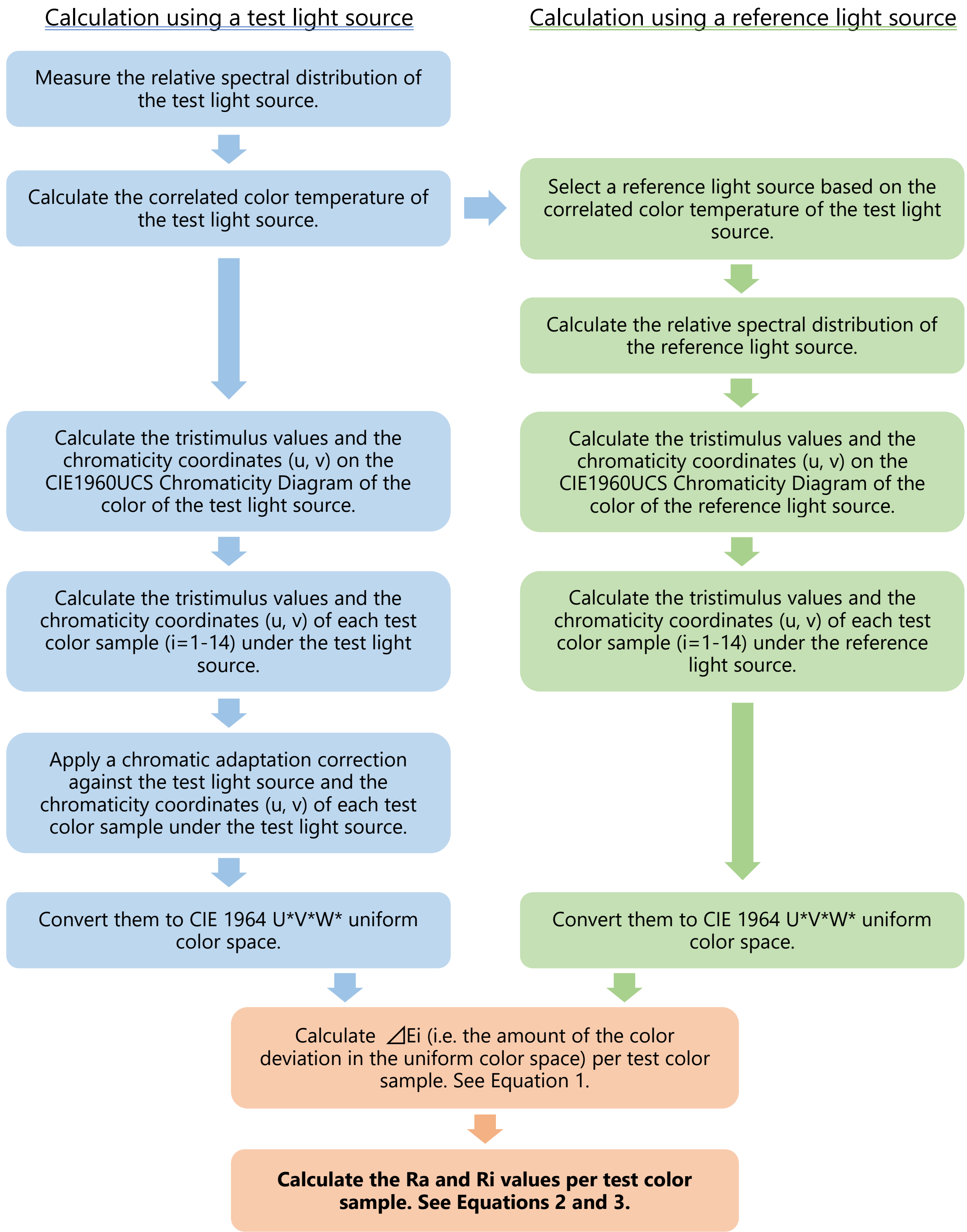

Figure 5. How to determine Ra and Ri values

Equation 1 shown below is used to determine ⊿Ei, the amount of the color deviation per test color sample. In other words, this equation derives the distance between the coordinates of the reference and test light sources in the U*V*W* color space. In this equation, the coordinates of test color sample i under the reference light source are described as ($U^*_{r,i}$, $V^*_{r,i}$, $W^*_{r,i}$), and the coordinates under the test light source are described as ($U^*_{k,i}$, $V^*_{k,i}$, $W^*_{k,i}$).

$$\Delta E_i = \sqrt{(U^*_{r,i}-U^*_{k,i})^2 + (V^*_{r,i}-V^*_{k,i})^2 + (W^*_{r,i}-W^*_{k,i})^2} \qquad \text{Equation 1}$$

Equation 2 shown below is used to determine an Ri value. The bigger the color difference is, the smaller the Ri value will be. The Ri will be a negative value when the ⊿Ei is greater than 22.

$$R_i = 100 - 4.6\Delta E_i \qquad \text{Equation 2}$$

Equation 3 shown below is used to determine an Ra value. This equation indicates that the average of the R1-R8 makes the Ra value.

$$R_a = \frac{1}{8}\Sigma_{i=1}^{8} R_i \qquad \text{Equation 3}$$

5. TM-30

5.1. Standards

IES established IES-TM-30 (i.e. TM-30) in 2015 to provide a new evaluation method for color rendering. As with the CRI standard, the TM-30 method evaluates the color difference between the test color samples when viewed under the reference light source and the test light source. However, this new evaluation method compensates for the imperfections of the CRI standard that have been pointed out in the past. For example, the color difference is calculated using a modern color space, the definition of a reference light source has been updated, there are more color samples, etc.
However, many companies prefer to continue to use CRI (Ra) rather than replace it with TM-30. It may be a long time before the new TM-30 evaluation method becomes widely adopted.

5.2. Indexes

In the TM-30 standard, the fidelity index (Rf) and the gamut index (Rg) are used to evaluate the color rendering performance of a light source. For the evaluation method, see Section 5.4.

5.2.1. Fidelity Index (Rf)

The Rf indicates how faithfully a light source can reproduce colors compared to the reference light source. The better the color fidelity is, the higher the Rf value will be: It will be 100 if the wavelength of a test light source is exactly the same as that of the reference light source. The evaluation approach is similar to the CRI method. The Rf value of a light source can sometimes be near the Ra value of the same light source; however, these two indexes are not related, the values are not exchangeable nor comparable. The fidelity of each color evaluation sample (CES) can be obtained as Rfi in the same manner as the CRI Ri (Each i corresponds to CES 1-99). Contrary to the CRI, the Rf is designed to always be a positive value.

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5.2.2. Gamut Index (Rg)

The Rg indicates the size of the gamut area of a test light source compared to the reference light source. The a'-b' plane color space is used to calculate the Rg. If the gamut area determined with a test color sample in the a'-b' plane color space is larger than that of the reference light source, the Rg value will be higher than 100; if it is smaller, the value will be lower than 100 (For detailed information, see Section 5.4). As shown in Figure 6, the rotating direction shows the change of hue. The farther the coordinates are from the origin point, the higher the color saturation (i.e. chroma) will be (i.e. the larger the size of the gamut area will be).

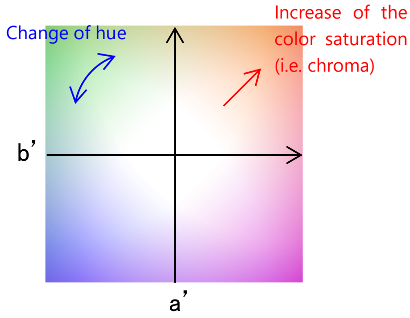

Figure 6. Reference image of the a'-b' plane color space

If the wavelengths of a test light source and the reference light source are identical, the Rg will always be 100. However, if the Rg is 100, it does not always mean that the wavelengths of a test light source and the reference light source are identical. This is because the coordinates of each test color sample may be different even if the size of the gamut area in the a'-b' plane color space is the same.

5.2.3. Relationship between the Rf and Rg

There is a correlation between the Rf and Rg. Figure 7 shows the practical limits of the Rf and Rg values. The higher the Rf value is, the more similar the wavelengths of a test light source and the reference light source are, the Rg value will also get closer to 100. If the Rf value is 100, the Rg will also be 100 since Rf=100 means that the wavelengths of a test light source and the reference light source are identical. Conversely, if the Rf value is lower, the Rg value can be farther from 100 since the difference in the wavelengths of a test light source and the reference light source is greater. Since the Rg value can be higher than 100, it is possible to lower the Rf value on purpose to obtain a light source with a high Rg value (i.e. a light source with a low color fidelity and a high saturation).

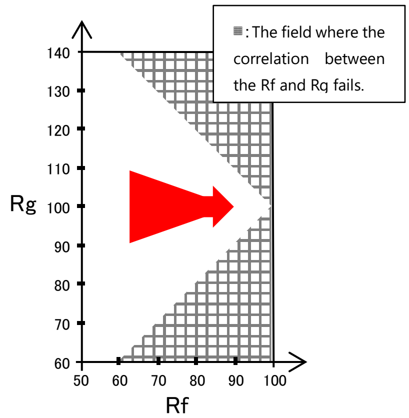

Figure 7. Relationship between the Rf and Rg

5.3. Color evaluation samples (CES)

The biggest difference between the TM-30 and CRI methods is the number of the test color samples. The CRI has as few as 14 (or 15) samples to be evaluated and uses only 8 samples out of them to calculate the Ra, the index to describe the color rendering for the general colors of objects. With this small number of samples, the evaluation may not be accurate for some test light sources since the variety of color samples greatly affects the evaluation.

The TM-30 method uses a set of 99 color evaluation samples (CES) as shown in Figure 8 to evaluate the color rendering. These samples were selected from the spectral reflectance properties of more than a hundred thousand different objects that exist in the real world to represent their typical properties. It is believed possible to evaluate almost all the colors of objects that exist in the real world with these 99 samples. The TM-30 method calculates the Rf based on the color difference between the CES when viewed under the test light source and the reference light source using all these 99 CES. This indicates that a more accurate evaluation is achieved with this method for any test light sources than with the CRI method, which has less color samples.

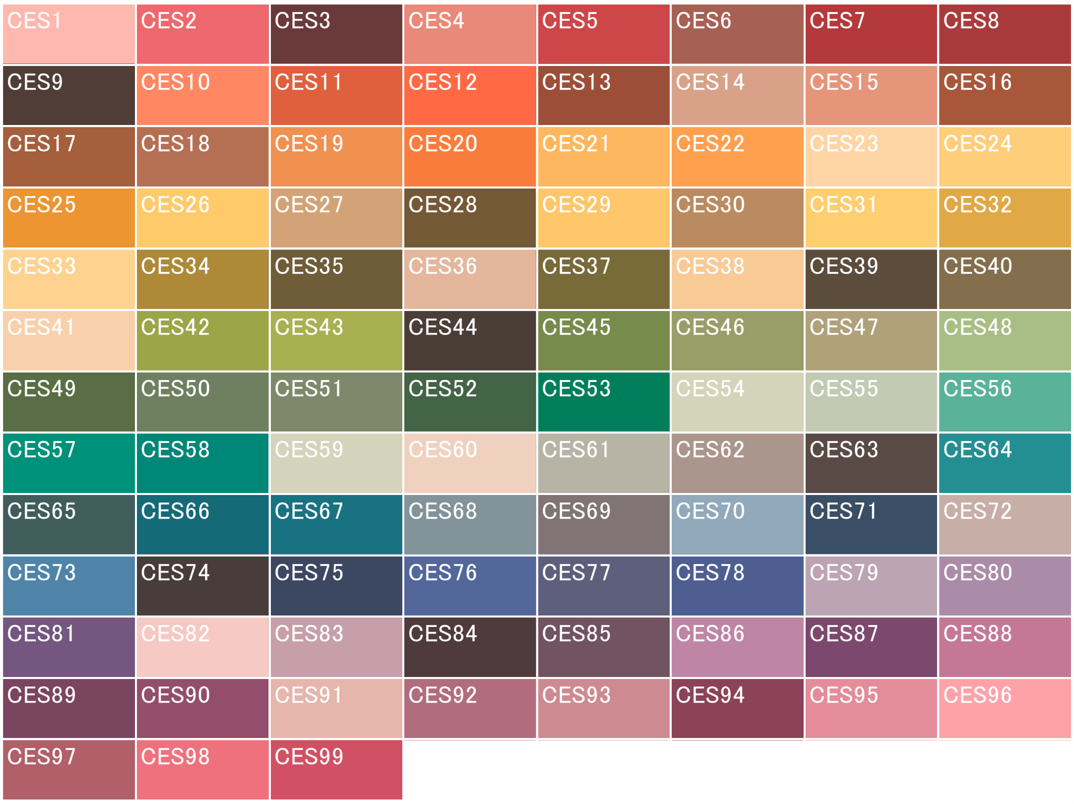

Figure 8. Example of the color evaluation samples (CES) in TM-30 standard[8]

Note:

[8] How a CES looks depends on the color temperature of the reference light source. The colors shown in Figure 8 are examples for reference only.

5.4. How to determine Rf and Rg values

Figure 9 shows how to determine an Rf and Rg value. For detailed information, see the applicable standards.

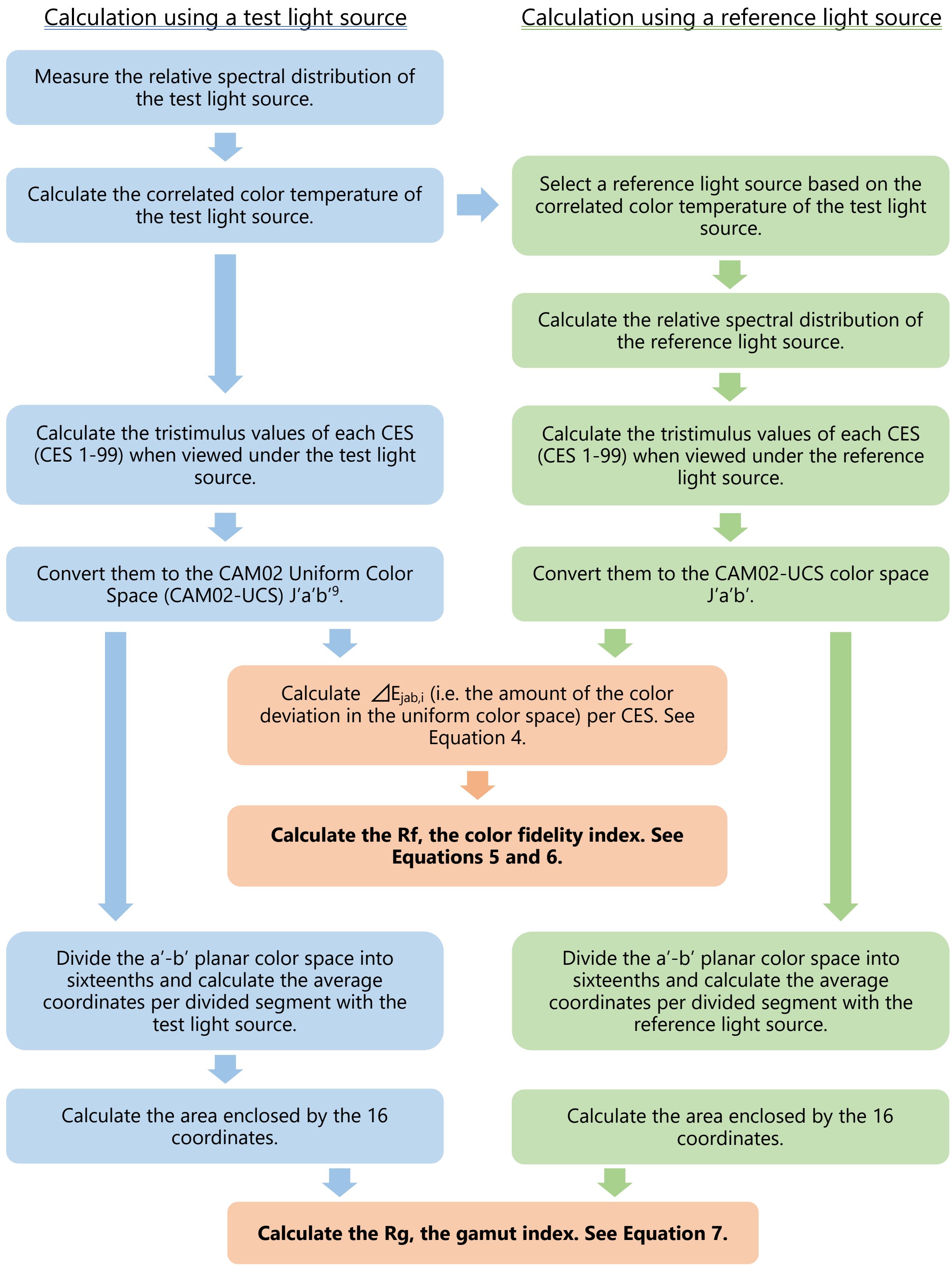

Figure 9. How to determine Rf and Rg values

Note:

[9] A chromatic adaptation correction is included in the CAM02-UCS.

Equation 4 shown below is used to determine $\Delta E_{jab,i}$, the amount of the color deviation per CES. In other words, this equation derives the distance between the coordinates of the reference and test light sources in the J'a'b' color space. In this equation, the coordinates of CES i under the reference light source are described as ($J'_{r,i}$, $a'_{r,i}$, $b'_{r,i}$), and the coordinates under the test light source are described as ($J'_{t,i}$, $a'_{t,i}$, $b'_{t,i}$).

$$\Delta E_{jab,i} = \sqrt{(J'_{t,i}-J'_{r,i})^2 + (a'_{t,i}-a'_{r,i})^2 + (b'_{t,i}-b'_{r,i})^2} \qquad \text{Equation 4}$$

Equations 5 and 6 shown below are used to determine an Rf value. First, determine the Rf' value by Equation 5 using the average of the color difference $\Delta E_{jab,i}$ of each CES obtained with Equation 4. The Rf' can be a negative value as with the CRI; make an adjustment using Equation 6 so that the minimum Rf value will be 0.

$$Rf' = 100 - 6.73 \left(\frac{1}{99}\Sigma_{i=1}^{99}(\Delta E_{jab,i}) \right) \qquad \text{Equation 5}$$

$$Rf = 10\ln \left(e^{R'f/10} + 1 \right) \qquad \text{Equation 6}$$

Equation 7 shown below is used to determine an Rg value. First, calculate the average coordinates of the coordinates representing each CES per segment of the a'-b' planar color space divided into sixteenths toward the angular orientation as shown in Figure 10. The area of the two polygons formed by connecting the average coordinates are Ar and At respectively. Ar is for the reference light source and At is for the test light source. By calculating the ratio of the area of Ar and At, it will determine if the gamut of the test light source is larger or smaller than that of the reference light source.

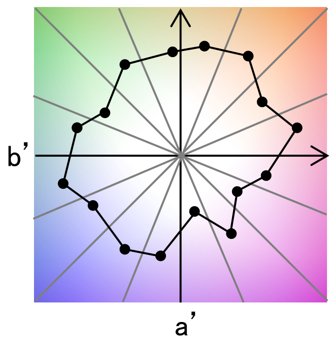

Figure 10. An example of Ar or At in the a'-b' planar color space

$$Rg = 100 \times \frac{A_t}{A_r} \qquad \text{Equation 7}$$

6. Summary

In this application note, Nichia has provided two types of evaluation methods for color rendering: the CRI, a widely used method in the lighting industry and the TM-30, a newer method. They are similar in that they both evaluate the color fidelity against a reference light source, which is an effective means of quantitatively evaluating color rendering. However, these methods do not include any sensory tests to evaluate the perception, preference, etc. by the evaluator or other observers. When evaluating the color rendering of a light source, it is recommended to perform a sensory evaluation with the chosen luminaires in addition to a quantitative evaluation described herein.

As mentioned in Section 3, Nichia offers LEDs with a variety of color rendering performances. For any questions regarding the products, contact a local Nichia sales representative.

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