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CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

IMPACT OF THE NORMALIZATION OF THE SPECTRAL RESPONSIVITY ON THE PERFORMANCE OF THE GENERAL *V*(*λ*) MISMATCH INDEX

Ferrero, A.[1], Thorseth A.[2]
[1] Instituto de Óptica "Daza de Valdés", Consejo Superior de Investigaciones Científicas, Madrid, SPAIN, [2] Technical University of Denmark, Roskilde, DENMARK
alejandro.ferrero@csic.es

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Abstract

Quality indexes are usually defined for measurement instruments in order to characterize some specific aspect of their performance. The $V(\lambda)$ spectral mismatch of photometers is evaluated by the general $V(\lambda)$ mismatch index, f_1', whose value must be correlated with the average measurement error introduced by this spectral mismatch. The objective of this work is to assess the correlation of several indexes of this type with this average error of photometers. The difference between the studied indexes is that the spectral responsivity of the photometer is normalized with different factors to that defined for f_1'. From this study, we conclude that the most suitable normalization in the definition of a f_1'-type quality index is not determined by the spectral distribution used in the calibration or by those of the light sources to be measured. The normalization factor presenting the best correlation in all studied cases was obtained by numerically minimizing the value of the index instead of by applying an explicit function, as it is done in f_1'.

Keywords: Photometry, LED sources, LED reference spectrum, photometric calibrations, spectral mismatch

1 Introduction

The $V(\lambda)$ spectral mismatch of photometers is usually evaluated by the general $V(\lambda)$ mismatch index, f_1', which considers the mismatch between the relative spectral responsivity of photometers, $s_{\text{rel}}(\lambda)$, and the spectral luminous efficiency function, $V(\lambda)$, as:

$$f_1'(f_{\text{N}}) = \frac{\int_{380\,nm}^{780\,nm} |s^*_{\text{rel}}(\lambda) - V(\lambda)| \mathrm{d}\lambda}{\int_{380\,nm}^{780\,nm} V(\lambda) \mathrm{d}\lambda}, \tag{1}$$

where $s^*_{\text{rel}}(\lambda)$ is the normalized spectral responsivity function:

$$s^*_{\text{rel}}(\lambda) = s_{\text{rel}}(\lambda) \cdot \frac{\int_{380\,nm}^{780\,nm} S_{\text{A}}(\lambda) \cdot V(\lambda) \mathrm{d}\lambda}{\int_{380\,nm}^{780\,nm} S_{\text{A}}(\lambda) \cdot s_{\text{rel}}(\lambda) \mathrm{d}\lambda}, \tag{2}$$

being $S_{\text{A}}(\lambda)$ the spectral distribution of the CIE Standard Illuminant A.

As shown above, in order to quantify this spectral mismatch, the spectral responsivity needs to be scaled by using a normalization factor. The present normalization factor is a function which includes explicitly $s_{\text{rel}}(\lambda)$, $V(\lambda)$ and the CIE Standard Illuminant A spectral distribution, $S_{\text{A}}(\lambda)$. This factor normalizes $s_{\text{rel}}(\lambda)$ to have a luminous responsivity of $1/K_{\text{m}}$ when calibrated with respect to S_{A}. Nowadays, most of the evaluated light sources are based on LEDs, and it is expected that the CIE Standard Illuminant A will be supplemented or even replaced by an LED-type illuminant as the preferred reference spectrum, proposed by the CIE Technical Committee CIE TC 2-90 (CIE 2021) and thoroughly justified in (Kokka 2018). It has raised interest in defining a complementary index for this upcoming scenario, better suited for assessment of LED-based light sources. To define this complementary index, the normalization in the present quality index can be simply modified, or a new different approach can be used. In this work, the former option is examined.

A more general expression for assessing the spectral dissimilarity between $s_{\text{rel}}(\lambda)$ and $V(\lambda)$ can be written as:

$$f_0'(f_{\text{N}}) = \frac{\int_{380\,nm}^{780\,nm} |f_{\text{N}} \cdot s_{\text{rel}}(\lambda) - V(\lambda)| \text{d}\lambda}{\int_{380\,nm}^{780\,nm} V(\lambda) \text{d}\lambda}, \tag{3}$$

where f_{N} is the normalization factor.

We think that the type of explicit normalization selected for f_1' is not the most adequate to scale $s_{\text{rel}}(\lambda)$ and $V(\lambda)$ in order to assess their spectral dissimilarity. We hypothesize that the highest correlation of f_0' with the mean photometric error from the spectral mismatch would be obtained if an optimal normalization factor, found by numerical optimization, is applied in the way:

$$f'_{0,\text{opt}} = \frac{\min_{f_{\text{N}}} \left(\int_{380\,nm}^{780\,nm} |f_{\text{N}} \cdot s_{\text{rel}}(\lambda) - V(\lambda)| \text{d}\lambda \right)}{\int_{380\,nm}^{780\,nm} V(\lambda) \text{d}\lambda}. \tag{4}$$

The reasoning behind this is that the normalization factor reaching the minimum value of f_0' provides the better overlapping of $s_{\text{rel}}(\lambda)$ and $V(\lambda)$, and that any other normalization factor would include a normalization-related dissimilarity component. The objective of this study is to show the impact on f_0' when different explicit normalization factors are used, and the improvement when using an optimal normalization factor.

2 Methodology

Different normalization options were evaluated, and their suitability was quantified with the linear correlation coefficients between the obtained f_0' indexes and the mean photometric errors from the spectral mismatch, calculated as the average of $|1 - F_i|$ across a set of spectral power distributions $\{S_i\}$ that describes a measuring scenario, and where F_i is calculated, similarly as in ISO/CIE 19476 (ISO/CIE 2014), as:

$$F_i = \frac{\int_{360\,nm}^{830\,nm} S_i(\lambda) \cdot V(\lambda) \text{d}\lambda \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S_{\text{R}}(\lambda) \cdot s_{\text{rel}}(\lambda) \text{d}\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S_i(\lambda) \cdot s_{\text{rel}}(\lambda) \text{d}\lambda \int_{360\,nm}^{830\,nm} S_{\text{R}}(\lambda) \cdot V(\lambda) \text{d}\lambda}, \tag{5}$$

where $S_{\text{R}}(\lambda)$ is the reference spectral distribution to be used in the calibration.

The average of $|1 - F_i|$ (hereafter denoted as ε), for a given scenario will be considered as the ground-truth value of the mean photometric error from the spectral mismatch, which it is what f_0' is intended to quantity. Therefore, both quantities, ε and f_0', must be correlated.

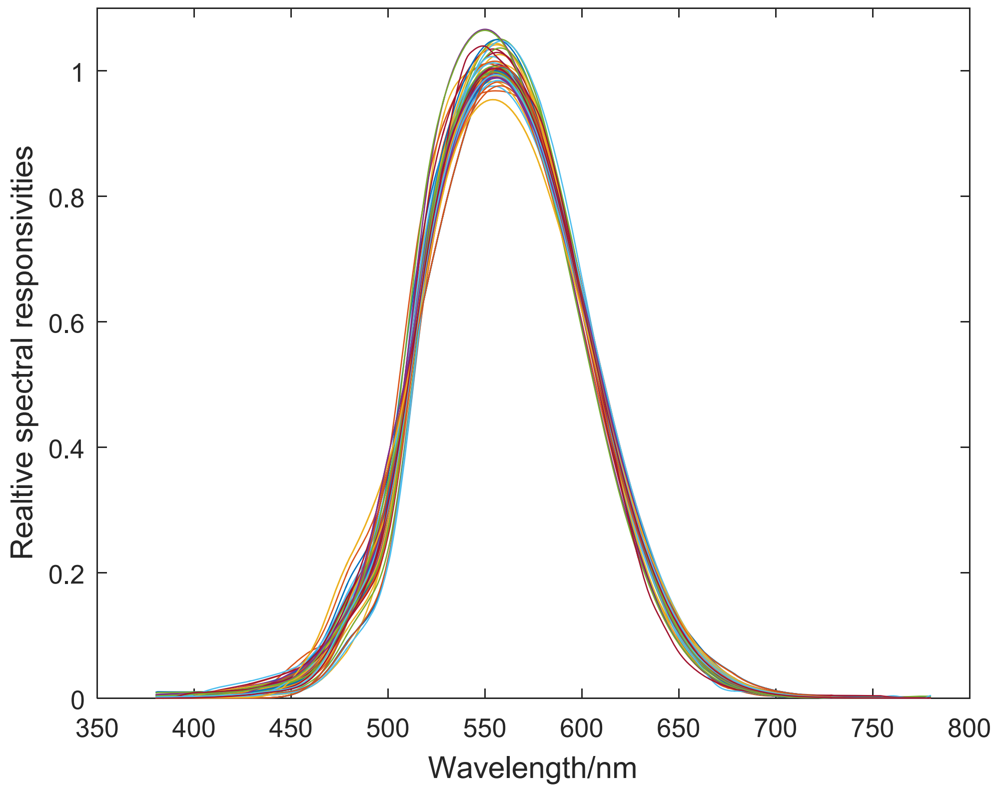


Figure 1 – Spectral responsivities of the 77 photodetectors used in this comparison.

On one hand, different types of indexes f_0' for 77 measured spectral responsivities of real photometers (shown in Figure 1) were calculated. The types are solely determined by the difference between the types of normalization factor used. Analogously as in Eq. (2) the normalization factor f_N was defined as:

$$f_N = f_{N,I} = \frac{\int_{380\,nm}^{780\,nm} S_I(\lambda) \cdot V(\lambda) \mathrm{d}\lambda}{\int_{380\,nm}^{780\,nm} S_A(\lambda) \cdot s_{\mathrm{rel}}(\lambda) \mathrm{d}\lambda}, \quad (6)$$

where the subscript I in S refers to the illuminant used in the normalization. In addition, an optimal normalization factor ($f_{N,O}$) was calculated by a numerical optimization procedure, minimizing the value of f_0' [Eq. (4)].

On the other hand, the spectral distributions from CIE recommended illuminants were used to calculate this correlation at different measuring scenarios and normalization factors. A measuring scenario defines the kind of spectral distributions to be measured by a photometer. Different scenarios must be defined in this study because the performance of the studied indexes might be very different for different sets of spectra distributions under test, as shown in [Ferrero 2018]. It is important that the spectral distributions included in the definition of a given scenario are complete and not redundant (avoiding a larger weight from one redundant distribution). We assume that, in such case, the correlation coefficients obtained in this study are representative of the scenario.

Two different measuring scenarios are defined here:

1) **Phosphor-based-LED scenario:** The values of F_i are calculated using the 9 phosphor-based-LED illuminants recently recommended by CIE (see Figure 2).

2) **Blackbody scenario:** The values of F_i are calculated using 9 blackbody illuminants at the same colour temperature as the CCTs in the phosphor-based-LEDs scenario, with the Standard Illuminant *A* as calibration illuminant (see Figure 3).

These scenarios are well defined and allow an evaluation in terms of families of functions.

When the average of $|1 - F_i|$ is calculated across the spectral distribution in a given scenario, $\{S_i\}$, but with a single reference spectral power distribution, $S_R(\lambda)$, we will call it **'specific' average of $|1 - F_i|$**. In contrast, if, in addition, a second average is done using all the spectral distributions $\{S_i\}$ as reference illuminants, $S_R(\lambda)$, we will call it **'general' average of $|1 - F_i|$**.

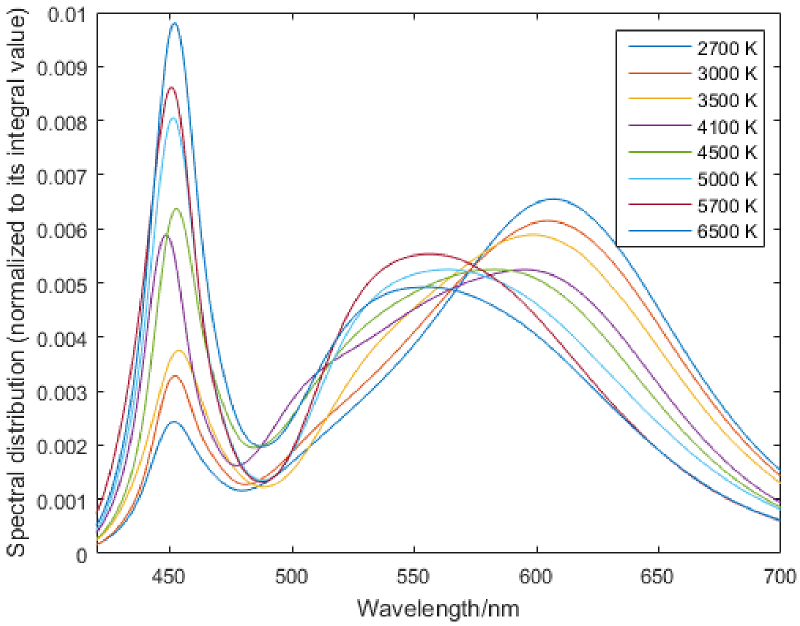


Figure 2 – Spectral distributions used to define the phosphor-based-LED scenario.

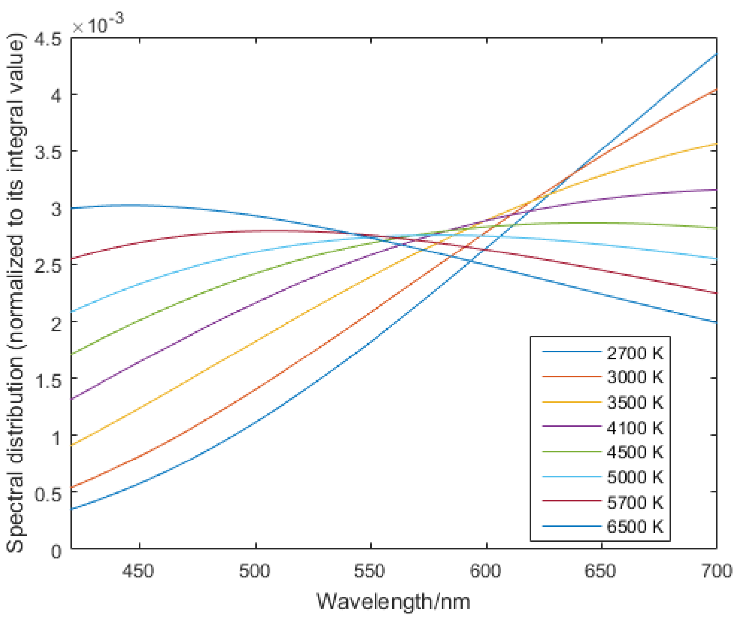
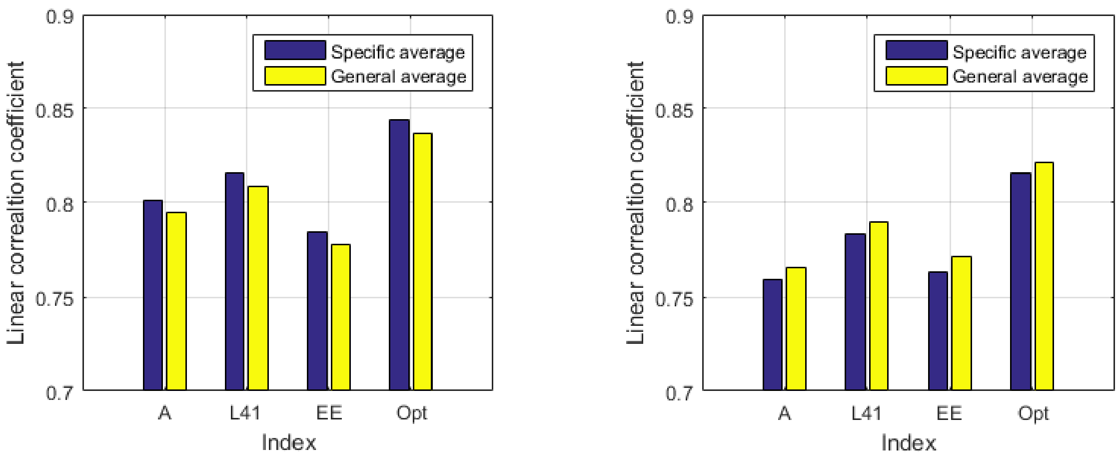


Figure 3 – Spectral distributions used to define the blackbody scenario.

3 Results

Linear correlation coefficients, ρ, between the f_0’ indexes (defined in Equations. 3-4 and 6) and ‘specific’ and ‘general’ average of |1 - F_i| were calculated both for a phosphor-based-LED scenario and a blackbody scenario, and the results are shown in Figure 4.

In the phosphor-based-LED scenario, the illuminant L41 (T_{cp} = 4100 K) was used as reference illuminant in the specific average; while in the blackbody scenario, the Standard Illuminant *A* was used as reference illuminant. In both scenarios, the use of specific or general average does not affect the conclusions on the relative performance of the studied normalizations. To start with, the optimal normalization, ‘Opt’ provides, as hypothesized, the better correlation (ρ = 0.82 – 0.84), being better for the phosphor-based-LED scenario. In general, for these two studied scenarios, it seems that an f_1’-type index provides a better performance for the phosphor-based-LED scenario than for the blackbody scenario. In addition, the use of the illuminant L41 in the normalization seems to provide a better performance than the use of the Standard Illuminant *A* or the equal energy illuminants. Similar values of correlation coefficients were obtained when using different phosphor-based LED illuminants than L41 for calculating f_0’, with values ranging between 0.82 and 0.83. The normalization with the phosphor-based LED of T_{cp} = 5700 K provides the quality index with better correlation with respect to the mean photometric error, although there is no significant difference with respect to the other LEDs. It is interesting to note that the normalization presenting a worse performance is the Standard Illuminant *A* in the blackbody scenario.



(a) Phosphor-based-LED scenario **(b) Blackbody scenario**

Figure 4 – Linear correlation coefficients between the f_0’, indexes (defined in Eqs. 4-5). and ‘specific’ (blue) and ‘general’ (yellow) average of |1 - F_i|, for (a) phosphor-based-LED scenario and (b) blackbody scenario.

4 Conclusions

The results of this study suggests that calculating the spectral mismatch index f_1’ based on a normalization using the CIE Standard Illuminant A does not produce the most optimal prediction of the general $V(\lambda)$ mismatch of photometers. This is the case for all of the examined scenarios. Using Illuminant A provides a similar prediction as when using the equal energy illuminant. A normalization based on phosphor-based LED produces performance predictions that are slightly better, not only under a phosphor-based-LED scenario, but also under a blackbody scenario. A normalization based on minimization of the spectral mismatch f_0’ produces the highest correlation between index and spectral mismatch errors.

We can conclude that the most suitable normalization in the definition of a f_1’-type quality index is not determined by the spectral distribution used in the calibration or by those of the light sources to be measured. In addition, the optimal normalization factor, obtained by minimizing the index and not by a function as in f_1', shows the best correlation in the studied cases, as hypothesized. However, it is not clear that the improvement of using an optimal normalization in the definition of the index justifies the revision of the present CIE recommendations. We suggest using a similar methodology to examine the suitability of indexes defined by alternative approaches as for instance the index proposed in (Ferrero 2018).

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