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# D5 : Evaluation of a complementary general V(λ) mismatch index

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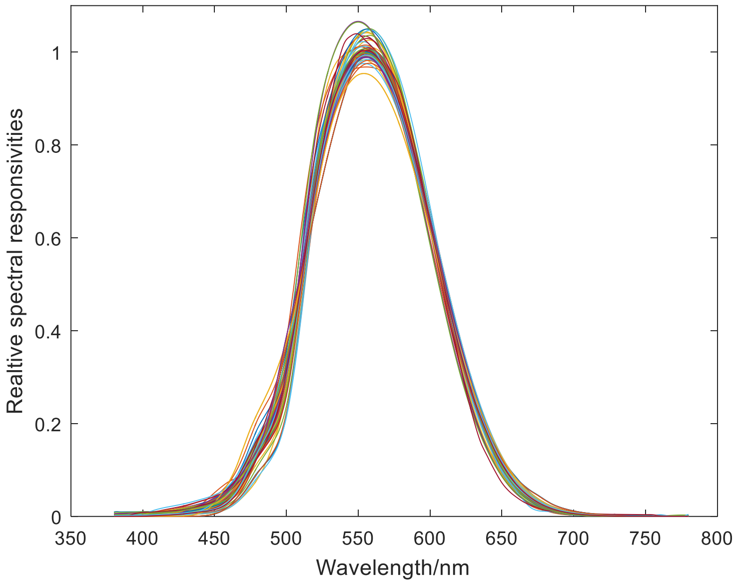
*Publication date:*
2023

*Document Version*
Publisher's PDF, also known as Version of record

# 19NRM02 RevStdLED

## D5 : Evaluation of a complementary general V(λ) mismatch index




Lead partner : DTU

Due date of the deliverable 31/12/2021

Actual submission date of the deliverable 26/01/2023,

Document version 1.0.1 (16/05/2023)


DOI: [10.5281/zenodo.7870877](https://doi.org/10.5281/zenodo.7870877)

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

This project (19NRM02 RevStdLED) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

This report is prepared in the EMPIR project *19NRM02 Revision and extension of standards for test methods for LED lamps, luminaires and modules* and forms part of the CIE Division 2 Reportership entitled CIE DR 2-89 “Definition of a complementary general V(λ) mismatch index“.

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This project (19NRM02 RevStdLED) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

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## Summary

This report is associated with the CIE Division Reportership DR 2-89 *Definition of a complementary general V(λ) mismatch index*, with the terms of reference

“To demonstrate the needs for a complementary general $V(\lambda)$ mismatch index, and propose a definition to fulfil these needs, especially for the discussion in relation to the revision of ISO/CIE 19476:2014(E) and CIE S 025/E:2015.”

The report presents parts of a detailed analysis of the issues related to a possible compliment to $f'_1$ the general $V(\lambda)$ mismatch index as presented in recent papers (Krüger et al., 2022b, 2021). It is shown that the issues related to the reliability of the general $V(\lambda)$ mismatch index is not strongly related to the specific definition of the index but rather to the spectral distribution of the device under test (DUT) and the spectral distribution of the calibration lamp. This is such that replacing CIE illuminant A with an LED source similar to L41 as the calibration source will decrease the expected error, measured by the spectral mismatch correction factor. This is shown by an investigation of the statistical relation between the various indices and the expected deviation in results from various combination of instruments, calibration sources and DUT spectral distributions.

The final conclusion of the authors is that the various changes proposed do not produce significantly different results from the status quo, so there is no need to change the current definition of the general $V(\lambda)$ mismatch index.

This report is based on the work detailed in publications (Krüger et al., 2022b, 2021), which was funded as part of the Joint Research Project within the European Metrology Research Programme EMPIR “Revision and extension of standards for test methods for LED lamps, luminaires and modules” (RevStdLED 19NRM02), the project has had active participation from countries Germany, Finland, Spain, Portugal, France, Turkey, Denmark, Ukraine and South Africa.

## Version history

| Version | Date | Description |
|---|---|---|
| Version 1 | 26/01/2023 | Main publication submitted |
| Version 1.0.1 | 16/05/2023 | Publication for permanent upload to zenodo.org with DOI 10.5281/zenodo.7870877, additionally the report is now licensed under the Creative Commons Attribution 4.0 International License<br><br>A few editorial changes |

# 1 Introduction

LED-based light sources dominate the general lighting market and is consequently disrupting the market for calibration sources based on incandescent sources. It is likely that the availability of reasonably priced incandescent light sources of an appropriate quality will be drastically limited in the coming years. This brings about a situation where both the devices under measurement and the calibration light sources may soon be LED-based. This has brought forth the question whether $f_1$' is suitable as a quality index for photometer quality, since $f_1$' includes a normalisation using the incandescent spectrum of CIE illuminant A. It was for instance shown that there were improvements possible by altering the index both with respect to the normalisation (Ferrero and Thorseth, 2021) and also by changing the index in more fundamental ways (Ferrero et al., 2018b).

This report is intended to provide a more solid foundation for the forthcoming revisions of the standards CIE S 025/E:2015, ISO/CIE 19476:2014 and EN 13032-4, concerning $f_1$' and related issues.

This report will address:

- the needs of the measurement stakeholder community regarding a possible new index,
- the defining characteristics of proposed indices,
- the possibility of a complementary index with better correlation to the spectral mismatch error of photometers,
- the impact of the introduction of a complementary index on the uncertainty of photometric measurements,
- the relation between quality indices and the choice of calibration standard.

The report will be summarized in an internal summary delivered to the CIE based on the work done in the project. The report will be made available open access from the project website https://www.ptb.de/empir2020/revstdled/home/ .

## 1.1 History of $f_1'$

The very first mention of $f_1'$ is in the form of an informative note, and is found in (CIE, 1982). At this time, the preferred measure for the mismatch was the maximum required spectral mismatch correction factor for five defined light sources, $f_{1,\mathrm{CIE}}$. Later, the general mismatch index $f_1'$ was introduced as a CIE recommendation (CIE, 1987). In preparation for these CIE publications, numerous papers (e.g., (Krochmann and Reissmann, 1980), (Krystek and Erb, 1980)and a summary in (Krochmann and Rattunde, 1980)) were published, especially directed towards the German-speaking part of the world. These papers systematically showed that the proposed mismatch index, in its currently used form, was reasonable under the boundary conditions of that time and proved its advantages over other candidates under discussion. The derivation and justification for the normalisation of the spectral responsivity can be found in (Krochmann and Reissmann, 1980). A comprehensive summary of all the previous literature can be found in (Krochmann and Rattunde, 1980). Updated information of the background for $f'_1$ is described in (Krüger et al., 2021) and (Krüger et al., 2022b).

## 1.2 Defining characteristics of $f_1'$

In ISO/CIE 19476:2014 (ISO/CIE, 2014), the general $V(\lambda)$ mismatch index $f_1'$ is used specifically to characterise the spectral match of the spectral responsivity of a receiver to the spectral luminous efficacy function of the human visual system under photopic conditions. It is defined as

 

$$f_1' = \frac{\int_{\lambda=380\text{ nm}}^{780\text{ nm}} \left| s_{\text{rel}}^*(\lambda) - V(\lambda) \right| \cdot \mathrm{d}\lambda}{\int_{\lambda=380\text{ nm}}^{780\text{ nm}} V(\lambda) \cdot \mathrm{d}\lambda}, \quad (1)$$

where

$\lambda$ is the wavelength,

$V(\lambda)$ is the spectral luminous efficiency function for photopic vision,

$s_{\text{rel}}^*(\lambda)$ is the normalised spectral responsivity $s_{\text{rel}}^*(\lambda)$ which is calculated by weighting the absolute spectral responsivity of the detector, $s(\lambda)$, with the CIE Illuminant A standard distribution, $S_{\text{A}}(\lambda)$ (ISO/CIE, 2021), given by

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

$S_{\text{A}}(\lambda)$ $s(\lambda)$ Spectral mismatch is typically a systematic measurement error, causing similar deviation in measurement results for similar measurement situations. Systematic measurement errors can be corrected for, if the cause is determined and the size of the effect is known. For spectral mismatch, the cause can typically be determined and the effect can be calculated from the spectral mismatch correction factor (SMCF), $F(S_C(\lambda), S_Z(\lambda))$, applied to the luminous responsivity, $s_{\text{v,Z}}$, defined by:

$$s_{\text{v, Z}} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} S_{\text{Z}}(\lambda) \cdot s(\lambda)\mathrm{d}\lambda}{K_{\text{m}} \int_{360\text{ nm}}^{830\text{ nm}} S_{\text{Z}}(\lambda) \cdot V(\lambda)\mathrm{d}\lambda} \quad (3)$$

where $S_{\text{Z}}(\lambda)$ is the spectral distribution of the measured radiation, Z, and $K_{\text{m}} \cong 683$ lm·W$^{-1}$ (in air), and given by

$$F\big(S_C(\lambda), S_Z(\lambda)\big) = \frac{s_{\text{v,C}}}{s_{\text{v,Z}}} = \frac{\int S_C(\lambda) \cdot s(\lambda) \cdot d\lambda}{\int S_C(\lambda) \cdot V(\lambda) \cdot d\lambda} \frac{\int S_Z(\lambda) \cdot V(\lambda) \cdot \mathrm{d}\lambda}{\int S_Z(\lambda) \cdot s(\lambda) \cdot \mathrm{d}\lambda} \quad (4)$$

where

$S_{\text{C}}(\lambda)$ is the spectral distribution of the calibration source, C,

$S_{\text{Z}}(\lambda)$ is the spectral distribution of the measured radiation,

$s(\lambda)$ is the relative spectral responsivity of the detector.

Given sources for testing and calibration that are markedly different from CIE illuminant A, the spectral mismatch can sometimes cause a significant relative error if not corrected, by use of equatrion 4. The relation between $f_1'$, and the SMCF for LED sources was investigated by various authors (Krüger and Blattner, 2013), (Krüger and Blattner, 2008) and (Ferrero et al., 2018a).

 

## 1.3 Technological shift

The general $V(\lambda)$ mismatch index makes use of CIE illuminant A (see Figure 2) in the fundamental definition of the index. This raises a practical issue since the incandescent sources that are spectrally similar to CIE illuminant A, and which are used for calibration of photometers are getting less available, as incandescent light sources are phased out of the general lighting market (see Figure 1). Devices that are mass-produced are well suited as artefacts used for calibration, since the homogeneity between artefacts is typically high, due to the industrialised and dedicated production process. Although incandescent sources are expected to be available in the future, the price is expected to rise significantly for similar or lower quality. The sustainability of having a central quality index in photometry based on a technology that is in rapid decline, should therefore be considered. To prepare for this situation CIE established the technical committee TC 2-90, proposing an LED illuminant for use in calibration, heavily supported by the EMPIR project 15SIB07 PhotoLED (See the proposed L41 spectral distribution in Figure 2) (Kokka et al., 2018).

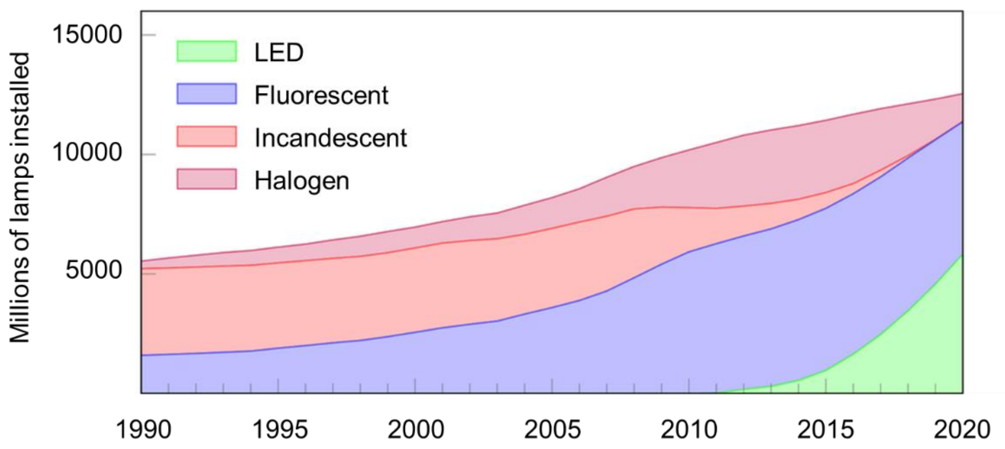


**Figure 1 - Total installed lamps in EU 1990-2020, adopted from Impact Assessment for Commission Regulation (EU) 2019/2020 pursuant to Directive 2009/125/EC** (Weinold, 2020)**.**

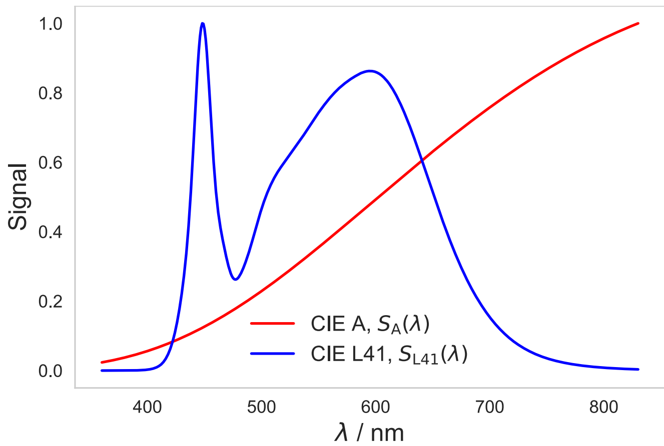


**Figure 2 - Spectral distribution of the CIE Standard Illuminant A, $S_A(\lambda)$, and of the CIE reference spectrum L41, $S_{L41}(\lambda)$**

# 2 Survey of stakeholder needs

In the research project RevStdLED 19NRM02, a survey was conducted; a questionnaire was distributed among partners and stakeholders. Unfortunately, only a small number of stakeholders responded. We bring here the results to show what the survey indicated, without claiming statistical significance or representability of the community as a whole.

The questions in this survey could be reused in a larger survey conducted within the CIE associates to gain better representability.

## 2.1 Information on the respondents

The following is self-reported information from respondents, about their activities and roles in photometry and lighting.

### 2.1.1 Activities

Respondent were asked to 'Select the activity where light measurement is most relevant for their organisation. Results can be seen in Figure 3. It is seen that many activities in the community are represented with a preponderance of “Testing in a laboratory environment”.

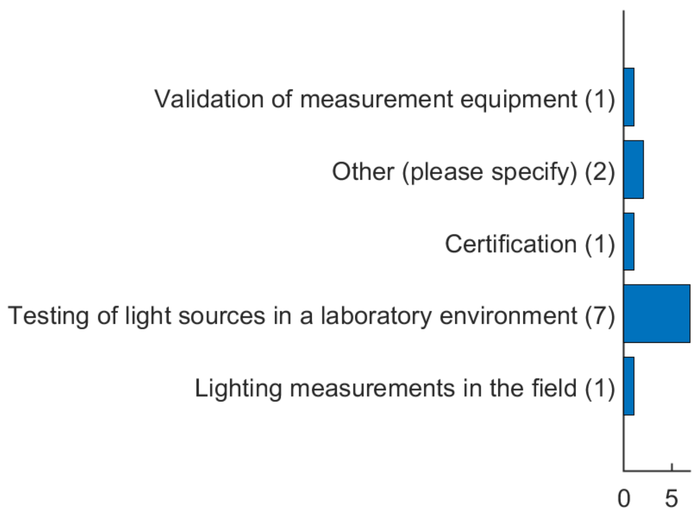


**Figure 3 – Main activities related to light measurement**

In the “Other (please specify)” the following entries were made

- 'Calibration of light sources and meters and intercomparisons'
- 'Characterisation and calibration of Light sources and detectors'

### 2.1.2 Roles

Respondents were asked to report the main role that their organisation fill within lighting. Answers can be seen in Figure 4. It is seen that various roles in the community are represented among respondents.

 

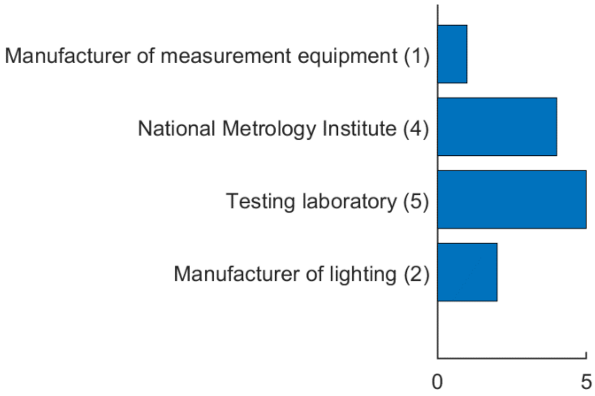


**Figure 4 – Roles of the respondent organisations within lighting**

## 2.2 Responses regarding the index

### 2.2.1 Applicability

Respondents were asked to report how widely applicable their organisation preferred the index to be. Widely applicable would mean applicable for white sources, coloured sources radiometry as well as sources and detectors alike, or narrowly applicable to only encompass photometry of white light sources. Figure 5 shows a majority wishing for a widely applicable index, while a minority prefer a less wide applicability. The comments (Table 1) on the other hand indicate a reluctance to have the index be too wide in applicability.

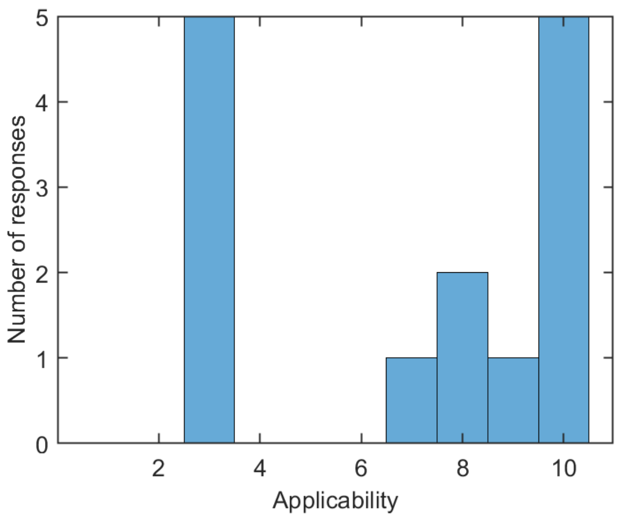


**Figure 5 – Applicability of the index, wanted by respondents (0: narrowly applicably, 10 widely applicable)**

**Table 1 - Free text responses about applicability**

| |
|---|
| It shouldn't be too complicated, and having another separate index for the sources might be a good option. |
| We mainly deal with white LED sources and use a spectroradiometer for measurement of coloured LEDs |
| It should be at least as useful as the current mismatch index. |

 

### 2.2.2 Complexity

Respondents were asked to report what level of complexity in the calculation of an index their organisation is prepared to handle in daily operations. With low complexity being the ability to perform calculation in a typical spreadsheet application, and high complexity involving advanced mathematics or heavy computation. Figure 6 shows a large spread in the responses. We believe this spread is indicative of the large spread in the level of effort committed to detailed analysis of measurement apparatus and results, generally seen in the lighting community, from NMIs with detailed characterisations, model calculations and large uncertainty budgets to field practitioners making field measurement with equipment of unknown quality and calibration status. Table 2 shows free text responses show a somewhat similar spread in views.

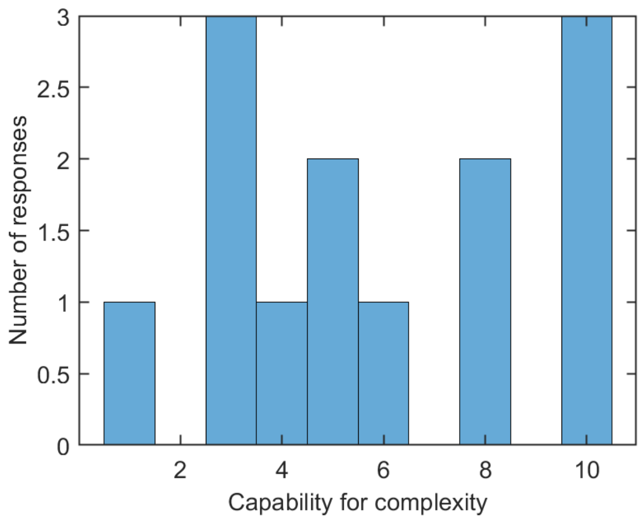


**Figure 6 – Capability to handle complicated calculations in daylily operations (0: low complexity, 10: high complexity)**

**Table 2 - Free text responses about complexity**

| |
|---|
| we have both methods implemented, but more widely used in daily business are typical spreadsheet applications. |
| A complex calculation would be useful as long as the software package is free and open source |
| Mainly make use of Excel spreadsheets |

### 2.2.3 Standardisation

Respondents were asked to report how widely applicable their organisation preferred the index to be. Widely applicable for white sources, coloured sources radiometry as well as sources and detectors alike or narrowly applicable to only encompass photometry of white light sources. Here respondents overwhelming preferred the high level of standardisation (ISO/CIE/IEC) and CIE Technical Report, to lesser tier publication methods such as CIE Technical Note or peer review journal publication (See Figure 7).

 

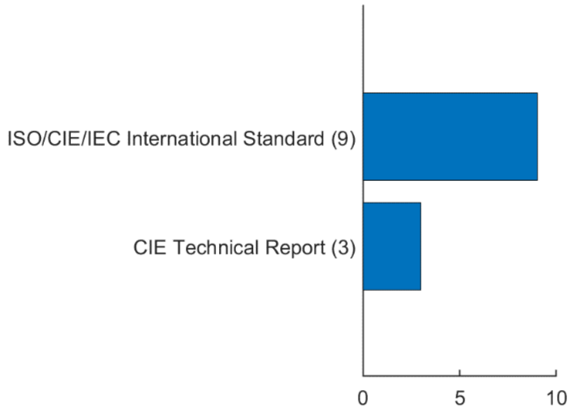


**Figure 7 – Responses regarding the wished level of standardisation**

### 2.2.4 Impact

Respondents were asked to report how large a change or impact regarding the current situation their organisation would prefer the index to achieve? Results can be seen in Figure 8. Here responses varied across most possibilities with a large preponderance of “middle” and lower values giving a somewhat ambiguous result. Table 3 shows the free text comments made, also pointing towards the need being more prospective than immediate.

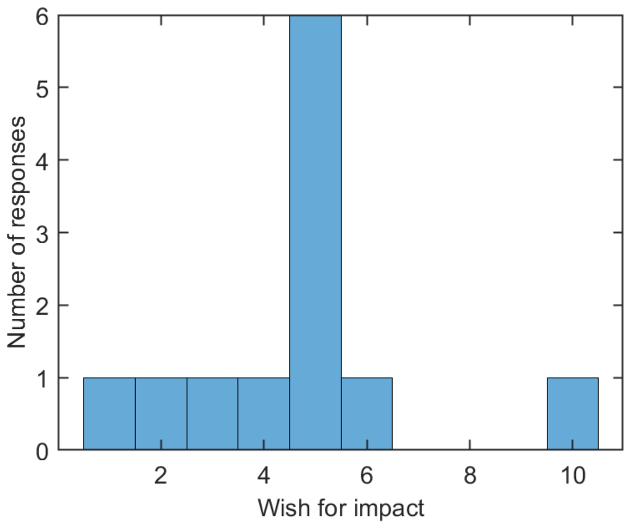


**Figure 8 - Responses regarding the wished level of impact**

**Table 3 - Free text responses about impact**

| |
|---|
| Yet we are planning to move ahead for calibration lab in lighting. So at the moment the situation is satisfying, but in the future especially in calibration it will be important. |
| a) This isn't a major issue as spectral methods of <5nm bandwidth are more and more common, both large scale and hand held but this would help with filter photometer assessments, as filter photometers are still used |
| Expect calibration requests vs LED source to pick up in future and therefore will have large impact |

## 2.3 Summary of survey

Although the current index is used by many in situations such as purchasing a photometer, the number of organisations with a key interest in the topic is small, so the number of respondents were expected to be small. However, even with the small number of respondents the survey gives an indication of the variation in interests within the community, and also shows that the needs regarding a new quality index are definitely not generally agreed upon. Taking the results of the technical work regarding a new index into consideration i.e., that only small effectual changes would be seen with a new index, it can tentatively be inferred from this survey that the general sentiment is that the status quo is perhaps to be preferred over a change of the index. Especially given the questionable utility of a change seen from a technical standpoint.

# 3 Candidates for a compliment to $f_1'$

In this section, the various candidates proposed as complementary or as replacements for $f_1'$ are discussed. The main focus is on photopic vision but scotopic vision is used to exemplify the method in section 3.2.

## 3.1 Complementary calibration spectral mismatch index for photopic vision

The complementary spectral calibration mismatch index for photopic vision $f'_{1,\mathrm{C}}$ (formula (5)) relates the spectral responsivity of the detector with the spectral luminous efficiency of photopic vision $V(\lambda)$ to indicate the quality of the spectral mismatch of the sensor including the used calibration light source, C, by the following formula

$$f'_{1,\mathrm{C}} = \frac{\int \left| s_{\mathrm{rel,C}}(\lambda) - V(\lambda) \right| \cdot \mathrm{d}\lambda}{\int V(\lambda) \cdot \mathrm{d}\lambda} \tag{5}$$

where

$V(\lambda)$ is the spectral luminous efficiency for photopic vision

$s_{\mathrm{rel,C}}(\lambda)$ is the normalized relative spectral responsivity of the sensor

$$s_{\mathrm{rel,C}}(\lambda) = \frac{\int S_{\mathrm{C}}(\lambda) \cdot V(\lambda) \cdot \mathrm{d}\lambda}{\int S_{\mathrm{C}}(\lambda) \cdot s_{\mathrm{rel}}(\lambda) \cdot \mathrm{d}\lambda} s_{\mathrm{rel}}(\lambda) \tag{6}$$

where

$S_{\mathrm{C}}(\lambda)$ is the spectral power distribution of the calibration source, C

$s_{\mathrm{rel}}(\lambda)$ is the relative spectral responsivity of the sensor

NOTE The complementary calibration spectral mismatch index for photopic vision $f'_{1,\mathrm{C}}$ is a methodological departure from the general $V(\lambda)$ mismatch index due to the fact that the calibration light source is no longer fixed to be illuminant A. Consequently $f'_{1,\mathrm{C}}$ is calculated using both the specific spectral distribution of the calibration sources and the spectral responsivity of the detector. This means that the index is dependent both on device characteristics and the calibration characteristics.

NOTE The index $f_{1,\mathrm{C}}^{'}$ is dependent on the calibration source and can therefore not be stated for a device independent of the calibration process. This also implies that a device that undergoes recalibration may need to have a new $f_{1,\mathrm{C}}^{\prime}$ assigned after recalibration.

NOTE Further discussion can be found in (Krüger et al., 2022b, 2021)

## 3.2 Complementary calibration spectral mismatch index for scotopic vision

The complementary calibration spectral mismatch index for scotopic vision $f_{1,\mathrm{CS}}^{'}$ relates the spectral responsivity of the detector with the spectral luminous efficiency for scotopic vision and the spectral distribution of the calibration source to indicate the quality of the spectral mismatch of the sensor given the used calibration light source, according to:

$$f_{1,\mathrm{CS}}^{'} = \frac{\int \left| s_{\mathrm{rel,C}}(\lambda) - V'(\lambda) \right| \cdot \mathrm{d}\lambda}{\int V'(\lambda) \cdot \mathrm{d}\lambda} \tag{7}$$

where

$V'(\lambda)$ is the spectral luminous efficiency for scotopic vision,

$s_{\mathrm{rel,C}}(\lambda)$ is the normalized relative spectral responsivity of the sensor.

$$s_{\mathrm{rel,C}}(\lambda) = \frac{\int S_{\mathrm{C}}(\lambda) \cdot V'(\lambda) \cdot \mathrm{d}\lambda}{\int S_{\mathrm{C}}(\lambda) \cdot s(\lambda) \cdot \mathrm{d}\lambda} s(\lambda) \tag{8}$$

where

$S_{\mathrm{C}}(\lambda)$ is the spectral power distribution of the calibration source,

$s(\lambda)$ is the relative spectral responsivity of the sensor.

NOTE The index $f_{1,\mathrm{CS}}^{'}$ is dependent on the calibration source and can therefore not be stated for a device independent of the calibration process. This also implies that a device that undergoes recalibration may need to have a new $f'_{1,CS}$ assigned after recalibration.

## 3.3 Complementary minimised spectral mismatch index (photopic vision)

The complementary minimised spectral mismatch index for photopic vision relates the spectral responsivity of the detector with the spectral luminous efficiency of photopic vision to indicate the quality of the spectral mismatch of the sensor using the normalisation that minimises the spectral mismatch between the spectral responsivity of the spectral luminous efficiency of photopic vision. It is defined by:

$$f_{1,\mathrm{Min}}^{'} = \min_{\alpha_{\mathrm{C}}} \int_{\lambda=360\ \mathrm{nm}}^{830\ \mathrm{nm}} \left| \alpha_{\mathrm{C}} s(\lambda) - V(\lambda) \right| \cdot \mathrm{d}\lambda \tag{9}$$

where

$V(\lambda)$ is the spectral luminous efficiency for photopic vision,

$\alpha_{\mathrm{C}}$ is the normalisation factor,

$\min\limits_{a_C}$ denotes minimisation operator by adjustment of $a_C$

$s(\lambda)$ is the relative spectral responsivity of the sensor.

NOTE The index $f'_{1,\mathrm{Min}}$ is independent of the calibration source and can therefore be stated for a device, independent of the calibration process. This also implies that a device that undergoes recalibration will not need to have a new $f'_{1,\mathrm{Min}}$ assigned after recalibration.

## 3.4 Complementary LED spectral mismatch index for photopic vision

Complementary LED spectral mismatch index for photopic vision $\boldsymbol{f'_{1,\mathrm{L}}}$, uses a weighting based on illuminant L, $S_\mathrm{L}(\lambda)$, described as B3 or L41 in the literature(CIE, 2018a), according to:

$$f'_{1,\mathrm{L}} = \frac{\int \left| \alpha_C s_\mathrm{rel}(\lambda) - V(\lambda) \right| \cdot \mathrm{d}\lambda}{\int V(\lambda) \cdot \mathrm{d}\lambda} \tag{10}$$

where

$V(\lambda)$ is the spectral luminous efficiency for photopic vision

$a_\mathrm{C}$ is the normalisation factor, given by

$$a_\mathrm{C} = \frac{\int_{\lambda=360\ \mathrm{nm}}^{830\ \mathrm{nm}} S_\mathrm{L}(\lambda) V(\lambda) \cdot \mathrm{d}\lambda}{\int_{\lambda=\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} S_\mathrm{L}(\lambda) s_\mathrm{rel}(\lambda) \cdot \mathrm{d}\lambda} \tag{11}$$

where

$s_\mathrm{rel}(\lambda)$ is the relative spectral responsivity of the sensor,

$S_\mathrm{L}(\lambda)$ is illuminant L (CIE, 2018b).

## 3.5 Complementary equal energy spectral mismatch index for photopic vision

Complementary equal energy spectral mismatch index for photopic vision, $\boldsymbol{f'_{1,\mathrm{E}}}$, does not use any weighting, being based on illuminant E, which has equal energy at all wavelengths:

$$f'_{1,\mathrm{E}} = \frac{\int \left| \alpha_\mathrm{E} s_\mathrm{rel}(\lambda) - V(\lambda) \right| \cdot \mathrm{d}\lambda}{\int V(\lambda) \cdot \mathrm{d}\lambda} \tag{12}$$

where

$V(\lambda)$ is the spectral luminous efficiency for photopic vision,

$a_\mathrm{E}$ is the normalisation factor, given by

$$a_E = \frac{\int_{\lambda=360\ \mathrm{nm}}^{830\ \mathrm{nm}} V(\lambda) \cdot \mathrm{d}\lambda}{\int_{\lambda=\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} s_\mathrm{rel}(\lambda) \cdot \mathrm{d}\lambda} \tag{13}$$

where

$s_\mathrm{rel}(\lambda)$ is the relative spectral responsivity of the sensor,

## 3.6 Complementary Fourier transform based spectral mismatch index for photopic vision

The complementary Fourier transform based spectral mismatch index for photopic vision uses a new structure that changes the handling of the spectral difference with a function $\delta_s(\lambda)$ defined by:

$$\delta_s(\lambda) = \frac{a_\mathrm{C}\, s_\mathrm{rel}(\lambda) - V(\lambda)}{\int_{\lambda=360\ \mathrm{nm}}^{830\ \mathrm{nm}} V(\lambda)\cdot d\lambda} \quad (14)$$

where

$a_\mathrm{C}$ is the normalisation factor, given by

$$a_\mathrm{C} = \frac{\int_{\lambda=360\ \mathrm{nm}}^{830\ \mathrm{nm}} V(\lambda)\cdot \mathrm{d}\lambda}{\int_{\lambda=\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} s_\mathrm{rel}(\lambda)\cdot \mathrm{d}\lambda} \quad (15)$$

For illustration $f_1^{'}$ can then be rewritten to

$$f_1^{'} = \int_{\lambda=\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} \left|\delta_s(\lambda)\right| \cdot \mathrm{d}\lambda \quad (16)$$

The complementary Fourier transform based spectral mismatch index for photopic vision $f_1''$ was introduced by (Ferrero et al., 2018c) and is defined as:

$$f_1^{"} = \sqrt{2 \int_{\nu_\lambda=0}^{\nu_{\lambda,c}} \left|\hat{\delta}_s(\nu_\lambda)\right|^2 \mathrm{d}\nu_\lambda} \quad (17)$$

where

$\hat{\delta}_\mathrm{s}(\nu_\lambda)$ is the Fourier Transform of $\delta_\mathrm{s}(\lambda)$

$\nu_\lambda$ is the spectral frequency,

$\nu_{\lambda,c}$ is the cut-off spectral frequency.

See

(Ferrero et al., 2018c; Krüger et al., 2022a) and (Ferrero et al., 2018b; Krüger et al., 2022b)for implementation details.

Note: It has to be noted that, as $f_1''$ and $f_1'$ are not of the same kind, they are not metrologically comparable.

The complementary Fourier transform based spectral mismatch index for photopic vision, $f_1''$, is also available in a version $\boldsymbol{f_{1,\mathrm{R}}''}$ where the frequency representation of the spectral difference $\delta_{s,\mathrm{R}}(\lambda)$ is based on the bandwidth-limited signal

$$\hat{\delta}_{s,\mathrm{R}}(\nu_\lambda) = \begin{cases} \hat{\delta}_s(\nu_\lambda) & |\nu_\lambda| \leq \nu_{\lambda,c} \\ 0 & \text{otherwise} \end{cases} \quad (18)$$

$$\delta_{s,\mathrm{R}}(\lambda) = \mathbf{DFT^{-1}}\left\{\hat{\delta}_{s,\mathrm{R}}(\nu_\lambda)\right\} \quad (19)$$

 

where

$\mathbf{DFT^{-1}}$ is the inverse discrete Fourier transformation

With the bandwidth-limited version of $\delta_{s,\mathrm{R}}(\lambda)$, we can calculate the new index according to equation (), leading to:

$$f_{1,\mathrm{R}}'' = \int_{\lambda=\lambda_{\min}}^{\lambda_{\max}} \left|\delta_{s,\mathrm{R}}(\lambda)\right| \cdot \mathrm{d}\lambda \quad (20)$$

NOTE: The values of $f_{1,\mathrm{R}}''$ are metrologically comparable with the usual $f_1'$ values and are fully correlated to the original $f_1''$ values.

# 4 Analysis

Analysis of the performance of the candidate indices can be found in the paper by Krüger et al. (Krüger et al., 2022b). This paper describes and evaluates the performance of the above spectral mismatch index candidates for a potential new general $V(\lambda)$ mismatch index, used for measurement of general lighting based on LED light sources. The candidate indices are classified as $f_1'$-type indices ($f_1'$ is modified only in terms of the normalisation factor of the relative spectral responsivity), and as indices derived by completely different approaches. The paper studies the linear correlations between the different indices and statistical parameters of $F_j^a(S_C(\lambda)) = \left|F(S_C(\lambda), S_j(\lambda)) - 1\right|$, particularly its mean, quantiles, and standard deviations. The study is performed using collected experimental data of relative spectral responsivities and white LED light sources, collected in EMPIR project 15SIB07 PhotoLED (Jost et al., 2021), using the free software package “empir19nrm02” (EMPIR 19NRM02 RevStdLED, 2022) as well as the freely available python package luxpy (Smet, 2021, 2020). The aim was to classify the different indices from these correlation coefficients, under the assumption that the statistical parameters of $F_j^a(S_\mathrm{C}(\lambda))$ are related with an expected deviation from the true value due to the $V(\lambda)$ mismatch. The following data is presented as representative examples of the results of the study.

## 4.1 Correlation between the indices

In (Krüger et al., 2022b) it was found that the linear correlation between the classic indices ($f_1'$, $f_{1,\mathrm{E}}'$, $f_{1,\mathrm{L}}'$ and $f_{1,\mathrm{Min}}'$) is very high (see Figure 9), which would imply that any reasonable normalisation of the relative spectral responsivity should not impact the index performance. As expected Figure 9 also shows a high correlation between the two Fourier indices ($f_1''$ and $f_{1,\mathrm{R}}''$), since the latter is based on the former.

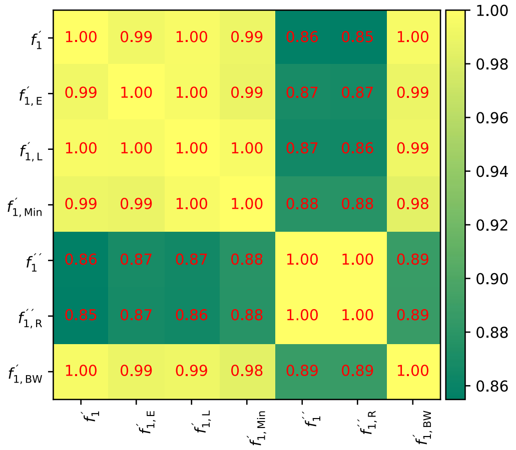

**Figure 9 - Correlation between the evaluated indices** (Krüger et al., 2022b)**.**

## 4.2 Statistical Evaluation

It was observed that the SMCF is much better correlated to $f'_{1,\mathrm{L}}$ than to $f'_1$ (see Figure 10) which is only due to the different calibration conditions.

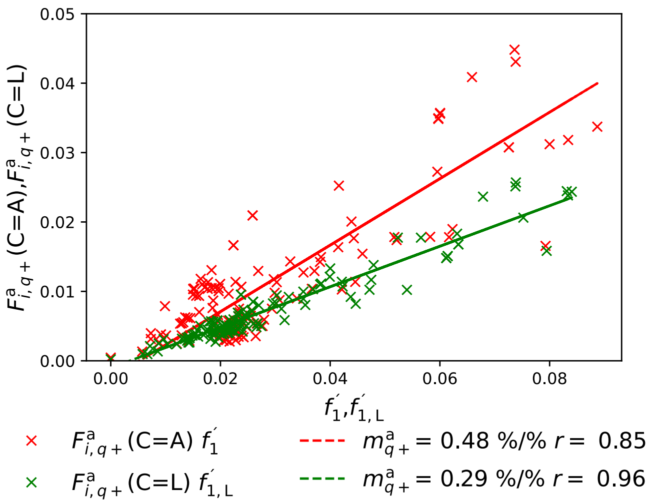

**Figure 10 - Upper 95 % quantiles of the SMCFs for the calibration condition C=A related to $f'_1$ (red) and C=L related to $f'_{1,\mathrm{L}}$ (green)** (Krüger et al., 2022b)**.**

 

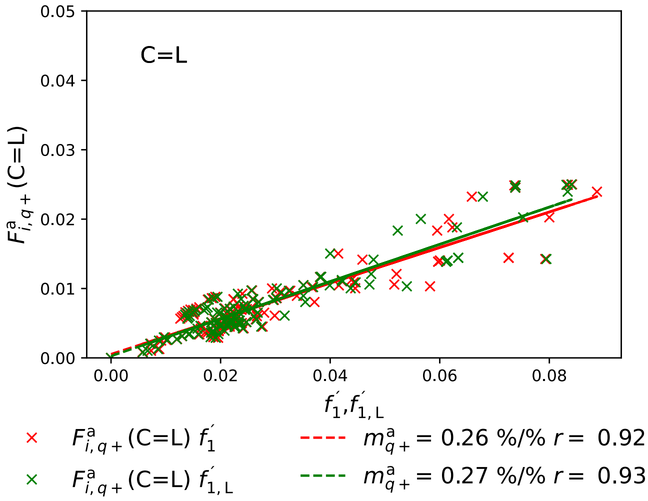


**Figure 11 - Upper 95 % quantiles of the SMCFs for the calibration condition C=L related to $f_1'$ (red) and $f'_{1,L}$ (green)** (EMPIR 19NRM02 RevStdLED, 2022)**.**

Figure 11 shows that there is no significant difference in the behaviour of the SMCF with respect to $f_1'$ or $f'_{1,L}$ in the case that photometers are calibrated with CIE reference spectrum L41.

Krüger et al. (Krüger et al., 2022b) also demonstrate how one of the key measurement uncertainty components of the $f_1'$ determination, the wavelength scale, is critical for the determination for all indices but also behave very similarly for all the indices.

## 4.3 Measurement uncertainty evaluation

Another important point is the determination of the measurement uncertainty for the characteristic values of the proposed indices. This is important because, during the classification of a photometer, the index value and its measurement uncertainty are needed. In the case of the general $V(\lambda)$ mismatch index the expected value of $f_1'$ depends on the measurement uncertainty of the spectral measurements for well-matched photometers, due to the absolute value function. For this purpose, a Monte Carlo simulation (MC) can be used.

In a first step, the sensitivities are only determined for the amplitude noise and the shift of the wavelength scale separately.

### 4.3.1 Impact of the mismatch at single wavelength positions

First, the effect of the mismatch at single wavelength positions for all the evaluated indices is evaluated. To do this, the index values are calculated for an ideal photometer with a small change $\Delta = 0.01$ in the relative spectral responsivity, $s_{\mathrm{rel}}(\lambda)$, at only one wavelength position, $\lambda_i$, according to:

$$s_{\mathrm{rel}}(\lambda) = \begin{cases} V(\lambda) + \Delta & \text{if } \lambda = \lambda_i \\ V(\lambda) & \text{if } \lambda \neq \lambda_i \end{cases} \quad (21)$$

 

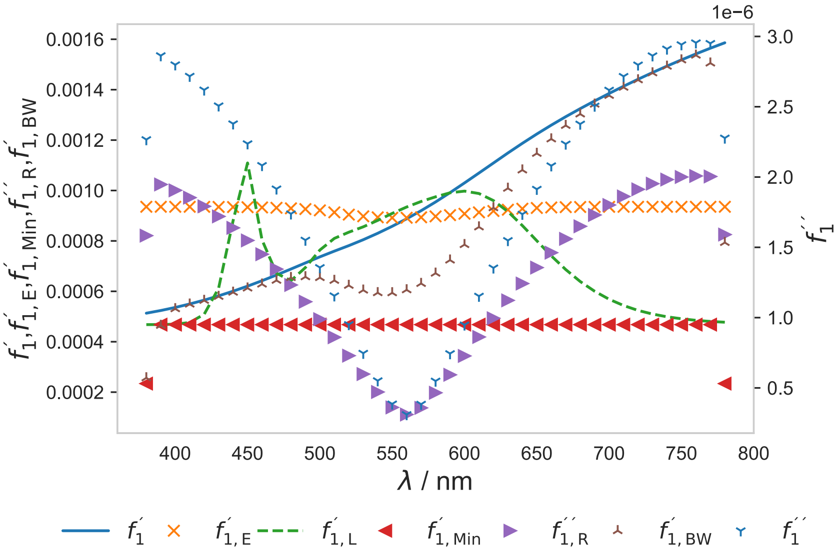

**Figure 12 - The influence of the normalisation for the different evaluated indices using the relative spectral responsivity of the photometer used in** (Krüger et al., 2022b)**.**

## 4.3.2 Impact of the wavelength shift

The next step is a rough estimation of the wavelength sensitivity of the quality indices. This can be analysed by shifts of $\Delta\lambda$ of the ideal photometer relative spectral responsivity, $V(\lambda)$. In the model used inside the Monte Carlo simulation, this is represented by a correlated wavelength uncertainty contribution, according to:

$$s_{\mathrm{rel},\Delta\lambda} = V\left(\lambda - \Delta\lambda\right) \tag{22}$$

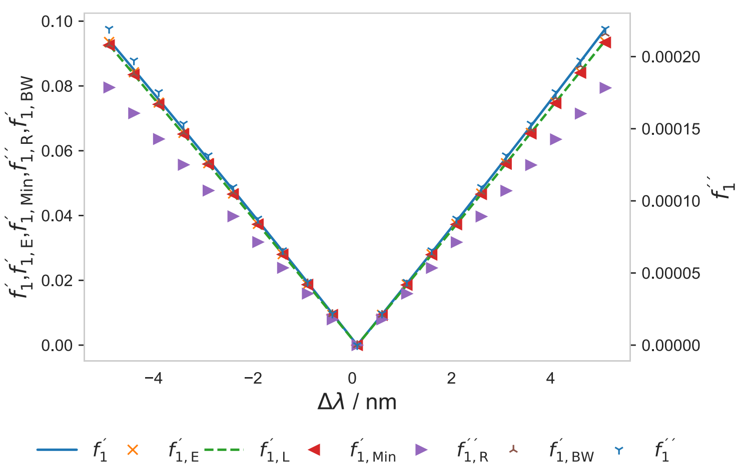

**Figure 13 - Change of the quality index as a function of the wavelength shift** (Krüger et al., 2022b).

Using the data shown in Figure 13, the change of the evaluated indices is about 0.02 nm$^{-1}$. This is a very critical value, which in practice means that great care must be taken to realise a very accurate wavelength scale when determining the relative spectral responsivities of photometers.

# 5 Summary and Conclusion

The following section is a short version of the summary presented in (Krüger et al., 2022b). This paper (Krüger et al., 2022b) describes and evaluates the performance of several indices for general $V(\lambda)$ mismatch under general lighting conditions based on LED light sources. They can be classified as classic indices (where the only modification with respect to the current $f_1'$ is the normalisation factor for the relative spectral responsivity), and those indices derived by a Fourier transform called Fourier indices.

It was found that the linear correlation between the classic indices ($f_1'$, $f_{1,\mathrm{E}}'$, $f_{1,\mathrm{L}}'$ and $f_{1,\mathrm{Min}}'$) is very high, implying that any reasonable normalisation of the relative spectral responsivity should not impact the index performance. There is also a high correlation between the two Fourier indices ($f_1''$ and $f_{1,\mathrm{R}}''$). This is expected, since the latter is based on the former.

The coefficient of correlation between the different indices and statistical parameters of the absolute value of the spectral mismatch correction factor minus one (absolute deviation), $F_j^{\mathrm{a}}(S_{\mathrm{C}}(\lambda)) = \left|F\left(S_{\mathrm{C}}(\lambda), S_{\mathrm{j}}(\lambda)\right) - 1\right|$, namely, the quantiles and standard deviations have been studied using experimental data of relative spectral responsivities and SDs of white LED light sources. The aim was to classify the different indices by performance, under the assumption that the statistical parameters of $F_j^{\mathrm{a}}\left(S_{\mathrm{C}}(\lambda), S_{\mathrm{j}}(\lambda)\right)$ are related with an expected deviation from the true value due to the $V(\lambda)$ mismatch.

The initial observation that the SMCF is much better correlated to $f_{1,\mathrm{L}}'$ than to $f_1'$ (see Figure 10) is only due to the different calibration conditions.

When the CIE reference spectrum L41 is used for the calibration, we might conclude that the Fourier indices seem to have a better performance measuring phosphor-based LEDs (broadband spectral distributions) compared to classic indices. However, this is not the case when evaluating general lighting based on RGB LEDs (narrowband spectral distributions). Here, classic indices have significantly better performance compared to the Fourier indices using a predefined cut-off frequency.

When CIE standard illuminant A is used for the calibration, and general lighting based on LEDs is evaluated, both types of indices have a bad performance.

This means that one can make the following more or less equal proposals for the time after changing the calibration illuminant from CIE standard illuminant A to CIE reference spectrum L41:

- since, in practice, the value of $f_1'$ does not change significantly with other reasonable normalisations of the relative spectral responsivities, one option would be to keep the current $f_1'$ definition without any change; **this is the simplest and prefered option for customers and manufacturers**;

- changing the quality index to $f_{1,\mathrm{L}}'$; this would be in line with the original idea, which is to include the weighting with the spectral distribution of the calibration light source (which will probably be CIE reference spectrum L41 in the future) into the calculation of the normalised relative spectral responsivity, $s_{\mathrm{rel}}(\lambda)$;

- an interesting option is to change the quality index to $f_{1,\mathrm{E}}'$ or $f_{1,\mathrm{Min}}'$; it would make the index independent of the spectral distribution of CIE standard illuminant A; this would be coherent with the idea that the spectral matching of a photometer should be independent of any form of light source spectral distribution;

- use of $f_1''$ as an alternative index for general lighting under phosphor-based LEDs; the advantage is that it correlates better with the $F_j^{\mathrm{a}}\left(S_{\mathrm{C}}(\lambda)\right)$ in those conditions; the drawback is its more complex implementation. Furthermore, one needs to change the cut-off frequency to get a good correlation to RGB-type LEDs, too.

It should be noted that the spectral mismatch correction factor $F\left(S_{\mathrm{C}}(\lambda), S_{\mathrm{j}}(\lambda)\right)$ allows the correction of the spectral mismatch deviation in the specific case of measuring a specific light source with a specific spectral distribution (SD). In contrast, the general $V(\lambda)$ mismatch index gives an indication of the mismatch but allows no correction. It is valid for describing the photometer's expected performance when measuring an arbitrary and unknown SD of a white light source. This information can be used for a first approximation in a measurement uncertainty budget. Using a photometer calibrated with CIE reference source L41 95 % of all SMCFs (absolute deviation) are smaller than $0.28 \cdot f_1'$ for phosphor-type white LEDs and smaller than $0.87 \cdot f_1'$ for RGB-type white LEDs with a very high coefficient of correlation.

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