Stabilization of the Spectral Power Distribution of a Tunable Multichannel LED Lighting System

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Abstract. The advancements in Light-Emitting Diodes (LEDs) have allowed spectrally tunable light sources to gain attention in many fields of research thanks to their ability to produce a specific light output. However, LED outputs can fluctuate with temperature, and aging components can lead to noticeable discrepancies in light characteristics. This study thoroughly examines the Telelumen Dittosizer light player LED panel to exemplify a commercially available device and the associated challenges in predicting and stabilizing its output. Then, we introduce an innovative algorithm aimed at addressing such a stabilization challenge, based on a straightforward characterization procedure along with an external spectrometer. The accuracy of the algorithm was validated with different inputs, achieving a $\Delta_{E,2000}$ lower than 0.5. Our findings demonstrate the ability to stabilize the spectral power distribution for a minimum of 30 min. The proposed algorithm is hardware-independent and adaptable to any combination of spectrally tunable light sources and spectrometers.

Keywords: Spectrally tunable light · LED lighting system · Dynamic adjustment · Luminous efficiency · Multichannel

1 Introduction

Light-Emitting Diodes (LEDs) have become a firmly established technology, dominating various lighting applications such as indoor and outdoor lighting [8,15], automotive lighting [12] and displays [7]. This is primarily due to their significant energy savings, ongoing reduction in manufacturing costs, durability, and compact size [25,26]. Furthermore, there is now a diverse array of LED options available from UV to IR through the visible range, allowing spectrally tunable light sources to gain attention in research works. Their ability to output a specific light spectrum in real time makes them valuable tools in many

R. Schettini et al. (Eds.): CCIW 2024, LNCS 15193, pp. 93–104, 2025.
https://doi.org/10.1007/978-3-031-72845-7_7

fields. For example they are used in psychophysical experiments related to human vision [14,18,24], light simulation [5], or for the construction of image datasets dedicated to machine vision [20]. Extensive work has been dedicated to optimizing these devices to produce light spectra with optimal characteristics, including color rendering, texture visibility, and energy efficiency [1,9,22,23].

While the light emitted from a multichannel LED panel can be finely adjusted by varying the drive level of each channel, ensuring that the device produces the expected spectrum is a significant challenge. Accurately predicting the output of a tunable LED device is complicated by the fact that the output of a light-emitting diode depends on its junction temperature [4,13,19]. This can result in decreased light efficiency and a slight shift towards longer wavelengths. Moreover, these fluctuations can vary significantly depending on the type of LEDs used. Another issue arises from the gradual degradation of LEDs over time, leading to a decrease of luminous efficacy [16].

In the literature, LEDs have been studied in order to model their behavior as a function of their junction temperature. Chhajed et al. [3] measured the junction temperature of 4 types of LEDs and reviewed their optical properties at different temperatures. Authors showed that increasing the temperature of LEDs induced a noticeable difference in light rendering. In order to fix such an issue, various approaches have been proposed. For example, Qu et al. [17] used the measurement of junction temperature to stabilize the output of a RGB LED lamp. Chen et al. [2] proposed a model using optical, thermal and electrical parameters. Li et al. [10] integrated photodetectors into the light-emitting diodes when Llenas et al. [11] integrated a compact spectrometer to stabilize the output of a tunable LED device using a closed-loop feedback system.

The goal of the work presented in this paper is to propose a new approach based on an algorithm able to dynamically adjust the drive levels of the different channels of any tunable multichannel light source in order to match a given spectrum and maintain it over a long period of time using a spectrometer. The following is divided into two main parts. Firstly, a full characterization of the spectrally tunable LED device used in our study will be presented. This characterization will highlight the technological difficulties faced when trying to stabilize the output of such a device. After then, the algorithm we propose will be described and the results it provides will be discussed. Since the proposed algorithm is independent of hardware the code will be made available.

2 Characterization of a Tunable Multichannel LED Panel

The measurements carried out to characterise a tunable multichannel LED lighting system used in this study were made on the basis of a range of power supply configurations applied over a long period of time to the lighting system. The goal was to quantify the evolution of the light output until reaching thermal stability and to identify the difficulties in getting a stable spectral power distribution over time.

2.1 Technical Specifications

The spectrally tunable LED panel used in this work is a Dittosizer light player from Telelumen (see Table 1 for its main characteristics). The unit was suspended to the ceiling of a 250 × 250 cm light booth with white walls. Nineteen out of the 24 available channels were retained for characterization purposes. The two ultraviolet (UV) and two infrared (IR) channels were excluded as they fall outside the visible range. Additionally, one channel was omitted due to its non-linear behavior in comparison to its drive level.

The measurements of the Spectral Power Distributions (SPD) of light sources were performed using a JETI spectraval 1511 spectrometer. The characteristics of this spectrometer are summarized in Table 2. The measured SPD of the 24 LEDs of the Telelumen panel are shown in Fig. 1. The range selected for the measurement was from 380 nm to 780 nm with 5 nm spectral resolution.

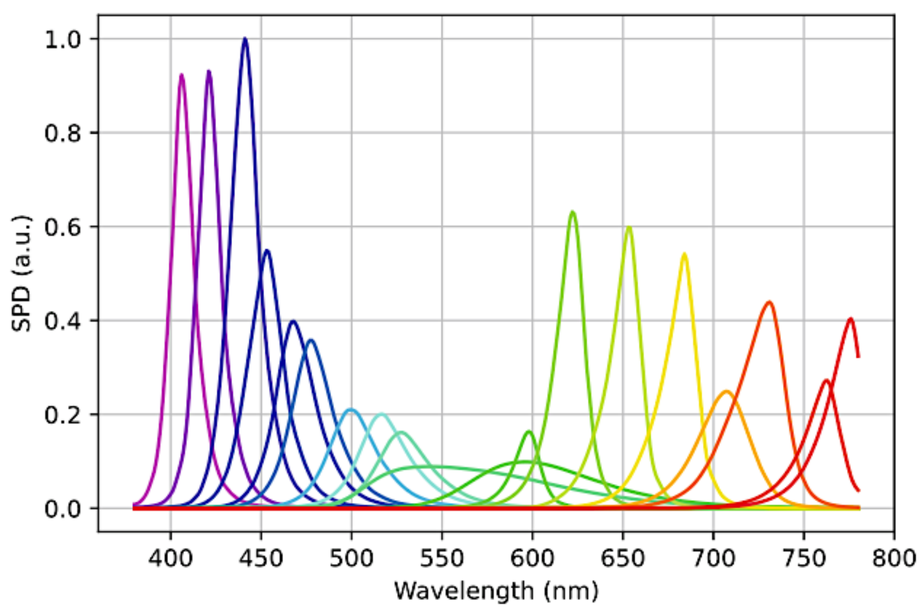


Fig. 1. Spectral power distribution of the 19 selected channels within the visible range of the Telelumen LED panel measured with a spectral resolution of 5 nm and interpolated to 1 nm with akima interpolation.

Both the tunable LED panel and the spectrometer were connected to a PC (i7, 32 GB RAM) using their respective Application Programming Interfaces (APIs), Python 3.10 and the Luxpy library [21]. The Telelumen panel can be controlled by sending directly an array of 24 float values between 0 and 1 representing the drive levels for each channel. The API of the Telelumen panel can also be used to get the readings of the internal temperature sensors.

Table 1. Characteristics of the Telelumen Dittosizer light player

Size	602 × 602 mm
Power consumption	∼100 W
N° of channels	24 (365–940 nm)
Max luminous output	∼5000 lm
Precision	250:1

Table 2. Characteristics of the JETI spectraval 1511 spectrometer

Spectral range	350. . . 1000 nm
Spectral resolution	5 nm
Measuring range	0.2. . . 140000 cd/m^2

2.2 Influence of the Temperature on the Light Output

The output of a LED depends on the temperature of its junction. Temperature fluctuations induce two primary effects on the output of a LED: dimming and spectral shift. As temperature rises, the luminous efficacy of LEDs decreases, which can be mitigated by gradually increasing the drive levels. Conversely, the spectral shift presents a challenge as it results in a noticeable color deviation. Both these effects are more pronounced for LEDs emitting longer wavelengths.

Measuring the junction temperature of a LED is not obvious. In an experimental setup, indirect estimation can be attempted by gauging the temperature of the heatsink on which the LED is mounted on. However, in a real device containing multiple LEDs of different nature and no control over the positioning and the number of temperature sensors, estimating the individual junction temperatures becomes unfeasible.

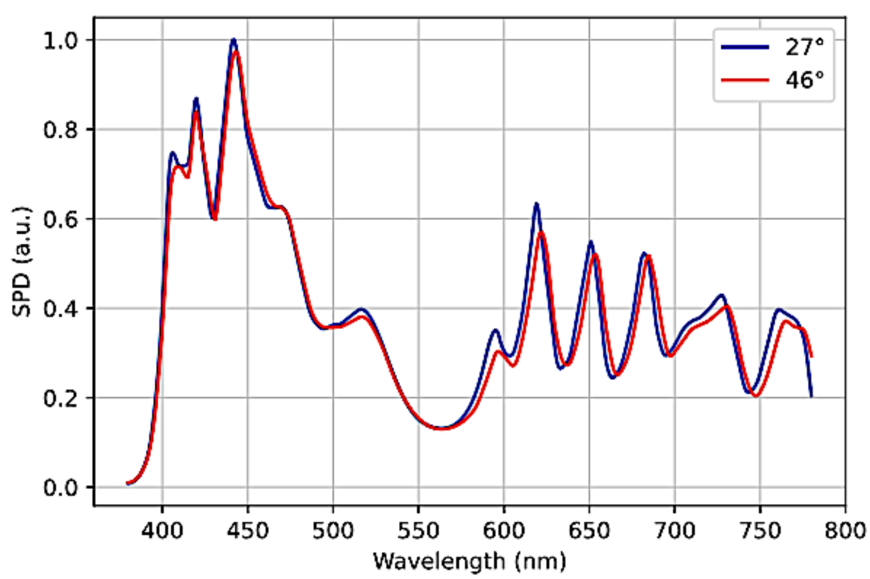


Fig. 2. Variations in spectral output with increasing temperature of LEDs.

To address this issue, the temperature reading from a sensor on the heatsink of the device, was used. Such a reading is easily accessible through the API without requiring disassembly of the device and it is considered to be closely correlated with the junction temperature.

Figure 2 illustrates the impact of temperature on the output of a mulichannel LED device. In this example, the drive level of all channels was maintained at 15% until the device reached thermal stability. A measure of the SPD was performed at internal temperatures of the luminaire of 27 °C and 46 °C. A significant variance in spectral output can be observed once the device stabilizes at its maximum temperature.

2.3 Characterization Procedure

As mentioned before, the objectives of the characterization were both to assess how temperature affects the light output of a multichannel LED lighting system and to identify the difficulties involved in stabilising over time the emitted spectrum. A method was devised to consistently measure the light output across various temperatures of the device. Since the 19 individual channels chosen are entirely independent, the characterization of the Telelumen LED panel was performed by measuring the light output from each channel separately. This was achieved across 100 different drive levels and over 15 temperature settings ranging from 30 °C to 45 °C. To regulate the device's temperature, all LEDs were turned on until the device reached the desired temperature just before each measurement. The detailed procedure for characterization is outlined in Fig. 3. Throughout the measurements, the spectrometer was positioned directly under the LED panel at a distance of about 55 cm.

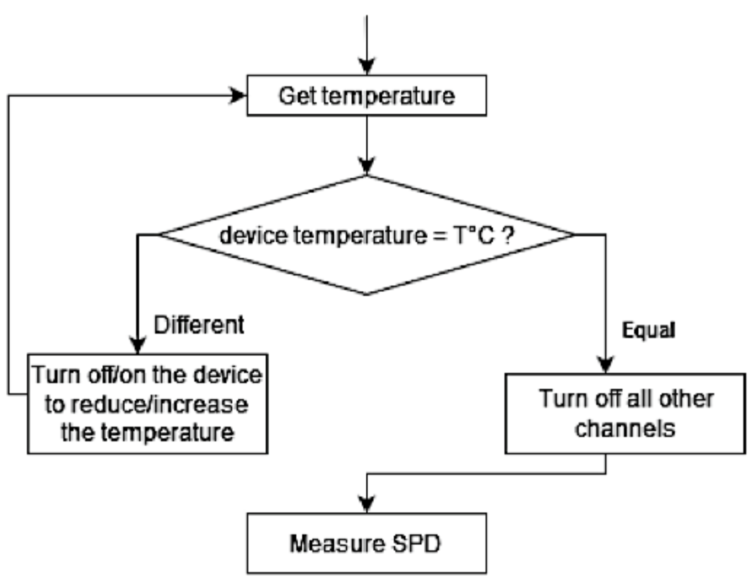


Fig. 3. Flowchart of the characterization procedure

2.4 Characterization Results

Measurement values obtained at minimum (30 °C) and maximum (45 °C) temperature of the heatsink are summarized in Table 3.

Measurement results clearly show that temperature affects all channels to varying degrees. Channels V1 to B1 are less sensitive exhibiting a reduced loss of luminous efficacy and no discernible spectral shift. B2 to G2 have a more pronounced loss of luminous efficacy along with a slight spectral shift. Channels L to FR3 exhibit a significant loss of intensity, reaching a maximum of 30% on channel R1, accompanied by a significant spectral shift towards the longest wavelengths of the visible range and is gradual with increasing temperature (noted as "grad" in Table 3).

In addition, the peak amplitude was measured to ascertain its proportionality with the drive level at different temperatures. It was confirmed that all selected channels exhibit almost linear properties, although the slope decreases with the decrease in luminous efficacy.

Table 3. Characterization of the 19 channels of the Telelumen LED panel in the visible range.

	V1	V2	RB1	RB2	B1	B2	C	G1	G2	L
Peak wavelength (nm)	406	421	441	454	468	478	500	517	528	544
Amplitude attenuation	7%	6%	4%	3%	4%	5%	16%	1%	15%	2%
Peak shift (nm)	no	no	no	no	no	<10	<10	<10	<10	grad

	PC-A	OR	R1	R2	DR1	DR2	FR1	FR2	FR3
Peak wavelength (nm)	594	624	636	654	686	708	732	765	777
Amplitude attenuation	8%	27%	30%	28%	6%	21%	28%	10%	7%
Peak shift	grad	grad	grad	grad	grad	grad	grad	grad	grad

3 Spectral Stabilization Algorithm

The characterization conducted in the previous section illustrates the challenges encountered in stabilizing the SPD of the light emitted by a tunable multichannel LED panel. In this section, we propose an algorithm able of determining the optimal drive levels for a specified output and maintaining its stability over an extended duration. This algorithm is based on a simplified characterization procedure consisting in only measuring the maximum output of each channel.

3.1 Theoretical Optimization

In theory, with a comprehensive characterization of the device, as outlined in the preceding section, and a thorough understanding of all parameters, it would be possible to precisely predict the input drive levels required to replicate a target spectrum.

Given that the output of a LED device is the sum of its individual channels, we could predict the precise output by performing the following calculation:

$$\forall \lambda \in [380, 780], S_{T,I}(\lambda) = \sum_{i=0}^{L-1} S^i_{T^i,I^i}(\lambda) \tag{1}$$

with L the number of channels, T^i and I^i the temperature and drive level of the i^{th} channel.

Then, a simple minimization of the mean squared error (MSE) can be performed to find the optimal drive levels:

$$I^{new} = \min_{I} \int_{380}^{780} \left(Ta(\lambda) - \sum_{i=0}^{L-1} S^i_{T^i,I^i}(\lambda) \right)^2 d\lambda \tag{2}$$

with Ta the target SPD to match.

However, without a full characterisation we cannot have access to the values of $S^i_{T^i,I^i}(\lambda)$. Therefore, we propose an approximation using only the measurements taken at the maximum drive level at a single temperature.

3.2 Approximation of the Impact of the Temperature

It is possible to approximate the output of a LED at any drive level using the spectrum of the output at the maximum drive level with a linear approximation [6]:

$$S_{T_0,I_0}(\lambda) = I_0 \times S_{T_0,1}(\lambda)$$

with S_{T_0,I_0} the SPD of an LED at the temperature T_0 and drive level I_0, and $S_{T_0,1}$ the SPD at its maximum drive level.

The primary limitation of this approximation is its viability solely under constant temperature conditions.

The impact of temperature on the output of the channels can be represented by incorporating a deviation in intensity dI and a shift in wavelength $d\lambda$ such as:

$$S^i_{T_1,I_0}(\lambda) = (I^i_0 + dI^i) \times S^i_{T_0,1}(\lambda + d\lambda^i)$$

We can obtain these deviations by minimizing the MSE criterion with a single measurement of the output of the device.

$$(dI_{min}, d\lambda_{min}) = \min_{dI,d\lambda} \int_{380}^{780} \left(M(\lambda) - \sum_{i=0}^{L-1} (I^i + dI^i) \times S^i_{T_0,1}(\lambda + d\lambda^i) \right)^2 d\lambda \tag{3}$$

with M the measured spectrum.

3.3 Optimization of the Drive Levels

Ultimately, to determine the updated drive levels, we simply substitute the theoretical values in Eq. 2 with the approximation obtained with Eq. 3:

$$I^{new} = \min_{I} \int_{380}^{780} \left(Ta(\lambda) - \sum_{i=0}^{L-1} (I^i + dI^i_{min}) \times S^i_{T_0,1}(\lambda + d\lambda^i_{min}) \right)^2 d\lambda$$

with Ta the target spectrum.

4 Experimental Results

To validate the accuracy of the proposed algorithm, various inputs were compared with and without stabilization following this protocol:

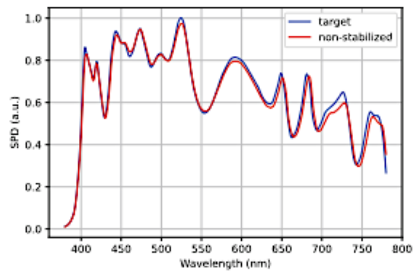
1. Turn on the LED panel at the selected drive levels.
2. Measure and record of the output as the target.
3. Let the device cool down.
4. Record the output **with** stabilization for 30 min.
5. Let the device cool down.
6. Record the output **without** stabilization for 30 min.

As an illustration, Fig. 4 and Fig. 5 show the contrasting behavior of the LED panel with and without the stabilization algorithm. Figure 4a/5a depicts the output after 30 min without stabilization while Fig. 4b/5b showcases the output with stabilization. This example illustrates that, as the device heats up, the LEDs experience a decrease in luminous efficacy, particularly those emitting longer wavelengths. This induces both a reduced illuminance and a color shift. With the stabilization algorithm, the loss of luminous efficacy is compensated by a gradual increase of the drive levels.

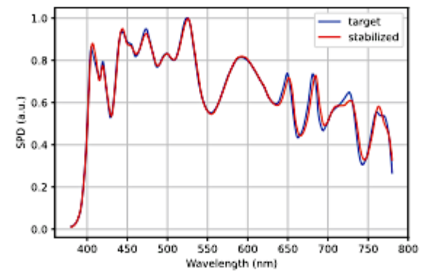
After 30 min, the stabilized output is kept under a $\Delta_{E,2000}$ lower than 0.5 compared to the target, whereas the non-stabilized output exhibits a $\Delta_{E,2000}$ difference exceeding 1. Additionally, the illuminance remains stable around 705 lux whereas it decreases to under 700 lux without stabilization.

The evolution of the difference to the target can also be compared using spectral similarity metrics such as the Mean Square Error as shown in Fig. 6.

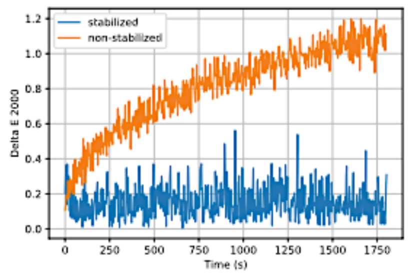
In order to quantify the color difference induced by the rising temperature of the device, a photo of an X-Rite ColorChecker was taken after one hour under a D65 simulation with and without stabilization. The resulting ΔE_{2000} color difference can be seen on Fig. 7. The background and over half of the squares of the ColorCheker display a ΔE_{2000} over 1, meaning that most of the image is perceivably shifted in colors.



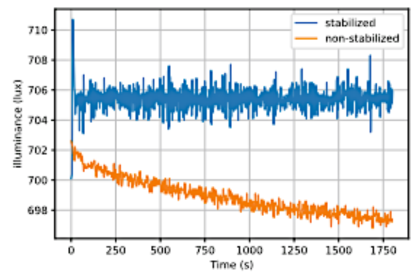
(a)



(b)

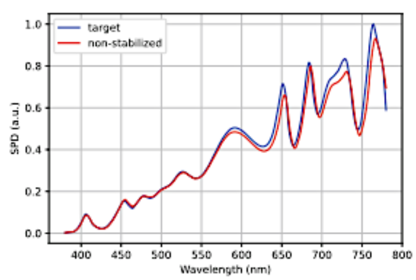


(c) Evolution of the $\Delta_{E,2000}$ differences.

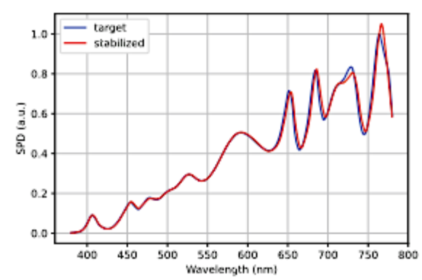


(d) Evolution of the illuminance.

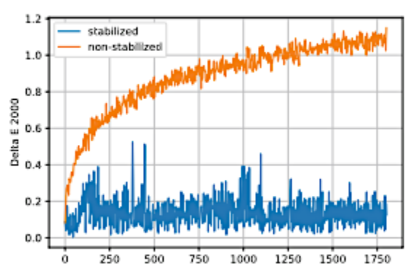
Fig. 4. Comparison of the output with and without stabilization (D65).



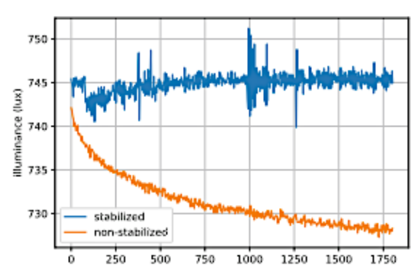
(a)



(b)

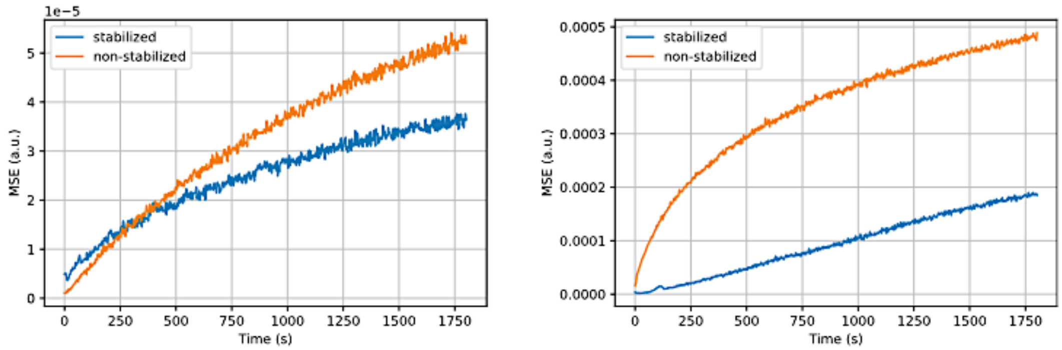


(c) Evolution of the $\Delta_{E,2000}$ differences.



(d) Evolution of the illuminance.

Fig. 5. Comparison of the output with and without stabilization (Illuminant A).



(a) D65 (b) Illuminant A

Fig. 6. Evolution of the MSE for the two examples

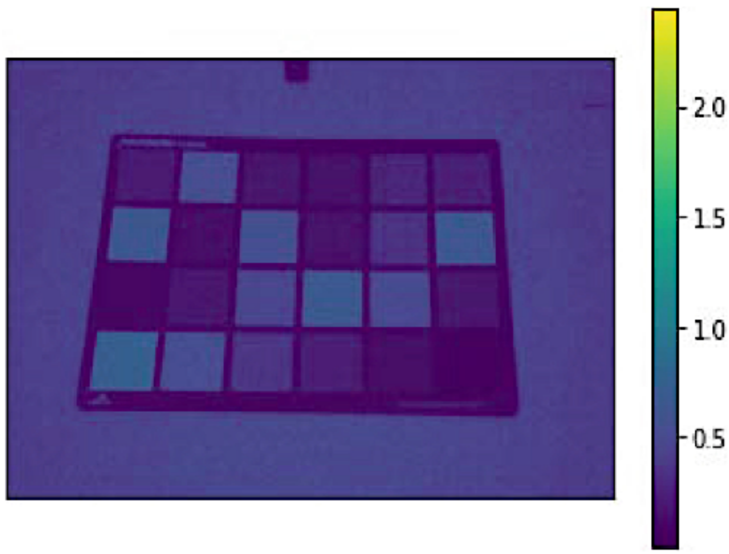


Fig. 7. ΔE_{2000} color difference between stabilized and non-stabilized light

5 Conclusion

In our study, we conducted a comprehensive characterization of the Telelumen Dittosizer light player LED panel, illustrating the challenges faced when trying to predict and stabilize the output of a commercially available spectrally tunable light. Then, we developed a simplified characterization procedure as the foundation for a stabilization algorithm. The proposed algorithm successfully achieved real-time stabilization of the output of a multichannel LED panel, both in terms of color and illuminance. Moreover, it effectively keeps the variations of the light output imperceptible to the human observer, making it usable in the context of human vision psychophysical experiments. Furthermore, the algorithm's hardware independence allows for adaptation to various combinations of spectrally tunable light sources and spectrometers.

There exist opportunities for improvement in this algorithm. Specifically, the computation time could be reduced optimizing the code, using a different optimizer and better positioning of the spectrometer. Different cost functions could also be investigated to better match specific light characteristics such as Color Rendering Index (CRI), Correlated Color Temperature (CCT), etc. This would improve both the precision and versatility of the proposed algorithm. This work focused on light in the visible range, but with minor changes it could be adapted to a wider spectral range.

Acknowledgements. This work has been funded by a public grant from the French National Research Agency (ANR) under the "France 2030" investment plan, which has the reference EUR MANUTECH SLEIGHT - ANR-17-EURE-0026.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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