Spectrally tunable LED illuminator for vision research.

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Abstract

Solid state lighting (SSL) [1] is expected to become a popular light source for colour vision experiments. One of the advantages of the light emitting diodes (LEDs) is the possibility to shape the target light spectrum according to the experimenters' needs. In this paper we present the LED based tunable illuminator designed specifically for colour vision research. The equipment we use consists of six Gamma Scientific RS-5B lamps, each containing 9 different LEDs and the 1 m integrating sphere. We describe the specification of the system and the preliminary work that we carried out in order to set the system up. Finally, we describe the spectral and colorimetric matching algorithms we developed to produce target light spectra.

Introduction

The popularity of LED sources as commercial lighting has been steadily growing over the last decade. This was due in large part to their energy efficiency and longevity. Another advantage of LED sources and the advantage of most relevance to this paper is that LED sources are often narrow-band and so it is easy, by combining multiple sources, to design an illuminator that has some desired spectral properties. The provision of specially designed illuminator is potentially of great use in colour psychophysics. More recently, controllable multi-LED sources have come on the market which can generate a diverse range of different light spectra. However, the use of multi-LED source illuminators in the vision community has so far been limited. In large part this has been due to the most flexible (and useful) illuminators being very expensive. Only recently have affordable (though, still very expensive) illuminators become available.

In this paper we describe such a multi-LED light system which was designed specifically for colour vision research. The illuminator comprises 8 narrow-band LED sources arranged across the visible spectrum and 2 broad band yellow LEDs. One of the challenges of using LED illuminators is that the shape of their spectral power distribution varies with the drive current. However, the proprietary design of the illuminator electronics allows for linear and repeatable luminance adjustment. Given this and the model of the LED chromatic shifts obtained through measurements we can drive the illuminator to meet a given target spectral shape (or a close match) or a colorimetric chromaticity match.

The paper is organised as follows. The remaining part of this section gives the background information related to the development of the LED light sources. In the next section, we describe the Gamma Scientific RS-5B illuminator that we use. This is followed by the discussion on the spectral and colorimetric match algorithms and the conclusions in the final section of the paper.

Background

The simplest tunable LED light source uses 3 different mono-chromatic LEDs with their peaks in red, green and blue parts of the spectrum, hence the name - RGB approach. While this setup can produce large number of colours [2], the light quality measures e.g. CIE Colour Rendering Index (CRI) [3] are usually low [4]. Therefore, there has been an effort to incorporate larger number of LEDs into the light sources to allow users to model the required spectrum of the light more closely. In literature, we have found the systems that use as many as 80 different LEDs [5]. A large amount of work on the development of the LED-based tunable light sources have been carried out at the National Institute of Standards and Technology and this is described in the series of papers [5–7]. They developed a flexible system where the outputs of 20 to 80 different LEDs were channelled to an integrating sphere. The individual LEDs were mounted on 8 to 10 different 'optical heads'. Each optical head had as many as 32 LEDs. The optical heads are equipped with a temperature controlled mounting plates designed to cool and stabilise the temperature of the LEDs. Stable temperature is crucial as like all other light sources, LED light spectrum changes with the temperature change. The output of LEDs driven to different intensities varies spectrally. The first part in controlling the output of the illuminator was to incorporate a fiber optic spectroradiometer as a real time measurement device in the system. Given on-line spectral measurements, the authors developed an optimisation algorithm that adjusts the drive currents of the LEDs based on the spectroradiometer measurements to create the light of the desired spectrum. Importantly, their method is based on the physics of the device and the mathematical idea of gradient descent optimisation (see their paper for details).

Although the method works, the authors report that it takes a long time for the algorithm to converge as it optimises over many small step adjustments to the LEDs intensities. Of course, after a specific spectrum has been calculated once, the correct driving intensities are known. And once a database of spectra are compiled, the optimisation can be begun at a spectrum close to the target that is sought.

The literature also reports efforts to design the algorithms that would optimise the CRI and other parameters of the LED-based light sources [8–10]. However, these papers are trying to design a fixed illuminator not a device that might produce a multitude of light spectra. Moreover, none of these algorithms presented in those papers take into account the intensity (LED drive current) dependent peak wavelength shift, which will be discussed here. Another theme in the LED light mixture optimisation discussed in the literature was concerned with spatial homogeneity of the LED arrays [11] in addition to their spectral and colorimetric characteristics.

The literature in the vision community was in general preoccupied with analysing LED sources with respect to the general light source applications [12, 13]. To our knowledge LED-based illuminators were not used to study specific aspects of the human vision. In this paper, we are describing a preliminary work in setting up the system that will allow us to perform visual psychophysics where the light spectrum can be tuned to the pschophysical experiment at hand.

Gamma Scientific RS-5B illuminator

The illuminator system we work with has been manufactured by Gamma Scientific [14] and consists of the 1 meter integrating sphere and six RS-5B spectrally programmable light sources (see Figure 1). The system contains a real-time optical feedback which allows for linear brightness control i.e. there is no need for the radiometer feedback. The RS-5B optical heads (each head contains all LED types) can be controlled either manually through their back panels or using the RS-5B Control Panel desktop software. This software uses a simple command protocol built on top of RS-232 ports to communicate with all six units. The RS-5B Control Panel is integrated with the SynthiColor^{TM}software which further enhances its utility by providing interactive spectral and colorimetric programming.

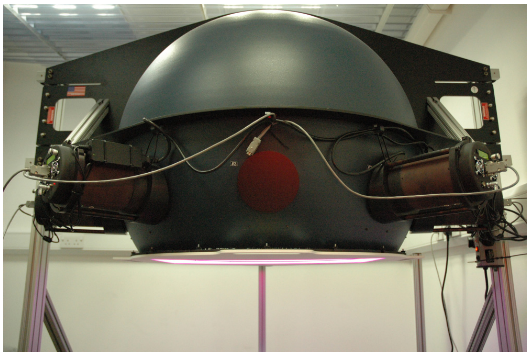

Figure 1. *RS-5B optical heads mounted onto the 1 m integrating sphere.*

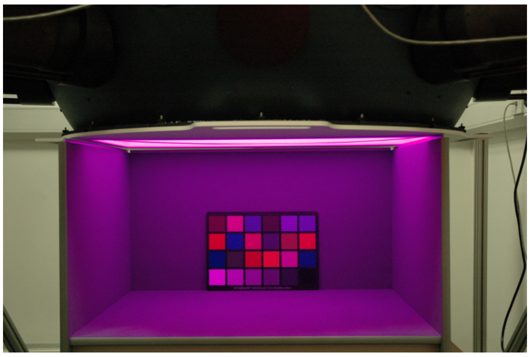

Figure 2. *RS-5B illuminating the viewing cabinet through the* 34 × 68 *cm (largest) aperture.*

Each of the six optical heads located on the perimeter of the integrating sphere contains 10 LEDs. 8 of the LEDs are different narrow band sources and the remaining two are the identical yellow phosphor broad band LEDs. The latter were incorporated into the RS-5B due to the difficulties in obtaining the narrow band LEDs operating in this part of the spectrum. The spectra of the LEDs at their maximum intensity can be seen in Figure 3. Note, that there are only nine spectra in this figure as we plotted only one spectrum of the two identical yellow phosphor channels and doubled it.

The integrating sphere can be fitted with three aperture sizes the largest being 34 × 68 cm. This allows for optimal utilisation of the light as well as some flexibility in construction of the viewing boxes (see Figure 2).

The calibration of the instrument was performed by Gamma Scientific using standards calibrated by the National Institute of Standards and Technology (NIST). The luminance measured through the medium size aperture for all LED channels set to max was 681 cd/m^2 and for the D65 metamer 205 cd/m^2. Using smaller aperture increases those figures by the factor of 1.39 and larger decreases it by the factor of 0.7.

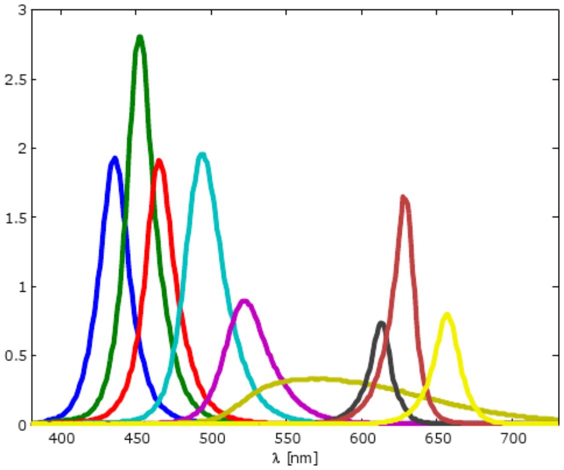

Figure 3. *Spectra of 9 LEDs in RS-5B illuminator at their maximum intensity.*

Calculating spectral and colorimetric matches.

In this section, we discuss how RS-5B can be used to generate the light with a target spectral shape or that has a target chromaticity.

The RS-5B was designed with an intention of avoiding this lengthy convergence procedure of the Fryc et al [7] measurement-feedback algorithm. The proprietary design of RS-5B allows for linear and repeatable luminance adjustment of each LED. Therefore, it is possible to optimise the spectrum (calculate the channel weights) off-line in software i.e. without any interaction with RS-5B.

We must proceed with caution however, since the LED sources exhibit the intensity (drive current) dependent peak wavelength shift [2]. All but one (yellow phosphor) LEDs manifest this behaviour, which was depicted in Figures 4 and 5. Moreover, this shifting is not a simple 1-d linear function. We illustrate this in Figure 7 for one of the RS-5B LEDs. We can see that for this particular LED, as the intensity increases, the peak wavelength shifts towards the shorter wavelengths. We found that even though the spectrum shifts, the variation of all spectra is captured by a 2-d linear model (which we discovered using principal component analysis). We plot the coordinates of each spectrum in this 2-d space in the figure. That the resulting line is curved is indicative of a changing spectral shape along with a changing intensity.

In Figure 6, we show the u'v' chromaticity diagram where we marked the locations of the individual LEDs at 10 different intensities by red crosses. We can see that the markers can be divided into 9 clusters corresponding to the 9 LED types. It is also apparent that the largest chromatic shifts occur for the green lights followed by the blue lights. The shifts in the red end of the spectrum are the smallest and interestingly due to the different LED material the opposite direction (towards the longer wavelengths). It is also clear that there is no chromatic shift for the one special LED - the yellow phosphor.

The existence of this 'spectral shifting' phenomenon prevents us from using the simple linear least-squares algorithm (e.g. non-negative least squares [15]) for matching a desired spectrum with a weighted mixture of the LED channels. This approach would produce a large error as it expects the spectrum of the light to scale by a scalar weight as the intensity of the light is changed.

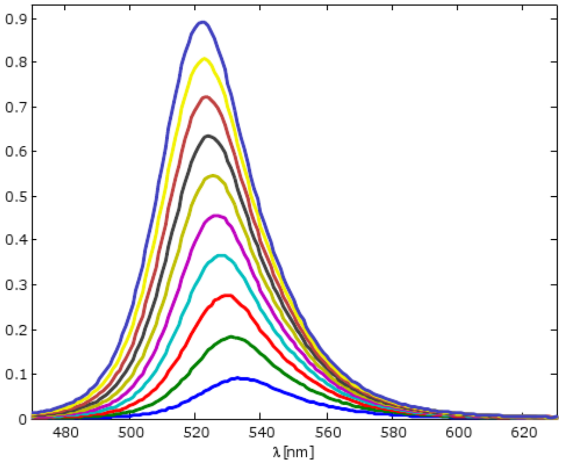

Figure 4. *Spectra of one of the LEDs for 10 intensities, ranging from the 0.1 of the maximum intensity to the maximum.*

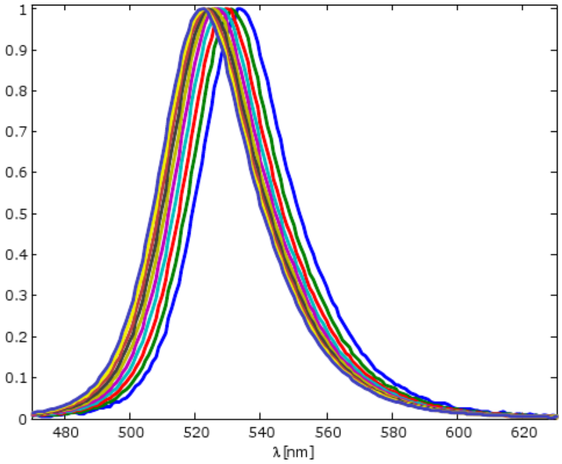

Figure 5. *Spectra from Fig. 4 after normalisation.*

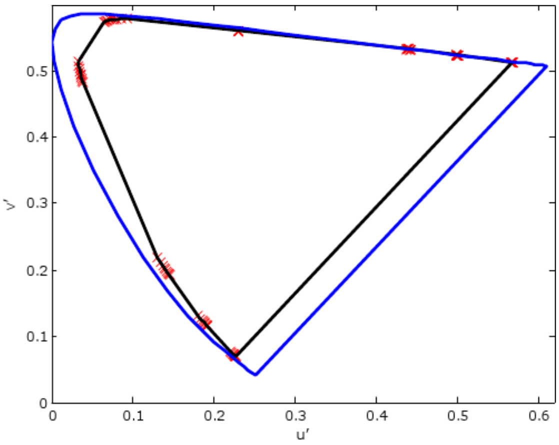

Figure 6. *Outline of the u'v' chromaticity diagram - blue, location of LED lights for different intensities - red x, RS-5B gamut.*

It is clear that one must take into account the chromatic shift phenomenon in the spectral/colorimetric match algorithms. Finding a spectral match is equivalent to solving the following optimisation:

$$\mathbf{x} = \underset{\mathbf{x}}{\operatorname{argmin}} \left|\left| \sum_{k}^{9} \mathbf{b}_k(\lambda, \mathbf{x}_k)\mathbf{x}_k - \mathbf{t} \right|\right|$$

$$\text{subject to } \mathbf{x}_i > 0,\ i = 1, \ldots, 9.$$

where $\mathbf{x}$ is a 9-vector of channel weights, $\mathbf{t}$ - the target spectrum and $\mathbf{b}_k$ - the spectrum of the k-th LED, which has just been shown to depend on the intensity of this LED ($\mathbf{x}_k$). The difficulty in solving this is that $\mathbf{b}_k$ is not known for every real value of $\mathbf{x}_k$. There are a few approaches for solving this, the one we are looking for should be fast and run independently of the illuminator. Therefore, we propose to model the LED shifting property using interpolation of the spectra measured for 10 predefined intensities. We choose the following 10 intensities: 0.1, 0.2...,1 of the maximum intensity and we store those intensities in a vector denoted by $\mathbf{q}$. The rationale for choosing a relatively large number of interpolation points can be found in Figure 7 which tells us that reducing this number would result in an error as any of the points marked with x on the plotted curve in general cannot be represented as a convex combination of the two neighbours. This is particularly true for the LED spectra of the lower intensities.

Next, we measure the spectra of all individual LED lights for those 10 intensities and store them in the 3-D array $\mathbf{A}$. The measured spectra for one of the channels can be seen in Fig. 4. Each subsequent algorithm will model the shape of the LED spectrum for the arbitrary intensity using interpolation i.e. as the convex combination of the measured spectra for the two neighbouring intensities.

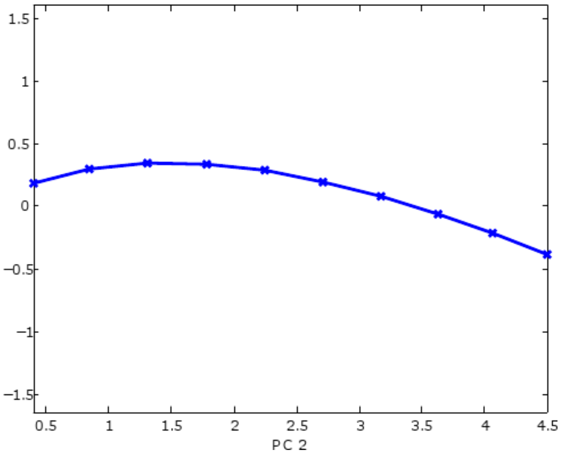

Figure 7. *First vs. second principal component of the 10 LED spectra from Figure 4. The 10 plotted points correspond to the 10 LED spectra of increasing intensities (from left to right).*

In the first iteration of the spectral match algorithm, we place the 9 spectra of all LEDs at maximum intensity in the columns of matrix $\mathbf{B}$ i.e $b_{i,j} = a_{i,j,10}$. We seek channel weights $\mathbf{x}$. The spectral match algorithm is given in Algorithm 1. We can see that in essence the algorithm is an iterative non-negative least squares (lines 2 and 3), which can be solved by standard methods. The channel weights $\mathbf{x}$ obtained in each iteration of the algorithm are used to recalculate the shape of each of the LED spectra for that particular set of weights. Moreover, in each iteration, the target spectrum and the channel weights are normalised by the same factor so that at least one channel is set to its maximum intensity (lines 4 and 6). This makes the spectral match algorithm able to produce the spectrum of the required characteristics at the maximum luminance that can be produced with the illuminator. Because of that, the input target spectrum can be in arbitrary units as it will be scaled up or down to the illuminator maximum luminance.

Algorithm 1

Input: **A** - $351 \times 9 \times 10$ array containing measured spectra of 9 LEDs for 10 intensities, **q** - intensities for which **A** were measured, **t** - target spectrum

Output: **x**- 9-vector of LED weights

```
1.  repeat
2.      $\mathbf{x} \leftarrow \underset{\mathbf{x}}{\text{argmin}} ||\mathbf{Bx} - \mathbf{t}||$
3.        subject to $\mathbf{x}_i > 0,\ i = 1, \ldots, 9.$
4.      $\mathbf{t} \leftarrow \mathbf{t} / \max(\mathbf{x})$
5.      $\mathbf{x}' \leftarrow \mathbf{x}$
6.      $\mathbf{x} \leftarrow \mathbf{x} / \max(\mathbf{x})$
7.      for $j \leftarrow 1$ to 9
8.          do
9.              $k \leftarrow 0$
10.             repeat
11.                 $k \leftarrow k + 1$
12.             until $\mathbf{x}_j \leq \mathbf{q}_k$
13.             if $k = 1$
14.                then $b_{i,j} \leftarrow a_{i,j,1}$
15.                else then
16.                     $w \leftarrow (\mathbf{x}_j - \mathbf{q}_{k-1}) / (\mathbf{q}_k - \mathbf{q}_{k-1})$
17.                     $b_{ij} \leftarrow (1 - w) a_{i,j,k-1} + w a_{i,j,k}$
18. until $||\mathbf{x}' - \mathbf{x}|| > 0.0001$
19. return x
```

The colorimetric match algorithm is almost identical to the spectral. Here, we only need to update the constraints of the optimisation. In addition to the non-negativity constraint (Algorithm 1, line 3), we add another constraint: $\mathbf{R}^T \mathbf{B} \mathbf{x} = \mathbf{R}^T \mathbf{t}$, where **R** denotes the CIE colour matching functions and ^{T} denotes the matrix transpose. This optimisation is also the case of quadratic programming and hence can be solved by standard techniques. Like the Fryc et al. measurement based approach, the above algorithm can also be thought of as a gradient descent type operation (and so will converge).

In Figures 8-16, we can see the results of the optimisations for the two algorithms and four illuminants: D65, D50, D75 and A. Both algorithms converge in 4 to 6 iterations (if we iterate more the 'red-lines' don't change). It can be also seen that the final result can be significantly different from the initial. Note, that the initial iteration result is what one would get if they used the (non-negative) least squares algorithm naïvely i.e. without taking into account the chromatic shift in the LEDs.

We carried out a simple test to evaluate the usefulness (or otherwise) of the lights we have created. We calculated the Color Rendering Indexes (CRI) for the colorimetric matches for the 4 illuminants (D65,D50,D75 and A) which were respectively: 95%, 93%, 95% and 91%. The same figures for spectral matches were: 93%, 91%, 95% and 86% and were similar to those for the colorimetric matches (same except for A).

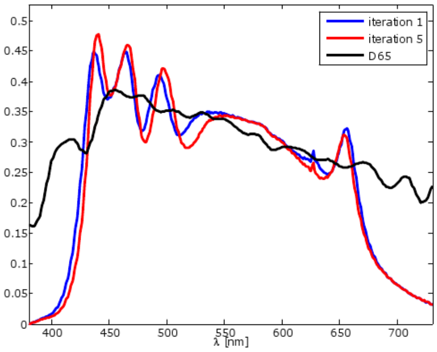

Figure 8. The results of the first and the last iteration of the algorithm for D65 colorimetric match.

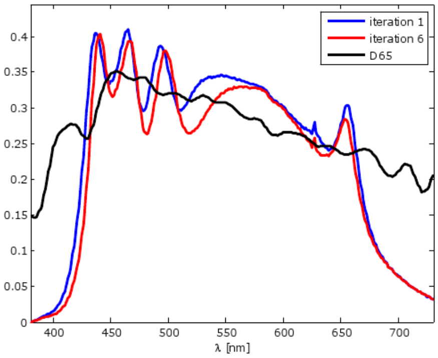

Figure 9. The results of the first and the last iteration of the algorithm for D65 spectral match.

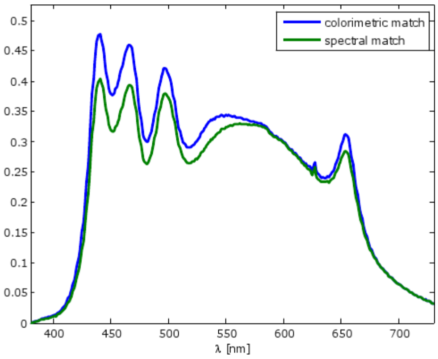

Figure 10. Comparison of D65 colorimetric and spectral matches.

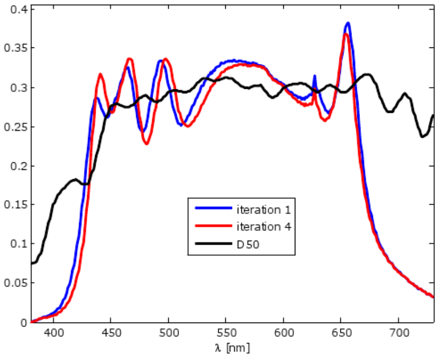

Figure 11. The results of the first and the last iteration of the algorithm for D50 colorimetric match.

Conclusions and Future Work

In this paper, we presented an LED-based illuminator system which has been specifically designed by Gamma Scientific for colour vision research. The system utilises the set of 6 optical heads mounted onto the 1 m integrating sphere. Each optical head contains 10 LEDs: 8 different narrow band LEDs and 2 identical broadband phosphor based LEDs. The system is capable of producing the light spectra of up to 1000 cd/m^2 through 17×34 cm aperture or around 500 cd/m^2 through 34×68 cm

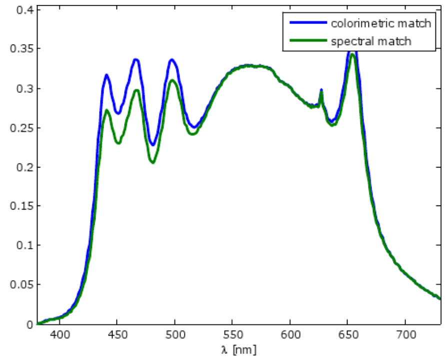

Figure 12. Comparison of D50 colorimetric and spectral matches.

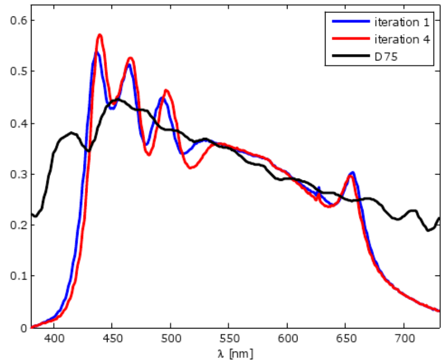

Figure 13. The results of the first and the last iteration of the algorithm for D75 colorimetric match.

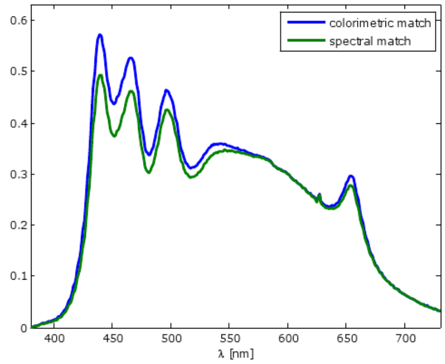

Figure 14. Comparison of D75 colorimetric and spectral matches.

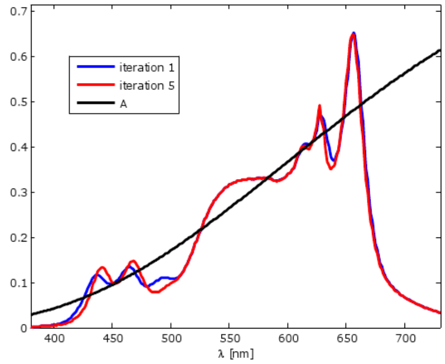

Figure 15. The results of the first and the last iteration of the algorithm for illuminant A colorimetric match.

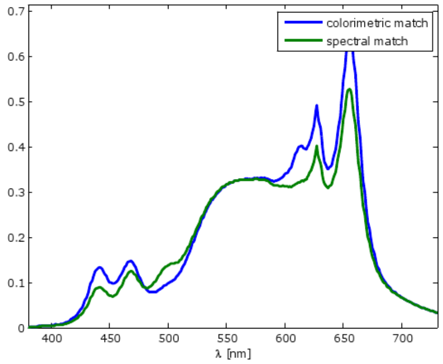

Figure 16. Comparison of illuminant A colorimetric and spectral matches.

aperture. We also presented the spectral and colorimetric match algorithms that are used to produce the light spectra of the desired characteristics. These algorithms address the problem of the LED intensity dependent chromatic shift and together with the linear brightness control capability of the illuminator system allow for fast execution time and flexibility in designing the illuminator spectra. Thanks to the large number of different types of LEDs in the system, the high quality spectral matches can be produced (CRI around 95%).

Our work in future will concentrate on the development of the algorithms that would allow us creation of the arbitrary metamers of different characteristics on that system. With regard to the human vision, we are planning the series of psychophysical experiments studying the effects of metamerism.

Acknowledgements

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