Emission spectrum design by using Particle Swarm Optimization

Maria Jose Rueda Montes

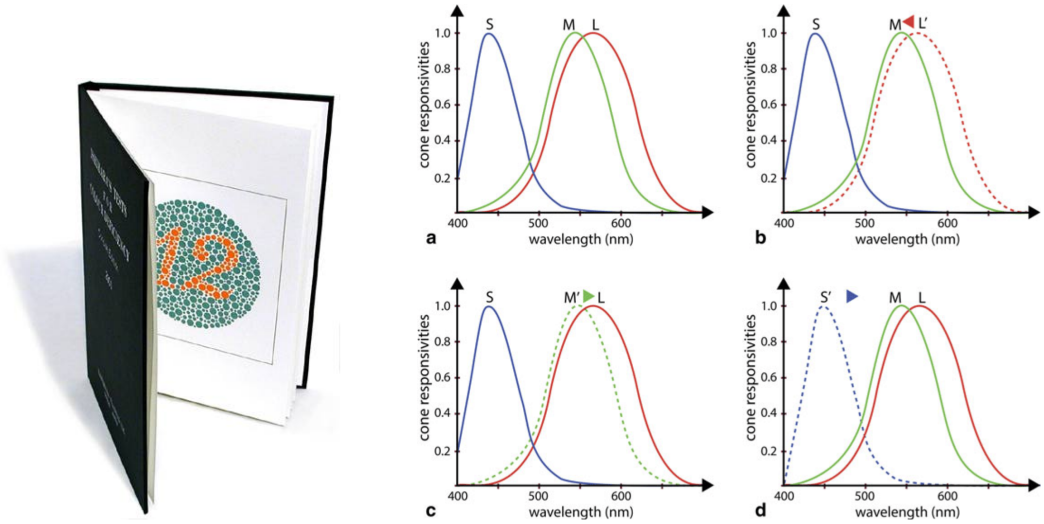
***Abstract*—Spectral design of light sources are commonly used to simulate different illuminants that allow us to collect colorimetric measurements or highlight different properties of an object. Due the importance of this process, and to study its different stages, in this work we calculate the optimal emission spectra of 6 new illuminants by combining the spectral power distribution from 10 different LEDs. We search for the ideal illuminant with Particle Swarm Optimization (PSO) and the final objective is to maximize or minimize the color and contrast differences between two points of the object, which in this case is the Ishihara test. The generated illuminants are simulated in the laboratory while their spectral power distribution (SPD) is measured using a spectrometer. From the results, we obtain good performance for each illuminant. They correctly maximize or minimize the differences between the two chosen object points. Finally, a comparative study is done using the experimental, numerical and visualization results.**

***Index Terms*—Spectrally tunable light source, LED, Spectral imaging, Particle Swarm Optimization (PSO), Color differences.**

1 Introduction

When an object is illuminated with different light sources we can observe a change in its color appearance. The different spectral power distributions (SPDs) that illuminate the same object, provide a different energy for each wavelength, thus generating different spectral reflectance. Based on this phenomenon, one of the techniques used in the detection of wanted features focuses on the modification of the light source [1]. In this way, applying Light Emitting Diodes (LEDs) with different spectral power distributions it is possible to generate a spectrally tunable light source. Using LEDs we can design a desired shape for the emission spectrum by controlling the radiometric output of each type of LED [2]. For this purpose, it is necessary the spectral data collection from the object of study. Spectral imaging allow us to obtain the spatial and spectral information [1]. Therefore, this data can be used to design a new emission spectra based on the spectral properties of the object.

As an object of study, in this practical work we use one of the Ishihara test plates, in particular the plate containing the number 8. Ishihara test is widely used in the detection of protanopia and deuteranopia color vision deficiencies (CVD). This test consists of 38 plates each of which is composed of different patterns of random dots with different shade and size. Observers with CVD will not be able to distinguish the shapes formed on the different plates, while an observer with normal color vision will be able to differentiate them [3]. This result is achieved because the dots on each plate are designed so that their reflectance peaks are close to each other. Thus, as we can see in Figure 1, protanomaly or deuteranomaly subjects will not be able to distinguish two colors because they do not have the sensitivity of the M and L cones well differentiated. It is also important to consider that for the correct detection of CVD we have to perform the test under D65 illuminant.



(A) (B)

Figure 1: A) Ishihara test. B) Spectral sensitivity functions: a) Normal trichromacy. b) Protanomaly. c) Deuteranomal. d) Tritanomaly.

Source: [4][5]

Based on the fundamentals explained above, by modifying the illumination source we could simulate the CVD effect for a normal sighted user (by choosing an illuminant that brings the reflectance peaks of the test points closer together), or get a person with CVD to distinguish the test points (by choosing an illuminant that separates the reflectance peaks sufficiently). Thus, in our practical work we will try to achieve these effects by maximizing or minimizing the color difference of two Ishihara plate dots.

In this practical work we carry out the following main steps:

1) Spectral Imaging from a plate of Ishihara test.
2) Calculation of the optimal emission spectra using particle swarm optimization.
3) Simulation of the optimal emission spectra using the LED-based spectrally tunable light source.

2 Methods and Materials

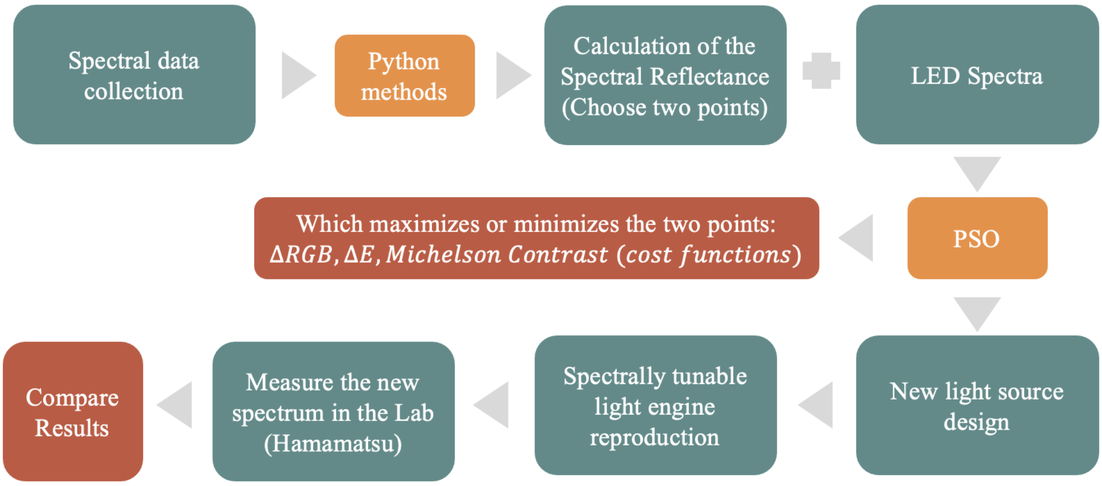
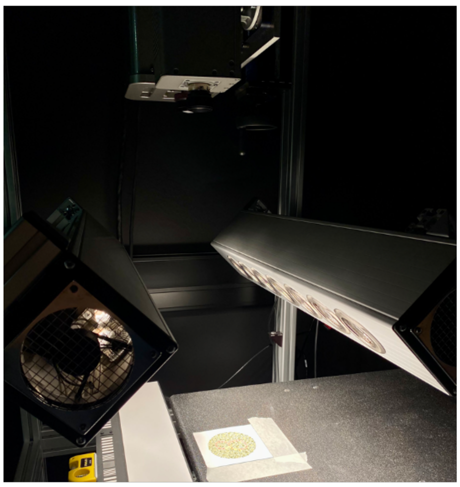


Figure 2: Flowchart of this practical work.

Source: [4]

As the first step, we collect the spectral data from the Ishihara plate by using the Specim V10E line-scanning spectral camera [6]. This device it works as a pushbroom type line scan camera and provides continuous spectral information for each pixel. It has 2184 pixels as spatial resolution, captures 1080 spectral bands and it covers visible and near-infrared (VNIR) portion of the electromagnetic spectrum (380nm - 1000nm).

(A)



(B)

Figure 3: (A) Specim V10E line-scanning spectral camera. (B) Setup geometry: 45º/0º.

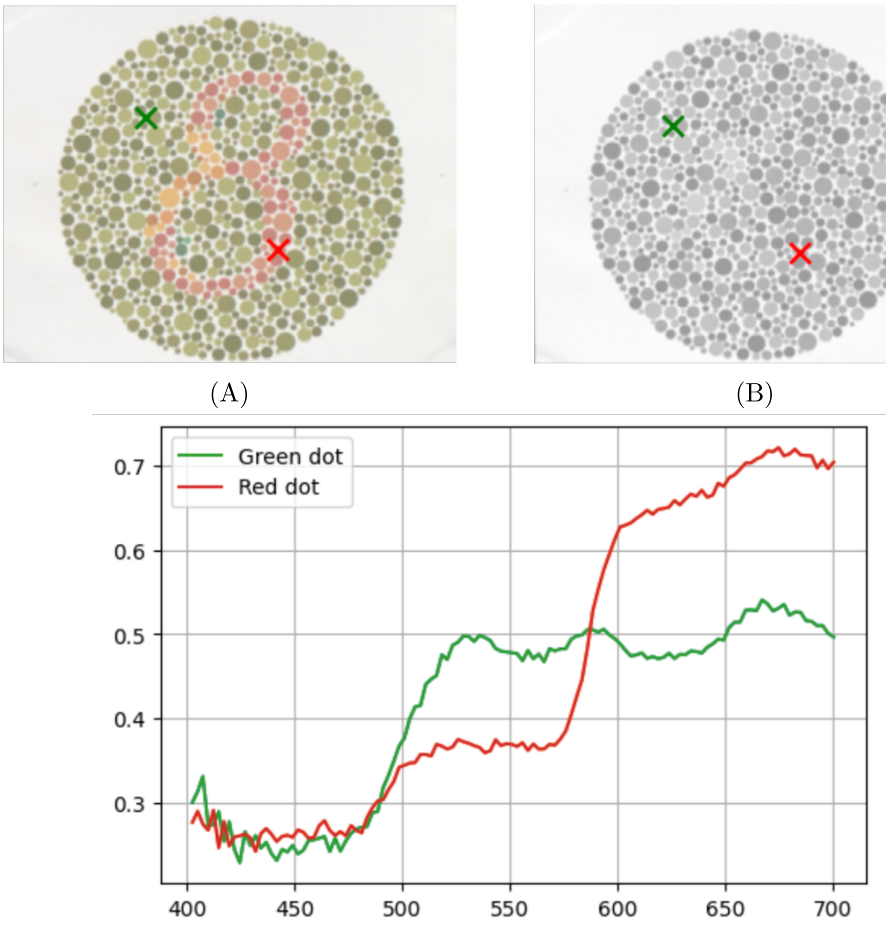
Source: Figure (A)[6]

The geometry formed by the spectral camera with the light source is 45º/0º as can be seen in Figure 3 (B). On the other hand, it is also important to note that together with the spectral information it is needed to measure the white sample reference and the dark noise [1]. Both are required to obtain the final object reflectance which is computed in python code. The spectral reflectance from the 3-D data cube is calculated utilizing the following equation

$$R_{sample}(x,y,\lambda) = \frac{s_{sample}(x,y,\lambda) - s_{dark}(x,y,\lambda)}{s_{white}(x,y,\lambda) - s_{dark}(x,y,\lambda)}, \quad (1)$$

where R is the spectral reflectance and s the spectral data, along the λ wavelengths for each x and y coordinates.

From the spectral reflectance cube obtained in the Ishihara plate measurements, we have selected two different points. These points correspond with the two crosses in Figure 4.



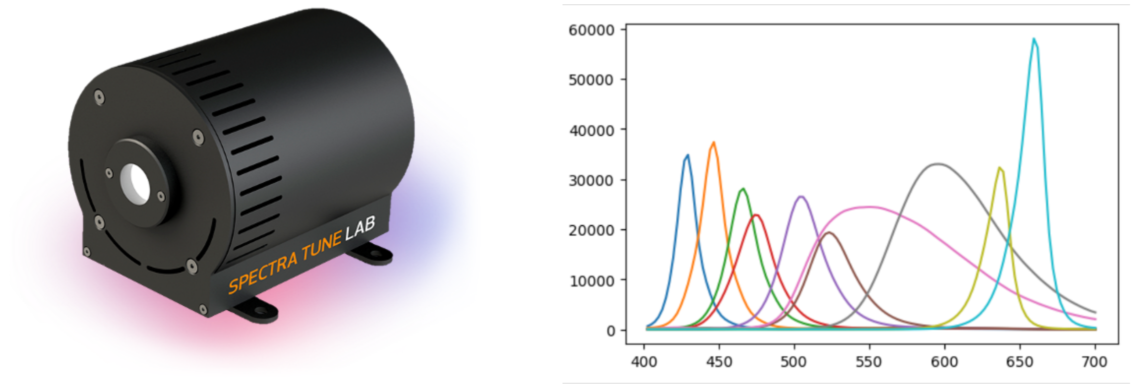
(A) (B)

(C)

Figure 4: (A) RGB sample image. (B) Grey scale sample image. (C) Spectral reflectance of the the two points selected from the Ishihara plate (on the y-axis is represented the reflectance and on the x-axis the wavelengths).

The algorithm (PSO) that computes the new emission spectra that we search for in this practical work, takes as inputs the spectral reflectance we previously calculated and the spectral power distributions from the spectrally tunable light source (Spectra Tune Lab [7]). The Spectra Tune Lab engine is composed of 10 independently addressable LEDs (Figure 5) that are combined to design the desired illuminant.

Before computing the iterative algorithm, we have to resize the spectral reflectance data and the LED spectral data to match in ranges. For this purpose the spectral reflectance is limited to a wavelength range between 400 - 700 nm and we also interpolate the LED spectral data for each intensity to match these same wavelengths.



(A) (B)

Figure 5: (A) Spectra Tune Lab engine. (B) 10 LEDs Spectral power distributions (on the y-axis appear the intensity and on the x-axis the wavelengths).

Source: Figure (A)[7]

Particle Swarm Optimization (PSO) is an iterative method applied to optimization solutions [1]. PSO is based on a swarm of randomized particles that search the optimal set of parameters which minimizes or maximizes the given cost functions. In this practical work the optimal light source spectrum is a convex combination of the LED spectra, the parameters are the LED relative intensities and the cost functions are two color difference equations and one difference contrast equation. Therefore, we obtain as output the optimized LED relative intensities that maximizes or minimizes the color difference between the two chosen points in the Ishihara plate. We implement this algorithm in python code and we use 65 iterations with 100 particles. The cost functions that PSO is minimizing o maximizing are shown bellow

RGB color difference ΔRGB in the RGB color space:

$$\Delta RGB = \sqrt{(R_1 - R_2)^2 + (G_1 - G_2)^2 + (B_1 - B_2)^2}, \tag{2}$$

where (R_1, G_1, B_1) and (R_2, G_2, B_2) are the red, green, and blue pixel values for the two selected points.

CIE ΔE color difference in the CIE$L^*a^*b^*$ color space:

$$\Delta E = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}, \tag{3}$$

where (L_1^*, a_1^*, b_1^*) and (L_2^*, a_2^*, b_2^*) are the color coordinates in CIE$L^*a^*b^*$ for the two selected points.

Michelson contrast:

$$c = \frac{max\{g_1, g_2\} - min\{g_1, g_2\}}{max\{g_1, g_2\} + min\{g_1, g_2\}}, \tag{4}$$

where g_1 and g_2 are the grayscale values for the two selected points.

Before applying each of the above equations we need to calculate the corresponding color coordinates. For this purpose we have to compute the CIE XYZ tristimulus values (X, Y, Z) for which we use our sample's reflectance spectrum, the light source's emission spectrum and the CIE standard human observer's color matching functions. All these calculations are executed in python code utilizing the functions provided by [1] while the color difference equations are implemented by ourselves.

Finally, the output from PSO is used to obtain the optimal light source's emission spectrum which maximizes o minimizes the color differences between the two points. To this final computation, we apply the following equation

$$L_{optimal}(\lambda) = \sum_{i=1}^{10} \mu_{i,best} L_{LED,i}(\lambda), \tag{5}$$

where λ is the wavelength, μ is the LED relative intensity obtained in PSO and L_{LED} is the LED's spectral power distribution.

After the above process we get 6 different illuminants, two for each color difference equation, one that maximizes and another that minimizes the differences between the two points of the Ishihara test. These 6 illuminants are tested in the laboratory using the Spectra Tune Lab engine [7]. To ensure that the calculations have been performed correctly, and that the expected values from the code calculation match the experimental values, we measured the produced spectrum intensity of the 6 designed illuminant with Hamamatsu PMA-11 spectrometer [8].

3 Results and discussion

In order to obtain and compare the results, we calculate the new RGB values of the Ishihara plate under the 6 different illuminants, as well as the color and contrast differences for each equation for these new illuminants.

	ΔRGB	CIE ΔE	Michelson Contrast
Under D65 Illuminant	0.1879	20.210	0.0796
Illuminant which maximizes	0.4993	24.970	0.2515
Illuminant which minimizes	0.1848	15.301	0.0694
The difference increases	0.3111	4.7598	17.187 %
The difference decreases	0.0030	4.9087	1.0184 %

Table 1: Numerical results for each pair of illuminants that maximize and minimize the corresponding color and contrast difference equations. The last two lines are calculated by comparing the two points previously selected from the Ishihara plate under the new illuminant and the D65 illuminant.

3.1 ΔRGB color difference

When we calculate the new spectrum emission using ΔRGB color difference, we do not obtain very significant results, both numerically in Table 1, and experimentally in Figure 8, with worse values for the illuminant that minimizes the difference between the two points. On the other hand, the spectral power distribution from both illuminants are as expected. The code shows same results as the measured by Hamamatsu PMA-11 spectrometer (Figure 7).

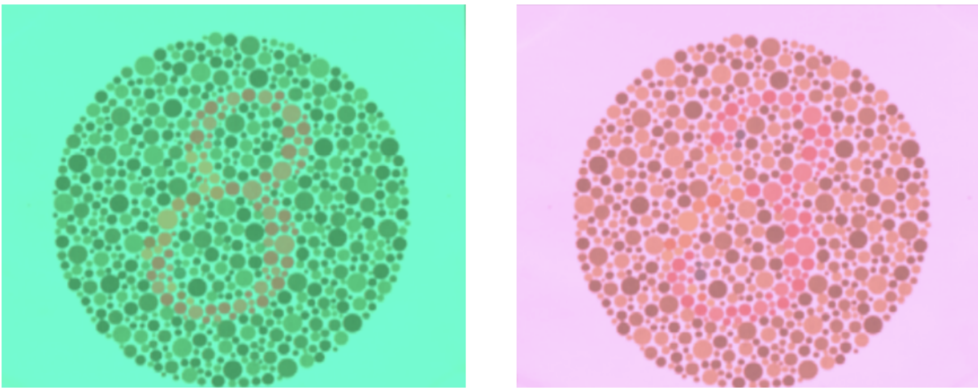
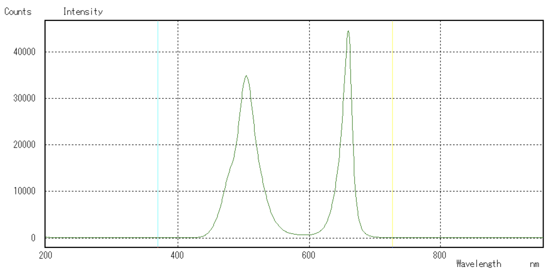
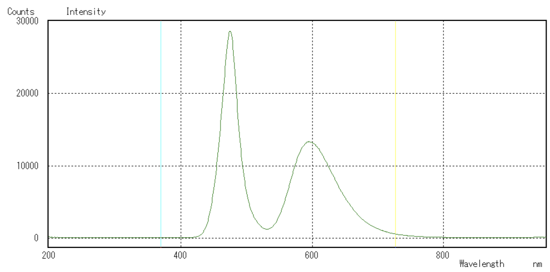


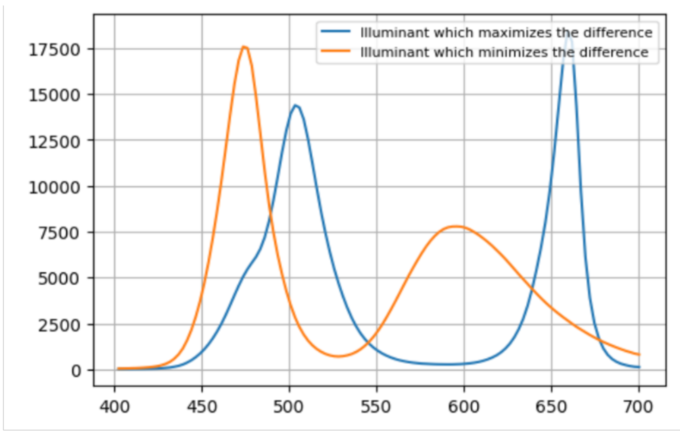
Figure 6: The figure on the left shows the Ishihara plate under the illuminant which maximizes the color difference for ΔRGB equation between the two points selected (Figure 4). The image on the right shows the illuminant that decreases the color differences also for ΔRGB.



(A)



(B)



(C)

Figure 7: (A) Spectrum intensity from the illuminant which maximizes ΔRGB, measured using Hamamatsu PMA-11 spectrometer. (B) Spectrum intensity from the illuminant which minimizes ΔRGB, measured using Hamamatsu PMA-11 spectrometer. (C) Spectral power distribution generated by python code simulator.

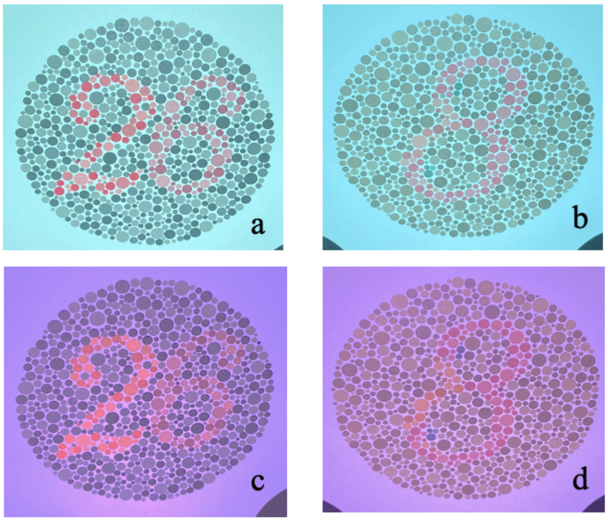


Figure 8: Lab pictures, the illuminants are simulated using Spectra Tune Lab engine. a) and b) are taken under the illuminant that maximizes the color differences between the two points (Figure 4) for ΔRGB. c) and d) are taken under the illuminant that minimizes the color differences between the two points (Figure 4) for ΔRGB.

3.2 CIE ΔE color difference

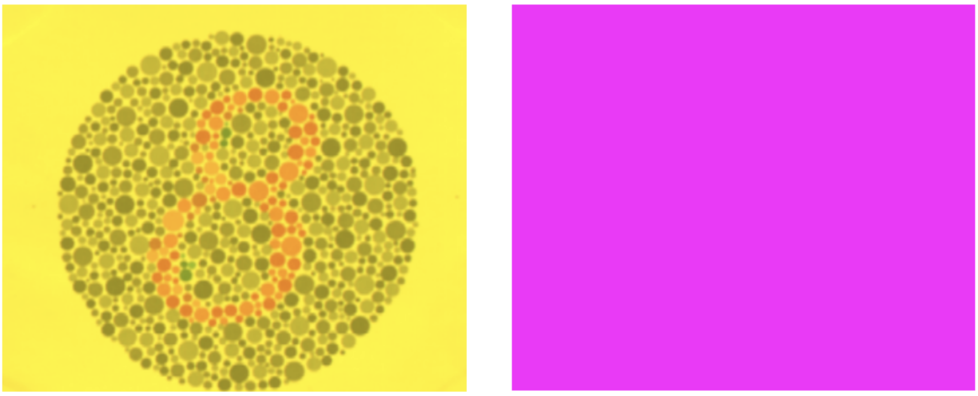
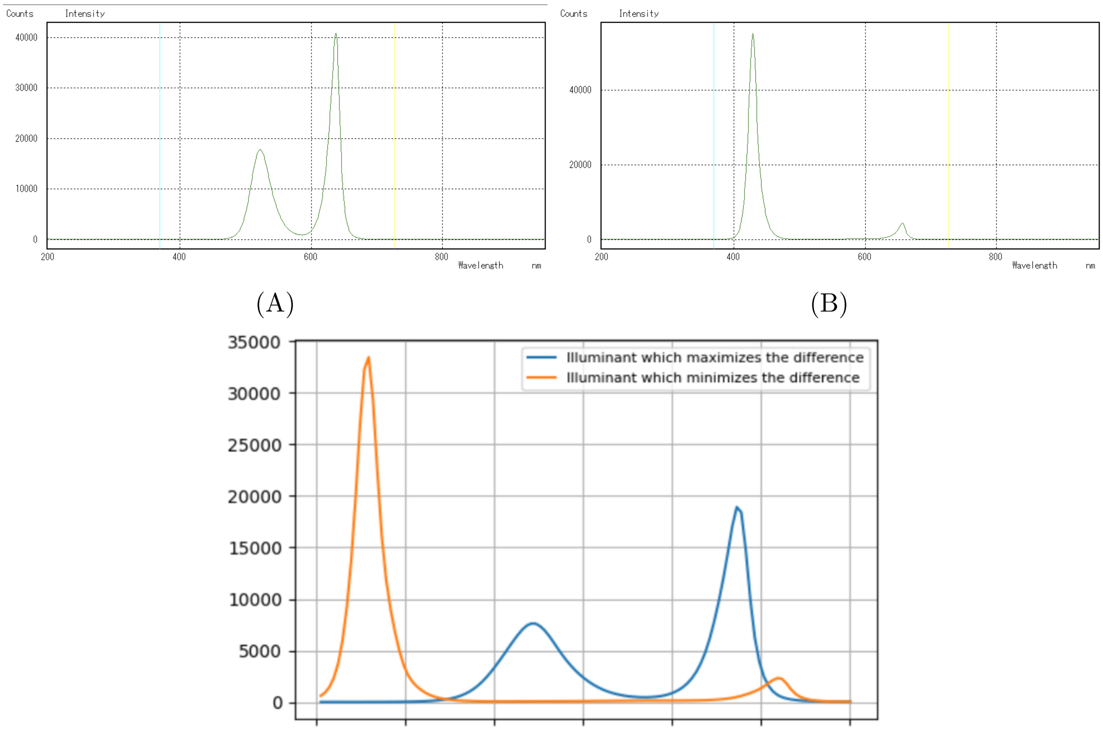


Figure 9: The figure on the left shows the Ishihara plate under the illuminant which maximizes the color difference for CIE ΔE equation between the two points selected (Figure 4). The image on the right shows the illuminant that decreases the color differences also for CIE ΔE.

Applying CIE ΔE color difference illuminants, we achieve better results compared with the previous analysis in RGB color space. Both for the emission spectra that maximizes the color difference and for the one that minimizes it, we get similar numerical values (Table 1). Although the camera color correction disturb the results, we can also notice an improvement in the results experimentally (Figure 9) and for the simulation in code (Figure 11). Moreover, in this case also match the measurements collected by Hamamatsu PMA-11 spectrometer with the spectral emissions that the code predicts (Figure 10). On this occasion, as Figure 9 shows, the output using the illuminant which minimizes the differences produces some problems due a mistake in the code implementation.



(A) (B)

(C)

Figure 10: (A) Spectrum intensity from the illuminant which maximizes CIE ΔE, measured using Hamamatsu PMA-11 spectrometer. (B) Spectrum intensity from the illuminant which minimizes CIE ΔE, measured using Hamamatsu PMA-11 spectrometer. (C) Spectral power distribution generated by python code simulator.

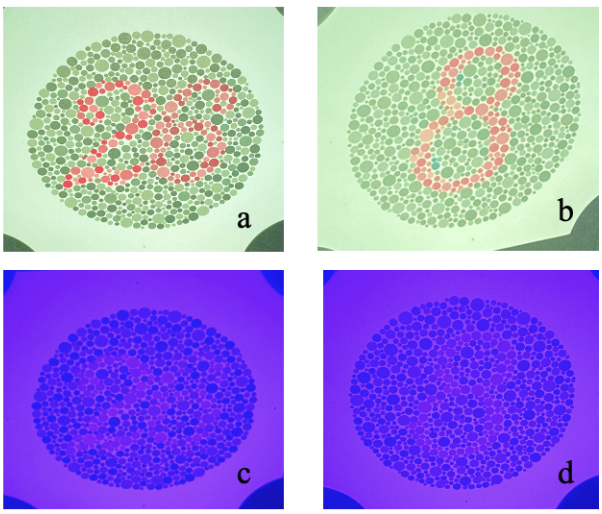


Figure 11: Lab pictures, the illuminants are simulated using Spectra Tune Lab engine. a) and b) are taken under the illuminant that maximizes the color differences between the two points (Figure 4) for CIE ΔE. c) ad d) are taken under the illuminant that minimizes the color differences between the two points (Figure 4) for CIE ΔE.

3.3 Michelson Contrast

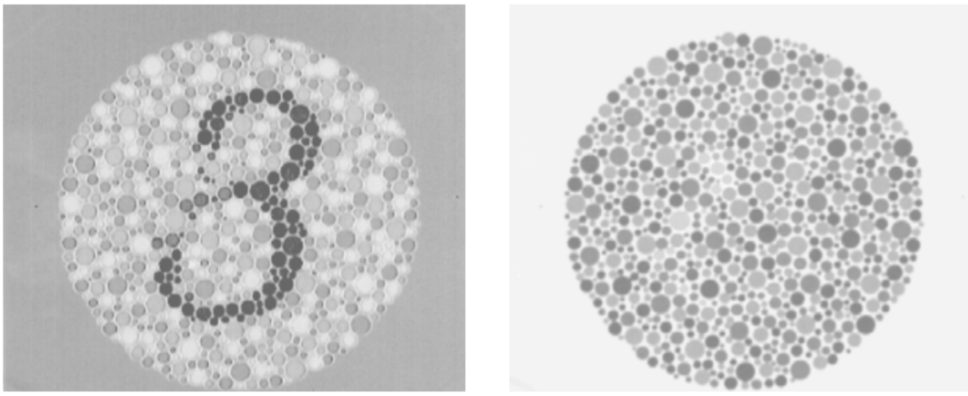
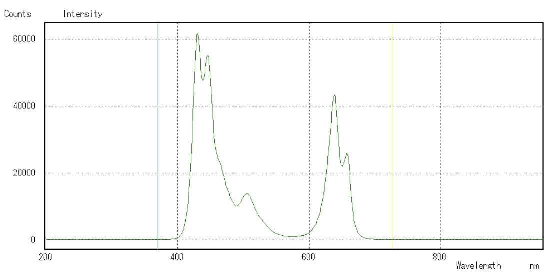
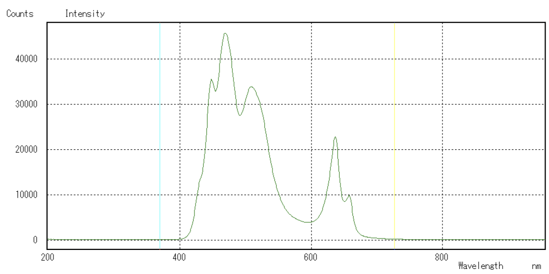


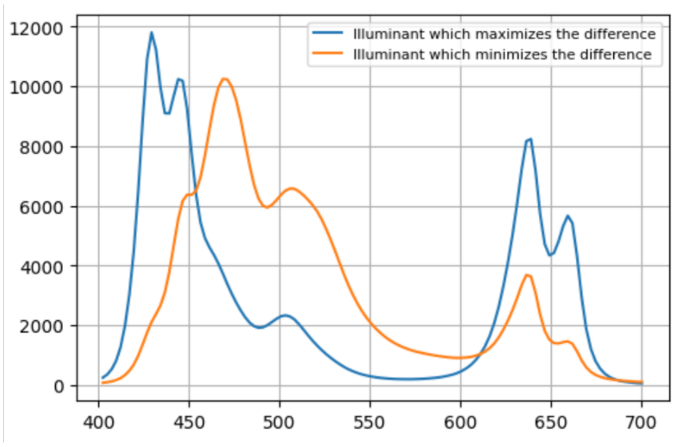
Figure 12: The figure on the left shows the Ishihara plate under the illuminant which maximizes the color difference for Michelson Contrast equation between the two points selected (Figure 4). The image on the right shows the illuminant that decreases the color differences also for Michelson Contrast.



(A)



(B)



(C)

Figure 13: (A) Spectrum intensity from the illuminant which maximizes Michelson Contrast, measured using Hamamatsu PMA-11 spectrometer. (B) Spectrum intensity from the illuminant which minimizes Michelson Contrast, measured using Hamamatsu PMA-11 spectrometer. (C) Spectral power distribution generated by python code simulator.

Finally, after calculating the contrast between the two points, we obtain a very good numerical value for the illuminant that increases the contrast, with a 17.2% increase, while with the other illuminant we only managed to minimize the contrast by 1% (Table 1). However, the RBG visualization, Figure 12, shows a good results for the two illuminants. Even thought we decreases the contrast difference by only 1%, we can see how the number in the Ishihara plate is almost imperceptible. Besides that, the spectrometer measurements again match the expected results of the code (Figure 13).

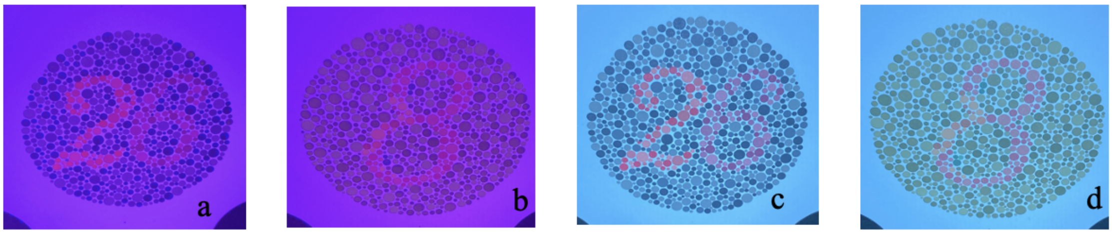


Figure 14: Lab pictures, the illuminants are simulated using Spectra Tune Lab engine. a) and b) are taken under the illuminant that maximizes the color differences between the two points (Figure 4) for Michelson Contrast. c) and d) are taken under the illuminant that minimizes the color differences between the two points (Figure 4) for Michelson Contrast.

4 Conclusions

During this practical work we managed to generate 3 pairs of illuminants that correctly maximize or minimize the color differences (Equation 2, Equation 3, Equation 4) between two chosen points of an Ishihara plate (Figure 4). Each of these illuminants are generated by PSO, setting 65 iterations and 100 particles. Once we obtain each optimal light source's emission spectrum, we successfully simulated them in the laboratory. For all the new illuminants we achieved the expected results from the code when measured with Hamamatsu PMA-11 spectrometer.

From the results obtained (Table 1) we observe that for the ΔRGB equation the results are significantly worse than for CIEΔE. This outcome may be due to the difference between the two color spaces RGB and CIE$L^*a^*b^*$. CIE$L^*a^*b^*$ color space is more uniform than RGB, moreover it is a color space that tries to simulate human vision, hence it produces more accurate results. On the other hand, another interesting result that we can highlight is the different performance between increasing and decreasing the contrast difference for Michelson contrast equation. Table 1 shows worse results when decreasing the contrast difference for the two points of the Ishihara plate. As a reason, we can argue that this is due to the design of the Ishihara test, since the difference between contrast should be as small as possible so that only the color differences are perceived and so that a CVD observer can be evaluated correctly.

In order to improve the results discussed above, in future works we could increase the number of particles and/or number of iterations in PSO. Due to lack of CPU capacity, the time consumed to run the algorithm was very high. Another way to improve the results would be to choose two different points from the Ishihara test. Depending on the points selected we obtain different results. Finally, the efficiency of the code could also be improved since it is a fundamental element in the generation of the optimal light source's emission spectrum.

Bibliography

[1] P. Fält, *Color Science Laboratory, course*. University of Eastern Finland, 2021.

[2] I. Fryc, S. W. Brown and Y. Ohno, 'Spectral matching with an led-based spectrally tunable light source', in *Fifth International Conference on Solid State Lighting*, International Society for Optics and Photonics, vol. 5941, 2005, p. 59411I.

[3] C. V. Correction. (). 'Ishihara color plate test for colorblindness', [Online]. Available: https://colormax.org/ishihara-color-plate-test/ (visited on 19/10/2021).

[4] G. Petrović and H. Fujita, 'Deep correct: Deep learning color correction for color blindness', in *New Trends in Intelligent Software Methodologies, Tools and Techniques*, IOS Press, 2017, pp. 824–834.

[5] W. Ophtalmics. (). 'Ishihara color test 14 plate edition', [Online]. Available: https://www.west-op.com/ishihara.html (visited on 19/10/2021).

[6] Specim. (). 'Scmos-50-v10e', [Online]. Available: https://www.specim.fi/products/scmos-50-v10e/ (visited on 18/10/2021).

[7] Ledmotive. (). 'Spectra tune lab', [Online]. Available: https://ledmotive.com/stlab/ (visited on 18/10/2021).

[8] U. of Eastern Finland. (). 'Sib labs colour research laboratory', [Online]. Available: https://www.uef.fi/en/sib-labs-colour-research-laboratory (visited on 18/10/2021).