ACTIVITY 7

COLOR SCIENCE

APPLIED PHYSICS 184

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CONTENTS

OBJECTIVES

01 TRICHROMATICITY OF COLOR MIXTURE

1. **Reproduce the boundaries of the CIE-xy Chromaticity Diagram by obtaining the CIE-xy chromaticity coordinates of monochromatic lights from 380nm to 780nm in increments of 10nm.**
2. **Obtain the Planckian Locus by computing for the CIE-xy chromaticity coordinates of a blackbody emitting from 1000K to 10,000K in increments of 1000K.**

OBJECTIVES

02 COLOR ORDER SYSTEM & COLOR DIFFERENCE SPECIFICATION

1. **Transform the tristimulus values of monochromatic lights and Planckian light sources absorbed under Illuminant D65 to u’v’ chromaticity coordinates and plot in u’v’ chromaticity space.**
2. **Determine the L*a*b* coordinates of three random Munsell color chips under two different lights - Illuminant D65 and a white LED.**
3. **Compute for the color difference of the chips observed in two different lights.**

OBJECTIVES

03 COLOR IMAGE CAPTURE & COLOR RENDERING

1. **Calculate the digital color of surfaces given the ambient light source, surface reflectance, and camera sensitivities.**
2. **Given the calculated R, G, and B values of a surface, render the color on a display device.**
3. **Simulate how CCD or CMOS sensors produce color images.**

METHODOLOGY

01 TRICHROMATICITY OF COLOR MIXTURE

I downloaded the table for the CIE Standard Human Observer 1964 and loaded the wavelengths (380 to 780nm in increments of 5nm) and their corresponding color matching functions in MATLAB. To obtain the tristimulus values X, Y, and Z for the monochromatic light, I performed integration using the equations below.

$$\begin{aligned} X &= \int P(\lambda)\bar{x}(\lambda)d\lambda \\ Y &= \int P(\lambda)\bar{y}(\lambda)d\lambda \\ Z &= \int P(\lambda)\bar{z}(\lambda)d\lambda \end{aligned} \tag{1}$$

Since the monochromatic light spectrum is a Dirac delta, the integration is the same as obtaining the color matching functions of the CIE 1964 for each given wavelength. Then, I normalized X, Y, and Z by their sum to obtain the CIE-xy Chromaticity Coordinates for the monochromatic light using the equations below.

$$\begin{aligned} x &= \frac{X}{X+Y+Z} \\ y &= \frac{Y}{X+Y+Z} \end{aligned} \tag{2}$$

METHODOLOGY

01 TRICHROMATICITY OF COLOR MIXTURE

I did the same to get the CIE-xy Chromaticity coordinates of a blackbody emitting from 1000K to 10,000K in increments of 1000K. This time, however, the spectrum of the blackbody is given by

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5(\exp(hc/\lambda kT)-1} \tag{3}$$

where k is the Boltzmann constant, h is the Planck constant, c is the speed of light, T is the temperature, and lambda is the wavelength. Notice that Equation 3 depends on both lambda and T. Therefore, I multiplied Equation 3 to the monochromatic functions of CIE 1964 and integrate in terms of lambda where the limit is from 380 to 780. I did this for all the values of T. Lastly, I converted the tristimulus values to CIE-xy using Equation 2 to obtain the Planckian Locus [1].

METHODOLOGY

01 TRICHROMATICITY OF COLOR MIXTURE

After obtaining all the CIE-xy coordinates for both the monochromatic light and the blackbody, I plotted them and embedded the CIE 1964 Chromaticity Diagram or the color tongue in Figure 1 to verify if the points obtained are accurate. Notice that this does not contain the Planckian Locus. For this, I used the CIE 1931 Chromaticity Diagram from Wikipedia shown in Figure 2.

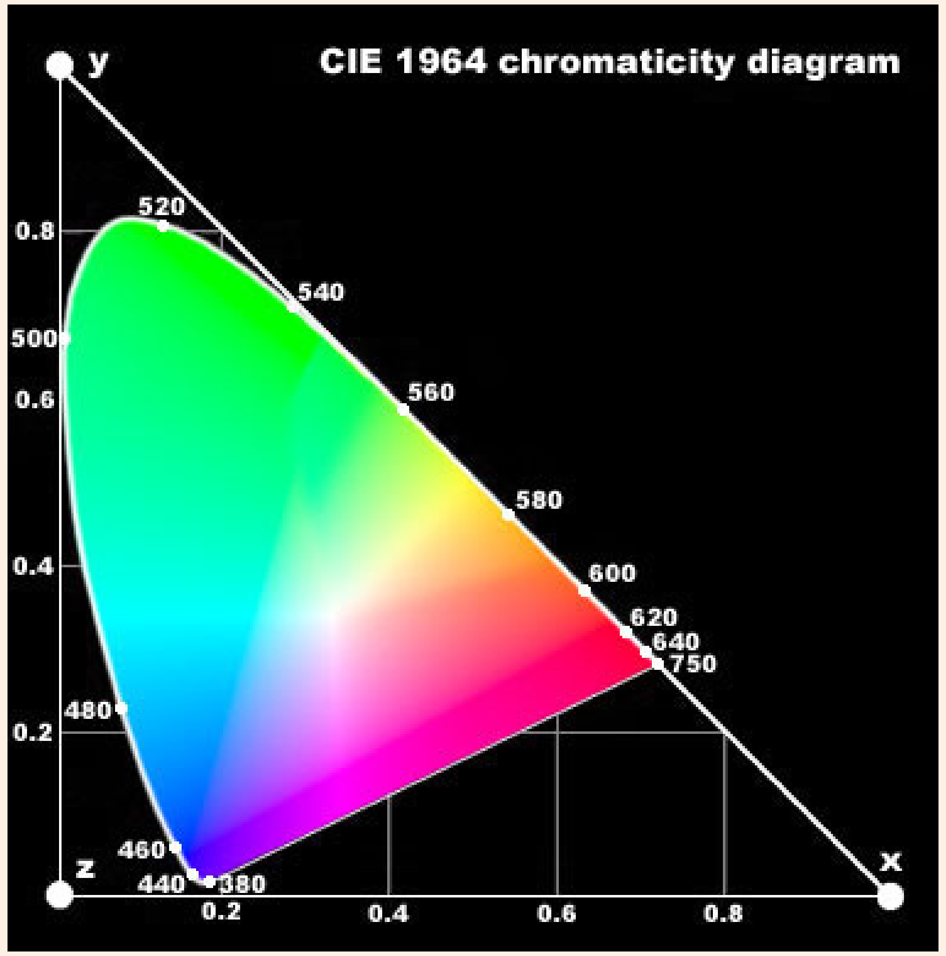

Figure 1. CIE 1964 Chromaticity Diagram.

https://www.handprint.com/HP/WCL/color6.html

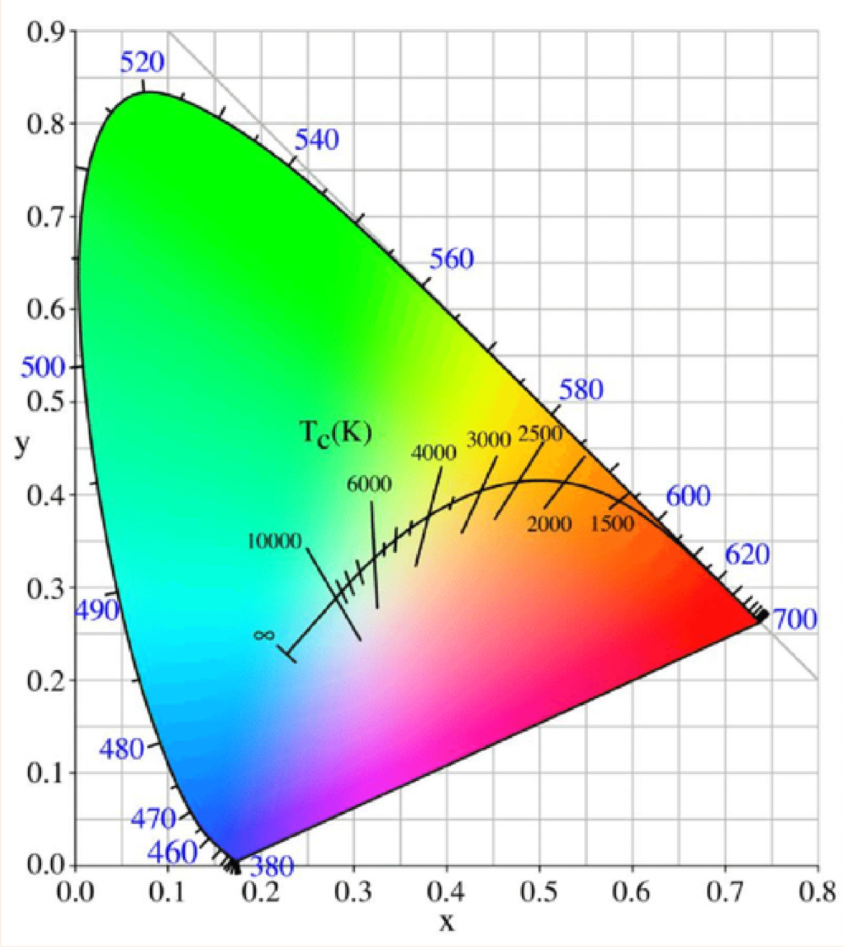

Figure 2. CIE 1931 Chromaticity Diagram with Planckian Locus.

https://en.wikipedia.org/wiki/Planckian_locus

METHODOLOGY

02 COLOR ORDER SYSTEM & COLOR DIFFERENCE SPECIFICATION

02.1 Obtaining u'v' chromaticity coordinates

It is assumed that the monochromatic lights and Planckian light sources from Part 01 are observed under the Illuminant D65. From the CIExy chromaticity values of these light sources, I solved for their corresponding u'v' coordinates using

$$\begin{aligned} u' &= \frac{4X}{X+15Y+3Z} &= \frac{4x}{-2x+12y+3} \\ v' &= \frac{9Y}{X+15Y+3Z} &= \frac{9y}{-2x+12y+3} \end{aligned} \quad (4)$$

where x, y corresponds to the CIExy values and X, Y are the tristimulus values. Moreover, I solved for the corresponding u'v' coordinates of the Illuminant D65 by first getting the tristimulus values of the light source using the equations below and substituting the obtained values to Equation 4 [2].

$$\begin{aligned} X_n &= \sum P(\lambda)\bar{x}(\lambda) \\ Y_n &= \sum P(\lambda)\bar{y}(\lambda) \\ Z_n &= \sum P(\lambda)\bar{z}(\lambda) \end{aligned} \quad (5)$$

METHODOLOGY

02 COLOR ORDER SYSTEM & COLOR DIFFERENCE SPECIFICATION

02.1 Obtaining u'v' chromaticity coordinates

I plotted the obtained u'v' coordinates from the light sources and the Illuminant D65. To visualize, I also embedded the 1976 CIE L'u'v' chromaticity diagram shown in Figure 2. This will show where these points lie in the L'u'v' color space.

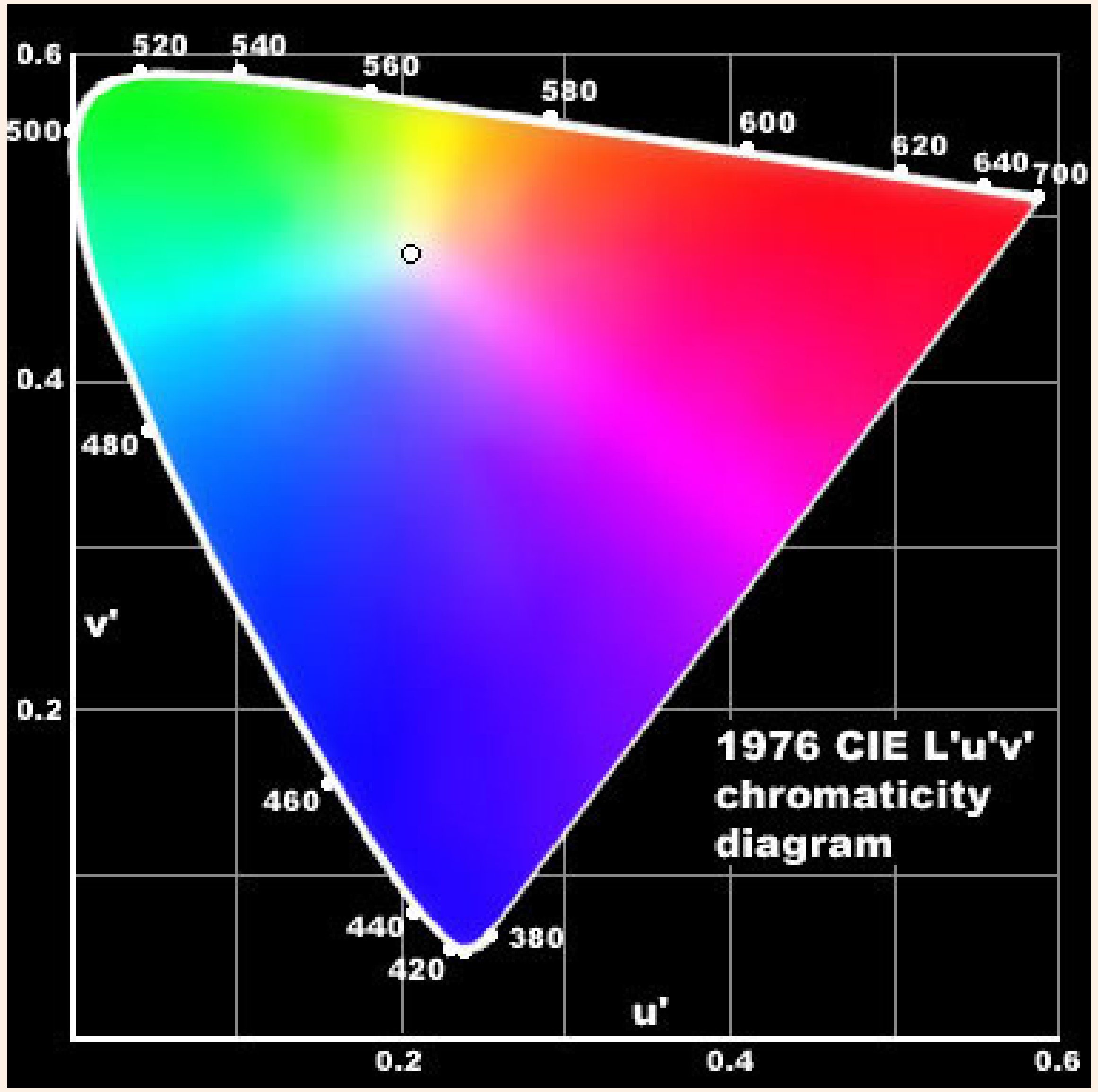

Figure 3. 1976 CIE L'u'v' chromaticity diagram.

https://virtualwalletapp.blogspot.com/

METHODOLOGY

02 COLOR ORDER SYSTEM & COLOR DIFFERENCE SPECIFICATION

02.2. Obtaining the color difference

I downloaded the mat file containing the reflectance measurements of 1200 Munsell color chips from 400nm to 700nm in increments of 5nm. I loaded this in MATLAB and chose three random chips to observe.

I assumed that these chips were observed under two different lights - Illuminant D65 and a white LED. The computation for the L*a*b* coordinates of these three chips is discussed in the next slide.

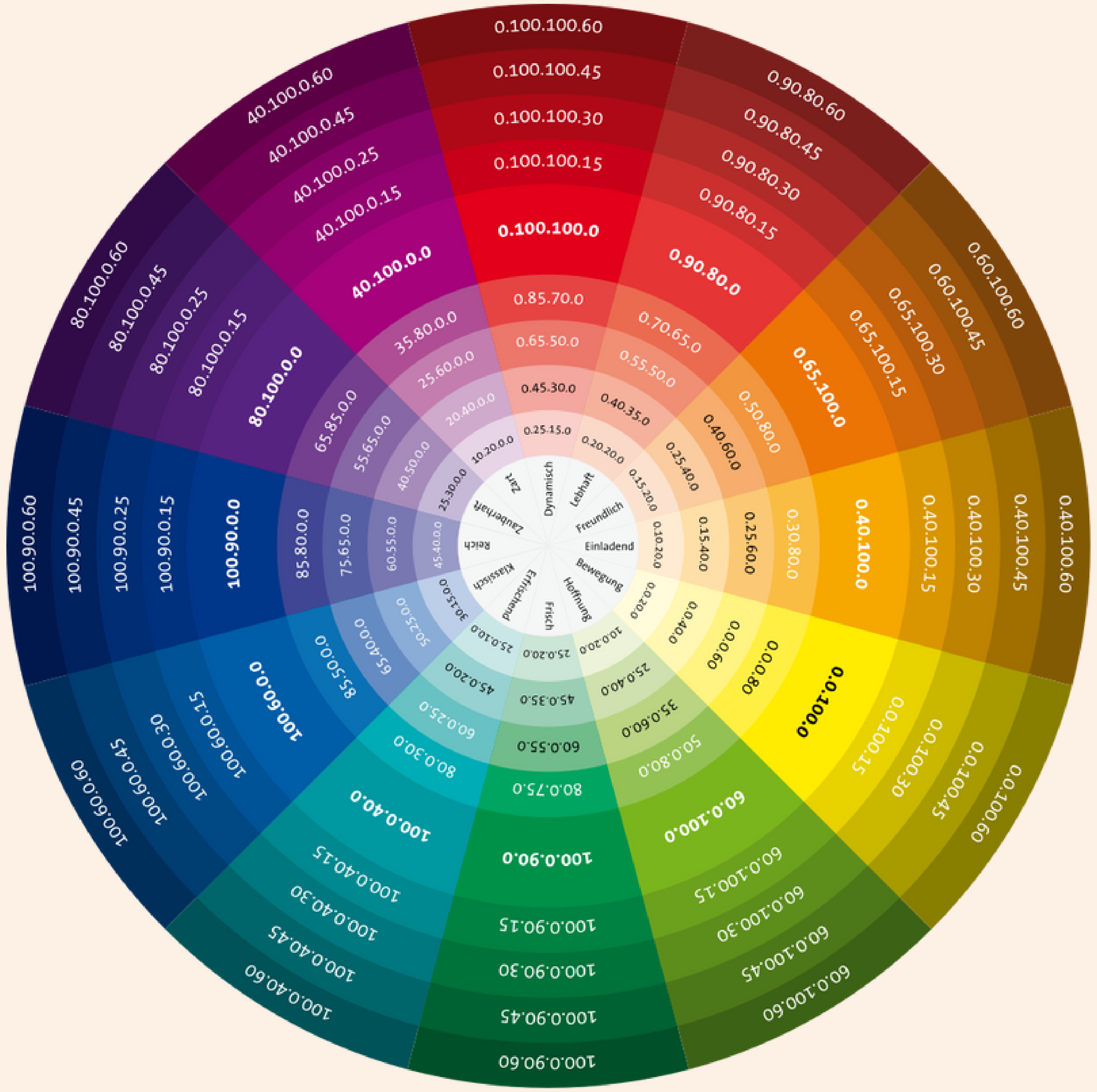

Figure 4. The Munsell Color System.

https://www.pinterest.com.mx/pin/300826450105950615/

METHODOLOGY

02 COLOR ORDER SYSTEM & COLOR DIFFERENCE SPECIFICATION

02.2. Obtaining the color difference

The first thing that I did is to compute for the tristimulus values of the colored object illuminated by the light source using

$$
\begin{aligned}
X &= \sum P(\lambda)R(\lambda)\bar{x}(\lambda) \\
Y &= \sum P(\lambda)R(\lambda)\bar{y}(\lambda) \\
Z &= \sum P(\lambda)R(\lambda)\bar{z}(\lambda)
\end{aligned}
\quad (6)
$$

where P is the spectral power distribution of the light source, R is the reflectance of the object, and x-bar, y-bar, and z-bar are the CIE 1964 color matching functions. I obtained these for both the light sources (D65 and White LED). Then, I computed for the tristimulus values of the light sources (Xn, Yn, Zn) using Equation 5 [2]. I used these values to compute for the L*, a*, and b* values, which is further discussed in the next slide.

METHODOLOGY

02 COLOR ORDER SYSTEM & COLOR DIFFERENCE SPECIFICATION

02.2. Obtaining the color difference

For the Lightness, L*, the equation is

$$L^* = \begin{cases} (\frac{29}{3})^3 \frac{Y}{Y_n}, & \frac{Y}{Y_n} <= (\frac{6}{29})^3 \\ 116(\frac{Y}{Y_n})^{1/3} - 16, & \frac{Y}{Y_n} > (\frac{6}{29})^3 \end{cases} \quad (7)$$

which is the same for either CIE L*a*b* or L*u*v* space.

The a* channel, green to red, and b* channel, blue to yellow is computed using

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$
$$b^* = 500\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right] \quad (8)$$

$$f(t) = \begin{cases} s^{1/3}, s > (6/29)^3 \\ 7.787(s) + \frac{16}{116}, s \le (6/29)^3 \end{cases} \quad (9)$$

After obtaining the L*, a*, and b* values for both the light sources, I then used these to get the color difference given by

$$\Delta E_{1,2} = \sqrt{\left(L_2^* - L_1^*\right)^2 + \left(a_2^* - a_1^*\right)^2 + \left(b_2^* - b_1^*\right)^2} \quad (10)$$

When the color difference is more than or equal to 2.3, the color difference of the chips is noticeable under the D65 and white LED. Converesly, the tolerance for the color difference in digital cinema is 4.0 [2].

METHODOLOGY

03 COLOR IMAGE CAPTURE & COLOR RENDERING

03.1. Color Rendering

I downloaded the excel file which contains the reflectance of each of colored patch in the Macbeth Color Chart shown in Figure 5. For the camera, I chose the Canon EOS 10D camera, shown in Figure 6, and downloaded its spectral sensitivity from the web.

The assumed light source is Illuminant D65 which I used to calculate for the digital number R, G, B, of each patch using,

$$DN_i = \frac{\sum P(\lambda)R(\lambda)S_i(\lambda)}{\sum P(\lambda)S_i(\lambda)} \quad (11)$$

DN_i : digital number of the ith color channel
$i \in$ [R,G,B]
$P(\lambda)$ light source emittance
$R(\lambda)$ · surface reflectance
$S_i(\lambda)$. sensitivity of the ith channel

Then, I scaled the obtained values to a number between 0 to 1 [3]. I then rendered each color and arranged the patch into an array like the Macbeth chart.

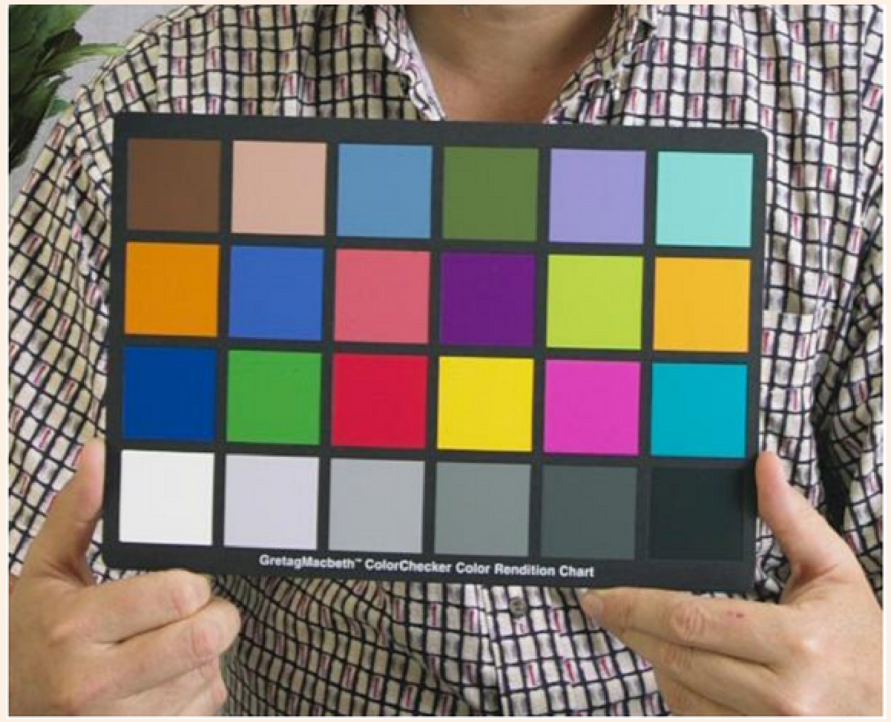

Figure 5. The Macbeth Color Checker Color Rendition Chart.

Figure 6. Canon EOS 10D camera.
https://global.canon/en/c-museum/product/dslr783.html

METHODOLOGY

03 COLOR IMAGE CAPTURE & COLOR RENDERING

03.2. Color Capture in Cameras

Figure 7 shows the two different setups for capturing three images corresponding to the RGB channels using the Basler monochrome camera. In the first setup we used colored RGB filters while in the second setup we used a projector that projects RGB lights on the object. We also made sure that the camera did not move for each of the picture captured to ensure that the recovered images will be aligned.

We then digitally overlayed the filtered images using GIMP and enhanced the image using automatic white balance and contrast stretching.

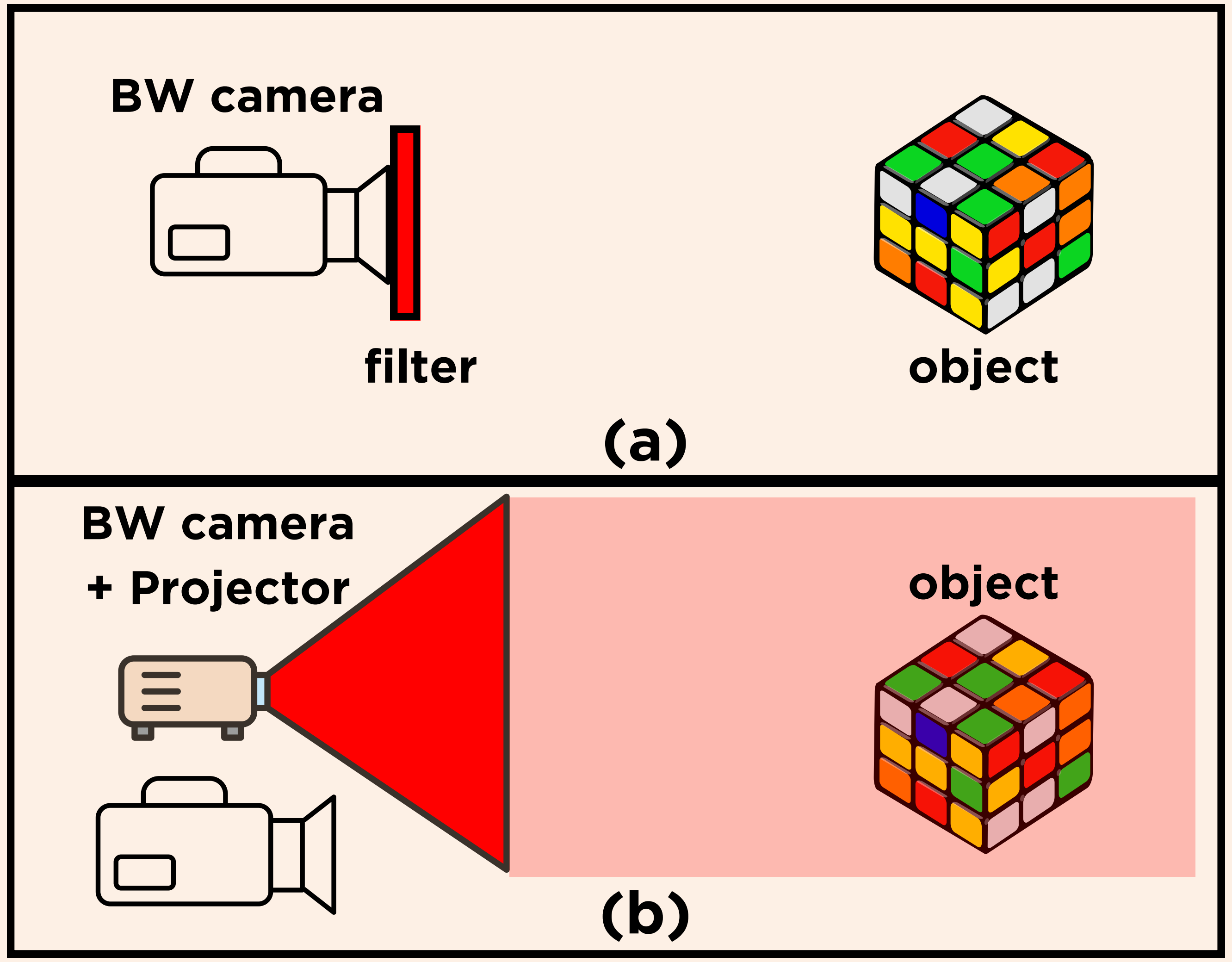

Figure 7. Experimental setup. (a) BW camera with RGB filter. (b) Projector projecting colored lights.

RESULTS & ANALYSIS

01 TRICHROMATICITY OF COLOR MIXTURE

The color matching functions of the CIE 1964 Standard Human Observer is shown in Figure 8. These three curves represent the relative sensitivity of the human eye to different wavelengths across the visible spectrum. These quantify the degree to which each type of cone cell responds to light at different wavelengths. Here, the wavelengths are 380nm to 780nm.

Understanding the color matching functions of the CIE 1964 Standard Human Observer is fundamental in color science, as they form the basis for various color spaces and models used in fields like color reproduction, image processing, and digital display technologies to ensure accurate and consistent color representation [4].

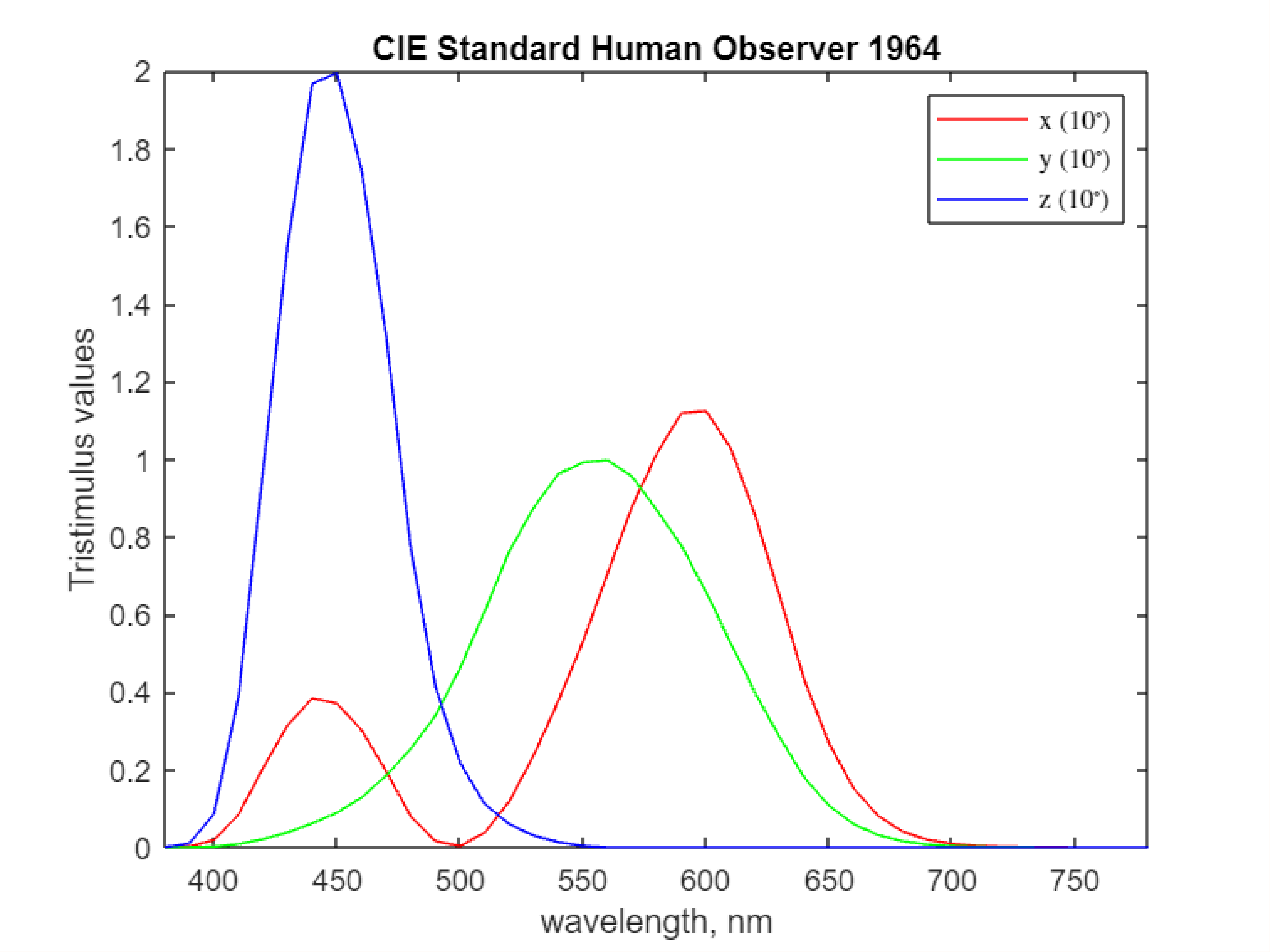

Figure 8. CIE 1964 Standard Human Observer color matching functions.

RESULTS & ANALYSIS

01 TRICHROMATICITY OF COLOR MIXTURE

Using the CIE 1964, the CIExy chromaticity coordinates of the monochromatic light and the Planckian Locus was plotted. The CIE 1931 diagram was embedded for visualization, as shown in Figure 9. The focus here is the Planckian Locus, which represents the colors emitted by a blackbody at certain temperatures. As shown, the obtained CIExy coordinates align with the Planckian Locus for each of the temperatures used. This shows that the obtained values are accurate.

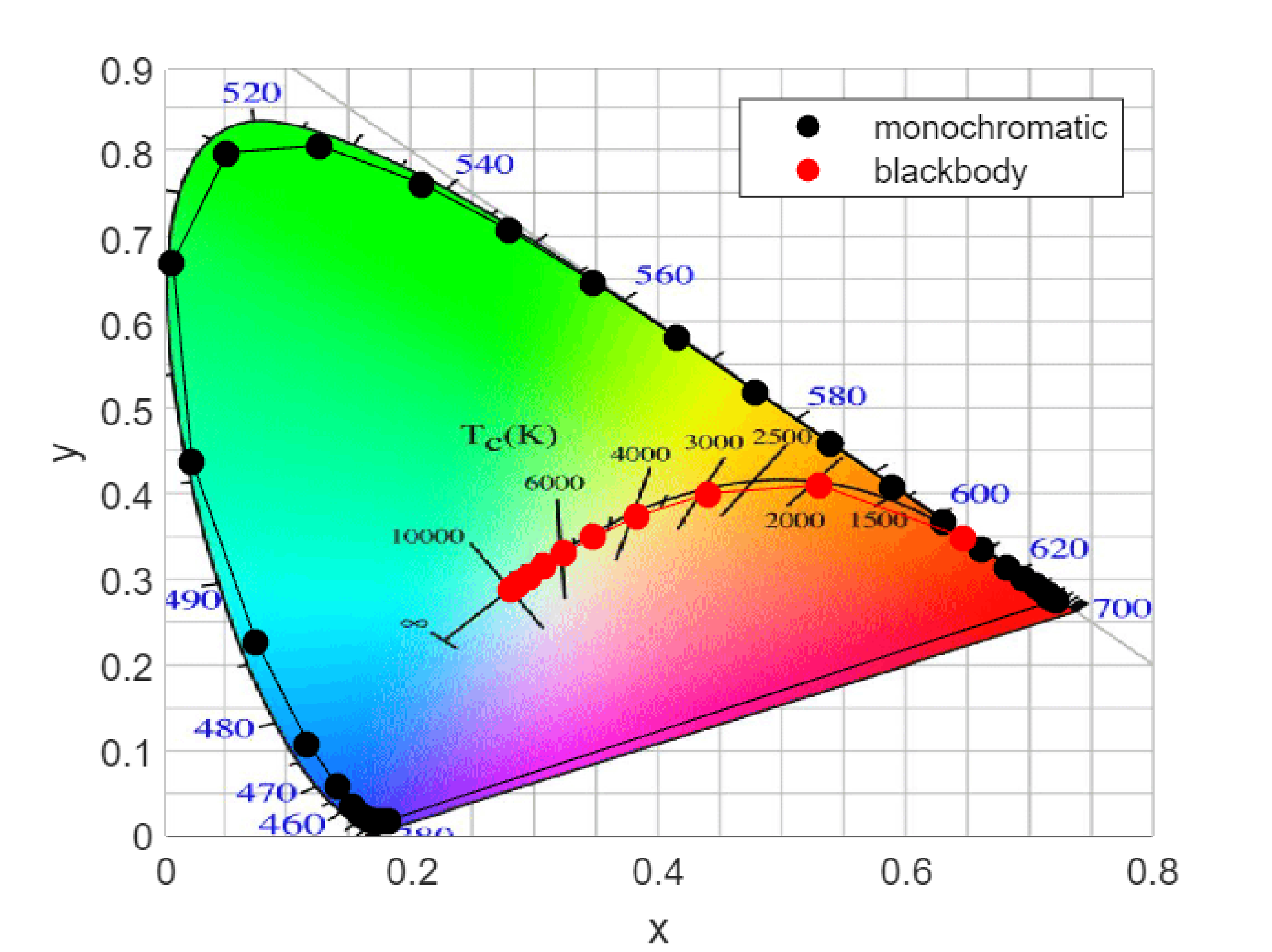

Figure 9. CIExy chromaticity coordinates of monochromatic lights and the Planckian Locus using CIE 1964 embedded in CIE 1931 diagram.

RESULTS & ANALYSIS

01 TRICHROMATICITY OF COLOR MIXTURE

Figure 10 shows the CIExy coordinates of monochromatic light and the Planckian Locus within the CIE 1964 diagram. It is evident that the CIExy coordinates of the monochromatic light align with the edge of the color tongue, and the points accurately approximate the CIExy values for each wavelength ranging from 380nm to 780nm in 10nm increments. Consequently, the obtained values are accurate.

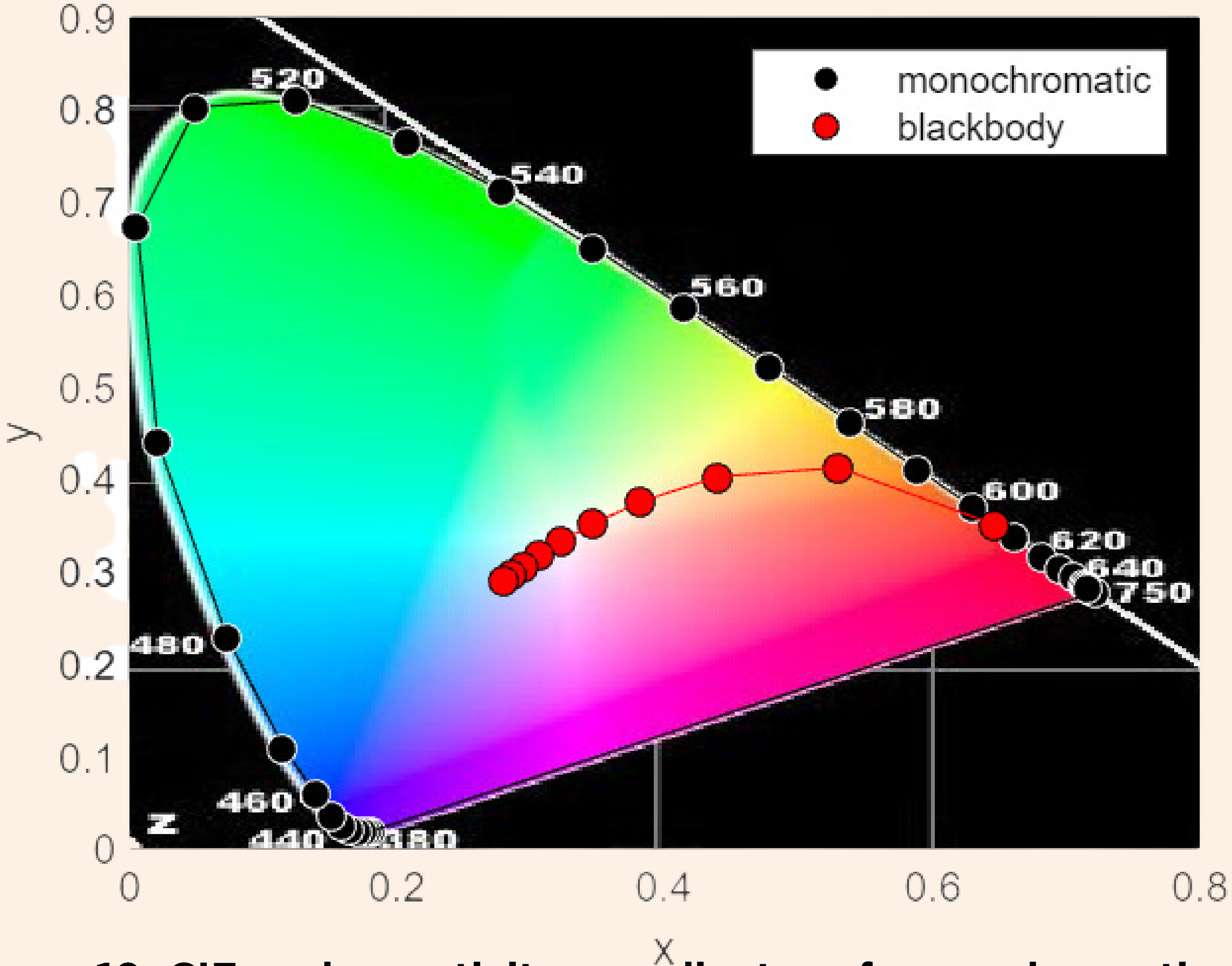

Figure 10. CIExy chromaticity coordinates of monochromatic lights and the Planckian Locus using CIE 1964 embedded in CIE 1964 diagram.

RESULTS & ANALYSIS

02.1 COLOR ORDER SYSTEM

The CIExy coordinates of the monochromatic light and the blackbody were converted to u'v' coordinates and embedded to the 1976 CIE L'u'v' chromaticity diagram as shown in Figure 11. The Illuminant D65 u'v' coordinate was also included.

It is noticeable that the u'v' coordinates of the monochromatic light accurately aligns with the edge of the color tongue. The points also match with the corresponding wavelengths.

Notice that the Illuminant D65 appears as a small point. This is because the diagram represents chromaticity, not luminance or brightness. It focuses solely on the hue and saturation of colors, not their brightness or intensity. Therefore, a light source in the (u′, v′) diagram is represented as a single point that denotes its chromaticity or color quality, while its brightness or luminance isn't accounted for in this particular representation.

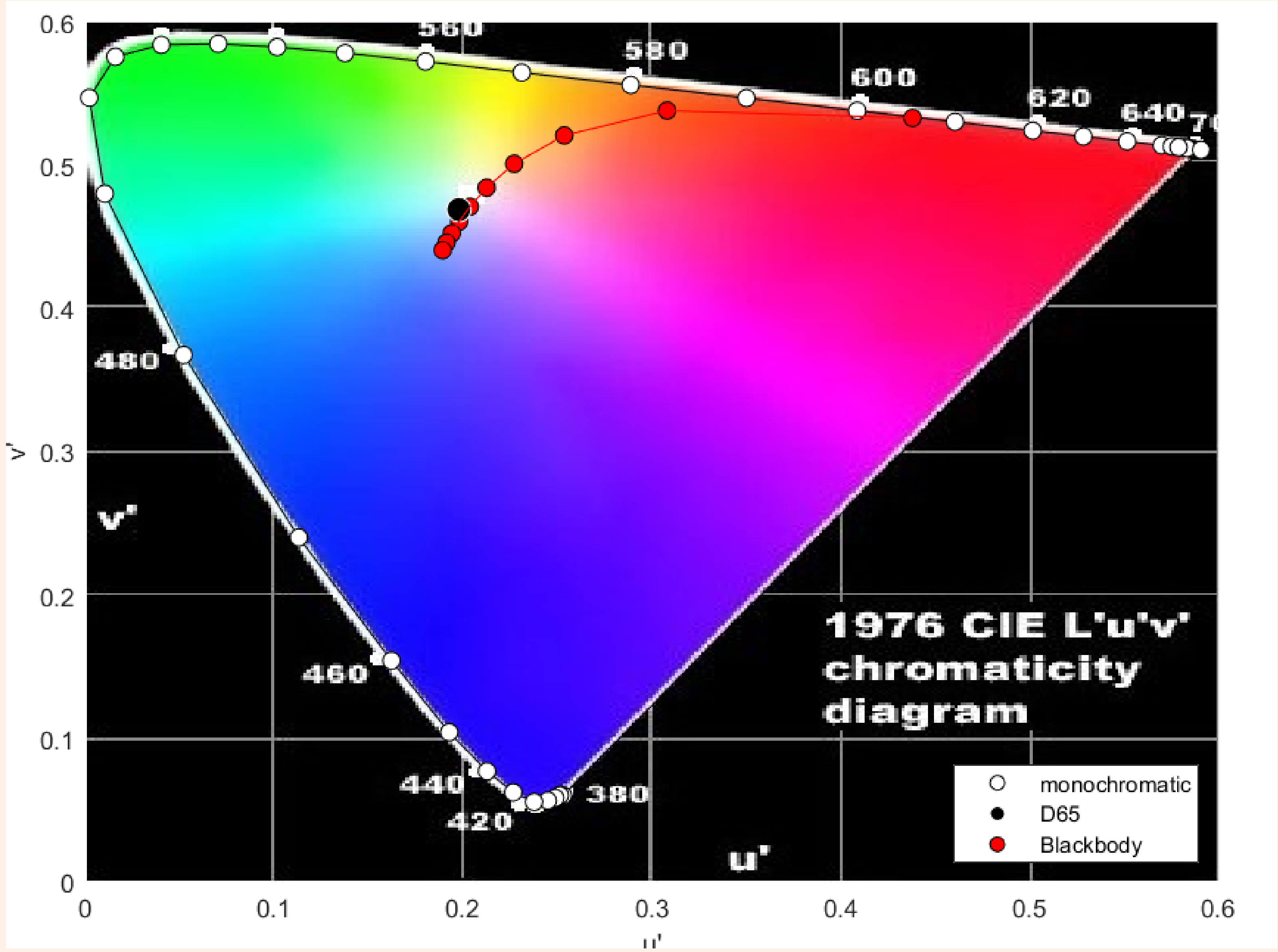

Figure 11. Monochromatic light, Planckian light source, and Illuminant D65 in u'v' space.

RESULTS & ANALYSIS

02.1 COLOR ORDER SYSTEM

Figure 12 shows the spectrum of the light sources that were used in this activity - Illuminant D65 and white LED. The spectrum is from 400nm to 700nm. Illuminant D65 represents the standardized daylight with a correlated color temperature around 6500K, resembling natural daylight. White LEDs, on the other hand, typically create white light using a combination of blue LED chips and phosphors or other methods.

D65 peaks around 560-570 nm, representing natural daylight, while white LEDs typically have a dominant peak in the blue region around 450-460 nm, but their spectral characteristics can vary based on the specific LED design and technology [5].

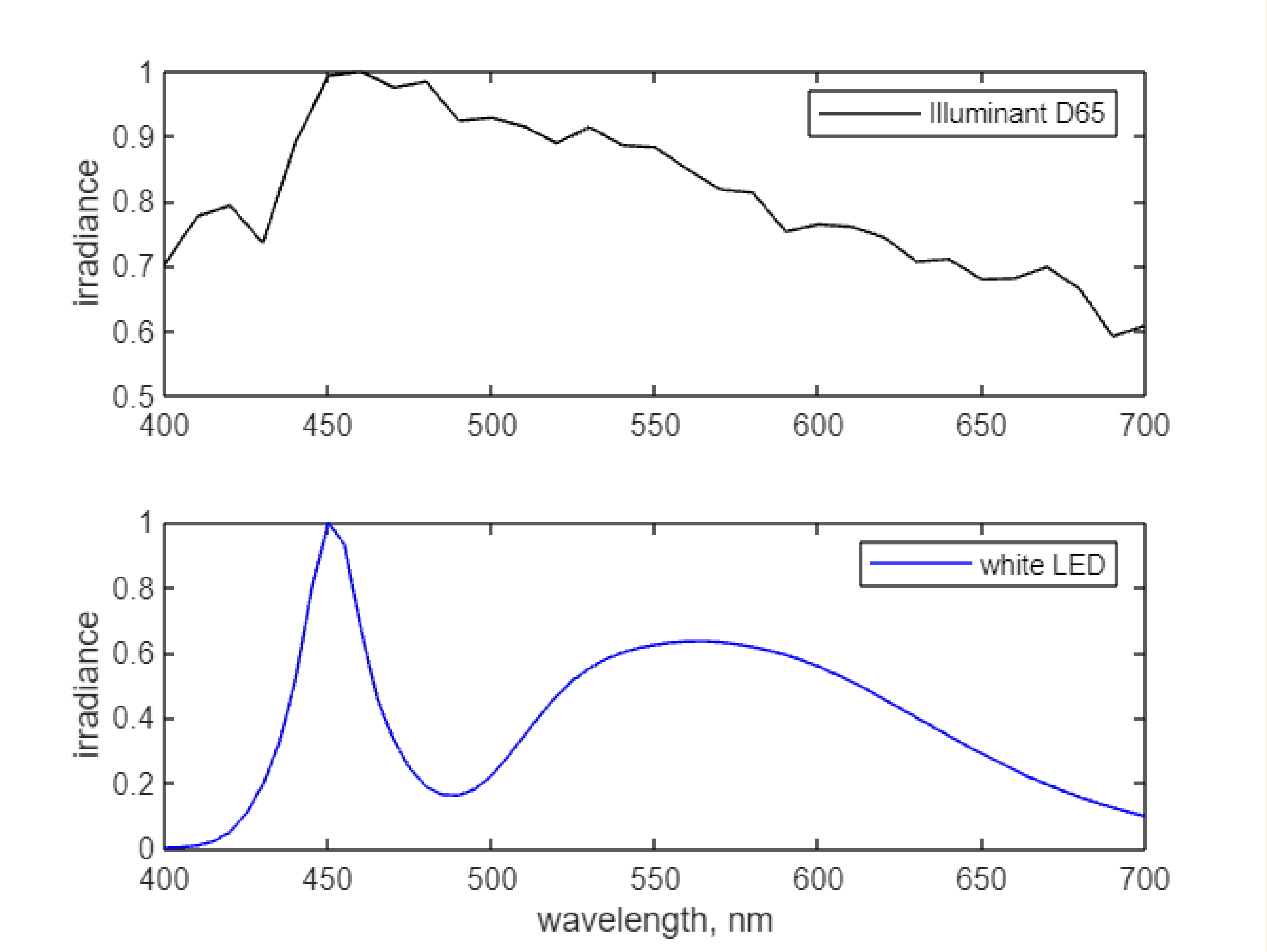

Figure 12. Spectrum of Illuminant D65 and white LED for wavelengths of 400nm to 700nm.

RESULTS & ANALYSIS

02.2 COLOR DIFFERENCE SPECIFICATION

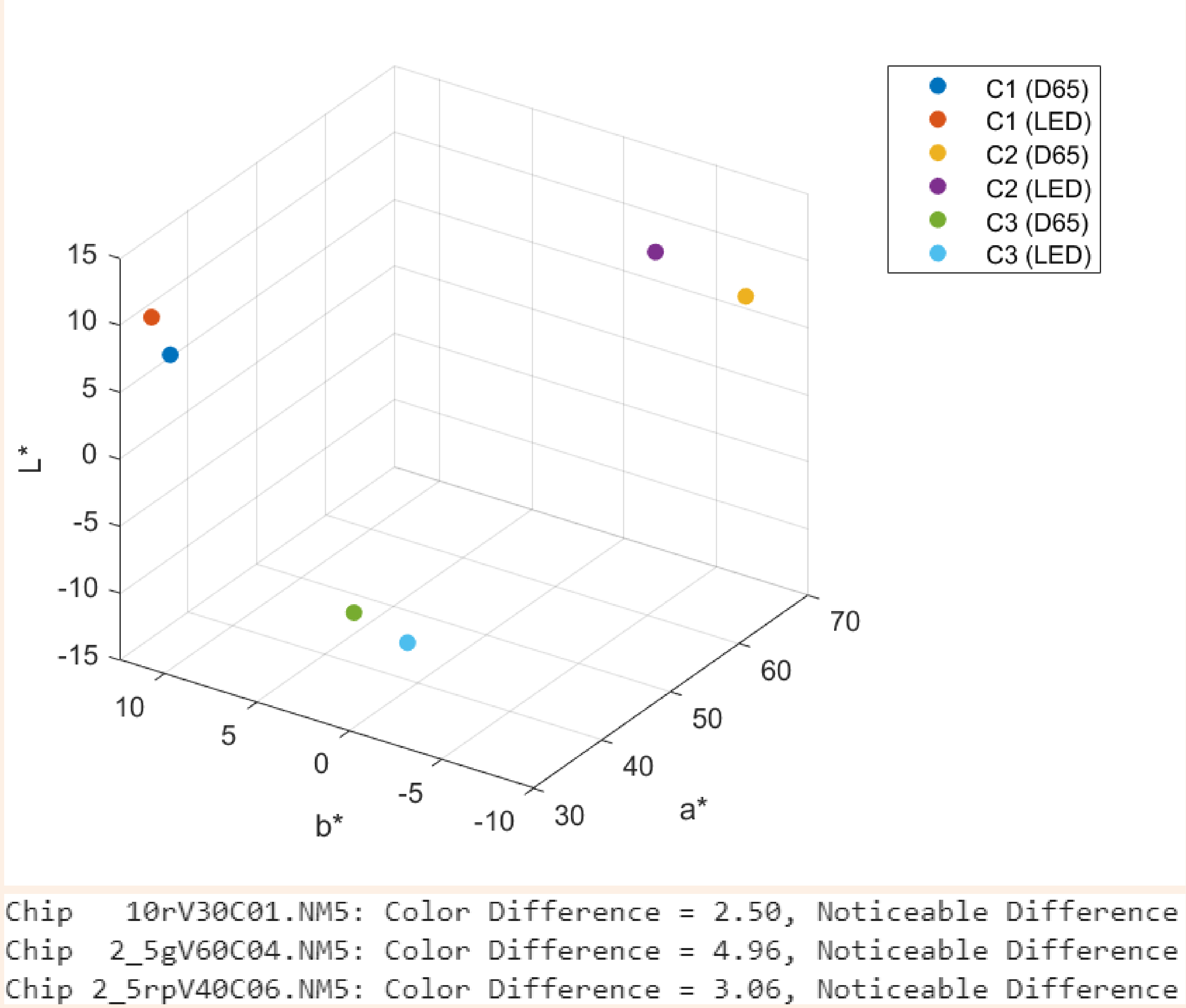

Figure 13. L*a*b* coordinates of three munsell chips viewed under Illuminant D65 and white LED, and their corresponding color difference.

Figure 13 shows the L*a*b* coordinates of the three randomly selected Munsell color chips and their corresponding color difference. Chip 2 (2_5gV60C04.NM5) has the biggest color difference, ΔE = 4.96, when viewed under two different light sources (D65 and white LED). It is also shown in the graph that these two points have the largest distance from each other. Conversely, Chip 1 (10rV30C01.NM5) has the smallest color difference, ΔE = 2.50, which also reflects in the graph. All the chips, however, has color differences greater than ΔE = 2.30 which means that their differences are noticeable.

In the context of digital cinema, the only noticeable difference is greater than ΔE = 4.0. This means that the only difference in color noticeable in digital cinema is the second chip (2_5gV60C04.NM5).

RESULTS & ANALYSIS

02.2 COLOR DIFFERENCE SPECIFICATION

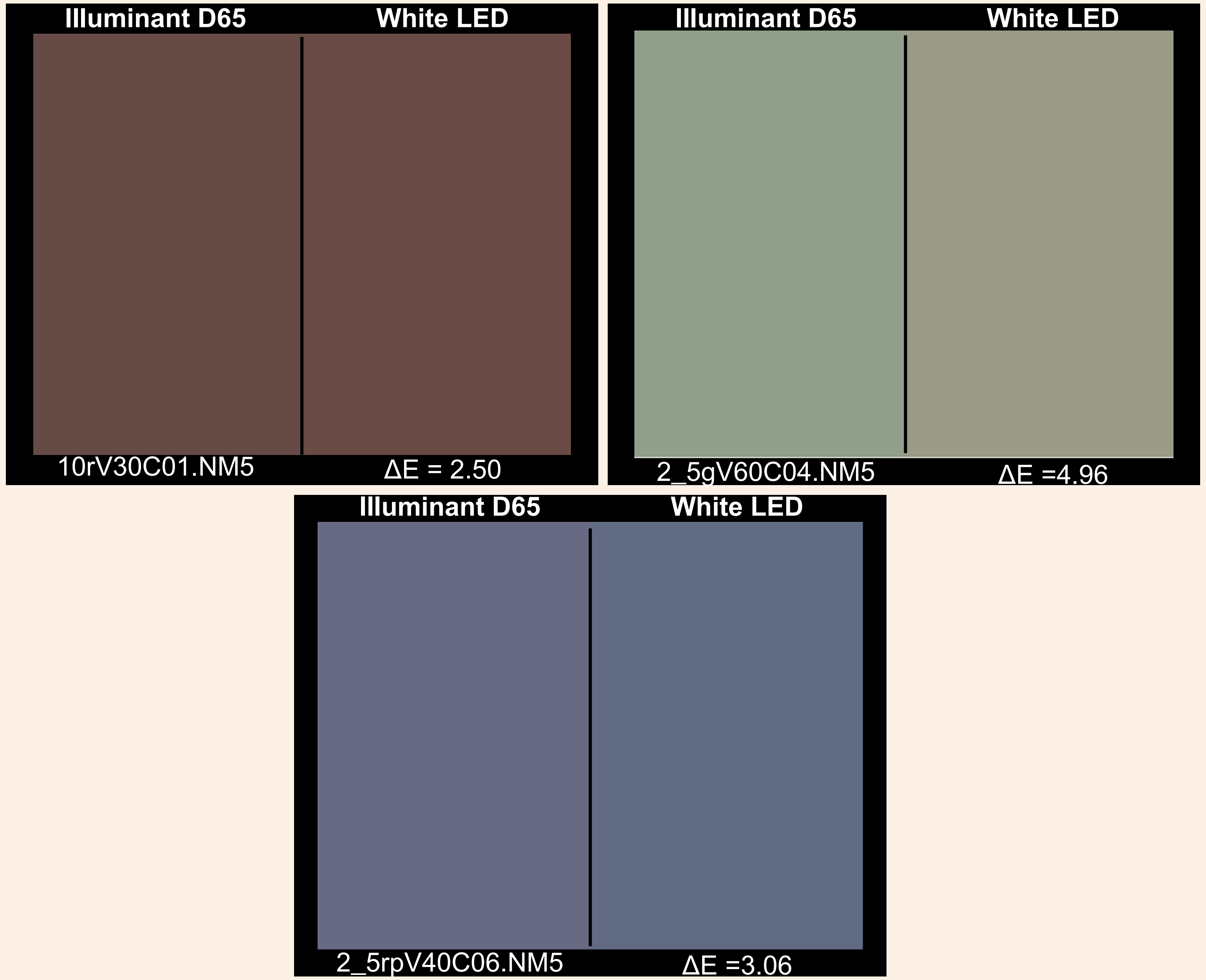

Figure 14. Three munsell chips viewed under Illuminant D65 and white LED in RGB color space for visualization.

To visualize the color chips and qualitatively observe the color difference, I transformed the L*a*b* coordinates of the chips to RGB color space as shown in Figure 14. The most noticeable difference is Chip 2_5gV60C04.NM5, where the it appears to be more saturated when viewed under the Illuminant D65 light source. This is also the same observation with Chip 2_5rpV40C06.NM5.

Conversely, it is difficult at first to notice the difference for Chip 10rV30C01.NM5 since its color difference (ΔE) is smaller. However, if we look closely, we can see that the color is more saturated in Illuminant D65.

This color difference is attributed to the fact that colors appear more saturated and vibrant when viewed under the natural daylight (Illuminant D65) than with artificial light sources like white LED. This is because D65 has a broader and more consistent spectral distribution across the visible spectrum. It is often considered the reference for color accuracy and is designed to emulate natural daylight conditions [5].

RESULTS & ANALYSIS

03.1 COLOR RENDERING

Since the spectral sensitivity of the Canon10D camera that I obtained has wavelengths in increments of 4nm, I had to perform interpolation to get the corresponding sensitivities in increments of 5nm. This has to be done since both the light spectrum and the CIE 1964 color matching functions are also incremented by 5nm. Figure 15 shows the interpolated values of R, G, and B spectral sensitivities of the camera.

The spectral sensitivity of the Canon10D camera mimics the response of the human eye to some extent, which is within the range of the visible spectrum from 400nm to 700nm. Like the human eye, Canon10D is more sensitive to green light, which decreases towards the longer and shorter wavelengths.

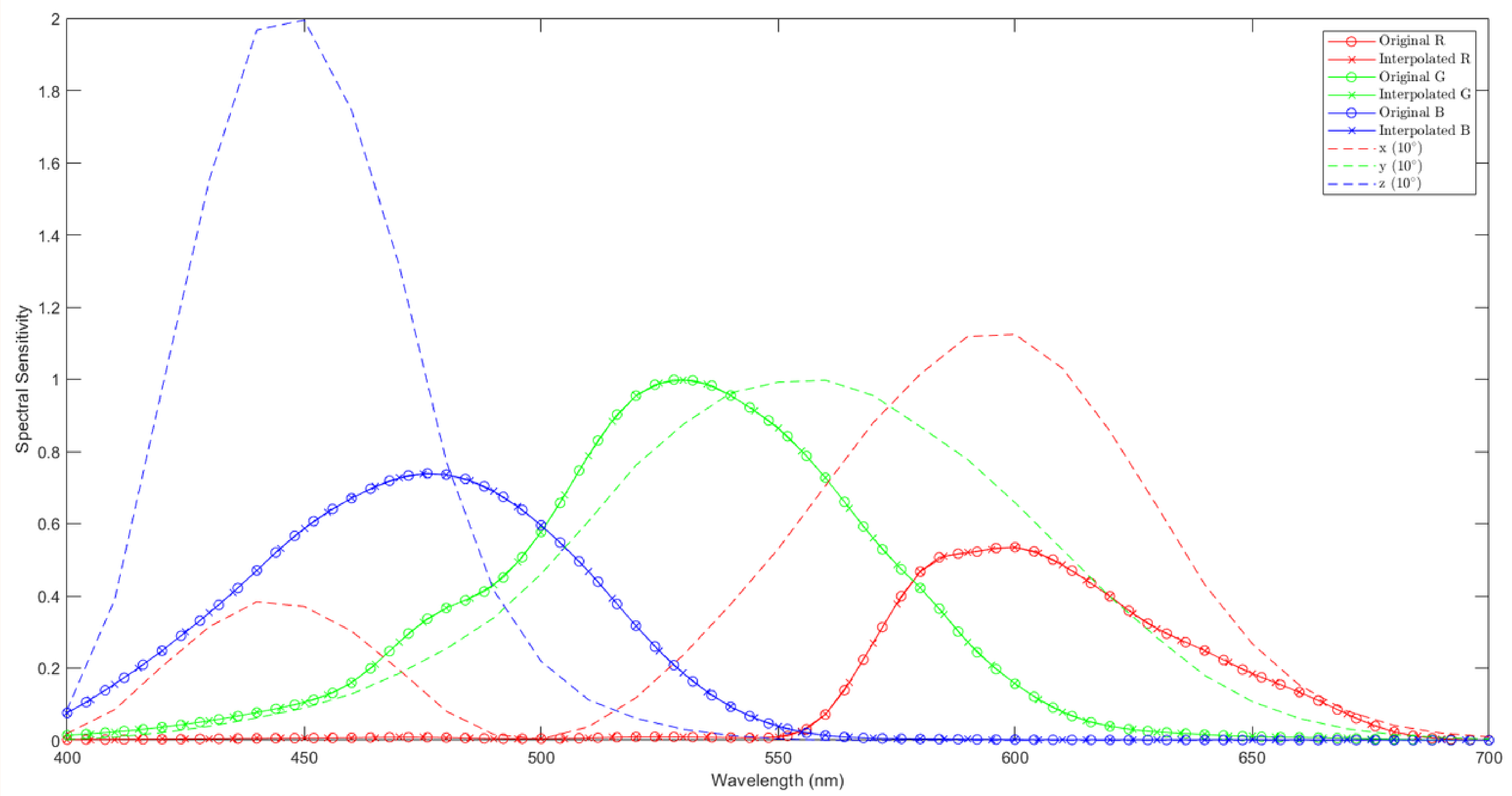

Figure 15. Interpolated values of R, G, and B spectral sensitivity of Canon10D to get 5nm increment values. The CIE 1964 Standard Human Observer color matching functions are also plotted for comparison.

RESULTS & ANALYSIS

03.1 COLOR RENDERING

Utilizing the sensitivity of the Canon10D, the color matching functions of CIE 1964, and the reflectance of the color patches, I was able to simulate how the camera perceives the colors within a Macbeth Color Checker, as depicted in Figure 16. It is evident that the rendered patches approximate the true colors in a Macbeth chart; however, discernible differences exist. Patches dominated by red hues appear darker, while those dominated by green and blue hues appear brighter or more vibrant. This discrepancy can be attributed to the spectral sensitivity of the camera. As illustrated in Figure 14, the camera exhibits a relatively higher sensitivity to blue and green compared to red, resulting in red colors appearing darker.

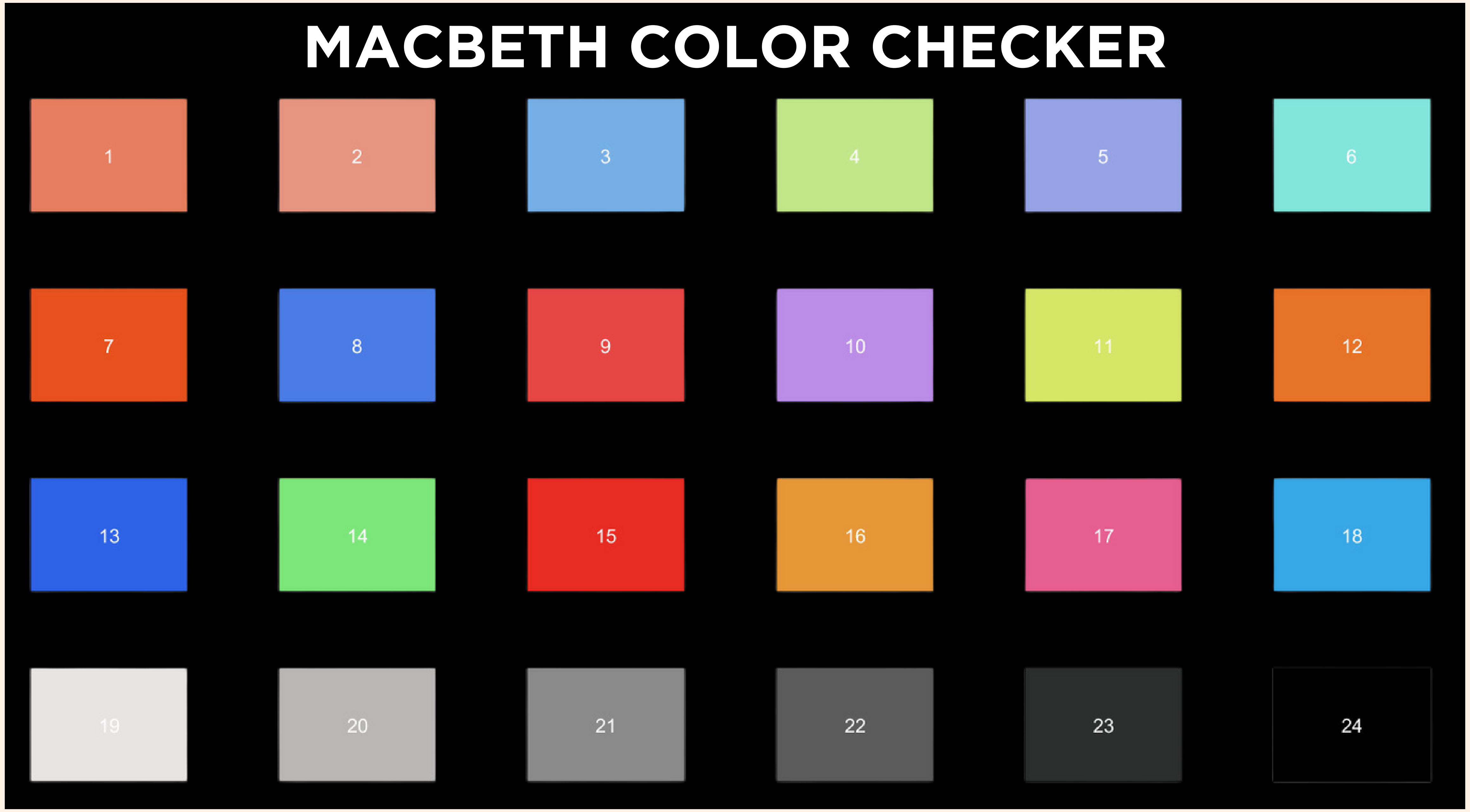

Figure 16. The generated Macbeth Color Checker using the spectral sensitivity of Canon10D.

RESULTS & ANALYSIS

03.2 COLOR IMAGE CAPTURE

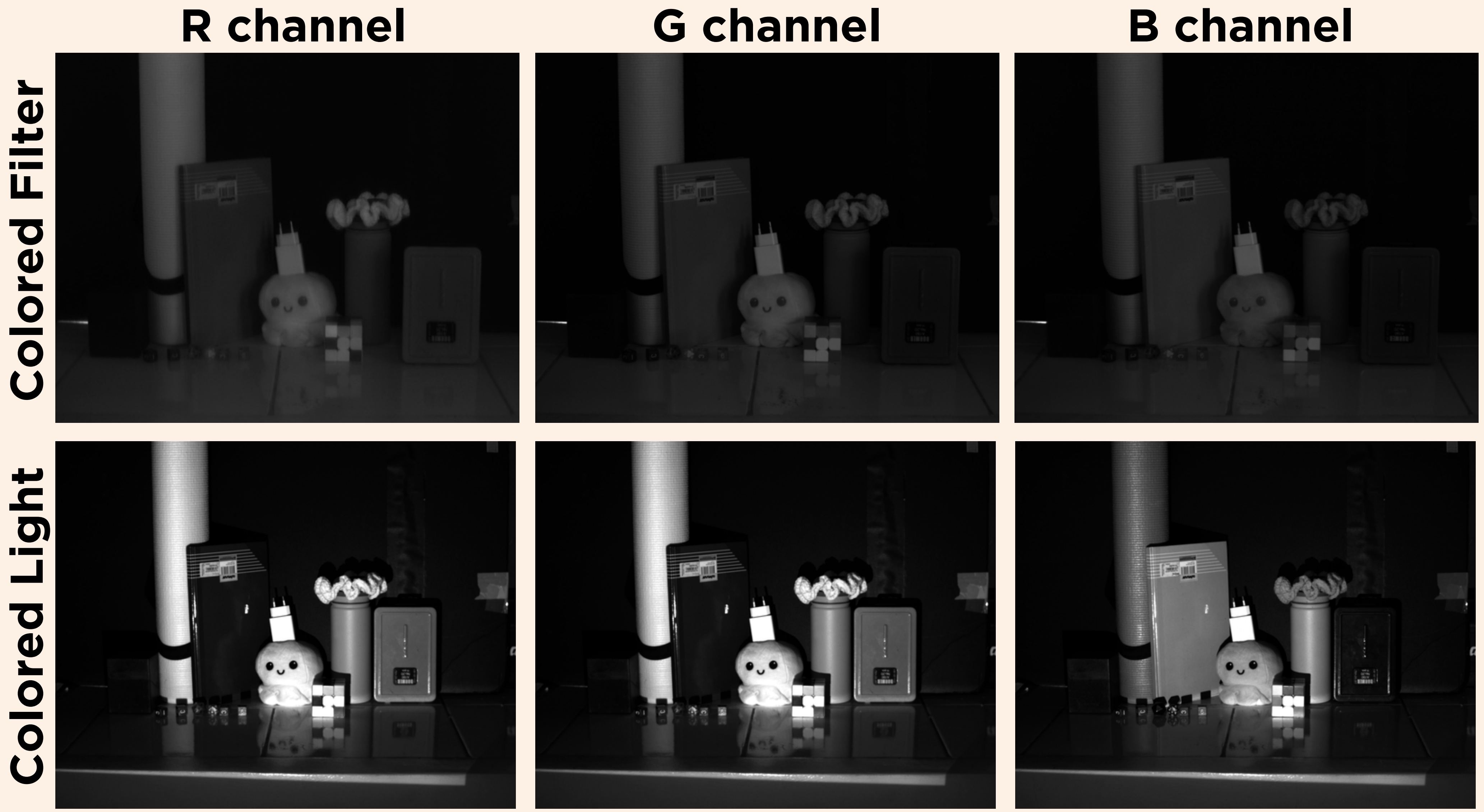

Figure 17. Captured images for the RGB channel using RGB colored filters and lights.

The grayscale pictures taken using a monochromatic camera which represents the red, green, and blue channels of an image are shown in Figure 17. Notice that some parts in the picture, regardless of the method it was taken, appear relatively lighter. These objects that appear lighter in a certain channel and darker in the other two means that they have a predominant color in that specific channel. For example, notice the notebook in the colored light images. In the R and G channel, it appears darker, whereas it is lighter in the B channel. This means that it reflects more blue and absorbs the others.

RESULTS & ANALYSIS

03.2 COLOR IMAGE CAPTURE

(a) (b) (c)

Figure 18. (a) The original colored image taken by a phone camera. The reconstructed colored image using (a) colored filters and (b) colored lights.

Figure 18a shows the original colored image of the objects. It is observable that both the reconstructed images using the different setups successfully obtained a colored image. However, the method using the colored lights produced a better reconstructed image as it captured the colors more accurately: yellow octopus appears yellow, blue notebook is blue, red box is red, and even the violet tumbler is violet. This may be due to the limitations of the cellophane used as filters. Nevertheless, we have shown that a monochromatic (B&W) camera can produce a colored image by taking advantage of the colored filters that allows only specific wavelengths of light to pass through, capturing different color information in separate images.

CONCLUSIONS

01 TRICHROMATICITY OF COLOR MIXTURE

Understanding the color matching functions of the CIE 1964 Standard Human Observer is fundamental in color science, forming the basis for various color spaces and models crucial in color reproduction, image processing, and digital display technologies. Using the CIE 1964 framework, CIExy chromaticity coordinates were plotted for monochromatic light and the Planckian Locus in Figures 9 and 10. These illustrations demonstrated accurate alignment with the Planckian Locus and the color tongue's edge, showcasing precise CIExy values across the visible spectrum from 380nm to 780nm in 10nm increments. This alignment signifies the reliability and accuracy of the derived values, reinforcing the significance of the CIE 1964 methodology in understanding color representation and analysis.

CONCLUSIONS

02 COLOR ORDER SYSTEM & COLOR DIFFERENCE SPECIFICATION

The converted CIExy coordinates to u'v' coordinates for monochromatic light demonstrate a precise alignment with the 1976 CIEL'u'v' color tongue's edge. The Illuminant D65 in the u'v' space is a single point, highlighting that the diagram emphasizes chromaticity over brightness.

The examination of the L*a*b* coordinates of the three Munsell color chips revealed varying color differences when observed under different light sources - Illuminant D65 and white LED. The color chip is more saturated and vibrant under D65 which is attributed to its broader and more consistent spectral distribution across the visible spectrum.

CONCLUSIONS

03 COLOR IMAGE CAPTURE & COLOR RENDERING

The color patches of the Macbeth Color Checker using the spectral sensitivity of the Canon10D camera are successfully rendered. Patches dominated by red hues appear darker, while those dominated by green and blue hues appear brighter or more vibrant. This is because the camera exhibits a relatively higher sensitivity to blue and green compared to red, resulting in red colors appearing darker.

Colored images were also successfully recovered by utilizing a monochromatic (B&W) camera and colored filters and lights. The method using the colored lights produced a better reconstructed image as it captured the colors more accurately. This may be due to the limitations of the cellophane used as filters. Nevertheless, we have shown that a monochromatic (B&W) camera can produce a colored image by taking advantage of the colored filters that allows only specific wavelengths of light to pass through, capturing different color information in separate images.

REFLECTION

At first, the division of this activity into three parts can feel overwhelming. Understanding the concepts beforehand demands considerable effort before delving into the required experiments and computations. Yet, once you grasp these concepts, you'll realize that the instructions are surprisingly straightforward. Overall, following the instructions isn't overly challenging. The primary setback I encountered was locating and downloading the necessary files, especially the white LED sensitivity. The available CIE file encompassed nine LEDs with different spectral sensitivities, necessitating the plotting to identify the white LED.

I particularly enjoyed the final segment, where we utilized a B&W camera to capture three images using RGB filters and lights. There's a unique satisfaction in witnessing grayscale images combine to form a colored image accurately capturing the objects' colors.

Despite spending a significant amount of time revising my code and adjusting my plots, I found this activity genuinely intriguing. Several concepts explored here hold practical applications applicable to my own thesis. Overall, I had a delightful experience and value the knowledge gained from this activity.

SELF-GRADE

CRITERIA	perfect score	my score
Technical correctness	30	30
Quality of presentation	30	30
Reflection	30	30
Ownership	10	10
TOTAL	100	100

I give myself a perfect score as I successfully met all the objectives set for this activity. Beyond meeting requirements, I extended the analysis by incorporating supplementary plots, enriching the depth and comprehensiveness of the results' discussion. Additionally, I take pride in independently crafting the MATLAB code, demonstrating my ability to generate the necessary tools for this project.
GITHUB

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