Light Emission from Cell Phones: Spectrum Analysis

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Cell phone screen quality is of great importance to the technology industry and consumers. In order to determine the quality of the LEDs in a Google Pixel 3 XL, the CIE 1931 xy chromaticity diagram was used. How screen brightness may affect color and the application of the built in blue light filter were also investigated. Plotting spectra data on the diagram and determining the dominant wavelength enabled us to comment on the purity of the color. It was found that color purity was good, brightness did not affect color, and the blue light filter did work as advertised.

Keywords: Spectroscopy, CIE 1931, Chromaticity, Excitation Purity, Cell Phones

I. INTRODUCTION

Cell phones are an integral part of modern life. The top and most popular cell phone manufacturers use the quality of the display as a selling point. This is usually at the forefront of the consumer's mind as well. So how good are cell phones at displaying color? Does screen brightness have any effect on the color you're seeing? Does the blue light filter that many manufacturers advertise as being easier on your eyes actually filter blue light? In order to answer these questions it is important to know how humans see, as well as understanding how to measure light and make observations on the color of that light.

Obviously humans see with our eyes. However, what is the specific process? Light enters the eye and is focused onto an area in the back of the eye by the lens. At the back of the eye is the retina which has many photoreceptor cells. These cells fall into two categories, cones and rods. The photoreceptor cells responsible for color vision are the cones. There are 3 types of cones; long, medium, and short cones. This system of 3 cell color vision is called trichromacy [1]. The long, medium, and short cones are called this because each one roughly corresponds to different parts of the visible spectrum. For example, the short cone has its response peak at about 440nm which is blue. However this can be misleading because each cone has a response for a wide range of wavelengths [2]. Electronic displays take advantage of trichromacy by displaying color through a similar process. Typically a single pixel is composed of 3 LEDs emitting red, green, and blue light. Different combinations of these the colors, called primaries, can make us see all the different colors we are able to see as humans.

Research was conducted in 1930 by W.D. Wright to quantify human perception of the visible spectrum. Subjects could adjust levels of red, green, and blue light shining in one of their eyes while viewing a sample in the other. For each wavelength it was measured what amount of red, green, or blue light for the subject to say that it matched [3]. This research laid the groundwork of the system the International Commission on Illumination (CIE) would develop in 1931. The CIE 1931 color space analytically describes color. The 1931 color space transforms the curves obtained by W.D. Wright into what are called the color matching functions. The main difference between them is that the curves obtained by W.D. Wright had negative values [3]. It is important to note that both W.D. Wright's curves and the color matching functions do not directly correlate to red, green, and blue. Instead they are more closely related to how humans perceive color. From the color matching functions values called the tristimulus values can be calculated. These values take the same meaning as the color matching functions used to obtain them. With these tristimulus values, points in a geometric color space may be obtained.

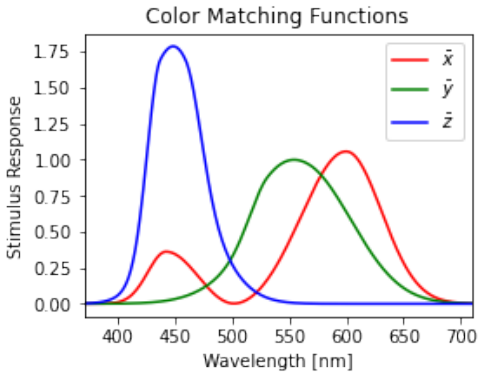

FIG. 1. $\bar{x}$, $\bar{y}$, and $\bar{z}$ represent the color matching functions. Being colored red, green, and blue is just a convention, they only roughly cover these parts of the visible spectrum.

The representation of the 1931 color space is the xy chromaticity diagram. A blank chromaticity diagram is shown in FIG. 2. Important features of this diagram are the boundary and the white point. The boundary is split into two parts. These are the spectral locus and the line of purples. The spectral locus represents monochromatic light across the entire visible spectrum, from 380nm to 700nm. This means that each point represents a spectra with intensity at only a single wavelength. Alternatively, the line of purples is the straight line on the bottom of the color map connecting the points representing 380nm and 700nm. There is no wavelengths of monochromatic light that can make these colors, they must be made of a combination of red and blue [4].

Another key part of the chromaticity diagram is the white point. The white point represents white light of the experimental system and is located in the center of the diagram. Some applications use illuminants for the white point that represent outdoor lighting, light from a light bulb, and so on. For this experiment, Illuminant E, the equal energy emitter was chosen. This illuminant represents pure white light and has equal intensity for all wavelengths. Since we are trying to make statements about the purity of the color, it is not necessary to take ambient lighting into account as we care about the color under all lighting conditions [4].

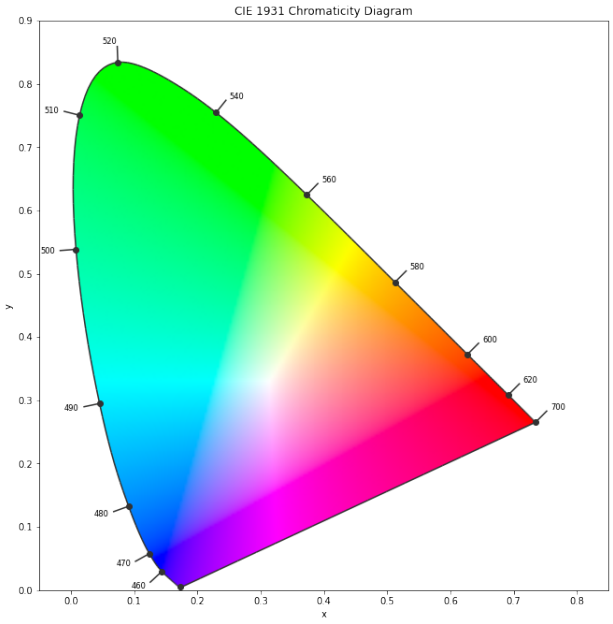

FIG. 2. The sides and the top of the boundary are the spectral locus. The line of purples is the straight line on the bottom.

II. METHODS

In this experiment, the excitation purity, also called color purity, of the LEDs within the display of a Google Pixel 3 XL were tested. Our experimental setup can be seen in FIG. 3. It consisted of the phone being tested, a fiber optic cable, an Ocean Optics USB spectrometer, and a computer running OceanView spectroscopy software. The fiber optic cable was hooked up to the spectrometer in order to measure only the sample it was being pointed at. As an extra precaution a covering was fashioned and fixed to the fiber cable and phone to make sure the only light being measured was from the phone. The environment was also made to be extremely dark to further try and eliminate any background light. The spectrometer was hooked up to a computer in order to use the OceanView spectroscopy software. It is important to note that the specific Ocean Optics spectrometer in use during this experiment had internal setting issues. Due to the COVID-19 pandemic, this was the only spectrometer we had access to. These issues limited the available range of wavelengths that could be measured. A range of only 200nm and 530nm could be measured. In terms of the visible spectrum, this corresponds to a range between UV light and Green light.

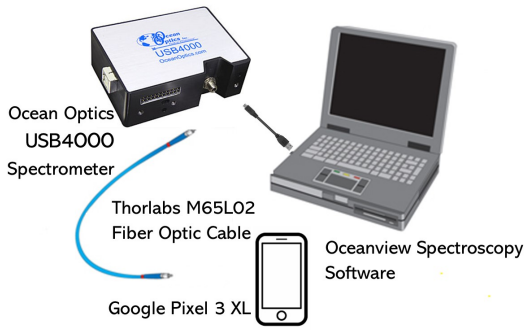

FIG. 3. Our experimental setup [5]

The process of taking samples involved selecting a single RGB color for the phone to shine upon the fiber optic cable. The RGB scale is measured from 0 to 255 for each of the primaries, Red, Green, and Blue. This can create a wide range of colors using various combinations of the primaries. We wanted to focus on pure colors, so we chose Green (0,255,0), Cyan (0,255,255) and Blue (0,0,255). These colors not only would have the best possible purity values, but also fit into our parameters of having wavelengths between 200 and 530 nanometers, except for the fact green is slightly cut off. With each color we tested them at 3 levels of screen brightness, 50%, 75% and 100%. Then we tested a built in function of the phone, a blue light filter while the phone was at 100% brightness. The Ocean Optics spectrometer that we were given used OceanView to capture the spectra of light. A background sample was taken and automatically subtracted out by the OceanView software. In order to get better data a longer integration time was used to get much more accurate spectra. An example of

a measured spectra can be seen in FIG. 4 Once data was captured it was analyzed. All data analysis was done in Google Colaboratory which is a Python interface.

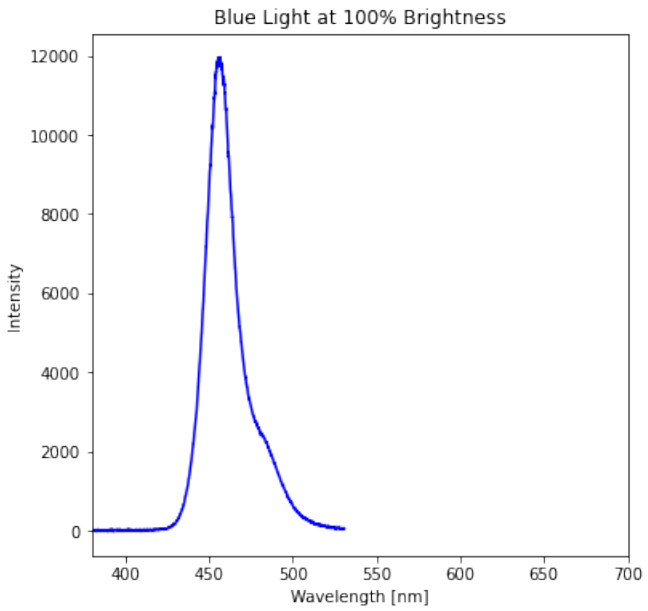

FIG. 4. Here you can see the limited range of wavelengths available to be measured. Blue light is relatively unaffected, but the cutoff is right in the green part of the visible spectrum.

The first step was to obtain the tristimulus values; X, Y, and Z. These are given by the equations:

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

Where $S(\lambda)$ is the spectral power distribution measured by the spectrometer and $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the color matching functions [4]. The color matching functions can be analytically approximated by Gaussian functions of the form:

$$G(\lambda, A, D, \sigma_1, \sigma_2) = A \exp - \frac{(\lambda - D)^2}{2\sigma^2} \tag{2}$$

Where A is the amplitude, D is the displacement of the peak, σ_1 is the left side peak width, and σ_2 is the right side peak width. That is to say:

$$\sigma = \begin{cases} \sigma_1 & \text{for } x < D \\ \sigma_2 & \text{for } x \geq D \end{cases} \tag{3}$$

The color matching functions are then just sums of these Gaussian functions.

$$\begin{aligned} \bar{x} &= G(\lambda, 1.056, 599.8, 37.9, 31.0) \\ &+ G(\lambda, 0.362, 442.0, 16.0, 26.7) \\ &+ G(\lambda, -0.065, 501.1, 20.4, 26.2) \\ \bar{y} &= G(\lambda, 0.821, 568.8, 46.9, 40.5) \\ &+ G(\lambda, 0.286, 530.9, 16.3, 31.1) \\ \bar{z} &= G(\lambda, 1.217, 437.0, 11.8, 36.0) \\ &+ G(\lambda, 0.681, 459.0, 26.0, 13.8) \end{aligned} \tag{4}$$

The amplitude values are appropriately dimensionless, however the values of D, σ_1, and σ_2 are all in nanometers [6]. After implementing the approximations of the color matching functions, the tristimulus values were calculated using numerical integration. Calculation of the integrands then became multiplying the spectral power at each wavelength by the color matching function value at that wavelength. The Scipy implementation of Simpson's rule was used to carry out the integration. After calculating the tristimulus values obtaining the xy pair is simple and is given by the equations:

$$\begin{aligned} x &= \frac{X}{X + Y + Z} \\ y &= \frac{Y}{X + Y + Z} \end{aligned} \tag{5}$$

Having obtained the xy pair we were now able to analyze the data points on the color map [4]. This analysis entailed finding the dominant wavelength, complimentary wavelength, and color purity. Conceptually this process is simple. Looking at FIG. 5, Example 1 demonstrates the process of finding dominant wavelength and complimentary wavelength. If you draw a line between the data point and the white point then extend the line, it will intersect the boundary in two places. Where it intersects the boundary closest to the data point is the dominant wavelength and where it intersects on the opposite side of the white point is the complimentary wavelength. Now that we know how to obtain the dominant wavelength, we can look at Example 2. We can define two distances, distance "A" and distance "B". Distance A is plotted in a dotted white line and is drawn from the white point to the data point (Example 2). Distance B is plotted in the black line and is drawn from the white point to the dominant wavelength. The color purity is the ratio of these distance, or

$$CP = \frac{A}{B} \tag{6}$$

It can be thought of as how close a data point is to the boundary or how far a data point is from white [7].

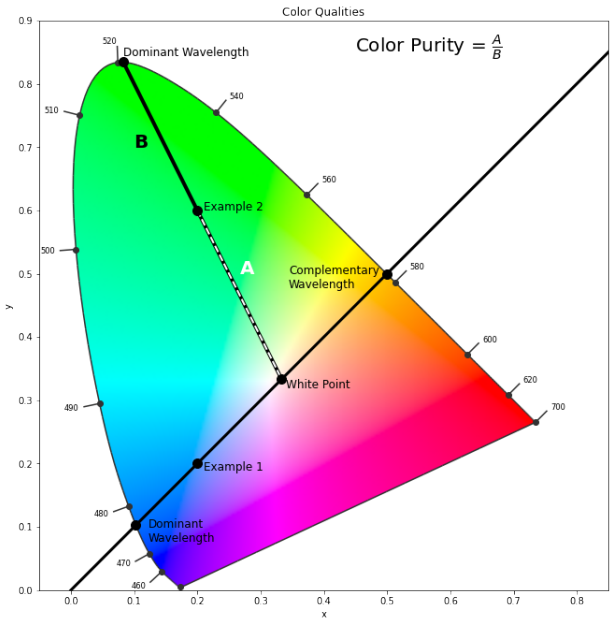

FIG. 5. If a line is drawn between a point and the white point and extended, the dominant and complimentary wavelengths are the intersection points with the spectral locus. Meaning whichever wavelength that creates those points are the dominant and complimentary wavelengths. Color purity is the ratio of the distances A and B.

These conceptual definitions are convenient for people but are not so straightforward in the context of computation. In general, linear regression was used to find the slope and intercept of the line between the given data point and the white point. These were used to recreate the line as well as extend it so that it would intersect the boundary. From there the distance between each point in the line and each point in the boundary would be calculated. The smallest value would be found and return the point in the boundary that created it. From this, not only the point is known, but the wavelength associated with the point. This process was carried out for both dominant and complimentary wavelengths.

This method is not very good if applied to the entire boundary of the color map. One reason would be that many points in the boundary that aren't needed would be taking up computations causing the process to take longer to execute and being much more inaccurate. Another is that the spacing between points changes depending where in the spectrum the point is. Points in the red area are very close together but points in the green area are far apart. You might get a dominant wavelength that is many nanometers off from the actual value. To compensate for these flaws the color map was split up into 6 sextants. The division into sextants was motivated by the slopes of lines. Two of the lines came from the ends of the visible spectrum. By splitting the color map into 4 parts based on the lines made between the point corresponding to 380nm and the white point and 700nm and the white point created a convenient fact. The spectral locus was split into 3 parts and the line of purples was an entire section by itself. This is convenient because if a point has a dominant or complimentary wavelength that would be on the line of purples, it does not exist and does not need to be calculated. This isn't entirely true because if a point would have a dominant wavelength on the line of purples it must be found to calculate the color purity. The third line, creating 6 divisions, is the $x = (1/3)$ line which has an undefined slope. This division also helps to break up the larger green section of the boundary.

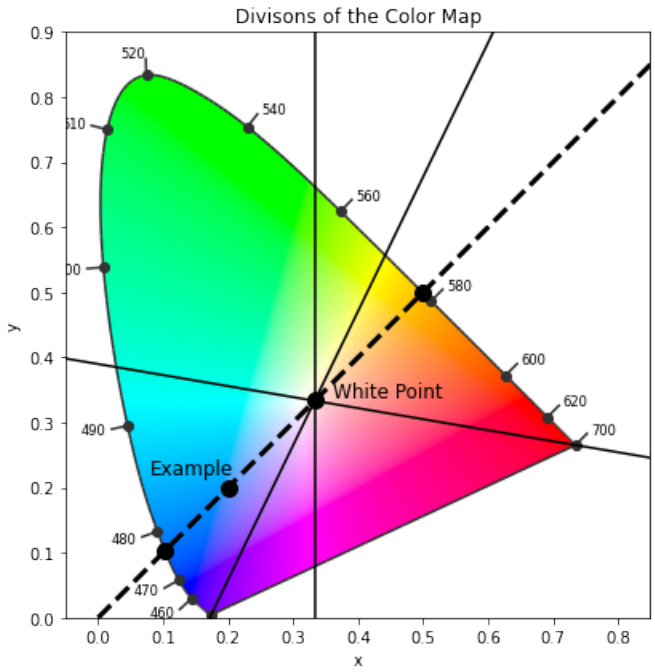

FIG. 6. This shows how the color map was divided up. The black lines are the divisions and the black dotted line is the slope of the line between the example point and the white point. We can see the slope is greater than zero but less than that of the line made by the 380nm point.

With these divisions in mind the slope of the point is analyzed and tested to see what sextant it is in. From there, either its x or y value is tested to see which side of the white point it is on. An example best demonstrates this process. In FIG. 6 an example point is plotted as well as the line between it and the white point. First the slope would be tested and found to be greater than the negative slope of the line created by the 700nm point, but less than the slope of the line created by the 380nm point. Next, a test would be done to see if the x value of the point is less than or greater than than of the white point, $x = (1/3)$. This would return that the example is left of the white point. From here only the piece of the spectral locus between 380nm and about 495nm would be calculated to find the dominant wavelength. Similarly, only the piece between about 570nm and 700nm would be calculated to find the complimentary wavelenth. For both of these the line segment would only be calculated

for x values between the points of the boundary pieces needed.

Precautions were taken to not apply this method to points that had special values. For example if the slope is the same as the line between the 380nm point and the white point then we already know the dominant and complimentary wavelengths. This was also applied to make sure the x or y coordinates were not the same as the white point. With this system in place, when the boundary and line sections are needed only the relevant pieces are calculated. Smaller boundary and line pieces give greater accuracy with less points. However more points can be used to drastically increase accuracy.

III. RESULTS

We expect to have some problems with the data, given the limited range of the spectrometer that does not include the entire visible spectrum, and that is what we see. In FIG. 7 we see that blue is a very pure blue as we would expect. However, cyan should be closer to a very bright cyan instead of a light blue as it seems in the figure. The green seems right, but if you look at TABLE II you can see that the color purity for green is the lowest out of all 3 colors. These make sense when thinking about the limitation of the spectrometer. The upper limit that could be measured was 530nm which partially in the area of green. This means that part of green is getting cut off. If the upper limit was in the yellow range then we expect the purity of green would be higher and cyan might shift upwards to where it should be.

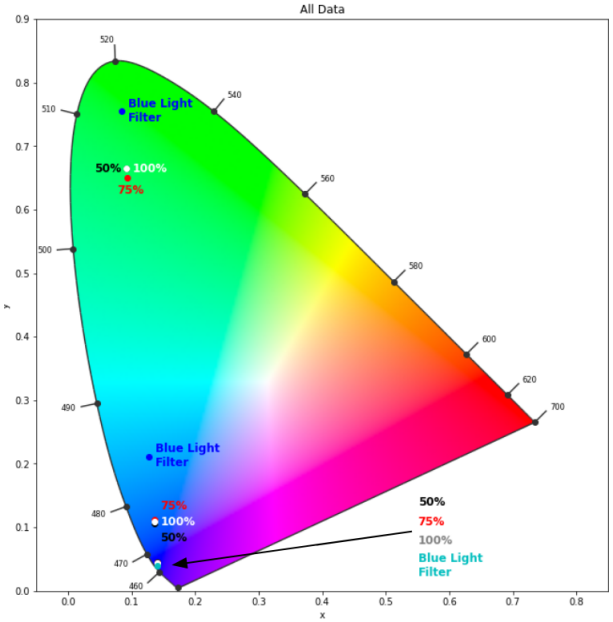

FIG. 7. All data points for Green, Cyan And Blue light.

It is most obvious when looking at FIG. 7 but it can also be seen in TABLE I that the brightness data points are very close together. It can also be seen that there is a significant different when the blue light filter is turned on. the only time this isn't the case is for the blue light data. We can expect this because the blue light filter can only dim the blue LEDs and can be thought of as just another brightness data point. If all the other brightness data points are grouped together then we would expect the blue light filter data point to also be grouped with them.

Data Point	x	y
Blue Data		
50%	0.141	0.046
75%	0.141	0.045
100%	0.141	0.044
BL Filter	0.141	0.040
Cyan Data		
50%	0.136	0.107
75%	0.136	0.112
100%	0.136	0.109
BL Filter	0.128	0.212
Green Data		
50%	0.091	0.666
75%	0.093	0.650
100%	0.092	0.666
BL Filter	0.084	0.755

TABLE I. Table of xy pairs

Data Point	Dominant	Complimentary	Purity
Blue Data			
50%	464.73	573.25	97.6%
75%	464.37	573.17	97.8%
100%	464.26	573.16	98.0%
BL Filter	463.29	572.97	98.7%
Cyan Data			
50%	474.01	576.35	89.4%
75%	474.58	576.64	88.9%
100%	474.33	576.51	89.2%
BL Filter	483.69	584.60	79.6%
Green Data			
50%	511.03	N/A	76.8%
75%	510.20	N/A	75.5%
100%	511.06	N/A	76.7%
BL Filter	516.08	N/A	86.6%

TABLE II. Table of color quality values

IV. CONCLUSION

We can make educated guesses as to how the limited range of the spectrometer affects our data but we can

not know for sure since we are unable to measure the red LED. Our data indicates that the color purity of the Google Pixel 3 XL has decent quality of color. This is supported by all reported color purity values being above 75%. If we are to assume that being able to measure the full visible spectrum would increase the color purity of the green data then we could conclude the Google Pixel has excellent color quality. We have determined that color brightness does not affect the color, as all of the colors at each brightness did not change significantly on the color map. This matches our expectations of what we know about the color map. Intensity does not matter but the relative shape of the spectra. However, when the blue light filter was on, it did change the colors significantly by making the colors less blue; which is how the blue light filter should work. We can say that for the Google Pixel 3 XL the blue light filter does actually work as advertised. Given that the blue light filter affected the green light data we can conclude that the blue LEDs must have been on while the blue light filter was off.

Given the opportunity to have access to a spectrometer that can measure the full visible range, we could fully investigate the color quality across the whole visible spectrum. Additionally, we could fully investigate the full extent of the blue light filter in operation. We do not know if there is an apparent pattern in how the blue light filter is applied that could enable us to make a conclusion about how it operates. The restrictions of COVID-19 made it possible to only measure a single cell phone's screen. Without the restrictions of the spectrometer and COVID-19 multiple brands of cell phone screens could be measured and compared. This could inform a conclusion on which brand actually has the highest quality screen.

ACKNOWLEDGMENTS

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