Using Colorimetry Methods to Characterize Phone Screen Qualities

Grant Sherrill,[1, *] Mason Lovejoy-Johnson,[1, †] and Drew Connelly[1, ‡]

[1] *Department of Physics, North Carolina State University, Raleigh, NC 27695, USA*

(Dated: November 26, 2023)

Modern smartphone technology has evolved to the point of being able show high-quality colored graphics in the palm of your hand. To be produce these images, smartphones use three fundamental LED pixel colors–red, green, and blue–in different superpositions to construct varying colors. The emission spectrum of each color of LED influences the size of the color space that the phone can output, as well as how well the phone can approximate any given color. In this work we use a spectrometer to measure the emission spectrum of the fundamental red, green, and blue pixel colors in various phone models and brands. From this we examine the purity of each color, and the color output space of each phone. These two factors serve to quantify the quality of a phone's screen. This way we are able to construct a metric for comparing phone screens, and examine whether or not upgrading phone models gives consumers a noticeable increase in quality.

Keywords: Colorimetry - Spectrometry - Spectral Analysis

I. INTRODUCTION

The visual component of modern smart phones operates by using interfering LED spectra to construct the image. Each phone is able to create a wide range of colors–also called a color gamut–by expressing combinations of red, green, and blue light in superposition. A phone's exact color gamut is not easily accessible information, as actual colors expressed by the LEDs often differ from their theoretical output in ideal conditions [1]. In this work we use spectrometry to acquire the true color gamut of many different phones, by precisely determining the emission spectra of each phone's red, green, and blue pixels.

Colorimetry refers to the study of color, and how humans see color. The field has been dutifully characterized over the years to join the physical definitions of color and the biological processing done by the eye [2]. The most commonly used colorimetry standard is the 1931 CIE color space, which defines red, blue, and green via the absorption spectra of receptors in the human eye [3]. Associated with this is a measure to describe how a spectrum over a range of wavelengths can be converted into the red, green, and blue as seen by our eyes. This gives us a method to convert from a source into what our eyes can perceive [4]. But this method does not determine whether a color is "green" or not, it simply takes an input and determines what color our eye would see it as. There are a variety of different conversion methods, but this 1931 CIE color space will be the model for the rest of the paper.

From spectroscopy, we can measure the emissions from phone screens, and using our colorimetry conversion, we can determine what colors are being shown. This technique gives us two main characteristics among the phones; the purity of the color, and the percentage of the color range that can be expressed from the total range of color our eyes can see [5]. Through these two qualities, a measure of how effective the screen technology is can be determined. An ideal phone would contain perfectly pure colors, and maximize the possible color space that can be expressed by the phone. We aim to affirm that phones have been advancing over the years by increasing these two qualities, and if buying the new phone each year delivers discernible increase in quality.

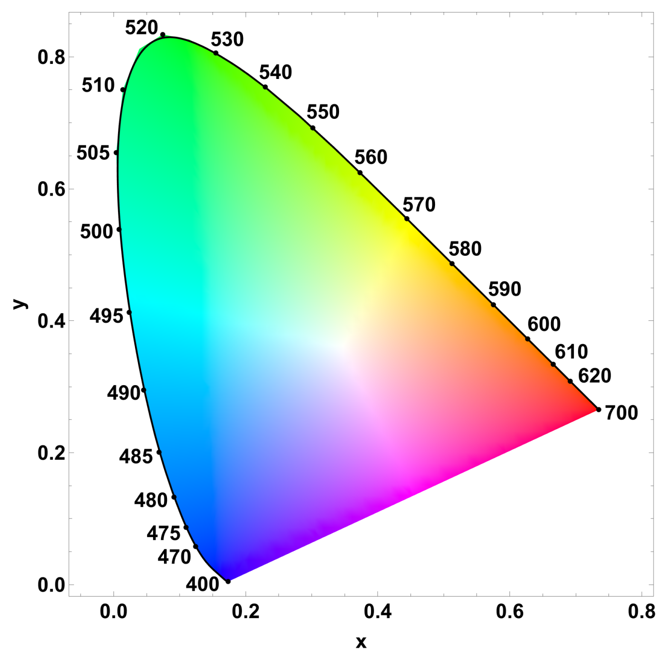

FIG. 1. The CIE 1931 Chromaticity Diagram. The black border represents the monochromatic spectrum, with selected wavelengths enumerated.

* mgsherri@ncsu.edu
† malovej2@ncsu.edu
‡ ajconne2@ncsu.edu

II. THE CHROMATICITY DIAGRAM

The so-called "Chromaticity Diagram" (Fig. 1) displays the colors associated with each normalized response from the CIE 1931 standard observer ; the standard that defines absorption spectra associated with how the human eye perceives red, green, and blue [6].

A. Chromaticity Coordinates of a Spectrum

We can convert a given emission spectrum $S(\omega)$ to a tristimulus vector $[X, Y, Z] \in \mathbb{R}^3$ like so:

$$X = \int_{-\infty}^{\infty} \phi_R(\omega) S(\omega)\ d\omega,$$
$$Y = \int_{-\infty}^{\infty} \phi_G(\omega) S(\omega)\ d\omega,$$
$$Z = \int_{-\infty}^{\infty} \phi_B(\omega) S(\omega)\ d\omega.$$

Where ϕ_R, ϕ_G, and ϕ_B are the three CIE 1931 standard tristimulus functions, which represent the normalized red, blue, and green absorption spectra of the human eye, respectively. Since we could not access the official CIE tristimulus function data freely, we have approximated these functions with sums of gaussian distributions in our work [7]. The three chromaticity coordinates (x,y,z) are then calculated from the tristimulus values like so [3]:

$$x = \frac{X}{X+Y+Z},$$
$$y = \frac{Y}{X+Y+Z},$$
$$z = \frac{Z}{X+Y+Z}.$$

Thus, chromaticity vectors in this space are normalized such that valid colors are all unital under the L^1 norm, meaning that given any $\vec{v} = [x, y, z]^\intercal$, we have

$$\|\vec{v}\|_1 \equiv |x| + |y| + |z| = 1.$$

The positivity of x, y, and z tells us that $z = 1-(x+y)$, so we see that our color vectors only have two independent degrees of freedom. Therefore, by removing the third coordinate z, projecting our color vectors onto $\mathbb{R}^2$, we construct a 2-dimensional representation of the complete normalized color response space according to the CIE 1931 standard observer. This vector space of colors (specifically the L^1-unital subset thereof) will hereafter be referred to as the "color space". This color space is the domain of the Chromaticity Diagram–shown in Fig. 1–which pairs each (x, y)-coordinate with the color that the human eye would perceive when presented with that particular stimulus.

B. Monochromatic Light

In order to put a border on the Chromaticity Diagram, we find the coordinates of monochromatic light as a function of wavelength λ. The normalized emission spectrum associated with λ-wavelength monochromatic light is the Dirac delta function centered at λ, $\delta(\omega - \lambda)$. Thus, we can find the tristimulus values of λ-wavelength monochromatic light like so:

$$X_\lambda = \int_{-\infty}^{\infty} \phi_R(\omega)\delta(\omega-\lambda)\ d\omega = \phi_R(\lambda),$$
$$Y_\lambda = \int_{-\infty}^{\infty} \phi_G(\omega)\delta(\omega-\lambda)\ d\omega = \phi_G(\lambda),$$
$$Z_\lambda = \int_{-\infty}^{\infty} \phi_B(\omega)\delta(\omega-\lambda)\ d\omega = \phi_B(\lambda).$$

This yields the following λ-dependent parametric equations for the border of the Chromaticity Diagram:

$$x(\lambda) = \frac{\phi_R(\lambda)}{\phi_R(\lambda) + \phi_G(\lambda) + \phi_B(\lambda)},$$
$$y(\lambda) = \frac{\phi_G(\lambda)}{\phi_G(\lambda) + \phi_G(\lambda) + \phi_B(\lambda)}.$$

A parametric plot of these two coordinates in mathematica yields the black border around the colored part of the Chromaticity Diagram in Fig. 1.

C. Spectral Purity

The purity of a spectrum is a number between 0 and 1 that measures the spectrum's similarity to that of the nearest monochromatic light on the chromaticity diagram [5]. A perfect white light source in the center of the diagram will have a purity of 0, whereas any monochromatic light will have a purity of 1. The following formula is used to calculate color purities:

$$P(\vec{x}) = \frac{\|\vec{x} - \vec{w}\|_1}{\|\vec{x} - \vec{x}_{\text{mono}}\|_1}.$$

Where $\vec{w}$ is the white-point color vector, and $\vec{x}_{\text{mono}}$ is the color vector of the monochromatic light found by extending the line between $\vec{w}$ and $\vec{x}$ to the boundary. In the case where $\vec{x}$ is in the purple regime of the diagram, there is no such boundary to intersect with, so the line must be extended from $\vec{x}$ through $\vec{w}$, and then to the border of the plot in the complementary color regime to find $\vec{x}_{\text{mono}}$.

In this work we use purities as a metric for comparing the display technology of different devices. Higher purity measurements indicate to us that the device is better able to produce a pure red, green, or blue color, meaning the color will be sharper on the screen.

D. Color Vector Properties & Gamuts

A device's gamut is the set of all possible colors that can be displayed by the device. Since modern devices use the RGB pixel system–whereby colors are constructed from fundamental red, green, and blue pixels lighting up at different intensities–a device's color gamut is the space of all linear combinations of the red, green, and blue color vectors. Due to the nature of the L^1-unital color vectors in the color space, the space of linear combinations of two colors in the Chromaticity Diagram is the line joining the two points in the plane. Therefore, the triangle with vertices at each of the three pixel colors represents the border of a device's color gamut. We represent a device's color gamut with a grey triangle, as shown in 2, with the proportion in the center representing gamut coverage. The numbers at each corner of the gamut are the RGB purity values.

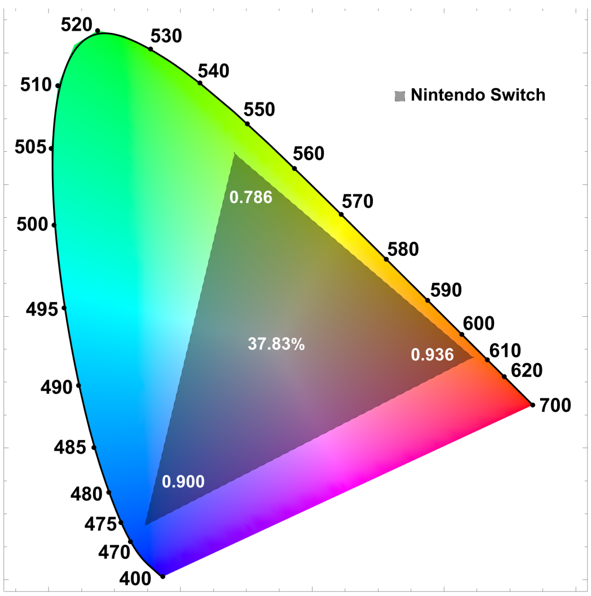

FIG. 2. The gamut coverage of the Nintendo Switch.

III. METHODS

A. Experimental Design

Measurements were taken using a Ocean Insight Flame spectrometer (Model:Flame-S-XR1-ES). The spectrometer collects data through an optical fiber attachment channeling light from a source to the spectrometer device. Samples are probed by placing the end of the fiber towards the output signal.
To minimize the measurement error from sources such as the light in the room, a dark chamber was created to place our samples inside of. The chamber was constructed

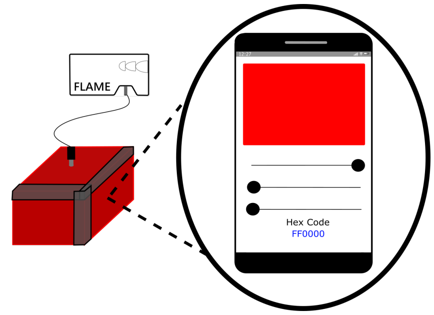

FIG. 3. Experimental Setup Diagram. The phone (right) is intended to be prepared and placed inside of the box (left) which can then be measureed by the spectrometer (top).

using a box with modifications as shown in Fig. 3. Each edge was taped over multiple times to prevent light from coming into our sample space. An overhang was designed to allow for samples to be interchanged and adjusted during experiments. Our fiber was inserted into the hole on the top of our chamber and positioned to collect measurements. Putty was then affixed around the probe at this position to close the hole where the probe was inserted.

Samples are prepared by turning up the brightness of a given phone to the maximum setting and disabling any brightness adjustment settings. We then control for a singular color to be shown on screen, most times using an app. The chosen apps are picked to allow for us to show only red, green, blue, and black using the associated hex codes. For the iPhone devices the "Easy RGB" app was used, and the "Color Grab" app was used for the Google Pixel 2. When collecting data with the iPhone 5, Google Pixel 4, and Nintendo devices, apps could not be downloaded and an online website was used. The website met the prior specifications, with the color of interest being zoomed in to cover a majority of the screen.
Data was collected using the OceanView software, with no modifications made to the program data collection. Data was exported from this software as a list of intensities as a function of wavelength. Data was taken and imported into Mathematica for processing.

B. Error Mitigation

One will note that these apps do not change the entire screen color into the selected color, as demonstrated by the schematic in Fig. 3. During data collection, measurements are made for each color, with an additional measurement showing the color black in the color block. This reports the amount of background light admitted into the probe from the background app design. Along with our dark box, we intend to mitigate most of the error in our sample using these methods. This error can be subtracted from the signal to eliminate false peaks

Device Measurement List				
Device	R	G	B	Gamut Coverage
IPhone 5	0.894	0.753	0.907	35.3 %
IPhone XR	0.912	0.757	0.906	36.7 %
IPhone 11	0.923	0.775	0.901	37.3 %
Google Pixel 2	0.982	0.835	0.919	43.2 %
Google Pixel 4	0.951	0.815	0.905	42.7 %
Nintendo 3DS XL	0.811	0.867	0.871	30.3 %
Nintendo Switch	0.936	0.786	0.900	37.8 %

TABLE I. Table of device measurements. Values in the R,G, and B columns refer to the purities of the the colors being expressed. The gamut coverage value is the percentage of the Chromaticity Diagram covered by the device's color gamut.

which may be a source of error.

In all tests, the phone brightness was set to maximum for the data collection. In one set of testing we used the lowest brightness setting on our phones to determine if this was a significant factor on the phone data. The error in this experiment was on magnitude with the signal we had hoped to measure. For maximum brightness this is not the case, and we believe the measurements are valid at high brightness. The errors from the measurement device have been mitigated for in this way, and conclusions made with our data are unaffected. We have no reproduction of data using the same measurement technique, and cannot make any claims about associated statistical error.

After measuring the iPhone 5 we lost our background data, making it impossible for us to remove the background noise from our data. We approached the problem by using the iPhone XR background data instead of iPhone 5 background data. Therefore, we may be underestimating the purities of our iPhone 5 RGB pixel colors, as the background is not entirely eliminated.

IV. RESULTS & DISCUSSION

We report our two metrics of performance–Gamut coverage and RGB purities–in Table *I* across the various devices available to us. The data is organized based on the company manufacturing the devices, Apple, Google, and Nintendo respectively. Among the Apple phones, the iPhone 5 has the lowest purity values, and consequently a smaller gamut coverage percentage of 35.3%. This phone came out the earliest, with the later phones increasing to 36.7% and 37.3% for the iPhone XR and iPhone 11 respectively. This suggests that Apple has not made significant improvements on their color representation and is outperformed by the Google Pixel.

The Google Pixel devices have the highest purity and gamut coverage percentages, and it appears that the Google Pixel 4 is worse than the Google pixel 2, having lower purities for each color. From this data, we believe that the Google Pixel 2 or the original model had its' screen developed above the capabilities of other phones, and has not made any significant improvements since this first iteration.

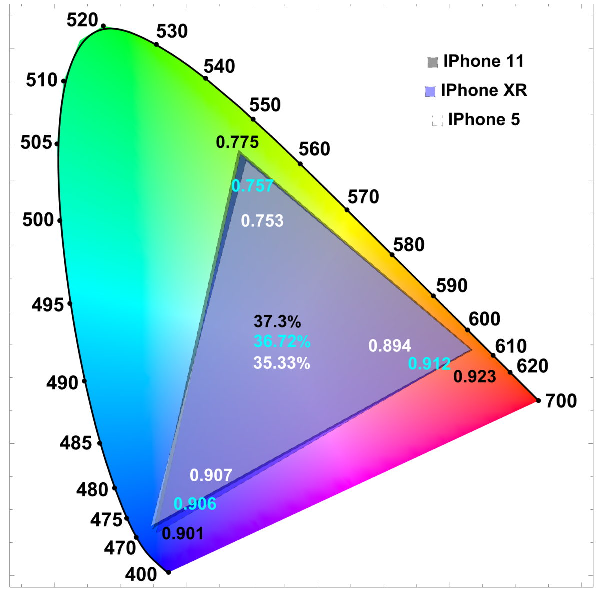

FIG. 4. The RGB purities and gamut coverages for the three iPhone devices.

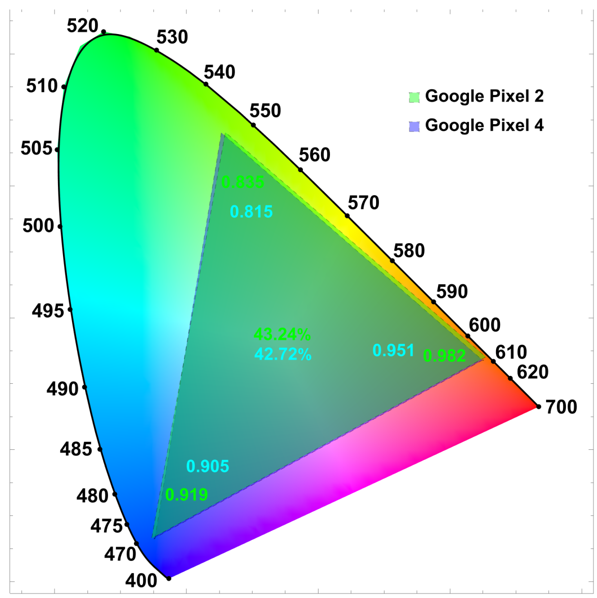

FIG. 5. The RGB purities and gamut coverages for the two Google Pixel devices.

The Nintendo 3DS XL has the best green purity value of any device we tested. This is the result of the green spectrum optimizing its own purity rather than its contribution to gamut coverage. The 3DS has the lowest purities values for Red and Blue as well causing for the lowest gamut coverage. The Switch has drastic improvements over the 3DS XL because of its larger form factor, which allows for bulkier, more adavnced, screen technology to be installed inside the device.

V. CONCLUSION

Our data suggests that display technology is stagnating in recent years amongst both Apple's and Google's smartphones. This stagnation is most clear in the case of the Google Pixel 2 and 4, where in Fig. 5 we see that the gamut is almost exactly the same between the two devices, although the Pixel 4 was released two years after the Pixel 2. The two years of development do not seem to have yielded a significant increase in gamut coverage.

Furthermore, all three iPhone models–the iPhone XR, 11, and 5–are shown in Fig. 4 to have almost identical gamut coverages as well, despite the seven years of development between the three models' release dates. We see very little evidence of long-term improvement in iPhone screen technology in Fig. 4 by the fact that the iPhone 5's gamut coverage is only slightly smaller than those of the more recent models.

Ultimately, modern smartphone phone display technology shows little improvement in recent years amongst big brands like Apple and Google. While the technology is always evolving, we see very little incentive for consumers to upgrade their phones on the premise of improved color.

ACKNOWLEDGMENTS

We thank Dr. Sun for his guidance during the duration of this project. We also thank Dr. Sun's postdoc, Dr. Sun for helping us with lab procedures.

[1] A. T. Lee, H. Chen, S.-C. Tan, and S. Hui, IEEE Transactions on Power Electronics **31**, 65 (2015).
[2] F. M. Clydesdale and E. Ahmed, Critical Reviews in Food Science & Nutrition **10**, 243 (1978).
[3] J. Schanda, "Cie colorimetry," in *Colorimetry* (John Wiley Sons, Ltd, 2007) Chap. 3, pp. 25–78.
[4] H. S. Fairman, M. H. Brill, and H. Hemmendinger, Color Research & Application **22**, 11.
[5] A. Chowdhury, "Using instruments to quantify colour," (2014) pp. 270–317.
[6] D. I. A. MacLeod and R. M. Boynton, J. Opt. Soc. Am. **69**, 1183 (1979).
[7] C. Wyman, P.-P. Sloan, and P. Shirley, Journal of Computer Graphics Techniques (JCGT) **2**, 1 (2013).