

Feasibility of Low-Cost Color Sensors In Graphic Communications Virtual Classroom Learning

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Abstract

This work presents the process of selecting and assessing a low-cost color sensor suitable for illustrating essential concepts within pre-established graphic communications curricula for virtual learning. The suitability of the device was determined based on its ability to evaluate concepts presented in the curriculum, such as the whiteness and opacity of the substrates; and the optical density, tone reproduction, color balance, hue error, grayness, and overprint trapping of inks. Many of these evaluations require measurement of color and optical density. The selected sensor provides measurement of CIE $L^*a^*b^*$. Established conversions can then translate the $L^*a^*b^*$ values into optical densities. The evaluations performed by the low-cost color sensors were compared to those from a standard device, X-Rite eXact, for the purpose of explaining similar observations. The comparison was conducted in the virtual classroom, with the actual learning delivery and device exploration taking place in parallel. The initial collection of data from the virtual classroom indicates statistically significant differences between the low-cost device and X-Rite eXact; however, the concept illustration was not impeded by the differences.

Introduction

Classroom learning and instruction changed drastically in 2020 due to the widespread Coronavirus pandemic. In most circumstances, in-person teaching was no longer an option due to the health and safety concerns of students, faculty, staff, and their families. These concerns drove many academic institutions to offer online courses exclusively and launched faculty into virtually delivering course content with no alternative. In a discipline such as graphic communications or printing,

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where hands-on interaction with tools and equipment is one of the main focuses of the curriculum, this sudden shift presented a whole new set of challenges.

This work aims to identify a portable and affordable color measurement device for virtual classroom use and to assess its feasibility with respect to class curriculum requirements. Measurement devices sampled in this work are classified as portable color sensors. They are affordable, with a cost similar to textbooks, and are easy for students to acquire and use. Past research has assessed the performance of similar sensors in terms of success rates of identifying the color of established color chips and has indicated the attractiveness of these sensors for applications not requiring high accuracy (Kirchner et al., 2019). Research containing color elements has used these portable color sensors to document changes. For example, the Nix Pro color sensor was used by Post and Schlautman to categorize flower petals' colors as defined by Royal Horticultural Society (RHS) Colour Chart, and by Stiglitz and others to examine soil color relative to Munsell color codes. Typically, the primary users of these devices are graphic designers, photographers, interior designers, paint suppliers, contractors, etc.

This paper will focus on the capability of the device to define color using standards such as CIE $L^*a^*b^*$ and optical density. The goal is for the low-cost sensors to provide a comparable understanding of concepts introduced in our curriculum. Examples of these concepts include color and color difference (ΔE^*), tone reproduction, whiteness and opacity, color balance, and even hue error, grayness, and overprint trapping, typically measured for process colored prints. In the existing in-person curriculum, the X-Rite eXact and X-Rite i1io spectrometers have been the standard instruments. As it is not feasible to provide every student with a standardized spectrophotometer for at-home use, an affordable replacement is essential.

The hypothesis of this study is that one or more low-cost color sensors would exhibit sufficiency in the demonstration of colorimetric concepts, such as CIE $L^*a^*b^*$ color space and color difference (ΔE^*). In addition, the conversions of CIE $L^*a^*b^*$ values to optical densities are of sufficient accuracy to reflect some of the effects caused by the print process. The goal is for the low-cost sensors to present similar outcomes when contrasted to the X-Rite eXact. This study seeks to assess the devices by addressing the following research questions:

- Can the low-cost sensor differentiate colors in the definition of CIE $L^*a^*b^*$?
- Can optical densities estimated from the $L^*a^*b^*$ values discern a difference between dot area coverage when there are changes in the print system?

- Can the low-cost sensors be a reliable tool in the print evaluations in the curriculum? This study focuses on determining what the low-cost sensor can do and to what extent.

This paper presents the content according to the following categories: selecting a low-cost color sensor, sensor feasibility determination, and results and discussion. This paper will also share the initial outlook on the accuracy and variation of the low-cost devices when compared to the standardized measurement systems.

Selecting a Low-Cost Color Sensor

Color measurement devices can be categorized into the following types: colorimeters which provide CIE L*a*b* values that correlate to the way humans perceive color, densitometers which provide density readings that correlate to the amount of ink on a substrate, and spectrophotometers which capture a set of reflection values that describe the reflectance across the visible spectrum (Seymour, personal communication, August 2021).

In the simplest form, color sensors emit a known amount of light and return a measurement of the light that is reflected back off of a given object. These devices use a set of three or four filters to measure tri-stimulus values that are similar to the way humans perceive color (Mouw, 2019). Both the Nix Mini 2 and the Color Muse device discussed in this paper are classified as colorimeters.

Densitometers, on the other hand, are blind to color. They emit light onto the object being measured through red, green, or blue filters at specific wavelengths and return density measurements by taking the negative log of the reflected light. By limiting the color (or wavelength) of light, the object being measured can reflect, it is easier to detect subtle changes in the presence of inks (Lakacha, 2013). For example, when measuring the magenta density of an object or the density of magenta ink, the green filter within the densitometer is used. Magenta absorbs green light, so when the green filter is used, the reflectance of a magenta object is minimal. Density values are useful in print evaluation because there is a correlation between the density and the ink film thickness.

Spectrophotometers can be used to achieve even more precision as this type of instrument uses narrow filters to split the emitted light into thin bands that record the reflectance at certain intervals, typically every 10 or 20 nanometers. The resulting measurements describe the object's color and reflectance across the entire measured spectrum and can be used to generate spectral curves (Lakacha, 2021).

Prior to introducing the devices into the curriculum, two low-cost sensors, Color Muse, or "Muse" in this paper, and Nix Mini 2, or "Nix", were examined. Both of the sensors tested represent the base model for each respective manufacturer. Brief

device specifications for both Muse and Nix, as well as the X-Rite eXact Advanced or “eXact”, can be found in Table 1 (Color Muse, 2020; Nix, 2020; X-rite eXact, 2020).

			
*Per Published Technical Specifications	Color Muse colormuse.io	Nix Mini 2 nixsensor.com	X-Rite eXact xrite.com
Price (in US Dollars)	\$59.99	\$99.00	~\$835.00
Optical Geometry	45°/0°	45°/0°	45°/0°
Standard Illuminant	A, D50, D65, F2, F7	D50	D50, D55, D65, D75
Observer Functions	2°, 10°	2°	2°, 10°
Measurement Conditions	Closer to M0 than M1	Similar to M2	M0, M1
Measurement Size	4 ^{mm}	15 ^{mm}	1.5 ^{mm} , 2 ^{mm} , 4 ^{mm} , 6 ^{mm}

Table 1: Device Specifications*

Table 1 indicates that the three devices have some commonalities that are shown in bold. According to the manufacturers’ published technical specifications, all three devices have an Optical Geometry of 45°/0°, Illuminants of D50, and the Observer Functions of 2°. Therefore, these settings were used as the standards in this research. One difference among the devices is the size of the apertures 4mm, 15mm, and a range between 1.5mm to 6mm for Muse, Nix, and eXact, respectively. The other key difference between the devices is the Measurement Condition, as the eXact’s measurement conditions are set to CIE standards where the Muse and Nix are approximations.

To compare the Muse and Nix devices, measurements were taken from cyan, magenta, yellow, and black (“CMYK”) ink patches as well as solid overprint combinations, red, green, and blue (“RGB”). Measurements of L*a*b* data of CMY ink and RGB overprints indicated that both low-cost sensors showed significant color differences with respect to eXact. In Table 2,

ΔE_{00} were calculated (using ColorTools, a Microsoft Excel Add-in) by comparing the L*a*b* data obtained with each sensor to those with the eXact (Edgardo, 2021). Table 2 indicates that Muse differed from eXact by 2.7 ΔE_{00} and Nix by 1.4 ΔE_{00} . As indicated in Table 2, the color differences between Nix and eXact appeared smaller for most of the six colors sampled.

Color	Color Muse	Nix Mini 2
Cyan	2.3	3.0
Magenta	3.3	0.6
Yellow	1.0	1.2
Red	3.0	1.1
Green	3.8	1.1
Blue	2.6	1.5
Mean	2.7	1.4

Table 2: Color differences of Muse and Nix when compared to X-Rite eXact (ΔE_{00})

Since these low-cost sensors perform the functions of a colorimeter, only $L^*a^*b^*$ data were relied upon during the selection process. Ultimately, the Nix Mini 2 color sensor was selected for testing in the virtual classroom setting because initial testing showed that when compared to X-Rite eXact, the Nix device reflected smaller ΔE_{00} the Color Muse. While the initial tests showed promising results that lead to device implementation in the classroom environment, the ΔE_{00} values recorded would not meet the tolerance needs of most production environments.

Sensor Feasibility Determination

Nix feasibility testing was implemented in six of the eight labs in the semester. The concepts tested with Nix included visualizing $L^*a^*b^*$ space, whiteness and opacity of substrates, opacity of inks, tone reproduction, dot gain, print contrast, hue error/grayness, trapping, gray balance, color balance, and color differences. Nix measured $L^*a^*b^*$ values. Other print evaluations required optical densities, which were obtained through conversion from $L^*a^*b^*$. Formulas used to calculate CMKY optical densities from CIEL^{*} a^*b^* data can be found on the attached formula sheet.

Nix measurements were conducted by 46 students in the Fall 2020 semester and 38 students in Spring 2021 semester. The eXact measurements were conducted by the teaching assistant and the instructor. This paper will focus on the two lab assignments that evaluate $L^*a^*b^*$ color space and tone reproduction as examples.

Visualizing $L^*a^*b^*$ Color Space. “Getting Started with Colorimeters and $L^*a^*b^*$ ” is the introductory laboratory to help students visualize the color space. The assignment was designed to prepare students to use the Nix device and to provide a basic understanding of the $L^*a^*b^*$ color space and the meaning of neutral. Although a standardized test target like the FOGRA Media Wedge can be used here, the test target presented in Figure 1 was devised to present a simplified introduction of the $L^*a^*b^*$ concept. Figure 1 consists of process-colored inks (CMYK), overprint patches (RGB), a lightness scale, and pseudo- $L^*a^*b^*$ cross-section. The pseudo- $L^*a^*b^*$ cross-section contains some extremely saturated colors

(that may range substantially on the L* axis). Therefore, it does not represent a true a*b* cross-section at a given L*. The lightness scale L* contains three levels of grays. Samples used to provide this data were produced on the same paper stock in one run (per semester).

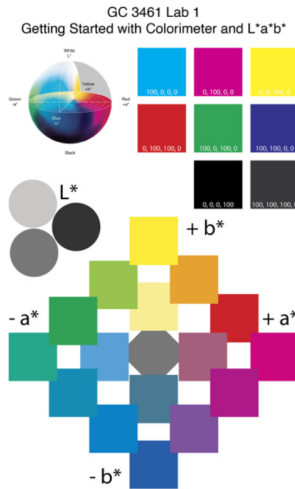


Figure 1: Getting Started with Colorimeters and L*a*b* Test Target

In this assignment, students are provided with an Excel Data Template and a printed Test Target (Figure 1). Students are instructed to install the Nix Digital smartphone app, pair the Nix device, and to record the L*a*b* values for the instructed patches. The students then apply Formula 1: 1976 ΔE^*_{ab} to calculate the color difference (ΔE^*_{ab}) between the measurements from their Nix and a sample of data collected using an eXact provided by the instructors.

$$\Delta E^*_{ab} = \sqrt{L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}$$

Formula 1: 1976 ΔE^*_{ab}

Tone Reproduction. Tone reproduction is used in many areas to characterize the print production process. The laboratory of “Banded Roll” intends to illustrate the selection process of an anilox roll that would provide the optimal ink volume to the impression of the images in flexographic printing. Different ink coverage would behave differently in the print process and would be reflected in the outcome of tone reproduction, dot gain, and print contrast. With this laboratory, samples of tone scales (0 to 100% dot coverage) were produced with an anilox roll which is a combination of five bands for five different ink volumes; thus, the term banded roll.

For this assignment, students measured tone scales for all five bands from a press sample (all samples were produced in the same press run). The five bands carried 0.95, 1.58, 2.10, 2.61, and 3.01, in billion of cubic microns per square inch area (bcm/in²). The flexographic plate was imaged at 150 LPI line screen. The data

template converted the L*a*b* values to CMYK density and applied the Formula 2: Murray-Davies Dot Area Formula listed below. Students completed charts for the tone reproduction, dot gain, and print contrast to make recommendations for which band to use for the given substrate.

$$\text{Dot Area} = \frac{1 - 10^{-\text{Density}_{\text{print}}}}{1 - 10^{-\text{Density}_{\text{solid}}}}$$

Formula 2: Murray-Davies Dot Area Formula

Results and Discussion

Visualizing L*a*b* Color Space. Figure 2 depicts L*a*b* data collected from the “Getting Started with Colorimeters and L*a*b*” laboratory. Nix a*b* data (small semi-transparent colored circles) was collected by 34 students and is compared to 20 eXact a*b* data points (×’s) that were collected by one user with four devices and five samples. Figure 2 compares data from Nix to those from eXact (×’s) on an a* (horizontal axis) and b* (vertical axis) plane for the colors of CMYRGB. Collections of colored circles, or data points, mark a region of a* and b* values for the corresponding color. For example, the cyan circles (in Figure 2) are grouped around ~ -33 a* and ~ -47 b*. The square boxes around each data cluster indicate roughly the spread of the data from the measurements. All squares are 10 by 10 units, except green, which is 20 by 20 units, underlining a larger variation from the green data.

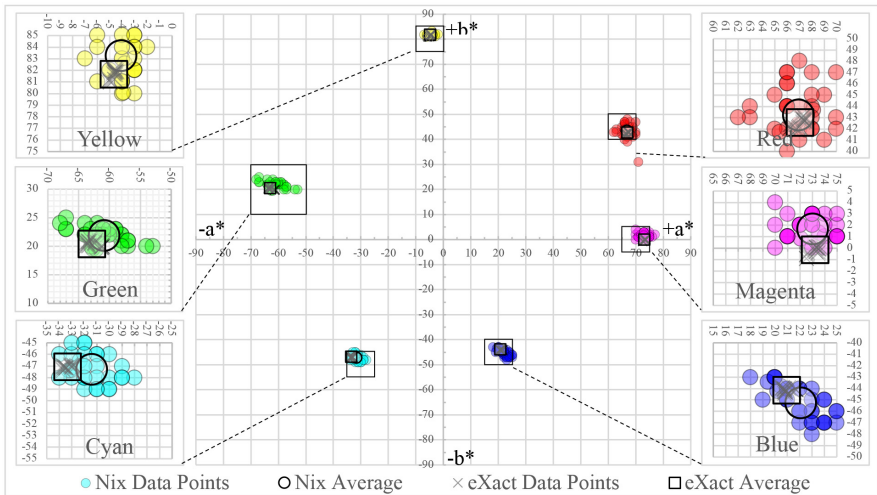


Figure 2: Comparing Nix a*b* values (small semi-transparent colored circles) to eXact (×'s).

The enlargements shown in Figure 2 emphasize the approximate regions where measurements for the CMYRGB colors reside. The larger circle and square near the center of each color group locate the mean a* and b* values for the Nix and eXact, respectively. For example, the cyan data in the bottom left enlargement shows the mean a* and b* are -31.4 and -47.3 respectively for the Nix while -33.34 and -47.06

respectively for the eExact. Figure 2 also highlights the smaller variation of eExact than Nix, as the \times data points from eExact are tighter than those from the Nix data.

Table 3 presents a statistical comparison between Nix and eExact. Table 3 contains data collected in the Spring 2021 semester. The 34 independent sets collected for the Nix were, presumably, collected by 34 unique students using 34 unique samples and devices; the 20 measurements analyzed for the eExact were collected on four different devices, each measuring five samples, all performed by the same user. The table shows the mean values, standard deviations, and ranges of a^* and b^* for CMYRGB, as well as of L^* for three gray patches labeled as Light, Medium, and Dark, respectively. The Nix data are in the top three rows and eExact in the next three rows. The bottom row of the table displays the results from a two-sample t-testing to identify the differences between the Nix data and the eExact data.

Spring 2021 Nix (34 independent sets) eExact (20 Measurements 4 devices 5 samples)																
		Cyan		Magenta		Yellow		Red		Green		Blue		Light	Medium	Dark
		a^*	b^*	a^*	b^*	a^*	b^*	a^*	b^*	a^*	b^*	a^*	b^*	L^*	L^*	L^*
Nix	Mean:	-31.4	-47.3	73.0	1.7	-4.1	83.3	66.9	43.3	-60.9	21.9	22.1	-45.2	76.4	48.3	23.3
	Deviation:	1.5	1.2	1.8	1.0	1.2	2.2	2.0	3.1	3.5	1.4	1.8	1.4	1.1	1.3	1.4
	Range:	6.0	4.0	7.0	4.0	5.0	9.0	9.0	17.0	15.0	5.5	7.0	5.0	4.0	5.0	6.0
eExact	Mean:	-33.3	-47.1	73.2	-0.2	-4.7	81.6	67.0	42.6	-62.8	20.4	20.9	-44.1	78.6	49.7	24.3
	Deviation:	0.3	0.1	0.4	0.3	0.2	0.4	0.4	0.4	0.9	0.4	0.4	0.2	0.2	0.3	0.3
	Range:	0.9	0.5	1.1	1.1	0.6	1.2	1.3	1.3	2.5	1.2	1.2	0.5	0.7	1.0	1.0
P-Value:		0.00	0.31	0.48	0.00	0.02	0.00	0.69	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3: Statistical Analysis of Nix Compared to eExact

Close observation of the table reveals that for all CMYRGB and L^* sampled, Nix consistently attains larger standard deviations and range of values than eExact. For example, while eExact measurements produce standard deviations in the fractional values, Nix’s standard deviations are all greater than one. This is particularly striking for the color green, where Nix has a standard deviation of 3.5 and a range of 15. This is consistent with the visibly larger a^* spread of green values in Figure 2. Similar observations of other colors also highlight the eExact’s superior performance over Nix.

The two-sample t-test compares the mean values of Nix and eExact. The Null hypothesis assumes that the two means are equal. If the p-value is less than or equal to 0.05, or less than or equal to 5% probability, then the Null hypothesis is rejected, and the two means are declared to be different. As exhibited in the bottom row of the table, 11 of 15 of the Null hypotheses are rejected. Therefore, in these 11 cases, the data from Nix and eExact are proven to be statistically different.

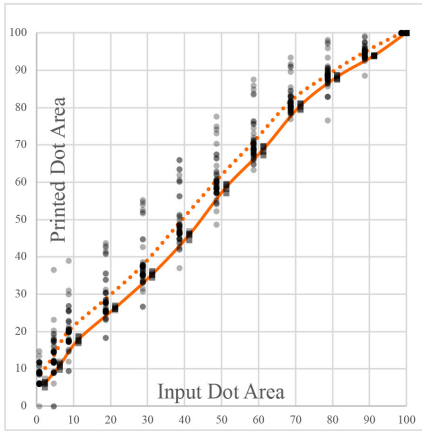
For the concept demonstration, however, students can visualize the differences in colors presented by the patches in the test target presented in Figure 1. In addition, the students can measure the $L^*a^*b^*$ values associated with each patch to visualize a^* changes and b^* changes individually or jointly. The differences detected in the statistical analysis is insignificant towards the demonstration of CIE $L^*a^*b^*$.

Tone Reproduction. Tone reproduction curves are used frequently to examine the dot gain effects caused by the print process. In the banded roll assignment, the intention is to identify the anilox roll that provides a tone reproduction curve near a one-to-one input dot-to-output dot coverage ratio.

For this assignment, the substrate and procedures were standardized, so the Nix data presented in Figure 3 represents a collection of density values (total 60 submissions) by students in both Fall 2020 and Spring 2021. There was no significant difference between the data collected in each semester. The eXrite means were obtained by averaging five measurements taken on five different eXact devices by the instructors and six students in Spring 2021.

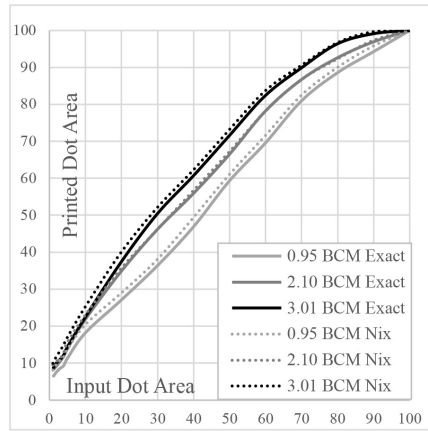
Figure 3 depicts tone reproduction curves from Nix's L*a*b* measurements, converted to densities. Figure 3a on the left shows an example of Nix's measurements in gray-filled circles that are plotted to the left of each vertical marker and eXact's in gray-filled squares that are plotted to the right of each vertical marker (Note that the symbols are semi-transparent – as the data points stack on top of each other, they overlap and darken). The example in Figure 3a is for the anilox band that carries 0.95 bcm/in² volume of ink (where bcm means billion of cubic microns). eXact data in Figure 3a in gray-filled squares are tightly super-positioned on each other, indicating consistent results from measurement to measurement. In contrast, the gray-filled circles of Nix data scattered over a 20%-30% range.

Figure 3b on the right replots the tone reproduction curve from the 0.95 bcm/in² band with the mean values from both Nix and eXact. Also included in Figure 3b are the tone reproduction curves from both the 2.01 bcm/in² and 3.01 bcm/in² anilox bands. Figure 3b shows that the tone reproduction curves from eXact underline the effects of increasing dot gains as the ink volume from the anilox band increases. The tone reproduction curves from Nix in Figure 3b also present a message that is consistent with that of the eXact. We do notice a statically significant difference by applying the student's t-test throughout the majority of the data points. Although data points are scattered and different from eXact, the Nix appears to be sufficient in differentiating the individual bands from one another and allowed the students to make expected recommendations.



b. Tone Reproduction Data and Average Curves for 0.95 bcm/in² Band

The data are scattered for Nix measurements (circles) compared to eExact (squares)



b. Tone Reproduction Average Curves .95bcm/in², 2.10 bcm/in² and 3.01bcm/in²

Averaged output dot areas to show the dot gain effect from increasing input ink volumes from anilox rolls

Figure 3: Tone Reproduction Data Captured Fall 2020 and Spring 2021

Conclusion

The work presented here supported the hypothesis that low-cost sensors can provide sufficient accuracy for virtual classroom use. The examples shown here for “visualizing color space” and “tone reproduction” illustrate that reasonable and consistent outcomes can be expected from the Nix for the curriculum cases. For example, Nix can provide data that allows students to grasp the L*a*b* model conceptually, and the converted CMYK density can show the overall trend to allow students to distinguish the effects of dot gain and ink film thickness. On the contrary, Nix does not perform with the accuracy and precision that is necessary in most color measurement environments outside the classroom. When high sensitivity is called for, Nix becomes ineffective in showing the differences in the prints, as it lacks the precision that standardized devices like the eXact provide. In conclusion, low-cost devices such as Nix can be utilized as a tool for most print evaluations in the online curriculum.

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