5-2022

Analysis of Low-Cost Color Sensor Device Performance as Compared to Standardized Spectrophotometers

Bethany Wheeler
bawheel@g.clemson.edu

ANALYSIS OF LOW-COST COLOR SENSOR DEVICE PERFORMANCE AS COMPARED TO STANDARDIZED SPECTROPHOTOMETERS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Graphic Communications

---

by
Bethany AnneMarie Wheeler
May, 2022

Accepted by:
Dr. Shu Chang, Committee Chair
Dr. Liam O'Hara
Dr. Nona Woolbright
Mr. Robert Congdon
Mr. Kern Cox

ABSTRACT

This work presents the process of assessing and selecting 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.

The initial testing and data collected 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. After initial success implementing a color sensor into the virtual classroom, further research was performed to evaluate the devices' ability to obtain repeat measurements (repeatability and reproducibility) and its accuracy (or ability to conform to accepted values for a given printed sample) using the MCDM (mean color difference form mean) and Zc (Z-score of color) methods for evaluating color difference.

In this research, the values collected using low-cost color sensors were compared to those from a standard device, X-Rite eXact. This work accepts the values collected by the X-Rite eXact as true and considers them to be accepted values for the given printed sample.

ACKNOWLEDGMENTS

Initially, I want to thank Dr. Chang for all of her guidance throughout my graduate school career. I owe a great deal of who I am today to the advice and encouragement she has provided me throughout this journey. I cannot imagine a better mentor, coworker, or friend. Thank you for acting as my academic compass and supporting me in my research endeavors.

To my other committee members, thank you all for the role you played in this process. I am incredibly grateful to have such a knowledgeable group of people to turn to at any point. The support you have given me from the very start has meant so much.

I would also like to thank Mr. John Seymour for his numerous correspondence. I am so appreciative for your time - for all of the meetings and emails, and for advising me throughout the statistical analysis process. I would have been lost without your aid.

To the Graphic Communications and Packaging Science students who enrolled in Inks and Substrates during Fall 20' and Spring 21', I commend your patience during the implementation of the Nix and value your efforts in assisting in the data collection.

Additionally, I am grateful for the original donation that X-Rite Pantone made in 2018 that allows us to provide students with hands-on experience using the eXact spectrophotometers in our labs. I would like to thank Nix Sensor Ltd and Variable, Inc for the support I received through conversations discussing technical specifications.

Lastly, to my friends and family, who were always there for me to celebrate when things were going well and to commiserate whenever I struggled. I'm so thankful for the friendships I've gained during my time at Clemson. Working and learning alongside you has made me a better person. Thank you from the bottom of my heart!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

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 suspend face-to-face classes in favor of offering courses exclusively online. This decision launched faculty into virtually delivering course content with no alternative. In a discipline such as graphic communications or printing, where hands-on interaction with tools and equipment is one of the main focuses of the curriculum, this sudden shift to online instruction presented a whole new set of challenges for instructors. When attending courses in a virtual classroom, students were limited to learning without the aid of software, machinery, and standardized devices typically employed to facilitate laboratory assignments. Illustrating the diverse set of concepts presented within the curriculum without the aid of these devices was a topic of great concern. Providing students with suitable alternatives to interact with at home was a primary objective when transitioning to online course delivery. This work aims to identify a measurement device that proves sufficient in illustrating classroom concepts within the pre-established graphic communication curriculum and to discuss the devices' ability to measure color when compared to a standardized device.

Measurement devices sampled in this work are classified as portable color sensors. They are affordable, with costs similar to textbooks, and are easy for students to acquire and use. 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 graphic communications curriculum.

Examples of these concepts include the following:

- Color – CIE $L^*a^*b^*$
- Color Difference – ΔE^*
- Solid Ink Density
- Tone Reproduction
- Whiteness and Opacity of Paper Substrates
- Color Balance
- Hue Error and Grayness of Process Color Inks
- Overprint Trapping

In the existing, in-person curriculum, the X-Rite eXact spectrophotometer is used as the standard instrument. As it is not feasible to provide every student with a standardized spectrophotometer for at-home use, an affordable substitute is essential for online learning. This work aims to identify a portable and affordable color measurement device for students to use in virtual classroom environments and to assess its feasibility with respect to class curriculum requirements. Additionally, this work will evaluate the ability of the selected device in terms of repeatability, reproducibility and accuracy as compared to the standard device, X-Rite eXact.

This paper presents the content according to the following categories: background, research objective, and methodology results with subcategories designated as initial evaluation, implementation in virtual classroom curriculum, and statistical evaluation of the devices repeatability, reproducibility, and accuracy of reporting CIE $L^*a^*b^*$ values compared to a standardized spectrophotometer.

CHAPTER TWO

BACKGROUND

Color Measurement Devices

Instrumental color measurement allows for objective data about color to be captured and recorded, and creates a common language that supersedes the limits of human perception and defines a descriptive vocabulary which facilitates color communication between industries all around the world (Phillips, 2020). Color measurement devices can be generally categorized into the following three categories: 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 given substrate, and spectrophotometers, which capture a set of reflection values that describe the reflectance of an object across the visible spectrum (Seymour, personal communication, August 2021). As demonstrated in Table 2.1, these devices each have their own way of describing the same color. Colorimeters and spectrophotometers are the two most advanced color measurement instrument types, both of which use sophisticated technologies to accurately and precisely quantify and define color (Phillips, 2020).

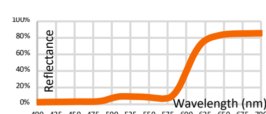
Colorimeters	Densitometers	Spectrophotometers
L* 50.62 a* 51.29 b* 49.48	C 0.26 M 1.05 Y 1.42 K 0.59	 Specular Reflectance
Colorimeters use XYZ filters to measure tri-stimulus values that are similar to the way humans perceive color.	Densitometers use RGB filters to measure CMYK densities by taking the negative log of the reflected light.	Spectrophotometers split the emitted light into thin bands and record the reflectance at 10-20nm intervals.

Table 2.1: Functionality and Data Collated by Colorimeters, Densitometers and Spectrophotometers

Colorimeters

Philips explains that colorimeters are designed to perform a type of psychophysical analysis of the sample, which means that the measurements correlate to human perception (2020). In the simplest form, colorimeters emit a known amount of light (at a fixed illuminant) and return a measurement of the light that is reflected back off of a given object. These devices use a set of three to four filters called tri-stimulus absorption filters to isolate specific wavelengths that are applied to the sample. The device then returns tri-stimulus values like X, Y, and Z to identify the color, with characters that represent the different dimensions of its visual appearance. Tri-stimulus values measure light intensity based on the three primary color values (red, green, and blue) and are typically represented by X, Y, and Z coordinates (Phillips, 2015). The tri-stimulus values supply the user a set of color data that can be easily converted into CIE $L^*a^*b^*$ and HLS models, which are intuitive models because of how closely they relate to the way humans perceive color. Both the Nix Mini 2 and the Color Muse device discussed in this paper are classified as colorimeters.

Densitometers

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. With the proper conversions, density values can also be obtained from other color measurement devices like colorimeters and spectrophotometers.

Spectrophotometers

Spectrophotometers offer even more complexity and can be used to achieve even more precision. This type of instrument uses a prism or a set of narrow filters to split the emitted light into thin bands that record the reflectance at certain intervals, typically every 10 or 20 nanometers. These wavelength-by-wavelength measurements produce precise data beyond that observable by the human eye and can be used to describe the sample's specular reflectance (Phillips, 2020). 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).

Color Measurement Device Application

These three types of devices share some similarities, but their ideal applications vary quite a bit. The biggest difference is the capability of the device to measure and describe color. For this reason, these devices do not all have the same end use. When tight color control is not necessary, colorimeters may be sufficient to capture color measurements and perform basic color evaluation. As such, they are useful for calibrating monitors and specifying colors for use in graphic design. Spectrophotometers are more comprehensive in their measurement, as they measure and provide color data on the entire spectrum (What Is A Colorimeter?, n.d.). When posed with the question: "Which color instrument is right for you?", Tim Mouw states:

> Colorimeters are a great way to capture color and do basic evaluation for applications that don't require tight color control. Since spectrophotometers measure the entire spectrum instead of just red, green and blue, they provide more accurate color data; making them useful for a broad range of applications in R&D, color formulation, and quality control (2019).

Colorimeters in Related Research

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 the Royal Horticultural Society (RHS) Colour Chart, and by Stiglitz and others to examine soil color relative to Munsell color codes. In research from Holman and Hopkins, the Nix Colour Sensor Pro was compared to the HunterLab MiniScan Spectrophotometer in its ability to assess the color stability of aged beef.

Analyzing Color Difference in CIE $L^*a^*b^*$

CIELAB is a three-dimensional color space based on the color opponent theory that is used to describe and order colors. This model describes a color in terms of its lightness (L^*) and the color's hue in terms of opponents sets of red/green (a^*) and yellow/blue (b^*). Every color is uniquely located within the color space by its position on the L^*, a^* and b^* axes, and can be described by a set of L^*, a^* and b^* coordinates (Berns, 2019; *Color Differences & Tolerances*, 2008; *Colorimetric Fundamentals*, 2008). There are several methods for analyzing color difference; ΔE^* is widely used in the print industry to calculate the difference in two single samples, Mean Color Difference from Mean (MCDM) is a method used to evaluate a data point when compared to the mean of the data set, and lastly, multivariate statistical methods that allow for joint analysis of inter-related variables like CIE $L^*a^*b^*$.

Color Difference - ΔE^*

Color difference, between any two colors in CIE $L^*a^*b^*$ color space, is the distance between the colors' locations and is usually expressed as ΔE^* (called Delta E). ΔE^* (total color difference) is calculated based on the three-dimensional change observed in L^*, a^*, and b^* axes. Changes for each axis can be expressed as ΔL^*, Δa^*, and Δb^*. ΔE^* is calculated based on the combined differences ΔL^*, Δa^*, and Δb^* and represents the distance of a line between the two colors (Gordon, 2022).

There are multiple ΔE^* formulas that can be used to calculate color difference. The ΔE^*_{ab} formula is a sum of squares equation developed by the International Commission on Illumination (CIE) in 1976 to describe the Euclidean distance between two unique points within the CIE $L^*a^*b^*$ color space (Berns, 2019; Schuessler, n.d.).

In many applications, the use of $L^*a^*b^*$ in conjunction with the ΔE^*_{ab} formula is limited by the non-uniformity of the color space. To address the fact that the desired perceptual uniformity of $L^*a^*b^*$ color space has not been realized, alternative ΔE^* formulas were developed (*Color Differences & Tolerances*, 2008). For example, ΔE^*_{94} was created to take into account certain weighting factors for each lightness, chroma, and hue value (Schuessler, n.d.). The weighting factors presented in ΔE^*_{94} did not adequately resolve the perceptual uniformity issue; therefore, the ΔE^*_{00} formula was developed to include an additional five corrections (*CIELAB ΔE* Color Difference*, 2020). ΔE^*_{00} is the current and most accurate color difference formula. In this research, both ΔE^*_{ab} and the ΔE^*_{00} formulas will be used.

Mean Color Difference from Mean (MCDM)

Mean Color Difference from Mean (MCDM) is explained thoroughly in Billmeyer and Satltzman's *Principles of Color Technology* (Berns, 2019). MCDM is a metric used to compare the mean ΔE^* of a group of CIE $L^*a^*b^*$ data points. To calculate the MCDM, mean L^*, a^*, and b^* values are obtained from the sample set. Then the distance, in ΔE, between each measurement and the mean for the sample set is obtained. The MCDM is then calculated by taking the mean of all ΔE^* values obtained throughout this process. This method can be applied to any of the ΔE^* color difference formulas. If the L^*, a^*, and b^* data within the sample set are normally distributed and uncorrelated, and they have the same standard deviation, the distribution in three-dimensional color space appears as a sphere where the value calculated for MCDM is the radius. However, if significantly different standard deviations within L^*, a^*, and b^* are observed, the MCDM will average the worst case and provide an exaggerated view of the precision of the data set (Nadal et al., 2011). Limitations for using this method as a measure of variability include poor approximation of elongated ellipsoids and the tendency for color differences to have a non-normal distribution (Berns, 2019). The MCDM method will be used in this research to evaluate the Nix device in terms of repeatability, the devices' ability to repeat identical measurements over short or long periods of time, and reproducibility, the devices' ability to obtain identical measurements when external variables are changed, such as the operator.

Multivariate Statistical Methods

According to Roy Berns in *Satltzman's Principles of Color Technology*, despite the limitations of using the MCDM, it is reasonable to continue to use MCDM as a measure of variability. However, alternative methods for evaluating color difference distributions are outlined by Nadal, Miller and Fairman to evaluate multi-valued measurements like specular reflectance or tri-stimulus values without reducing the data to a single-valued parameter (color difference). In *Statistical Methods for Analyzing Color Difference Distributions*, data was analyzed using a Chi-Square Distribution, Hoteling T^2 analysis, and a Resampling approach (using bootstrap). The research concluded that the MCMD approach did provide an "optimistic" evaluation of the results due to the naturally skewed distribution of color difference values and proposed that the resampling method should be used for multi-valued measurements.

Research on statistical process control of color by John Seymour poses that color difference (ΔE) and the MCDM process is inappropriate for statistical process control (2018). His paper details the deficiencies of using color difference for evaluating process control and introduces a method called "ellipsification" which is used to quantify a set of data points within a three-dimensional color space and allow for a Z-score (*Zc*) to describe the relationship of a group of values to the mean, or a target value. The *Zc* method that Seymour proposes is similar to the Hotelling's T^2 statistic. Both methods allow for multi-dimensional analysis and will lead to the same statistical conclusion. The major difference between the T^2 and the *Zc* is that the *Zc* results in linear units while the T^2 is in squared units (Seymour, 2018). As both methods will result in the same statistical inference, the *Zc* method will be used in this research to evaluate the accuracy of the Nix device or its ability to collect values that conform to "accepted" values for a given sample. Accepted values would traditionally be collected in a high-accuracy laboratory such as the national metrological institute. However, in this research, values collected with the X-Rite eXact will be considered "accepted" values.

CHAPTER THREE

RESEARCH OBJECTIVE

Areas of Interest

This study seeks to assess portable color sensor devices by addressing the following research questions:

- Can the low-cost sensor differentiate colors in the definition of $L^*a^*b^*$?
- 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 current Graphic Communications curriculum?
- To what extent can color sensors replicate measurements taken from standardized devices?

This study focuses on determining what the low-cost sensor can do and to what extent.

Objectives and Scope

The objective of this research is to test affordable color sensors and make recommendations on a specific make and model to be used in a virtual classroom setting when access to a standardized device is not feasible. Initially, the Color Muse and Nix Mini 2 Color sensors will be evaluated in terms of their ability to capture $L^*a^*b^*$ values like those collected with the X-Rite eXact. Following initial selection, the best performing device will be implemented into current Graphic Communications curriculum within Clemson Universities' GC 3460 Inks and Substrates course to aid in teaching color concepts and allow students to evaluate standard print metrics explored in the class.

Assuming the device performs with enough precision to adequately illustrate classroom concepts, a deeper analysis will be explored to evaluate the devices' ability to capture similar values to those obtained using the X-rite eXact.

Hypothesis

The hypothesis of this study is that one or more low-cost color sensors will exhibit sufficiency in the demonstration of colorimetric concepts, such as color specification within the $L^*a^*b^*$ color space and color difference (ΔE^*). In addition, the conversions of $L^*a^*b^*$ values to optical densities will be of sufficient accuracy to illustrate 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. However, it is hypothesized that these devices will not provide sufficient accuracy to meet industry standards for color evaluation in the field.

CHAPTER FOUR

METHODOLOGY

Initial Evaluation – Muse vs. Nix

Prior to introducing the devices into the curriculum, two low-cost sensors, the Color Muse, and Nix Mini 2, were examined. Both of the sensors tested represent the base model for each respective manufacturer. Brief device specifications for both the Color Muse and Nix Mini 2, as well as the X-Rite eXact Advanced, can be found in Table 4.1 (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	~$8350.00
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 4.1: Device Specifications for Color Muse, Nix Mini 2 and X-Rite eXact as Outlined in Published Technical Specifications by Respective Manufactures

Table 4.1 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 15 printed color samples including achromatic samples like paper white, black and neutral grey tones, solid ink patches of cyan, magenta, yellow, and black ("CMYK"), solid overprint combinations of red, green, and blue ("RGB"), and process color builds referred to here as purple, orange, slate, and lime. Refer to Appendix A for information on the printed target. Data for the initial analysis was collected by measuring a set of five sample prints using five unique devices of each model (see Appendix B).

Each device specifies fractional data to a different degree. The Color Muse, Nix and eXact all measure and report a different number of digits. Data collected with the eXact was measured using a tethered device, DataCatcher and Microsoft Excel (2019, 2022). This data collection process allowed for data to the ten-thousandths place (four digits) to be seamlessly collected without user intervention or human error recording the values. At this time, there is no software solution that would remove user intervention or alleviate human error when using the Muse or Nix Device. Data collected with these devices was obtained by pairing the Bluetooth color sensor device to the users' smart phone and measuring the sample with the appropriate smartphone app (*Color Muse*, 2021; *Nix Digital*, 2022). Values displayed within the app to the user were then input manually into Excel. Color Muse devices measure and report to the hundredths place (two decimals), while the Nix devices report values rounded to the nearest ones place or the nearest whole number.

The resulting 25 measurements were averaged to obtain a single $L^*a^*b^*$ data set per color patch to be analyzed for each model. Data collected with the Color Muse and Nix device was compared to that collected by the X-Rite eXact using the ΔE^*_{ab} and the ΔE^*_{00} formulas outlined in CIE 15:2004 (see Appendix C) (Commission Internationale de L'Eclairage, 2004). ΔE^*_{ab} calculations were performed by comparing the $L^*a^*b^*$ data obtained with each sensor to those with the eXact directly in Microsoft Excel, while ΔE^*_{00} were calculated using a macro developed by Doug Gray (see Appendix D) (2018).

Testing in Virtual Classroom Curriculum

Nix feasibility testing was implemented in six of the eight lab assignments throughout the Fall 2020 and Spring 2021 semesters. The concepts tested with Nix included visualizing the $L^*a^*b^*$ color 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. Other print evaluations required optical densities, which were obtained through conversion from $L^*a^*b^*$. Formulas used to calculate CMYK optical densities from $L^*a^*b^*$ data can be found in Appendix C.

Nix measurements were conducted by 46 students in the Fall 2020 semester and 38 students in the Spring 2021 semester, following instructions that can be found in Appendix E. The eXact measurements were collected by the researcher using DataCatcher and Microsoft Excel. This paper will focus on the two lab assignments that evaluate $L^*a^*b^*$ color space and tone reproduction as examples.

$L^*a^*b^*$ Color Space

"Getting Started with Colorimeters and $L^*a^*b^*$" is the introductory laboratory assignment that was developed to help students visualize the $L^*a^*b^*$ color space. The assignment was designed to prepare students to use the Nix device moving forward 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 4.1 was devised to present a simplified introduction of the $L^*a^*b^*$ concept. For more information on the printed test target, refer to Appendix A. The target consists of process-color inks (CMYK), overprint patches (RGB), a lightness scale, and a 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 fixed L^* value. The lightness scale L^* contains three levels of "neutral" grays built with cyan, magenta and yellow ink. Samples used to provide this data were produced on a Konica Minolta AccurioPress C3080 on the same paper stock in one run (per semester).

Figure 4.1: "Getting Started with Colorimeters and $L^*a^*b^*$" Test Target

In this assignment, students are provided with an Excel data template (see Appendix F) and a printed test target (Figure 4.1 and Appendix A). Students are instructed to install the Nix Digital smartphone app, pair the Nix device, and record the L^*, a^*, and b^* values for the instructed patches. The students then apply the 1976 ΔE^*_{ab} Formula 4.4 to calculate the color difference (ΔE^*_{ab}) between the measurements from their Nix device and a sample of data collected using an eXact provided by the instructors.

$\Delta L^* = L^*_1 - L^*_0$	$\Delta a^* = a^*_1 - a^*_0$	$\Delta b^* = b^*_1 - b^*_0$
Formula 4.1: Change in L^*	Formula 4.2: Change in a^*	Formula 4.3: Change in b^*

Formula 4.1-3: CIELAB L^* a^* b^* Differences

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

Formula 4.4: CIE 1976 ab Color Difference 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. Changes in ink coverage 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.

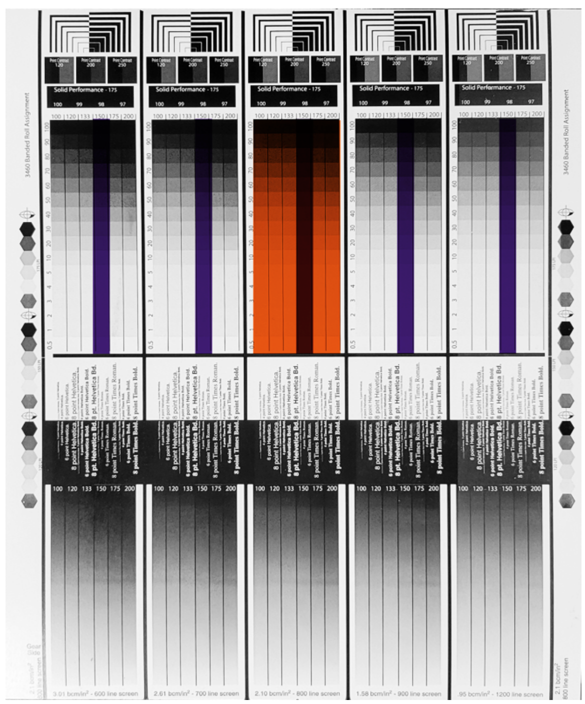


Figure 4.2: Banded Roll Test Target
All samples were produced in the same press run.

For this assignment, students are provided a printed flexography test sheet featured in Figure 4.2 and an Excel data template (see Appendix G). They are instructed to measure the tone scales highlighted in orange and purple to observe the impacts of ink film thickness and lines per inch (LPI) on the given substrate. The orange cells fall within the 2.10 BCM/in^2 (billions of cubic microns per square inch area) band that features different printing resolutions of 100, 120, 133, 150, 175, and 200 LPI, while the purple cells represent halftones produced at 150 LPI within each band containing cell volumes of 0.95, 1.58, 2.10, 2.61, and 3.01 BCM/in^2. Traditionally, the data template accepts dot area or tonal value measurements values collected with the eXact. For online instruction, the template was altered to accept $L^*a^*b^*$ values, convert them to CMYK density (using the formulas in Appendix C), subtract the density of the measured substrate, and apply Formula 4.5, the Murray-Davies Dot Area Formula, listed below. Students complete tone reproduction charts to visualize the impact of dot gain, and evaluate print contrast to make recommendations for which ink volume to use for the given substrate and press configuration.

$$Dot\ Area = \frac{1 - 10^{-Density_{tint}}}{1 - 10^{-Density_{solid}}}$$

Formula 4.5: Murray-Davies Dot Area Formula

Statistical Evaluation

Procedures for Data Collection Outlier Identification

The Nix data used for statistical evaluation was collected using the procedure outlined in Appendix E. To evaluate the repeatability and reproducibility, measurements were taken on both the white and black areas of a Leneta 3NT-31 sheet. Three users used the same device to take 20 sequential measurements on the black portion of a Leneta card without repositioning the device. The users then moved the device to the white portion of the Leneta card and took an additional 20 (sequential) measurements of the white area. To minimize the chance of imperfection or damage of the card impacting the data collection process, the first card was removed/discarded from the Leneta pad and the second sheet was measured. Leneta 3NT-31 sheets are not 100% opaque. To minimize the impacts of unwanted background colorants, the sheet was measured on top of the remaining sheets in the pad.

When measuring the values used to assess the accuracy of the device, each of the 10 devices were used to measure 10 sheets of the test target outlined in Appendix A. 15 measurements were taken for each of the 10 sheets. Color samples were measured in the following order: paper, cyan, magenta, yellow, red, green, blue, black, light (grey), medium (grey), dark (grey), orange, purple, slate, and lime for sheets 1 through 10 sequentially. A similar process was used to collect the eXact data. As previously mentioned in the initial evaluation section, Nix data was collected (to the nearest whole number) using Nix Digital, the accompanying smartphone app, and eXact Data was collected (to the fourth decimal place) using DataCatcher and Excel. Data was manually transferred from the Nix Digital app into Excel.

After collecting the data, statistical parameters including sample size (n), population mean (μ), standard deviation (σ), minimum/maximum value and range were computed. Additionally, the QUARTILE function in Excel was used to determine the first (Q1) and third (Q3) quartiles, and the difference (Q3-Q1) was taken to provide the interquartile range (IQR). Outliers are values that stray an abnormal distance from other values in the dataset. The L^* a^* and b^* values were evaluated as independent datasets and outliers were identified and highlighted using conditional formatting. Data points were considered to be outliers if they were < *Q1 - (1.5*IQR)* or > *Q3 + (1.5*IRQ)* for L^*, a^*, and b^* independently. Numerous outliers were identified and considered but were ultimately included as part of the data set in hopes of representing the true behavior of the devices. When evaluating the color data captured with the Nix Mini 2 devices, the Nix Device 2 (id: 763F) was determined to be dysfunctional because 191 of the 450 values (or 42.44% of the data points) collected with that specific device were considered to be outliers of the population collected with the Nix devices as a whole. Data collected with Device 2 was retained but excluded from further calculations. Another trend that became evident during the process of identifying outliers within the data was discrepancies in print variation of test target sheet nine. These discrepancies were not evident within the dataset collected with the Nix but became apparent in the measurements collected with the eXact. All data collected for sheet nine was retained but removed from both the Nix and eXact datasets moving forward.

Mean Color Difference from Mean (MCDM)

When evaluating the data using the MCDM method, the mean value of L^*, a^* and b^* coordinates were obtained separately. The MCDM Formula (Formula 4.6) was then applied to obtain a MCDM value for each device as compared to the mean value collected by that device and the mean value collected by all of the Nix devices, where the subscript i represents the i^{th} measurement, $\overline{L^*}$, $\overline{a^*}$, and $\overline{b^*}$ are the average CIE L^*, a^*, and

b^* coordinates of the data set, and *N* in the number of samples (Berns, 2019; Nadal et al., 2011).

$$MCDM\ \Delta E^*_{ab} = \frac{\sum_i \sqrt{(L^*_i - \overline{L^*})^2 + (a^*_i - \overline{a^*})^2 + (b^*_i - \overline{b^*})^2}}{n}$$

Formula 4.6: Mean Color Difference from Mean (MCDM)

Zc Multivariate Statistics

To statistically evaluate the accuracy of the Nix device, an Excel template provided by John Seymour was employed to obtain the Zc scores used to determine the probability that the device will be able to capture the "accepted" values collected with the X-Rite eXact for each color. The template accepts a set of CIE $L^*a^*b^*$ coordinates, calculates the mean L^*, a^*, and b^* values ($\overline{L^*}$, $\overline{a^*}$, and $\overline{b^*}$), and determines ΔL^*, Δa^*, and Δb^* for each measurement compared to the mean of the data set using Formulas 4.1-3 (Seymour, personal communication, July 2020). The template then calculates a covariance matrix that describes the covariance between each pair of elements of a given random vector and an inverse covariance matrix which is used to calculate the Zc of each datapoint. The Zc scores describe the number of three-dimensional standard deviations between the datapoint and the mean datapoint. The Zc scores are then used to identify outliers or datapoints that do not belong within the data set. Data points with Zc scores ≥ 4 were removed from the data set for further calculations as a $Zc \geq 4$ indicates a probability (P(Zc)) of .99 that the data point falls within the data set. Lastly, the template accepts a target CIE $L^*a^*b^*$ value and calculates a Zc score that describes the probability that the target value lies within the dataset being evaluated.

CHAPTER FIVE

RESULTS AND DISCUSSION

Initial Evaluation – Muse vs. Nix

The 15 measurements and ΔE^* values reported in Table 5.1 indicated that both low-cost sensors showed significant color differences with respect to the eXact. The data collected indicates that the Color Muse differed from eXact by 6.0 ΔE^*_{ab} and Nix by 3.1 ΔE^*_{ab}. As indicated in Table 5.1, the color differences between Nix and eXact appeared smaller for most of the six colors sampled.

Color Sample	Color Muse ΔE^*_{ab}	Nix Mini 2 ΔE^*_{ab}	Color Muse ΔE^*_{00}	Nix Mini 2 ΔE^*_{00}
Paper White	4.8	4.4	3.5	4.2
Black	5.8	1.6	2.1	1.2
Light Grey	12.2	2.5	3.3	1.5
Medium Grey	5.6	3.9	2.8	1.2
Dark Grey	12.0	3.0	3.3	1.4
Cyan	8.4	3.0	2.7	1.5
Magenta	8.3	4.0	3.2	1.8
Yellow	5.4	5.2	3.7	4.7
Red	3.8	3.4	3.2	3.2
Green	2.1	2.1	2.3	2.0
Blue	2.6	2.9	2.4	2.5
Orange	6.1	3.8	2.7	1.3
Purple	4.9	1.8	1.8	1.5
Slate	3.4	1.3	1.5	1.2
Lime	4.4	3.7	2.4	1.6
Mean	**6.0**	**3.1**	**2.7**	**2.1**

Table 5.1: Color Differences of CIE L*a*b* Data Collected with Color Muse and Nix Compared to X-Rite eXact in ΔE^*_{ab} and ΔE^*_{00}

Since these low-cost sensors perform the functions of a colorimeter, only $L^*a^*b^*$ data was 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^*_{ab} than the Color

Muse. While the initial tests showed promising results that led to device implementation in the classroom environment, the ΔE^* values recorded would not meet the tolerance needs of most production environments, where tolerances may be 4.0 ΔE^*_{ab} or 2,0 to 3.0 ΔE^*_{00} It is generally considered that instrument error should not use more than 30% of the tolerance window (Seymour, personal communication, February 2021).

Virtual Classroom Testing Outcome

$L^*a^*b^*$ Color Space

Figure 5.1 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 5.1 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 5.1) 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.

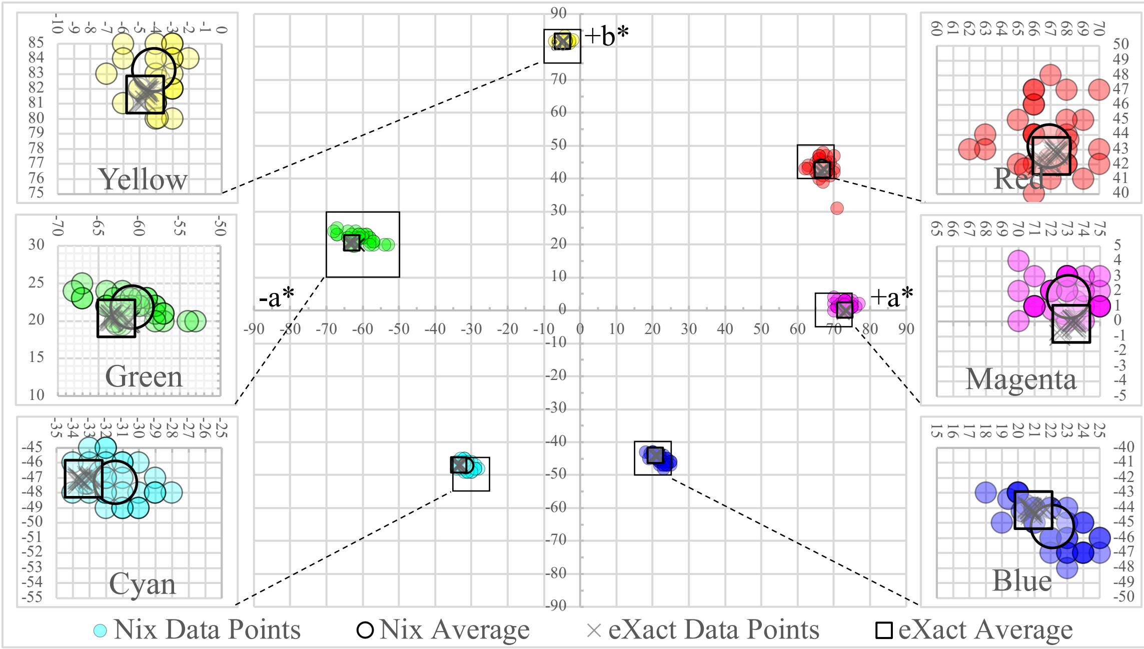


Figure 5.1: Comparing Nix a*b* values (semi-transparent colored circles) to eXact (×'s) The enlargements associated with each color show more significant variations from Nix data.

The enlargements shown in Figure 5.1 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 eXact. Figure 5.1 also highlights the smaller variation of eXact than Nix, as the × data points from eXact are tighter than those from the Nix data.

Table 5.2 presents a statistical comparison between Nix and eXact. Table 5.2 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 eXact 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 eXact 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 eXact data.

Spring 2021 Nix (34 independent sets) eXact (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
eXact	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 5.2: Statistical Analysis of Nix Compared to eXact

Close observation of the table reveals that for all CMYRGB and L* sampled, Nix consistently attains larger standard deviations and range of values than eXact. For example, while eXact measurements produce standard deviations in the fractional values, Nix's standard deviations are all greater than one. This is particularly alarming for the color green, where Nix a^* value 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 5.1. Similar observations of other colors also highlight the eXact's superior performance over Nix.

The two-sample t-test compares the mean values of Nix and eXact. 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 eXact are proven to be statistically different.

For the concept demonstration, however, students can assimilate the basic concept of the $L^*a^*b^*$ color space by exploring the colors presented in the printed patches on the test target (Figure 5.1). 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 are insignificant towards the demonstration of CIE $L^*a^*b^*$ concepts.

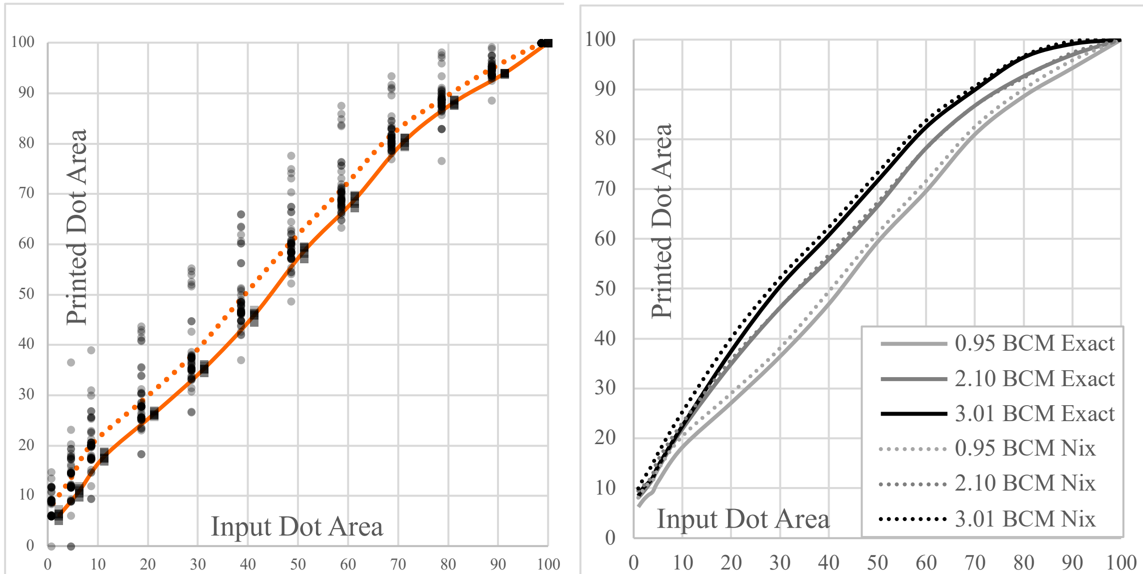
Tone Reproduction

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 5.2 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 eXact means were obtained by averaging five measurements taken on five different eXact devices by the instructors and six students in Spring 2021.

Figure 5.2 depicts tone reproduction curves from Nix's $L^*a^*b^*$ measurements, converted to densities. Figure 5.2a 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 5.2a is for the anilox band that carries 0.95 BCM/in^2 volume of ink (where BCM means billion of cubic microns). eXact data in Figure 5.2a where 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 5.2b on the right replots the tone reproduction curve from the 0.95 BCM/in^2 band with the mean values from both Nix and eXact. Also included in Figure 5.2b are the tone reproduction curves from both the 2.01 BCM/in^2 and 3.01 BCM/in^2 anilox bands. Figure 5.2b 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 5.2b also present a message that is consistent with that of the eXact. We do notice a statistically 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.



a. Tone Reproduction Data and Average Curves for 0.95 BCM/in^2 Band

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

b. Tone Reproduction Average Curves .95BCM/in^2, 2.10 BCM/in^2 and 3.01BCM/in^2

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

Figure 5.2: Tone Reproduction Data Captured Fall 2020 and Spring 2021

Statistical Evaluation

In hopes of better understating the how the Nix device functions, statistical evaluation was performed in hopes of providing quantifiable data to evaluate the devices' precision in terms of repeatability and reproducibility using the MCDM method and the accuracy the device provides using the *Zc* method.

Repeatability

Repeatability is a term used to describe the device's ability to repeat multiple identical measurements over a given period of time. In other words, it describes to what extent the device can replicate the measurements it takes, or its ability to make consistent measurements over time. Repeatability is often quantified in terms of short (seconds or minutes), medium (hours), or long periods (days, weeks or longer) of time between measurements (Berns, 2019). The data collected in this research was taken over a short period of time. The MCDM values found in this study are shown in Table 5.3. They are all very low and desirable, however this may misleading be primarily due to the fact that device reports only whole numbers. The rounding that occurs when using the Nix device can potentially over or underestimate the variability of the dataset. For example, you may notice that all of the black Nix readings for users two and three were the same resulting in a mean value that is identical to every data point collected within the data set and a MCDM of 0. This would likely not be the case if the device was reporting to even the first decimal place. The data presented in Table 5.3 shows that the repeatability of the eXact is superior to that of the Nix with an average MCDM of .03 ΔE^*_{ab} for black vs the .19 ΔE^*_{ab} obtained with the Nix. Measurements taken on the white sample area also support this trend with MCDM values of .04 ΔE^*_{ab} and .13 ΔE^*_{ab} for eXact and Nix respectively.

User	**Black**		**White**	
	Nix MCDM	**eXact MCDM**	**Nix MCDM**	**eXact MCDM**
1	.56	.03	0	.03
2	0	.02	.38	.03
3	0	.04	0	.05
Mean	**.19**	**.03**	**.13**	**.04**

Table 5.3: Repeatability MCDM values (in ΔE^*_{ab}) for CIE L* a* b* Taken by Three Users on One Device

Reproducibility

Reproducibility is a term used to describe a device's ability to take consistent readings when some aspect of the measurement condition has changed. Reproducibility is often tested by changing operator or instrument. In other words, reproducibility describes the device's ability to repeat identical measurements when conditions do not remain the same (Berns, 2019). The same 60 measurements utilized to examine repeatability are used to obtain the device reproducibility. However, at this point, the MCDM is calculated using each data point and the mean value of the entire data set (comprised of measurements taken by all three users). Table 5.4 presents the data collected to gauge the reproducibility amongst various (3) users. The data shows once again that the eXact exhibits better performance in terms of being able to reproduce identical measurements provided a change in user has occurred. The values presented here are once again impacted due to the measurement reporting limitations of the Nix device. The MCDM values posed by the Nix would presumably increase if the device reported more significant figures. The values shown in Table 5.4 illustrate the advantage of using the eXact over the Nix. When changing the user in a measurement condition, the eXact was able to reproduce measurements within a 0.18 ΔE^*_{ab} for black samples and 0.10 ΔE^*_{ab} for white samples while the Nix measurements varied in 1.23 ΔE^*_{ab} for black and 0.67 ΔE^*_{ab} for white. The Nix reproducibility values are of concern because they indicate that the same exact device when used by different users could produce two distinct values with color difference greater than one ΔE^*_{ab}.

User	Black		White	
	Nix MCDM	eXact MCDM	Nix MCDM	eXact MCDM
1	1.87	.23	.67	.08
2	.97	.24	.81	.13
3	1.13	.06	.53	.08
Mean	**1.32**	**.18**	**.67**	**.10**

Table 5.4: Reproducibility MCDM values (in ΔE^*_{ab}) for CIE L* a* b* taken by three users on one device

Accuracy

When examining the accuracy of the Nix device, the Zc (Z-score of color) method developed by John Seymour was employed. Similar to the traditional Z score, the Zc is a measure that describes the relationship between a data point and the mean of a group of values. More specifically, Zc represents the normalized three-dimensional standard deviation between two values, or between a set of values and a target value. The null hypothesis in this type of multivariant analysis states that the target value can be found within the dataset. Similar to a traditional Z score, Zc can be used with a set of significance levels used to understand the probability that the value in question belongs in the dataset, assuming that the dataset has a trivariate normal variation the Zc score will have a chi distribution with three degrees of freedom (Seymour, 2018).

Before applying the Zc to evaluate the set of 100 Nix values relative to the mean value obtained with the eXact, a Zc score was calculated using each of the Nix data points and the mean value of the data set. Single data points were removed if the Zc was > 4 when compared to the mean value, as a Zc greater than four indicates a 0.10% chance of observing that value within the sample population.

Table 5.5 presents the data used to evaluate the Nix's ability to capture accepted values. Please note that outliers were removed from the color patches labeled with an asterisk. When looking at the data in the Zc column, it is clear the mean value collected with the eXact varies from the values collected in the Nix data set. The Zc values listed describe the number of standard deviations the target value differs from the mean values of the data set. The P(Zc) values in Table 5.5 represent the probability that the target value belongs to a population that is statistically different than that of the Nix data set while the values found in the chance column describe the chance of attaining the target value within the data set.

Color Sample	**eXact Mean (Target)** $\overline{L^*}$	$\overline{a^*}$	$\overline{b^*}$	**Nix Mean** $\overline{L^*}$	$\overline{a^*}$	$\overline{b^*}$	**Standard Deviation** σL^*	σa^*	σb^*	**Zc**	**P(Zc)**	**Chance**
Paper	94.69	0.69	-1.57	93.1	-0.2	2.1	1.15	0.58	1.49	4.64	> 0.999	< 0.1%
Black	15.80	-0.32	-0.28	12.2	2.3	-1.7	1.85	3.35	1.90	2.84	0.98	2.0%
Light*	78.83	3.48	0.39	77.5	2.8	3.1	0.89	0.81	1.34	3.25	0.99	1.0%
Medium	50.31	2.74	-1.19	48.8	2.8	0.0	0.79	1.30	1.01	3.18	0.99	1.0%
Dark	25.07	2.65	-0.89	22.6	4.4	-1.4	1.04	2.08	1.44	3.76	1.00	0.2%
Cyan	52.12	-33.35	-47.13	51.0	-32.1	-47.8	0.55	1.80	1.09	3.00	0.98	2.0%
Magenta	47.13	73.29	-0.08	45.9	74.5	1.3	0.64	1.71	1.26	2.27	0.90	10.0%
Yellow	87.54	-4.72	82.16	86.1	-4.0	85.2	0.97	1.18	2.29	2.92	0.98	2.0%
Red	47.10	67.05	42.58	46.0	68.7	43.9	0.62	2.48	3.62	2.09	0.90	10.0%
Green	50.31	-63.32	19.80	49.4	-61.8	22.1	0.68	4.16	1.89	3.00	0.98	2.0%
Blue*	25.09	21.18	-44.03	23.4	23.9	-45.8	1.31	1.13	1.22	2.47	0.90	10.0%
Orange	70.33	22.96	61.91	69.0	24.0	64.9	0.83	1.66	2.60	2.52	0.95	5.0%
Purple*	40.85	39.08	-25.78	39.1	39.8	-25.4	0.84	1.45	0.77	2.38	0.90	10.0%
Slate*	43.75	-19.41	-26.64	42.5	-19.2	-26.7	0.66	1.70	0.64	2.35	0.90	10.0%
Lime	67.74	-32.86	50.88	66.6	-32.03	-54.05	0.75	1.88	1.94	3.44	0.99	0.5%
Mean										**2.94**		**> 2%** **< 5%**

Table 5.5: Accuracy Zc Scores Probability and Chance for 15 CIE L^* a^* b^* Color Samples

While some of the color samples evaluated in this research perform better than others, we see that in the best case scenario, (for magenta, red, blue, purple and slate) there is a 10% chance that the data cloud of Nix data will contain the accepted target value obtained with the eXact; meaning there is a 90% chance that that value belongs in a statistically different population. In other words, the user would have to take 10 measurements before the Nix would report the accepted value for a particular color sample. Based on the Zc scores, probability and chance observed in this research, the Nix devices have been found to provide statistically different CIE L^* a^* b^* values. The Nix devices do not provide the accuracy needed to conform to the accepted values attained with the eXact in this research.

CHAPTER SIX

CONCLUSION

The work presented here supported the hypothesis that low-cost sensors can provide sufficient accuracy for virtual classroom use but do not function with the precision needed to be implemented in an industry setting where tight color tolerance is needed. 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 a printed sample. In contrast, when statistically evaluated using the MCDM method and Zc scores to evaluate the devices in terms of repeatability, reproducibility and accuracy, the Nix does not perform with the precision that is necessary in most color measurement environments outside the classroom. When high sensitivity is called for, the Nix becomes ineffective in recording accepted values and showing subtle differences in the prints, as it lacks the precision that standardized devices like the eXact provide. In conclusion, low-cost color sensor devices such as the Nix Mini 2 can be utilized as a teaching tool for most print evaluations in online curriculum, but they should not be used for practical color evaluation or process control.

This methodology could be repeated to evaluate similar devices. Future research should be performed to outline best practice procedures for implementing color sensors into Graphic Communications curriculum and for use in industry training purposes.

Additional research to better understand the tolerance to witch these devices can detect changes in color or ink film thickness is necessary.

REFRENCES

Berns, R. S. (2019). *Billmeyer and Saltzman's Principles of Color Technology* (4th ed.). Wiley.

CIELAB ΔE Color Difference*. (2020, February 1). 3nhcolor.com. 3nhcolor.com/news/161-877.html

Color calculations in Excel - rgbcmyk. (n.d.). Rgbcmyk.com. rgbcmyk.com.ar/en/xla-2/

Color Differences & Tolerances. (2008, June 1). Datacolor.com. industrial.datacolor.com/support/wp-content/uploads/2013/01/Color-Differences-Tolerances.pdf

Color Math and Programming Code Examples. (n.d.). Easy RGB. Retrieved August 20, 2020, from easyrgb.com/en/math.php

Color Muse (11.2.5-min-api-21-null). (2021). [Mobile app]. Variable, Inc. colormuse.io/color-muse.html

Colorimetric Fundamentals. (2008, June 1). Datacolor.com. knowledgebase.datacolor.com/admin/attachments/color_fundamentals_part_ii.pdf

Commission Internationale de L'Eclairag. (2004). *CIE 015:2004: Colorimetry* (3rd ed.). Commission Internationale de L'Eclairag.

Compare Variable Color Sensors | Mobile Colorimeters and Spectrophotometers. (2020, November 2). Colormuse.Io. colormuse.io/compare.html

DataCatcher for Mac (1.3 3806). (2019). [Computer Software]. X-Rite. xrite.com/service-support/downloads/d/datacatcher-for-mac-v1_3_3806

eXact™ Advanced Handheld Spectro | X-Rite. (n.d.). Xrite.com. Retrieved November 2020, from xrite.com/categories/portable-spectrophotometers/exact-advanced

Gordon. (2022, January). *Brief Explanation of delta E or delta E**. Hunterlab.com. support.hunterlab.com/hc/en-us/articles/203023559-Brief-Explanation-of-delta-E-or-delta-E-

Gottenbos, R. (2017, February). *Yes, they arrived: cheap affordable ways to measure color! – CTC – Color Technology Consultancy*. Coltechcon.com. coltechcon.com/publication/yes-they-arrived-cheap-affordable-ways-to-measure-color-an-explanation/

Gray, D. (2018, June 18). *Excel VBA code to calculate delta E 2000* [Online Forum]. Forum.Luminous-Landscape.com. forum.luminous-landscape.com/index.php?topic=125397.0

Holman, B. W., & Hopkins, D. L. (2019). A comparison of the Nix Colour Sensor Pro™ and HunterLab MiniScan™ colorimetric instruments when assessing aged beef colour stability over 72 h display. *Meat Science*, *147*, 162–165. doi.org/10.1016/j.meatsci.2018.09.009

Kirchner, E., Koeckhoven, P., & Sivakumar, K. (2019). Predicting the performance of low-cost color instruments for color identification. *Journal of the Optical Society of America A*, *36*(3), 368–376. doi.org/10.1364/josaa.36.000368

Lakacha, A. (2013, May 7). *A Functional Comparison of the Densitometer and Spectrophotometer – Densitometers for Print and Packaging | Techkon USA*. Techkonusa.com. Retrieved June 2021, from techkonusa.com/a-functional-comparison-of-the-densitometer-and-spectrophotometer/

Lindbloom, B. (2017, April 8). *Bruce Lindbloom's Web Site*. Brucelindbloom.com.
Spectrophotometers
brucelindbloom.com/index.html?Eqn_DeltaE_CIE2000.html

Microsoft Excel for Mac (16.58 (22021501)). (2022). [Computer software]. Microsoft. microsoft.com/en-us/microsoft-365/excel

Mouw, T. (2019a, October 7). *Colorimeter vs. Spectrophotometer*. X-Rite. xrite.com/blog/colorimeter-vs-spectrophotometer

Mouw, T. (2019b, October 7). *What Is A Colorimeter? | Colorimeter vs. Spectro*. Xrite.com. xrite.com/blog/colorimeter-vs-spectrophotometer

Myers, B. (2021, June 20). *What is a SpectroDensitometer? – Densitometers for Print and Packaging | Techkon USA*. Techkonusa.com/. Retrieved June 2021, from techkonusa.com/what-is-a-spectrodensitometer/

Nadal, M. E., Cameron Miller, C., & Fairman, H. S. (2011). Statistical methods for analyzing color difference distributions. *Color Research & Application*, *36*(3), 160–168. doi.org/10.1002/col.20622

Nix Digital (1.7.2). (2022). [Mobile app]. Nix Sensor Ltd. nixsensor.com/apps/

Nix Sensor Ltd. (n.d.). *Nix Device Comparison*. Retrieved November 2020, from nixsensor.com/compare-nix/#1519315093017-f21bfe20-6786

Phillips, K. (2015, January 7). *Understanding Tristimulus Values & The CIE Color System*. Color Measurement Blogs. blog.hunterlab.com/blog/color-measurement/understanding-tristimulus-values-taking-guesswork-color-measurement-instrumentation

Phillips, K. (2020, August 6). *Spectrophotometer vs. Colorimeter: What's the Difference?* Color and Appearance Theory Blogs. blog.hunterlab.com/blog/color-and-appearance-theory/spectrophotometer-vs-colorimeter-whats-the-difference/

Post, P., & Schlautman, M. (2020a). Measuring Camellia Petal Color Using a Portable Color Sensor. *Horticulturae*, *6*(3), 53. doi.org/10.3390/horticulturae6030053

Post, P., & Schlautman, M. (2020b). Measuring Camellia Petal Color Using a Portable Color Sensor. *Horticulturae*, *6*(3), 53. doi.org/10.3390/horticulturae6030053

Schuessler, Z. (n.d.). *Delta E 101*. Zschuessler.Github.Io/. zschuessler.github.io/DeltaE/learn/

Seymour, J. (2017, July 13). *Of colorimeters and spectrophotometers*. John the Math Guy. johnthemathguy.blogspot.com/2017/07/of-colorimeters-and-spectrophotometers.html

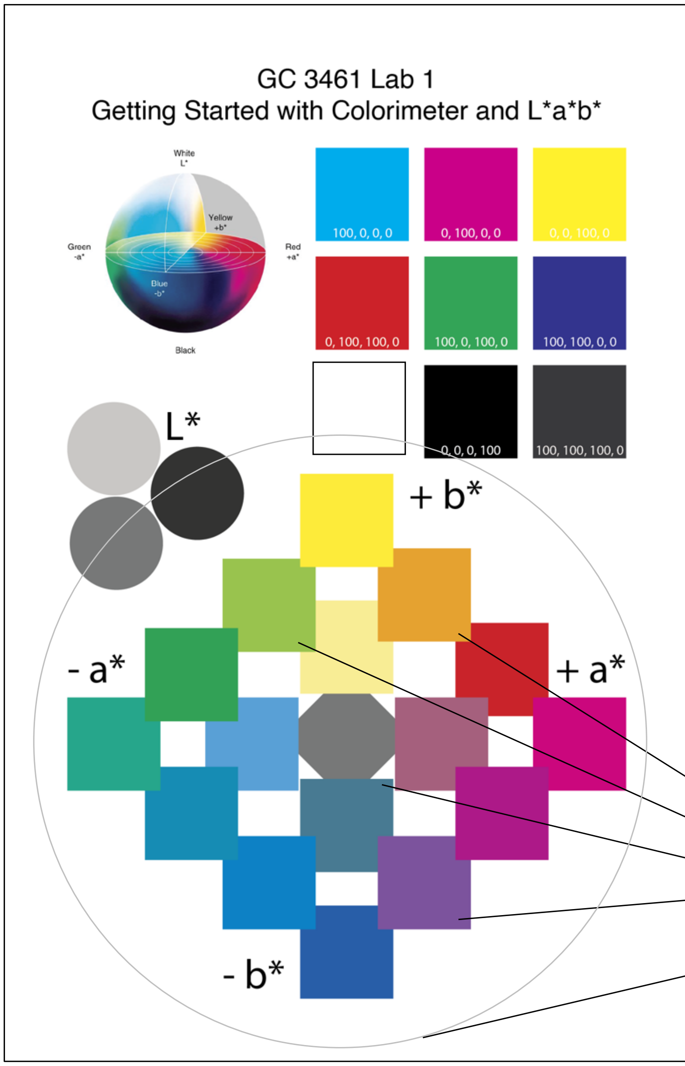
Seymour, J. (2018, March). *Statistical process control of color*. Technical Association of the Graphic Arts, Baltimore, MD. researchgate.net/publication/337632399_Statistical_process_control_of_color/references#fullTextFileContent

What Is A Colorimeter? (n.d.). X-Rite. xrite.com/learning-color-education/other-resources/what-is-a-colorimeter

APPENDICES

Appendix A

"Getting Started with Colorimeters and $L^*a^*b^*$" Test Target



	C	M	Y	K
Cyan	100	0	0	0
Magenta	0	100	0	0
Yellow	0	0	100	0
Red	0	100	100	0
Green	100	0	100	0
Blue	100	100	0	0
Paper White	0	0	0	0
Black	0	0	0	100
Process Black	100	100	100	0
Light Grey	20	17	18	0
Medium Grey	55	46	46	11
Dark Grey	70	64	63	61
Orange	0	41	100	0
Lime	53	0	100	0
Slate	84	36	29	10
Purple	53	8	0	0

Pseudo-CIE $L^*a^*b^*$ cross-section

Appendix B

Measurements taken with Color Muse and Nix Mini 2 as compared to X-Rite eXact

Sample	**eXact**			**Color Muse**							
	L^*	a^*	b^*	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE^*ab	ΔE^*00
Paper	94.6	0.69	-1.4	90.4	-0.1	0.79	-4.2	-0.7	2.23	4.8	3.5
Cyan	52.1	-33	-47	50.8	-31	-42	-1.4	2.36	5.17	5.8	2.1
Magenta	47.1	73.3	0.03	45.8	61.3	1.1	-1.3	-12	1.07	12.2	3.3
Yellow	87.6	-4.8	82.1	83.6	-4.4	78.2	-4	0.41	-3.9	5.6	2.8
Red	47.2	66.9	42.7	45.8	58.3	34.5	-1.4	-8.6	-8.2	12.0	3.3
Green	50.5	-63	19.9	49.2	-54	19.4	-1.2	8.32	-0.5	8.4	2.7
Blue	25.2	21.1	-44	27.9	17.4	-37	2.67	-3.7	7	8.3	3.2
Black	15.4	-0.3	-0.3	20.8	-0.7	-1.1	5.36	-0.4	-0.8	5.4	3.7
Light	78.9	3.48	0.52	75.7	2.4	2.23	-3.2	-1.1	1.71	3.8	3.2
Medium	50.6	2.83	-0.9	48.8	1.79	-0.2	-1.8	-1	0.62	2.1	2.3
Dark	25.1	2.71	-0.8	27.4	1.44	-0.7	2.31	-1.3	0.18	2.6	2.4
Orange	70.5	22.5	62.3	67.6	20.2	57.5	-2.9	-2.4	-4.8	6.1	2.7
Purple	40.9	39.1	-26	40.1	35.2	-23	-0.8	-3.9	2.79	4.9	1.8
Slate	43.8	-19	-27	43.2	-18	-24	-0.6	1.53	3	3.4	1.5
Lime	67.8	-33	51	65.2	-30	48.7	-2.6	2.64	-2.3	4.4	2.4
Mean							2.38	3.35	2.95	6.0	2.7

Sample	**eXact**			**Nix Mini 2**							
	L^*	a^*	b^*	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE^*ab	ΔE^*00
Paper	94.6	0.69	-1.4	92.9	-0.4	2.44	-1.7	-1	3.88	4.4	4.2
Cyan	52.1	-33	-47	51	-32	-48	-1.1	1.02	-0.6	1.6	1.2
Magenta	47.1	73.3	0.03	45.8	74.4	1.92	-1.3	1.11	1.89	2.5	1.5
Yellow	87.6	-4.8	82.1	86.1	-4.4	85.7	-1.5	0.36	3.61	3.9	1.2
Red	47.2	66.9	42.7	46.1	68	45.2	-1.1	1.18	2.51	3.0	1.4
Green	50.5	-63	19.9	49.6	-63	22.7	-0.8	0.1	2.84	3.0	1.5
Blue	25.2	21.1	-44	23.3	24	-46	-1.9	2.91	-2	4.0	1.8
Black	15.4	-0.3	-0.3	11.2	2.08	-2.1	-4.2	2.42	-1.8	5.2	4.7
Light	78.9	3.48	0.52	77.7	2.56	3.52	-1.2	-0.9	3	3.4	3.2
Medium	50.6	2.83	-0.9	49.1	2.64	0.56	-1.5	-0.2	1.43	2.1	2.0
Dark	25.1	2.71	-0.8	22.6	4.16	-1.3	-2.5	1.45	-0.4	2.9	2.5
Orange	70.5	22.5	62.3	69.3	23.2	65.8	-1.2	0.62	3.54	3.8	1.3
Purple	40.9	39.1	-26	39.3	39.8	-25	-1.6	0.72	0.41	1.8	1.5
Slate	43.8	-19	-27	42.4	-20	-27	-1.3	-0.1	0.11	1.3	1.2
Lime	67.8	-33	51	66.6	-33	54.5	-1.3	-0	3.51	3.7	1.6
Mean							1.61	0.95	2.1	3.1	2.1

Appendix C

Differences between two samples (subscripts 0 and I) are calculated as follows:

CIELAB lightness difference:

$$\Delta L^* = L_1^* - L_0^*$$
$$\Delta a^* = a_1^* - a_0^*$$
$$\Delta a^* = a_1^* - a_0^*$$

CIE Delta E 1976 a,b (CIELAB) colour difference, ΔE^*_{ab} between two color stimuli is calculated as the Euclidean distance between the points representing them in the space:

ΔE^*_{ab} Formula:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

CIE Delta E 2000 The color difference, or ΔE, between a sample color (L^2, a^2, b^2) and a reference color (L^1, a^1, b^1) is:

ΔE^*_{00} Formula:

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}$$

Where:

$$\overline{L}' = (L_1 + L_2)/2$$

$$C_1 = \sqrt{a_1^2 + b_1^2}$$

$$C_2 = \sqrt{a_2^2 + b_2^2}$$

$$\overline{C}' = (C_1 + C_2)/2$$

$$G = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{C}^7}{\overline{C}^7 + 25^7}}\right)$$

$$a_1' = a_1(1 + G)$$

$$a_2' = a_2(1 + G)$$

$$C_1' = \sqrt{{a'_1}^2 + b_1^2}$$

$$C_2' = \sqrt{{a'_1}^2 + b_2^2}$$

$$\overline{C}' = (C_1' + C_2')/2$$

$$h_1' = \begin{cases} arttan(b_1/a_2') & \text{if } \arctan(b_1/a_2') \geq 0 \\ arttan(b_1/a_2') + 360° & \text{otherwise} \end{cases}$$

$$h_2' = \begin{cases} arttan(b_2/a_2') & \text{if } \arctan(b_2/a_2') \geq 0 \\ arttan(b_2/a_2') + 360° & \text{otherwise} \end{cases}$$

$$\overline{H}' = \begin{cases} (h_1' + h_2' + 360°)/2 & \text{if } |h_1' - h_2'| > 180° \\ (h_1' + h_2')/2 & \text{otherwise} \end{cases}$$

$$T = 1 - 0.17\cos(\overline{H}' - 30°) + 0.24\cos(2\overline{H}') + 0.32\cos(3\overline{H}' + 6°) - 0.20\cos(4\overline{H}' + 63°)$$

$$\Delta h' = \begin{cases} h_2' - h_1' & \text{if } |h_2' - h_1'| \leq 180° \\ h_2' - h_1' + 360° & \text{eles if } |h_2' - h_1'| > 180° \text{ and } h_2' \leq h_1' \\ h_2' - h_1' - 360° & \text{otherwise} \end{cases}$$

$$\Delta L' = L_2 - L_1$$

$$\Delta C' = C_2' - C_1'$$

$$\Delta H' = 2\sqrt{C_1' C_2'}\sin(\Delta h'/2)$$

$$S_L = 1 + \frac{0.015\left(\overline{L'} - 50\right)^2}{\sqrt{20 + \left(\overline{L'} - 50\right)^2}}$$

$$S_C = 1 + 0.045\overline{C'}$$

$$S_H = 1 + 0.015\overline{C'}T$$

$$\Delta\theta = 30exp\left\{-\left(\frac{\overline{H}' - 275°}{25}\right)^2\right\}$$

$$R_C = 2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}}$$

$$R_T = -R_C\sin(2\Delta\theta)$$

$K_L = 1$ default

$K_C = 1$ default

$K_H = 1$ default

Appendix D

ΔE^*_{00} Microsoft Excel Macro Developed by Doug Gray

```
' call like this in Excel: where L1 is the L* value of patch1 and L2 is the L* values of patch2, etc.
' =deltaE2000(L1,a1,b1, L2,a2,b2)
' deltaE2000(80,0,90, 80,0,95) yields .9685 which shows dE00 compression at high saturation
Public Function deltaE2000(Lstd As Double, astd As Double, bstd As Double, Lsample As Double, asample As Double, bsample As Double)
    Pi = 4 * Atn(1)
    cabarithmean = (Sqr(astd ^ 2 + bstd ^ 2) + Sqr(asample ^ 2 + bsample ^ 2)) / 2
    G = 0.5 * (1 - Sqr(cabarithmean ^ 7 / (cabarithmean ^ 7 + 25 ^ 7)))
    'x = WorksheetFunction.Atan2(2, 3)
    apstd = (1 + G) * astd
    apsample = (1 + G) * asample

    Cpsample = Sqr(apsample ^ 2 + bsample ^ 2)
    Cpstd = Sqr(apstd ^ 2 + bstd ^ 2)
    Cpprod = Cpsample * Cpstd
    zcidx = Cpprod = 0
    hpstd = WorksheetFunction.Atan2(apstd + 0.00000000001, bstd)
    hpstd = hpstd - 2 * Pi * (hpstd < 0)

    If (Abs(apstd) + Abs(bstd) = 0) Then
        hpstd = 0
    End If

    hpsample = WorksheetFunction.Atan2(apsample + 0.000000001, bsample)

    hpsample = hpsample - 2 * Pi * (hpsample < 0)

    If (Abs(apsample) + Abs(bsample) = 0) Then
        hpsample = 0
    End If

    dL = (Lsample - Lstd)
    dC = Cpsample - Cpstd
    dhp = hpsample - hpstd
    dhp = dhp + 2 * Pi * (dhp > Pi)
    dhp = dhp - 2 * Pi * (dhp < (-Pi))

```

Continued…

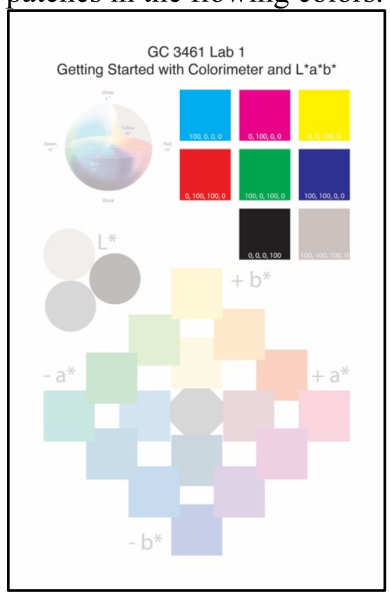
```
    If (zcidx) Then
        dhp = 0
    End If

    dH = 2 * Sqr(Cpprod) * Sin(dhp / 2)
    Lp = (Lsample + Lstd) / 2
    Cp = (Cpstd + Cpsample) / 2
    hp = (hpstd + hpsample) / 2
    hp = hp - (Abs(hpstd - hpsample) > Pi) * Pi
    hp = hp - (hp < 0) * 2 * Pi

    If (zcidx) Then
        hp = hpsample + hpstd
    End If

    Lpm502 = (Lp - 50) ^ 2
    Sl = 1 + 0.015 * Lpm502 / Sqr(20 + Lpm502)
    Sc = 1 + 0.045 * Cp

    Tx = 1 - 0.17 * Cos(hp - Pi / 6) + 0.24 * Cos(2 * hp) + 0.32 * Cos(3 * hp + Pi /
    30) - 0.2 * Cos(4 * hp - 63 * Pi / 180)
    Sh = 1 + 0.015 * Cp * Tx
    delthetarad = (30 * Pi / 180) * Exp(-(((180 / Pi * hp - 275) / 25) ^ 2))
    Rc = 2 * Sqr((Cp ^ 7) / (Cp ^ 7 + 25 ^ 7))

    RT = -Sin(2 * delthetarad) * Rc
    kl = 1
    kc = 1
    kh = 1
    klSl = kl * Sl
    kcSc = kc * Sc
    khSh = kh * Sh
    de00 = Sqr((dL / klSl) ^ 2 + (dC / kcSc) ^ 2 + (dH / khSh) ^ 2 + RT * (dC / kcSc)
    * (dH / khSh))
    deltaE2000 = de00
End Function
```

Appendix E

Student Procedure for Nix Data Collection

About

- You will be asked to use your Nix Mini 2 to record a total of 80 measurements.
- Recording the measurements should take a little over half an hour.
- The printed sample will resemble the image on the right (All extraneous patches have been lightened). The measurements will include patches in the flowing colors.
    - Cyan
    - Magenta
    - Yellow
    - Red
    - Green
    - Blue
    - Black
    - Paper White



- Ask for guidance on what set of data you will collect.
  Please provide personal preference if any.

Single Sheet

Students measuring a single sheet will record ten measurements for each of the selected color patches on the sheet.

Multiple Sheets

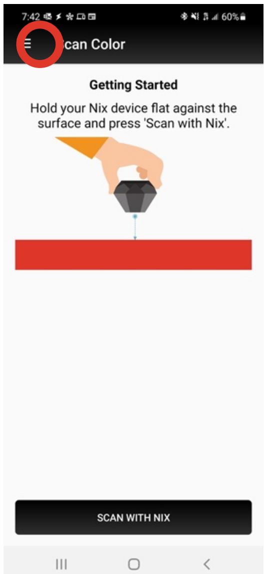
Students measuring multiple sheets will record one measurement for each of the selected color patches on ten unique sheets

Appendix E (Continued)

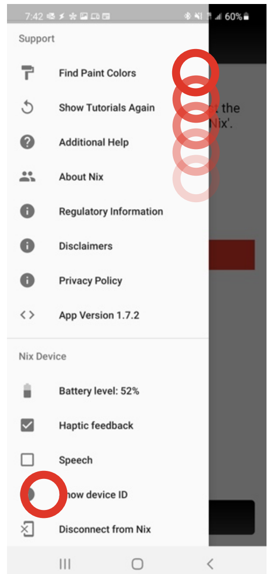
Procedures for Collecting Data

1. Open the Excel Spreadsheet
2. Insert your first and last name in the appropriate cells
   Optional - This will not be included in the research paper but will allow us to look at the data you previously collected and do some comparison
3. Launch the Nix Digital App and connect your phone to your Nix.
   If you need assistance, just ask.

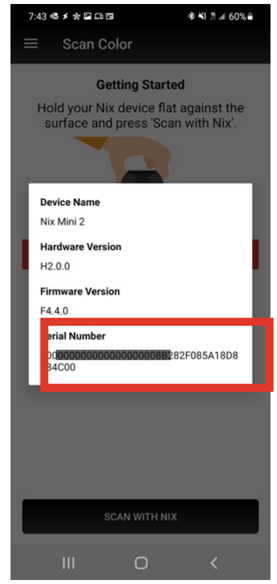
4. Record the Nix Device ID in the appropriate cell – Omit leading zeros



Click the menu icon in the top left of the screen.



Scroll up to view the bottom of the menu options. Then, click "Show device ID"



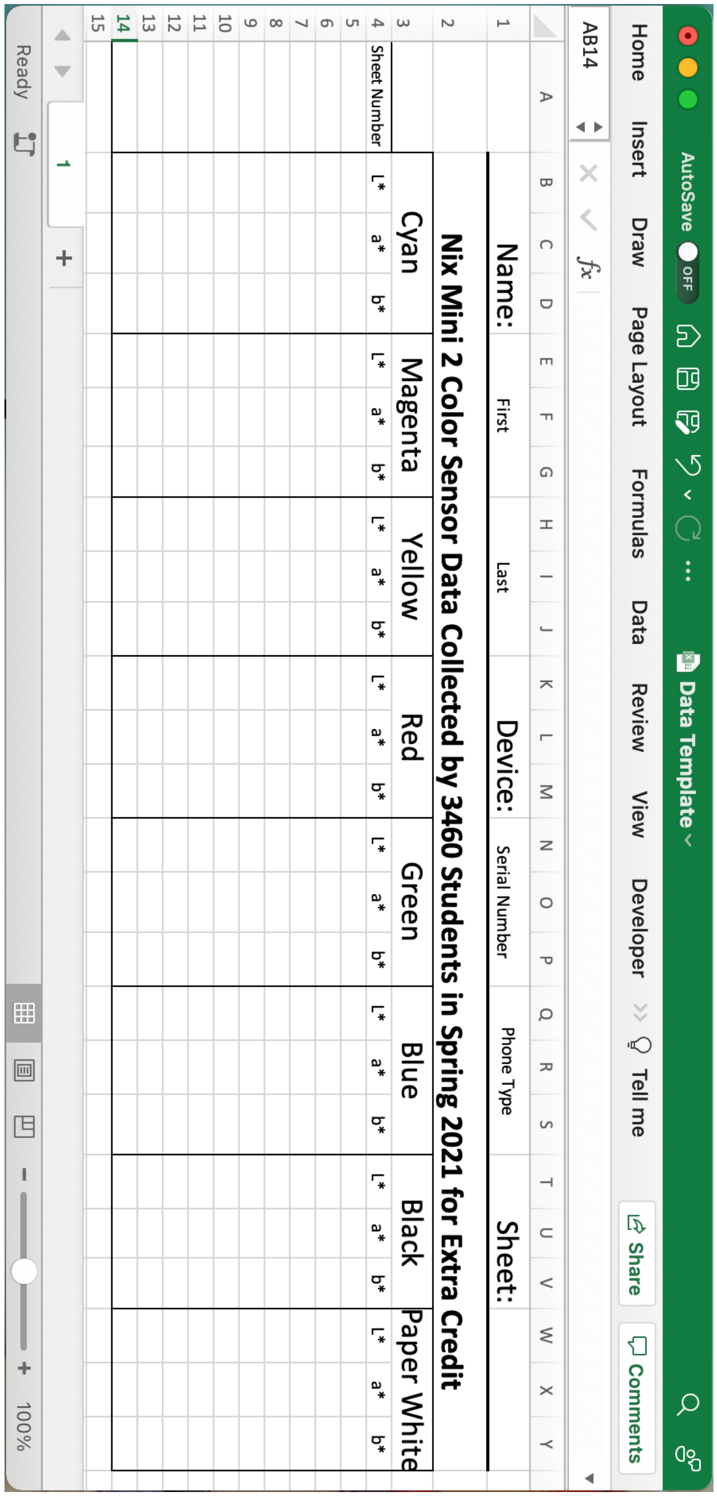
Record the Serial Number in the designated Excel Cell. Omit all leading zeros.

5. If you are measuring a single sheet, record the sheet number in the designated cell
6. If you are measuring multiple sheets, record "1-10" in the designated cell

7. Take the measurements
   Note: Students measuring a single sheet should record the measurement for each sample once and then start again with the first patch (cyan).
   Students measuring multiple sheets should measure all designated patches on the sheet before proceeding to the next sheet. The Sheets will be provided to you in a random order. Record the sheet number in the left-hand column, record the measurements for that sheet, then continue to the row that immediately follows.
   7.1. Position the sheet you are measuring on top of the white portion of the Leneta Card
   7.2. Position the Nix on the color patch you are trying to measure
   7.3. Press down gently on the top of the device
   7.4. Use the Nix Digital app to take the measurement
   7.5. Record the $L^*a^*b^*$ coordinates in the provided Excel Spreadsheet
8. Save your data using the following naming convention
   Single Sheet FIRSTNAME LASTNAME.xlsx or
   Multiple Sheets FIRSTNAME LASTNAME.xlsx
9. Email the file to bawheel@g.clemson.edu
   or upload to the GC Server/3460/Nix Extra Credit

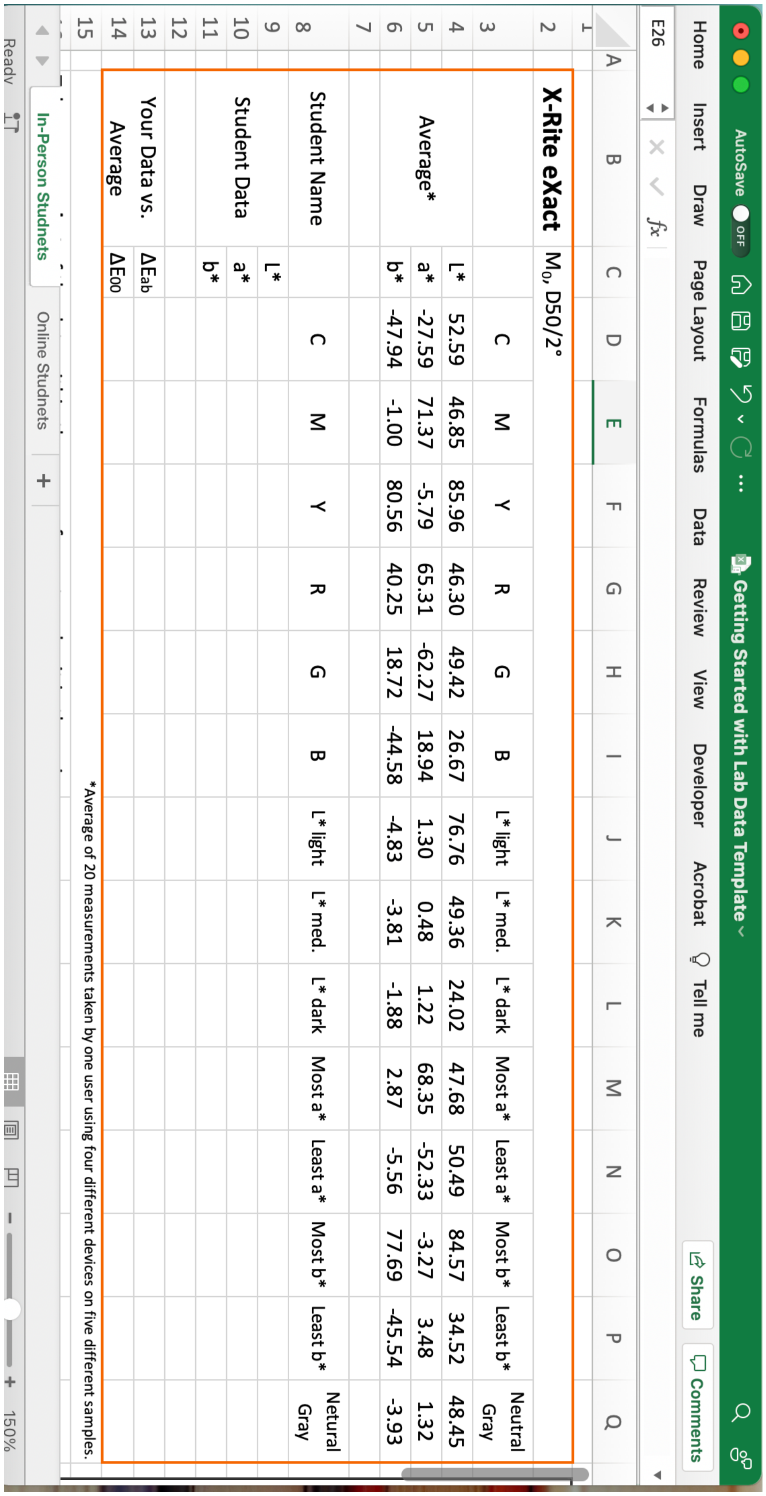
Appendix E (Continued)

Excel Template for Nix Data Collection



Appendix F

Getting Started with Colorimeters and $L^*a^*b^*$ Excel Data Template

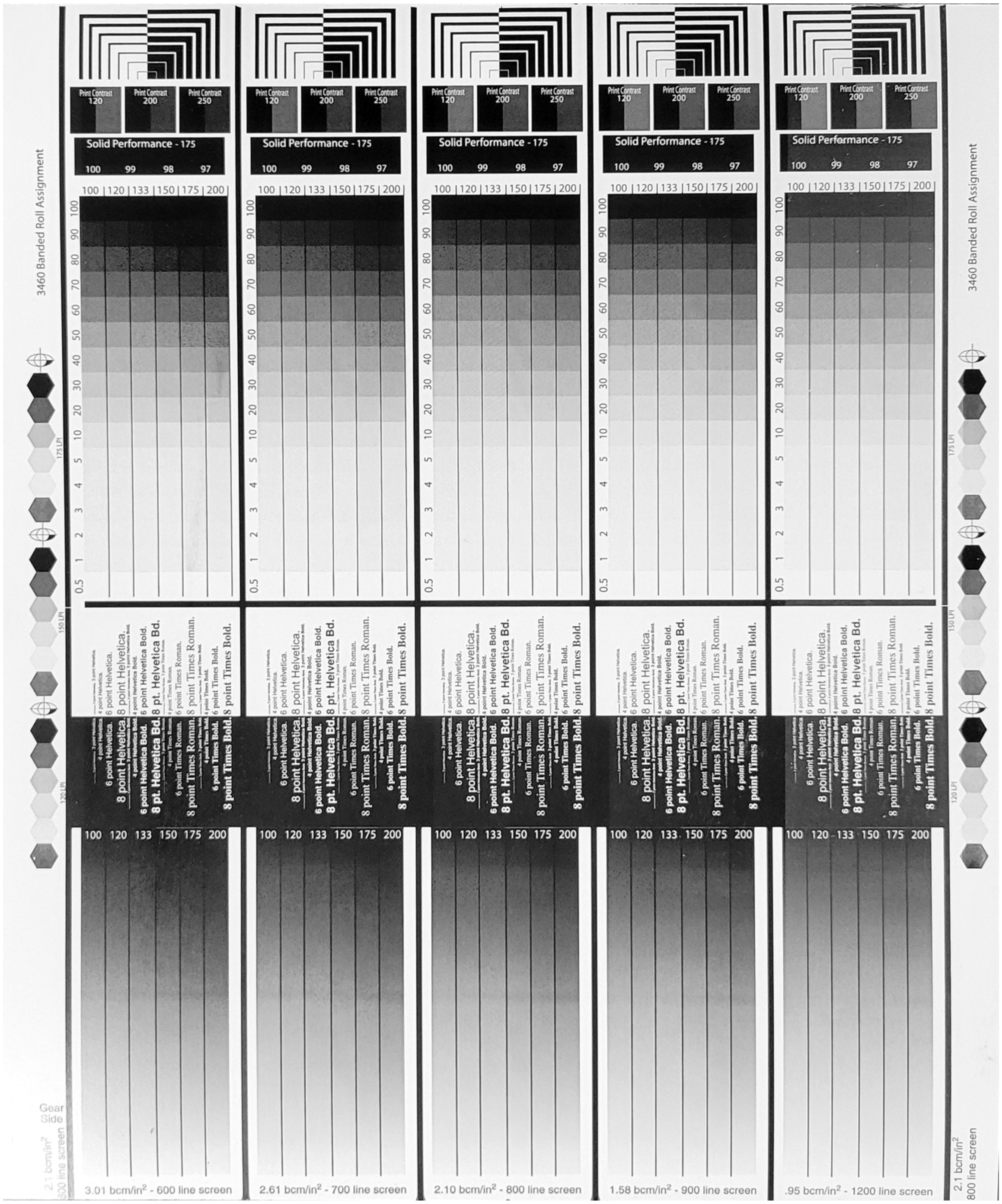


X-Rite eXact	M_0, D50/2°														
		C	M	Y	R	G	B	L* light	L* med.	L* dark	Most a*	Least a*	Most b*	Least b*	Neutral Gray
Average*	L*	52.59	46.85	85.96	46.30	49.42	26.67	76.76	49.36	24.02	47.68	50.49	84.57	34.52	48.45
	a*	-27.59	71.37	-5.79	65.31	-62.27	18.94	1.30	0.48	1.22	68.35	-52.33	-3.27	3.48	1.32
	b*	-47.94	-1.00	80.56	40.25	18.72	-44.58	-4.83	-3.81	-1.88	2.87	-5.56	77.69	-45.54	-3.93
Student Name		C	M	Y	R	G	B	L* light	L* med.	L* dark	Most a*	Least a*	Most b*	Least b*	Netural Gray
Student Data	L*														
	a*														
	b*														
Your Data vs. Average	ΔEab														
	ΔEoo														

*Average of 20 measurements taken by one user using four different devices on five different samples.

Appendix G

Photograph of Banded Roll Flexography Test Target



Appendix G (Continued)

Excel Template for Banded Roll