Color Measurement Instrument Uncertainty: Examining Real-World Strategies for Informed Conversations Regarding Instrument Agreement

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Abstract

Color measurement instrument uncertainty is a primary concern for printers as information is required for adherence to standards, specifications, and process control methodologies, however frank discussions of instrument uncertainty are rare and often involve manufacturers and vendors promoting costly schemas based on renewable revenue models. This TAGA Technology in Action content suggests spectrodensitometer users adopt CCS-II tiles and develop procedures that support analytical decision-making based on self-collected empirical data, which can increase confidence in readings while simultaneously increasing agency in the process.

A new type of color measurement instrument was introduced to the printing industry in the mid-1990s: the handheld spectrodensitometer. Popular models at that time included the X-Rite 939 and Gretag SPM 100. These instruments provided users with the ability to measure widely used densitometric attributes and colorimetric values such as CIELAB with a portable, handheld bi-directional (i.e., 0°/45°; 45°/0°) device. These instruments offered more functions and enhanced functionality and greater accuracy when compared to the tristimulus colorimeters which were incumbent at that time. These handheld spectrodensitometers represented the dawn of the age spectrally based color control for the printing industry.

In the years that followed, new models were introduced, and today spectrodensitometers are widely adopted by printers, often driven by mandates from print buyers and brand owners, and for adherence to industry specifications (e.g., ISO 12647) and calibration/process control methodologies (e.g., G7 from IDEAlliance). The accuracy of these devices, manifest in the concept of instrument uncertainty, is a concern for many adopters.

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Terminology

Berns (2019) offers helpful descriptions of instrument uncertainty, as being comprised of precision and accuracy. Precision is the closeness of agreement between test results obtained under prescribed conditions, and accuracy is described as the closeness of agreement between a test result and an accepted reference value (p. 125). Other important definitions include repeatability, reproducibility, inter-instrument agreement, and inter-model agreement. Repeatability can be defined as the degree to which an instrument produces consistent results when measurements are repeated. Reproducibility, on the other hand, adds changes in the conditions to the inherent variation of a single instrument and single operator represented by repeatability. These conditions can be different operators, instrument models, or other variables. Inter-instrument agreement is a special case of repeatability, when instruments of an identical design are compared, and inter-model agreement refers to comparisons of instruments of the same type but different design. It is expected that the variance represented by instrument uncertainty is the lowest for single instrument, single operator repeatability, whereas instrument reproducibility introduces more variance and uncertainty, with inter-instrument agreement exhibiting more variance than repeatability and inter-model agreement representing still more variation.

Myriad operating conditions can impact instrument uncertainty, and these can be informed by the tools of quality management. Among the foremost considerations are the specimens selected to evaluate the color measurement devices. It is also beneficial to review the information published by instrument manufacturers for the devices they supply, particularly when practitioners seek to implement quality management procedures that support instrument uncertainty analyses.

As an example, X-Rite Pantone, 2026, publishes inter-instrument agreement information for their popular eXact spectrodensitometer as follows:

> "Inter-Instrument Agreement
> Average: 0.25 ΔEab,
> Max: 0.45 ΔEab (for M3: 0.55 ΔEab)
> (Measurements using X-Rite manufacturing standards at a temperature of 23°C +/- 1°C, 40-60% RH for all measurement modes on 12 BCRA color tiles and a white ceramic reference (D50, 2°))"

Two main principles arise from this published specification: the use of BCRA color tiles, and the standard from which the color differences are calculated.

CCS-II Tiles

BCRA color tiles as mentioned by X-Rite Pantone are a set of 14 ceramic color tiles designed to support instrument validation and performance monitoring to describe inter-instrument agreement. These tiles are manufactured by Lucideon (formerly, CERAM), a materials science consultancy headquartered in Stoke-on-Trent, UK. BCRA tiles, also referred to as Lucideon tiles (e.g, Berns, 2019) or, more accurately, CCS-II (Colour Standards Series II) tiles. Lucideon makes available a special set of CCS-II tiles specifically for the portable, handheld Spectro densitometers popular in the printing industry, known as CCS-II Printing Standards (Lucideon, 2026).

According to Lucideon (2026) the 14 tiles which comprise the standards are "Robust standards set for the print industry ...The mount which holds the standards has been designed to enable the instrument optics to remain on the same plane as the standards, thus providing easy and accurate measurements..."

The appropriateness of ceramic tiles for this application is underscored by Hunter & Harold (1987), who state: "Materials for working standards for regular use are chosen for their permanence and resistance to change with use and cleaning. The majority of working and instrument standards and every day use are of ceramic materials…"Ideal" specimens are smooth, uniform, flat, non-directional, and opaque in nature" (p. 309.)

Advantages for adopters of CCS-II tiles for informing evaluations of color measurement instrument uncertainty include their consistency with published inter-instrument agreement specifications, and as they are not the proprietary offering from a specific instrument manufacturer or a subscription-based renewable revenue schema, users achieve greater agency in their operations versus current commercially available alternative methods. Compared to laminated ink on paper standards, CCS-II tiles offer stability advantages: they are generally less thermochromatic and exhibit greater fade resistance, are more uniform, and are easy to clean.

In using CCS-II tiles to inform instrument uncertainty, the next step involves defining digital standards from which differences can be calculated; the so called "master standard." For the X-Rite eXact inter-instrument agreement standard outlined above, the manufacturer compares all new instruments to a master standard to assure that they meet the published specification. As the master standard data from the manufacturer are unpublished and linked to a specific set of CCS-II tiles which will slightly differ from other sets, adopters are advised to create their own master standard based on their population of instruments when adopting procedures to inform instrument uncertainty.

Adopting Quality Procedures for Instrument Uncertainty

The tools of quality management initiatives, particularly a Gage Repeatability and Reproducibility (Gage R&R) study, can be advantageous for adopters seeking to better quantify color measurement instrument uncertainty. Practical challenges exist in creating the master standard for the population of instruments, as it is doubtful that many practitioners would begin with a population of new or newly certified instruments. Most users have a combination of instruments of varying ages, models, aperture sizes, time since the last factory recertification, and other variables. Nonetheless, quantifying the status of the population of instruments today can provide valuable information to better inform expected instrument uncertainty.

Procedures should include the ability to update the master standard based on new instrument purchases and factory recertifications. While this creates a dynamic master standard, over time the procedure can be used for future decisions, such as the interval for factory recertification. If properly and diligently implemented, questions about instrument uncertainty in the production environment can be isolated and assessed.

In the most common adoption of Gage R&R procedures involves isolating the variance of the measurement instrument (repeatability) and that of the operator (reproducibility). This is most useful when the variation of the operator, frequently termed as appraiser in common Gage R&R parlance, can be a main source of variation. Recalling that reproducibility can encompass other types of process-specific variation, using instrument model and serial number to represent reproducibility in this application can be a reasonable approach. Data were collected for a single instrument with reproducibility representing the operators and for a population of three instruments with reproducibility representing instrument serial number.

Preliminary Data

Preliminary studies began with a single X-Rite eXact 2 that was new and never used outside of an office environment. Three trained operators performed three different non-sequential readings of each CCS-II tile, and a master standard was created based on the mean values of all readings for each tile using a spreadsheet. An example for the blue tile is displayed in Table 1.

Operator	Reading	L*	a*	b*	ΔEab
1	1	14.49	15.93	-36.81	0.06
1	2	14.34	16.09	-36.95	0.23
1	3	14.33	16.26	-37.19	0.49
2	1	14.93	15.78	-36.78	0.47
2	2	14.31	16.13	-36.96	0.28
2	3	14.37	16.15	-36.98	0.27
3	1	14.51	15.76	-36.53	0.39
3	2	14.55	15.93	-36.82	0.06
3	3	14.63	15.81	-36.65	0.28
"Master Standard for Blue"		14.51	15.98	-36.85	

Table 1: Master Standard Created for Blue CCS-II Tile compared to individual readings

With the colorimetric master standard created for each tile, the resultant data were analyzed with MiniTab with the operator representing reproducibility. As illustrated in Figure 1, repeatability is likely under statistical control with no strong evidence of within-operator measurement noise. Tile (part-to-part) variation is large compared to measurement error, indicating that the instrument can discriminate between tiles. For analysis of the reproducibility, the historical standard deviation was set to the standard deviation for all readings from this instrument (0.166). In examining the interaction plot, the lines appear relatively parallel with limited crossing, suggesting that the operators are consistently measuring the parts with good reproducibility.

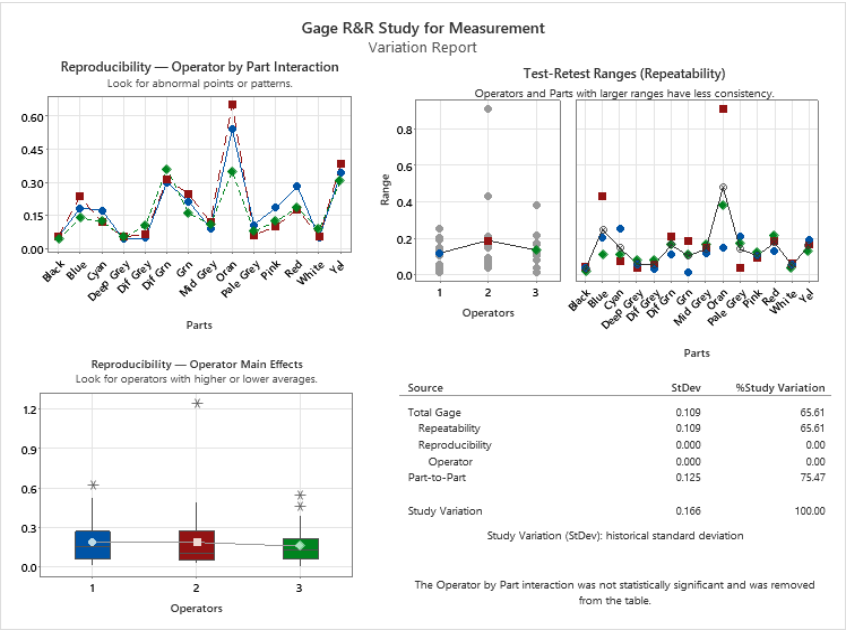


Figure 1: Gage R&R Results for Single Instrument

A second Gage R&R study was conducted with two other X-Rite eXact instruments added to the first spectrodensitometer. As in the first analysis, three operators took multiple readings of each tile. The readings were averaged into a single data point for the operator by tile. In this instance, reproducibility was defined as the instrument serial numbers. A new master standard was developed, based on all of the instruments analyzed, with a standard deviation of 0.6423. Table 2 represents an example of a readings from a single instrument versus the master standard based on the average of the three devices analyzed.

	3L*	3a*	3b*	1L*	1a*	1b*	ΔEab
Black	7.74	-0.89	1.48	7.80	-0.88	1.47	0.07
White	95.84	-0.21	1.54	96.22	-0.22	1.83	0.48
Deep Grey	27.49	0.05	-0.06	27.61	0.06	0.04	0.16
Dif Grey	56.23	-2.16	2.69	56.28	-2.15	2.85	0.17
Mid Grey	56.83	-0.65	-0.36	57.02	-0.65	-0.13	0.30
Pale Grey	82.71	-0.29	0.22	82.90	-0.28	0.46	0.31
Blue	14.64	16.04	-36.94	14.77	15.96	-36.93	0.15
Cyan	49.90	-17.66	-34.07	50.12	-17.81	-34.02	0.28
Dif Green	50.01	-32.43	16.56	50.95	-32.73	16.87	1.03
Green	50.93	-33.10	13.33	51.06	-33.08	13.45	0.17
Yellow	83.33	0.13	84.29	83.56	0.11	84.42	0.26
Orange	64.15	42.16	62.53	64.79	42.17	62.89	0.73
Pink	41.71	30.96	7.27	41.91	31.10	7.49	0.33
Red	40.97	52.38	29.57	41.19	52.57	29.76	0.34

Table 2: Master Standard Derived From Three Instruments Compared for a Single Instrument Using CCS-II Tiles

Figure 2 shows the Gage R&R results for the population of three instruments.

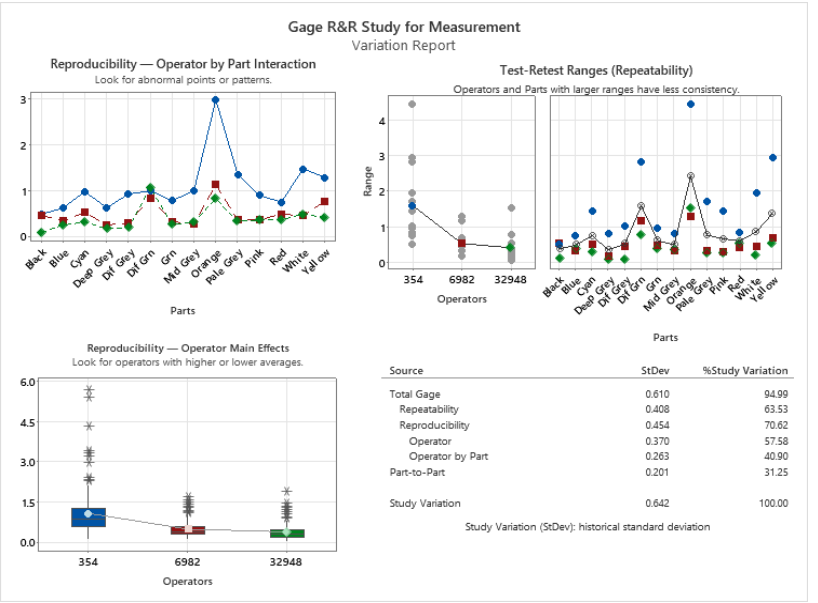


Figure 2: Gage R&R Results for Three Instruments

From a Gage R&R perspective, repeatability is very small, with highly consistent and repeated measurements and minimal noise. Reproducibility, here defined by instrument serial number, is also negligible. Part-to-part variation suggests strong discrimination capability, as expected. From a color measurement perspective, instrument 354 demonstrates greater variability than the other two instruments. The results for the remaining instruments would likely improve with this device removed from the master standard, suggesting that a factory recertification may be required to increase instrument uncertainty.

Conclusions

The adoption of CCS-II tiles to inform instrument uncertainty can be an advantageous method for making informed decisions about the total variance in color measurement systems and increase user agency in their operations. Users should be careful in creating their master standards and update them accordingly with new or newly certified devices. In addition to analyzing expected color measurement uncertainty, standard operating procedures here can also be useful tools to determine the frequency of recertification cycles and to troubleshoot potential issues as they arise on the production floor. An example here would be determining if questioned readings are the result of the instrument itself or if other factors, such as settings or operator training, are required. Practitioners are advised to be especially mindful of instrument settings and other variables such

as aperture size in their analyses, and to make their assessment readings in a consistent temperature and humidity environment.

Future research may involve a method of analysis separate from the Gage R&R method, such as using Hotelling's T^2 analysis to extend univariate control charts into the multivariate domain and may provide higher sensitivity due to subtle shifts which may not be otherwise apparent.

References

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