Consequences of Using a Number of Different Color Measurement Instruments in a Color Managed Printing Workflow

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Abstract

Since the recent revision of ISO 12647-2 and ISO 12647-7, specifiying the requirements for systems that are used to produce hard-copy digital proof prints, the use of color measurement instruments are more required in the printing industry. Currently, there are many different models of color measurement instruments used in the printing industry. Therefore, in a modern color managed workflow, most of the printing houses use more than one color measurement instrument, typically one instrument in each department (prepress, press, and post-press).

In this paper, a total of nine spectrophotometers are compared in terms of precision, accuracy and reproducibility. The BCRA series 2 ceramic gloss tiles from the BCRA series are used to confirm the accuracy and repeatability of these measuring instruments according to the manufacturer's standards.

Factors contributing to the measurement errors, in the colorimetric measurements by using more than one color measurement instrument in the printing workflow (from prepress to press and post-press) are studied using these 9 spectrophotometers. For this, four different materials are used, one proof print, one commercial print, and one reference print, along with the BCRA series 2 ceramic gloss tiles. Since the ISO standards have defined tolerances for the solids of the process colors, the accuracy of the color measurements are determined on these. The impact of the colorimetric measurement errors in the production workflow due to large inter-instrument variability between different measuring instruments used in the workflow (instrument in the printing house, and the instruments used at the customer's site for inspection and certification) is demonstrated in this paper.

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Introduction

Recent ISO standards (ISO, 2004; 2007) for the graphic arts have defined the colorimetric parameters for process control, and tolerances for their acceptance. However, the color measurement devices used in a production workflow (from the costumer, designer, prepress, to printing house) may show variations in terms of precision (repeatability, reproducibility) and accuracy of the measurements made. Furthermore, in the context of PSO (Process-Standard Offset) certification, test prints and proofs are printed according to certain aim parameters. The prints and proofs are measured twice, firstly in the printing house with the instrument of the company, and secondly by the certification body to ensure that prints are made within the predefined tolerances. Assuming both measuring tasks results in values, which are within the given tolerances, there will be no issue. However, in case of the certification body measuring values outside the tolerances, the issue of which measurements are reliable may arise.

The aim of the presented work is to evaluate the performance of nine color measurement devices in terms of precision (repeatability, reproducibility) and accuracy. Furthermore, the consequences of the inter-instrument reproducebility in a color-managed workflow will be demonstrated. Specific methods for the correction of instrument errors are outside of the scope of this work.

To illustrate how measurement uncertainties in a production workflow may cause unexpected discussions, Figure 1 shows a simplified diagram of a practical scenario in which two instruments are used to measure the same target in a color workflow. Given a certain color patch reference and measuring the patch with the color measurement instrument of the customer will result in ΔE^*_{ab} 3.5. Although the inter-instrument reproducibility between the customer and print house measurement devices is ΔE^*_{ab} 3.0, the color difference measured with the print house measurement device on the color patch is almost twice the one measured with the instrument of the customer. Furthermore, assuming having a certain color difference tolerance of e.g. ΔE^*_{ab} 5.0 the result of the print house measurement of ΔE^*_{ab} 6.5 would not be accepted.

According to Berns (2000), measurement uncertainty can be divided into two categories, precision and accuracy (Figure 2). Precision describes the dispersion of the measurements taken. Accuracy describes the distance between the measurements taken by the color measurement instruments and the actual target value (Figure 3).

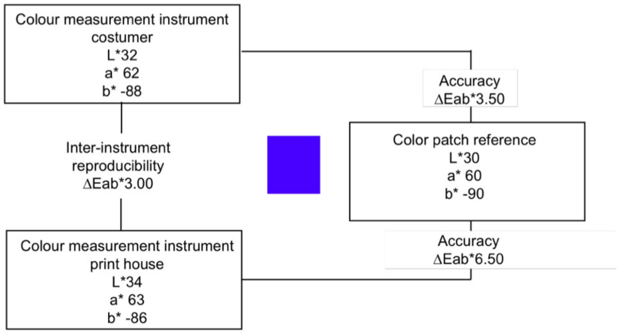


Figure 1. *Simplified diagram of a practical scenario using two instruments in a workflow measuring the same target/reference.*

Precision can be further divided into repeatability and reproducibility. ASTM Standard E 284 (ASTM, 2008) defines the repeatability as "the closeness of agreement between the results of successive measurement of the same test specimen, or test specimens taken at random from a homogeneous supply, carried out in a single laboratory, by the same method of measurement, operator, and measurement instrument with a repetition over a specified period of time". On the other hand, changing conditions such as the operator, measuring instrument, laboratory, or time, gives a measure of reproducibility.

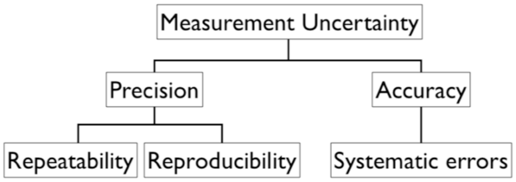


Figure 2. *Overview over measurement uncertainty.*

Typically, repeatability can be tested over three periods of time. First is the short-term repeatability which is based on measurements made in succession, second is the medium-term repeatability which can be based on measurements made over a period of hours and finally the long-term repeatability which is based on measurements made over weeks or longer. The short-term measurements can be performed either with or without replacement of the measuring instrument from the color tile/patch to be measured. When measuring without replacement, the tile/patch is left in place at the instrument's aperture. This approach might be dependent on the instrument technology and the user interface.

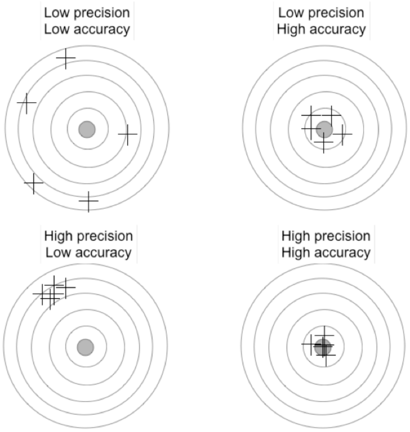


Figure 3. *Accuracy describes the distance between the measurement and the target and precision the dispersion of the measurement taken.*

In the past, various studies and research regarding measurement uncertainities have been presented. A work by Radencic (2008) concluded that the maximum color difference obtained for precision and accuracy is in the blue region of the spectrum. Previously, reports by Rich *et al.* (2008) have reported rather large color differences considering inter-instrument reproducibility. Furthermore, the inter-instrument agreement between the colorimeters and spectrophotometers used for emission measurement show a very large color difference. However, our main contribution is studying consequences of using a number of different color measurement instruments in a color managed printing workflow.

Experimental Approach

In this paper, nine commercial spectrophotometers have been used. Table 1 presents the instruments and their specifications. Because one of the manufacturers is requesting not to publish their name we anonymised the names by identifying the instruments with instrument 1, instrument 2 … instrument 9.

Although various ways are used to describe this color difference, a common value is the average or mean value for a series of twelve British Ceramic Research Association (BCRA) Ceramic Color Standards Series II (CCS II) ceramic tiles. In this paper, 14 BCRA ceramic gloss tiles and printed substrates were measured using these nine spectrophotometers, according to the measurement procedures outlined by ISO 13655 (ISO, 1996).

Instruments

The instruments resemble the commercial measuring instruments used in the graphic arts industry. As stated in ICC (2008) when comparing, instruments can be divided into product families which are instruments of the same model from the same manufacturer using equal parameters (e.g., in this work instrument 1–3 can be considered as one family and instrument 6–9 another). In terms of repeatability, or reproducibility, instruments with identical design (inter-instrument) or different design (inter-model) can also be compared.

	Measuring without replace-ment	**Aper-ture**	**Measuring geometry**	**Equipment accordance**	**Spectral range and interval**	**Short-term repeatability**
Instrument 1	Yes	4mm	45°:0°	Mean ΔE^*_{ab} 0.3 Max ΔE^*_{ab} 0.8 on by 12 BCRA tiles ceramics	380nm to 730nm at 10nm	ΔE^*_{ab} 0.02 (Standard shift from 10 measurements at 10 sec. interval on white)
Instrument 2						
Instrument 3						
Instrument 4	No	2mm	45°:0°	Mean $\Delta E^*_{94} < 1.0$ on by 12 BCRA tiles ceramics	380nm to 780nm at 10nm	$\Delta E^*_{94} < 0.2$
Instrument 5	Yes	4.5mm	45°:0°	Mean ΔE^*_{ab} 0.3 on by 12 BCRA tiles ceramics	380nm to 780nm at 10nm	ΔE^*_{ab} 0.02 (Standard shift from 10 measurements at 10 sec. interval on white)
Instrument 6	Yes	4.5mm	45°:0°	Mean ΔE^*_{94} 0.4 Max ΔE^*_{94} 1.0 on by 12 BCRA tiles ceramics	380nm to 780nm at 10nm	$\Delta E^*_{94} < 0.1$ (From 10 measurements at 3 sec. interval on white)
Instrument 7						
Instrument 8						
Instrument 9						

Table 1. *Overview of the nine instruments used in this work and the corresponding specifications.*

Test procedure on BCRA tiles

A set of 12 color standard series II (BCRA ceramic gloss tiles) plus one Black and one White BCRA ceramic gloss tile have been used to determine the accuracy and repeatability of each instrument.

Before conducting the measurements, normal warmup and calibration procedures were followed. To warm up the instrument, 25 measurements in a row on its own white standard were made. Consequently, each spectrophotometer has been calibrated on its own white reference tile supplied by the manufacturer along with the instrument.

For the short-term repeatability measurements, all the 14 BCRA ceramic gloss tiles were measured 15 times in a sequence with all the nine measurement devices. To obtain the most reproducible results, measurements have been restricted to the central region of the tiles.

Test procedure on printed substrates

To determine the measurement uncertainities of the used color measurement instruments on commercial printed substrates measurements were conducted on the Ugra/Fogra Media Wedge (CMYK), which includes 46 color patches. The Media Wedge was printed on three different paper substrates. The first paper substrate was a hard-copy digital proof print, printed according to the ISO 12647-7 graphic art standards for paper type 1 simulation by a commercial printing house. The second paper substrate was paper type 1 printed by the same commercial printing house aiming the ISO 12647-2 graphic art standards. And the third paper substrate was paper type 5 Altona testsuite reference print.

Before measuring the color patches of the Media Wedge, warm up and calibration procedure was followed as mentioned previously. The Media Wedge was measured three times in a sequence with each instrument. White backing material in accordance with ISO 13655 was used.

Data collections

All instruments used in this paper reported spectral reflectance factor values from 380nm to 730nm with 10nm interval. Spectral measurements were converted to CIEXYZ tristimulus values according to the CIE 1931 2° observer and the CIE Standard illuminant D50. Furthermore, CIELAB (D50 as the reference white) values were calculated according to CIE (2004) specifications. Colorimetric difference ΔE^*_{ab} and ΔE^*_{94} (as some manufacturers quoted the color difference in ΔE^*_{94}) values were computed between the BCRA reference data and the measurements data obtained using each instrument.

Experimental Results and Discussion

As mentioned previously the aim of the presented work is to evaluate the performance of a number of color measurement devices in terms of precision (repeatability, reproducibility) and accuracy. Furthermore the consequences of the inter-instrument reproducibility in color-managed workflow will be demonstrated. First the results of the accuracy evaluation will be presented.

Measurement accuracy

As mentioned earlier ISO defines accuracy as the conformance of a series of measurements to the accepted value for a given sample. In other words how closely an instrument can conform to a certain reference. In this work the reference values have been provided by CERAM who is the manufacturer of the used 14 BCRA tiles.

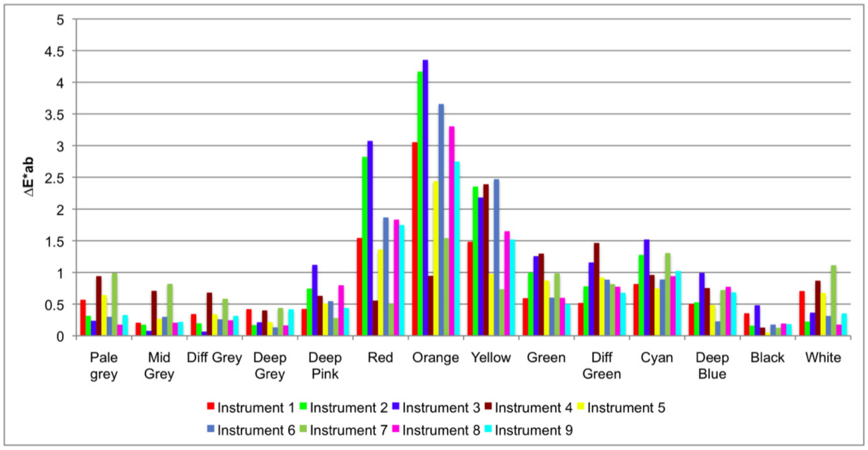


Figure 4. *Color difference of nine instruments according to the 14 BCRA tiles reference.*

Figure 4 shows the color difference for each instrument on each BCRA tile. Overall, it can be observed that almost all instruments produce values greater than ΔE^*_{ab} 0.5 for all 14 tiles measured. On the Black tile all instruments performed good with the least color difference. On the other hand, almost all instruments performed poorly on the Red, Orange and Yellow tiles.

Figure 5 shows the color difference of all the instruments measured on the Red, Orange and Yellow tiles. Except for the instrument 4 the Orange tile produces the largest color difference. Instrument 7 shows the least color differences for these three tiles. Considering the color differences within the product families (instrument family A includes instruments 1–3, and family B includes instruments 6–9) on the tiles Red, Orange and Yellow, there is no obvious trend visible.

Another way of examining the measurement distribution is to assess the dispersion of the measurements on the CIELAB a*- b*plane. Figure 6 illustrates the measurements of nine instruments on the Orange tile including the distance to the reference itself.

Although the results of all measurements show a rather low accuracy, a relatively high precision of the instruments can be considered due to the measurement dispersion, which lies almost in one quadrant in the CIELAB system. Figure 7 shows the measurement value distribution of all instruments on the Orange tile including reference displayed on CIELAB L*, C* plane. It can be seen that except for instrument 4, the C* color differences comparing to the reference can be considered as rather large. On the other hand, the L* differences can be considered as low. Addressing the product families, it can be noticed that instrument 4 performes best on Orange comparing to the other instruments with different designs.

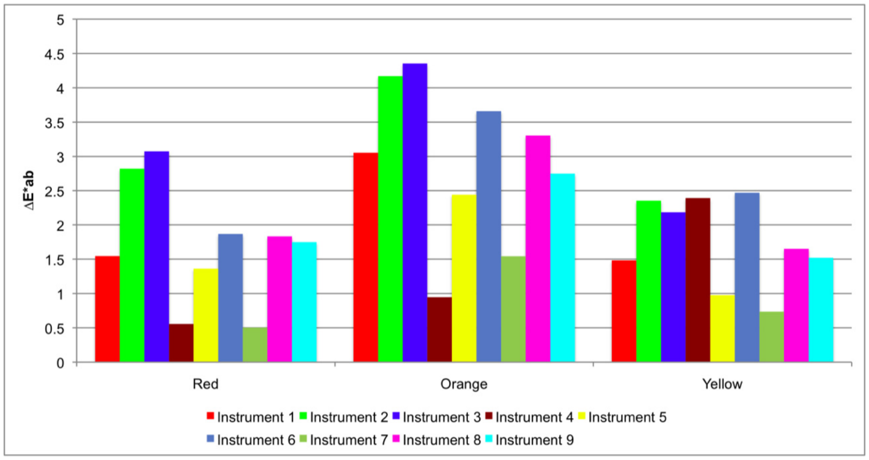


Figure 5. *Color difference of nine instruments according to the BCRA tiles Red, Orange, and Yellow reference.*

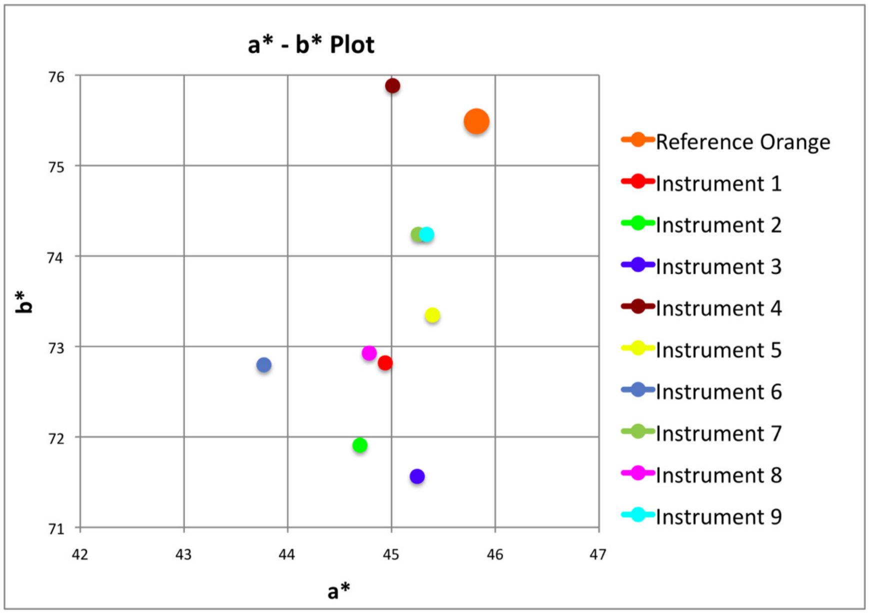


Figure 6. *Measurements of nine instruments on BCRA tile Orange including reference displayed on CIELAB a*, b*plane.*

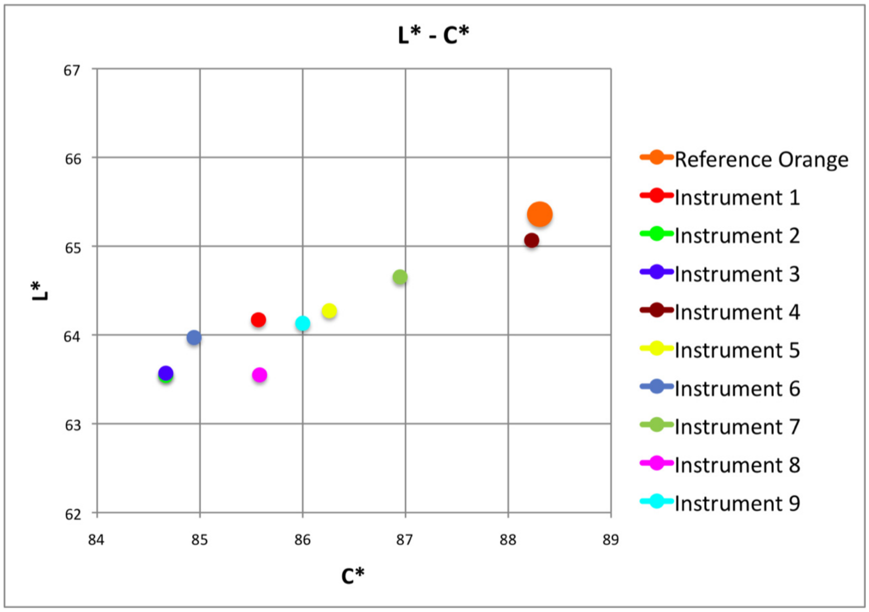


Figure 7. *Measurements of nine instruments on BCRA tile Orange including the reference displayed on CIELAB L*, C*plane.*

Figure 8 illustrates the spectral reflectance of all nine instruments measures on the Orange tile. It can be observed that all instruments show similar reflectance factor at the orange part of the visible spectrum (380nm to 730 nm wavelength). The reflectance factors of the instruments are below the reference reflectance factor. Furthermore, it can be noticed that instrument 4 shows the closest spectral reflectance curve to the reference and again confirms the least color difference on the Orange tile as seen in Figure 5.

Inter-instrument agreement

The instrument manufacturers define certain inter-instrument agreements within their instrument families (Danuser, 2009). For the instrument family B (instruments 6-9) the manufacturer has defined an inter-instrument agreement of mean ΔE^*_{94} of 0.4 and Max ΔE^*_{94} of 1.0 for single measurement mode on 12 BCRA tiles (D50, 2°). Figure 9 shows their performance considering the inter-instrument agreement. It can be seen that instrument 6, 8 and 9 meet the manufacturer's requirements both in terms of mean $\Delta E^*_{94} < 0.4$ and Max $\Delta E^*_{94} < 1.0$. On the other hand for the instrument family A the manufacturer has defined an inter-instrument agreement of mean ΔE^*_{ab} 0.3 and Max ΔE^*_{ab} 0.8 for single measurement mode on 12 BCRA tiles (D50, 2°). Figure 10 shows the inter-instrument agreement within the instrument family A (instrument 1-3). It can be seen that even though the direct comparison between instrument 2 and instrument 3 is within the inter-instrument agreement given by the manufacturer regarding max and mean ΔE^*_{ab} have been slightly exceeded. The comparisons between instrument 1 and instrument 2, and instrument 1 and instrument 3 exceed the manufacturer's requirements distinctly in terms of mean and max ΔE^*_{ab} Instrument 7 exceeds the requirements noticeably in both the mean value and Max value.

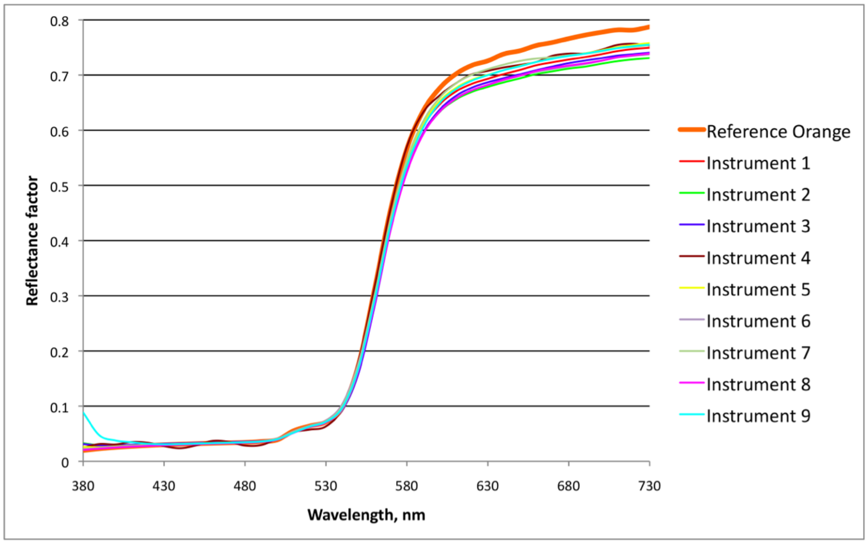


Figure 8. *Spectral reflectance measurements of nine instruments on BCRA tile Orange including the reference.*

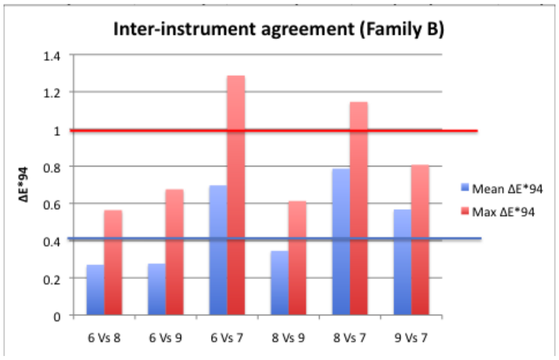


Figure 9. *Inter-instrument agreement within the instrument family B, compared to the manufacturer's specifications.*

Short-term and long-term repeatability

To determine the measurement variation in terms of color stability over time the quality factor repeatability is required (Morovic and Nussbaum, 2003). The time period has been quantitatively defined as short term (15 readings) and long term

(10 weeks). The sample used for this test is normally a white tile and the color differences were calculated between the mean of the 15 measurements and each individual measurement called as mean color difference from the mean (Berns, 2000). It is worth mentioning again that before the 15 actual measurements have been conducted a warm up procedure including 25 measurements in a row on its own white standard has been performed. Six instruments only have been used to determine the repeatability performance.

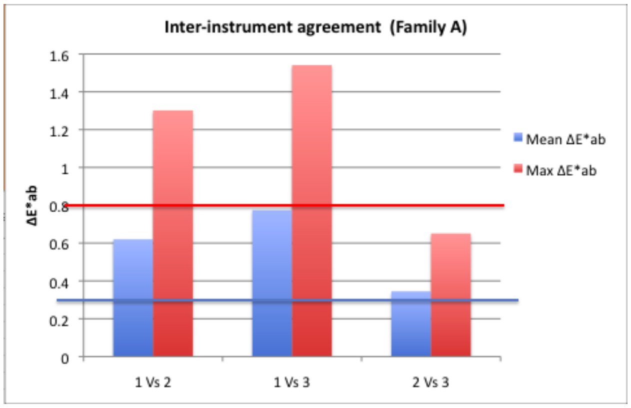


Figure 10. *Inter-instrument agreement within the instrument family A.*

Table 2 shows the manufacturer's agreement and the corresponding results in terms of the short and long-term measurements. Repeatability defines how well an instrument is able to repeat identical measurements. Although the manufacturers do not specify any particular measurement agreements for the long-term repeatability it might be obvious that it is the degree to which the instrument makes identical measurements over a long time.

Instrument	Manufacturer's agreement	Short-term repeatability	Long-term repeatability
Instrument 8	$\Delta E^*_{94} < 0.1$ from 10 measurements at 3 sec. interval on white)	Pass	Pass
Instrument 9		Pass	Pass
Instrument 5	ΔE^*_{ab} 0.02 (standard shift from 10 measurements at 10 sec. interval on white)	Fail	Pass
Instrument 2	ΔE^*_{ab} 0.02 (standard shift from 10 measurements at 10 sec. interval on white)	Pass	Pass
Instrument 3		Pass	Pass
Instrument 4	$\Delta E^*_{94} < 0.2$	Pass	Pass

Table 2. *Overview over short and long-term repeatability performance of six instruments.*

Figure 11 shows the performance of the short and long term repeatability of the instrument 9 and the manufacturer's agreement which is defined with ΔE^*_{94} 0.1

with respect to the mean CIELAB value of 10 measurements on white. The x-axis indicates the short-term and long-term repeatability variations whereas on the y-axis the color difference is represented. The closer the horizontal mean-lines (Oct08 E94 Mean and Jan09 E94 Mean) are, the more identical are measurements and hence better the long-term performance can be considered.

It can be seen that both the short and long-term repeatability performs almost equally and within the manufacturer's agreement. Furthermore, the graph shows that the largest variations are in the beginning of the measurement sequence. Hence, increasing the number of measurements in the warm up time precedure would increase the total performance of the repeatability for this instrument. The results of the measurements of instrument 7 show a very similar performance.

For the instrument 5 the manufacturer reduces the short-term repeatability to ΔE^*_{ab} 0.02. In Figure 12 it can be observed that the overall repeatability measurements are just above the manufacturer's agreement for the instrument 5. Furthermore, the graph shows some minor short-term measurement variations. However, the long-term repeatability can be considered as very good due to the almost identical measurements between the 10 weeks interval.

In our paper, the manufacturer of the instrument 4 has defined the largest repeatability agreement with ΔE^*_{94} of 0.2. Although the mean measurements are strongly inside the manufacturer's agreement, the short-term measurement variations are rather large as can be seen in Figure 13. On the other hand, the long-term repeatability illustrates almost the same variations. Hence, the long-term repeatability can be considered as acceptable. However, comparing the short and long-term repeatability performance with another instrument family the variations are rather large, e.g. the short and long-term variation of the instrument 4 is much larger then the manufacturer's short-term agreement for e.g. the instrument 5. The rather large variations might be explained due to instrument technology and the user interface of the instrument 4. The short-term measurements have been performed with replacement/UpDown settings, which means that the tile is not left in place at the instrument's aperture when measuring.

Results of print measurements

The following are the results from the measurements performed with seven instruments on three types of substrates. Due to some practical reasons we had no access to the instruments 6 and instrument 7 in this task of the work. Firstly, the results on substrate proof according to the ISO 12647-7 standard will be presented. To recap, the proof has been created in a commercial printing house, simulating ISO 12647-2 paper type 1 46 color patches of the UGRA/FOGRA media Wedge CMYK (Figure 14) have been measured with seven instruments three times in sequence.

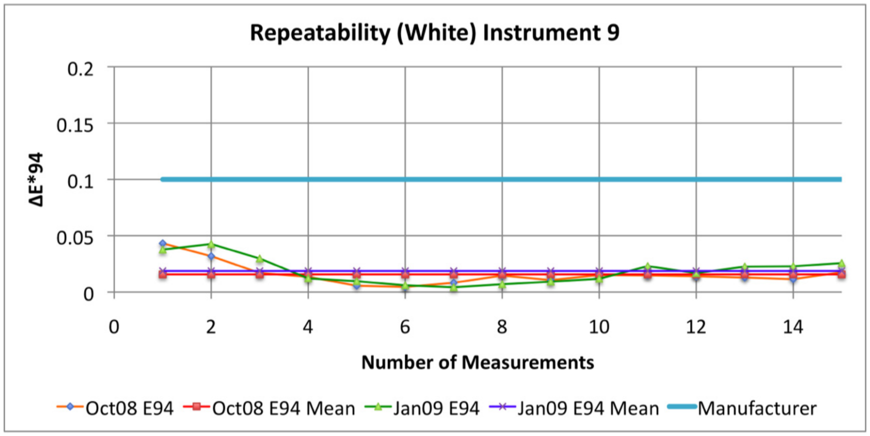


Figure 11. *Short- and long-term repeatability on white including manufacturer's agreement* ΔE^*_{94} *0.1 for the instrument 9.*

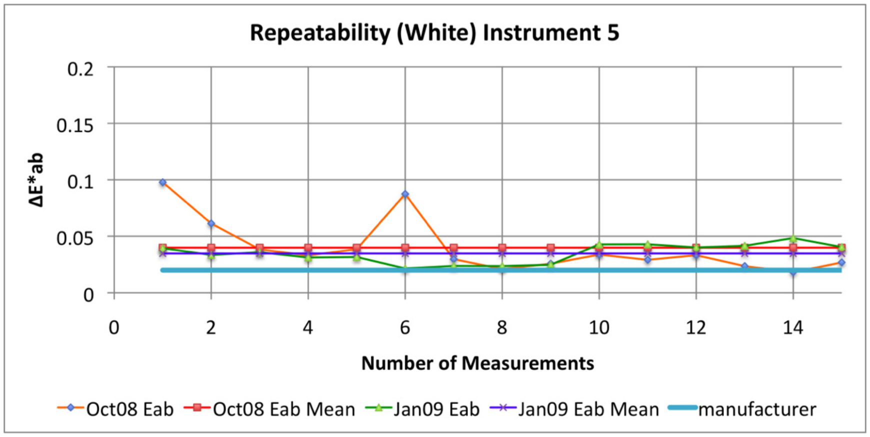


Figure 12. *Short- and long-term repeatability on white including manufacturer's agreement* ΔE^*_{ab} *0.02 for the instrument 5.*

The mean value (of the three measurements per patch) have been used to calculate the color difference between the reference and each single instrument. The calculated color difference have been compared with the CIELAB ΔE^*_{ab} tolerances according to ISO 12647-7:2007. Table 3 shows the ΔE^*_{ab}values calculated between the reference and the measurements on proof using the seven instruments. It also includes the CIELAB ΔE^*_{ab} tolerances according to ISO 12647-7:2007. It can be seen that five instruments (instrument 1, instrument 2, instrument 3, instrument 5 and instrument 8) have performed measurements which are within the acceptable tolerances given by ISO 12647-7:2007. The measurements of the instrument instrument 4 and instrument 9 show results which are far outside the defined tolerances.

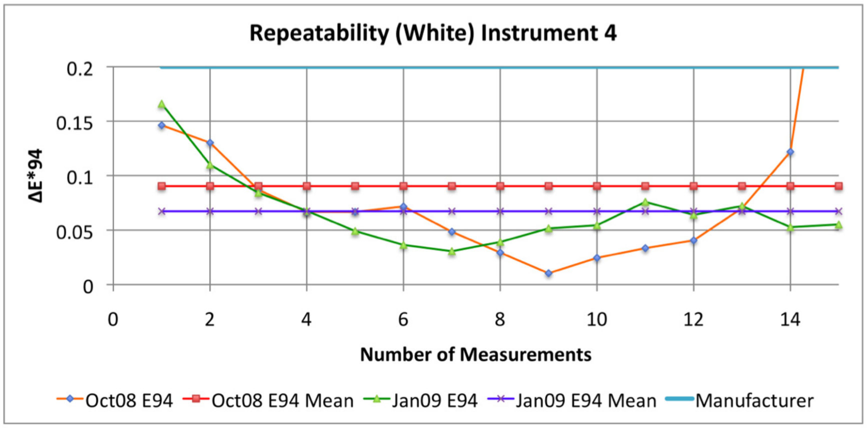


Figure 13. *Short- and long-term repeatability on white including manufacturer's agreement* ΔE^*_{94} *0.2 for the instrument 4.*

Figure 14. *Ugra/Fogra Media Wedge CMYK.*

	Substrate	Mean	Max	Primaries								Composed grey
	ΔE^*_{ab} 3	ΔE^*_{ab} 3	ΔE^*_{ab} 6	ΔE^*_{ab} 5				(ΔH) ΔE^*_{ab} 2,5				(ΔH) ΔE^*_{ab} 1,5
				C	M	Y	B	C	M	Y	B	Average
Instrument 1	1.36	1.39	2.65	1.2	1.52	1.81	1.23	0.76	0.81	0.4	0	0.48
Instrument 2	1.69	1.28	3	0.9	1.51	0.66	1.2	0.48	1.36	0.04	0	1.08
Instrument 3	1.52	1.4	3.12	1.43	1.7	0.9	1.38	1	1.59	0.45	0	0.93
Instrument 5	0.92	1.26	2.46	0.87	1.17	2.05	1.04	0.26	0.86	0.15	0	0.71
Instrument 8	1.4	1.12	2.67	0.66	1.07	1.48	1.1	0.31	0.92	0.06	0	0.71
Instrument 9	6.34	3.04	6.34	3.27	2.36	2.49	1.68	3.14	2.19	0.33	0	3.47
Instrument 4	1.4	2.54	7.5	2.96	3.03	7.5	1.36	2.56	0.05	0.71	0	0.55

Table 3. *Color differences on proof of seven instruments including the CIELAB* ΔE^*_{ab} *tolerances according to ISO 12647-7:2007 (Orange marked values are outside the tolerance).*

Although instrument 4 performs satisfactorily for most of the colors, the color difference between the instrument's measurement and the reference on the primary color yellow is $\Delta E^*_{ab} > 7$, which is a considerably large color difference. Instrument 9 is the only device which is using an UV cut filter. Therefore it is obvious that the measurement on the proof substrate exceeds the tolerance due to the concentration of optical brighteners which effects the CIE b* value most (from reference b* -2 to measured b* +4).

Looking at the above measured values, if the proof would have been measured initially in the print shop (where the proof is generated) with, e.g., the instrument 1 and then measured by the customer with e.g. the instrument 4 or instrument 9 (which contains the UV Cut filter), then, only the measurement performed by the instrument 1 would have been considered as within the tolerance. However, the customer would not have accepted the proof as the measurements made by his instrument are not within the tolerances.

It has been observed previously that the instrument 4 results in a large color difference in the primary color yellow when compared with the reference. Figure 15, which shows the measurements of seven instruments on proof substrate on the primary color yellow including reference displayed on CIELAB a*, b* plane can confirm this finding. However, looking at the precision of the other instruments, the graph illustrates a very small dispersion of the measurements taken. Furthermore, the instrument family B (instrument 1-3) can clearly be recognised as the one with the highest precison. Instrument 9, on the other hand, shows a larger difference in the CIE b* value as seen earlier due to the concentration of optical brighteners in the proof substrate and the measurement with a UV cut filter.

Looking at the measurement results on CIELAB L*, C*plane (Figure 16) the precision within the instrument families can be considered as good. Although, the difference in L* value between the instrument 4 and the other instrument families is rather small, the difference in C* value can be recognised as very large.

Similar measurement patterns can be observed in other primary (cyan and magenta) and secondary colors (red, green and blue). Figure 17 shows the measurements of seven instruments on proof substrate on the primary color cyan including reference displayed on CIELAB a*, b*plane. Overall, it can be observed that the color difference in CIE b* is larger then on CIE a*. Although the dispersion of the measurements on proof within the instrument families is slightly larger compared to the primary color yellow, the variations can still be considered as acceptable. It has to be emphasised that in this task the dispersion of the instruments measurements should be taken into account and not the color difference between the instrument measurements and the reference.

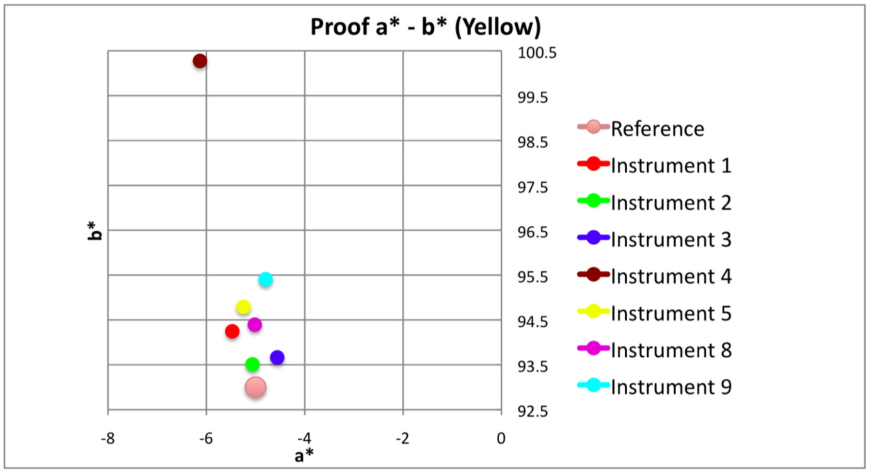


Figure 15. *Measurements of seven instruments on proof substrate primary color yellow including reference displayed on CIELAB a*, b*plane.*

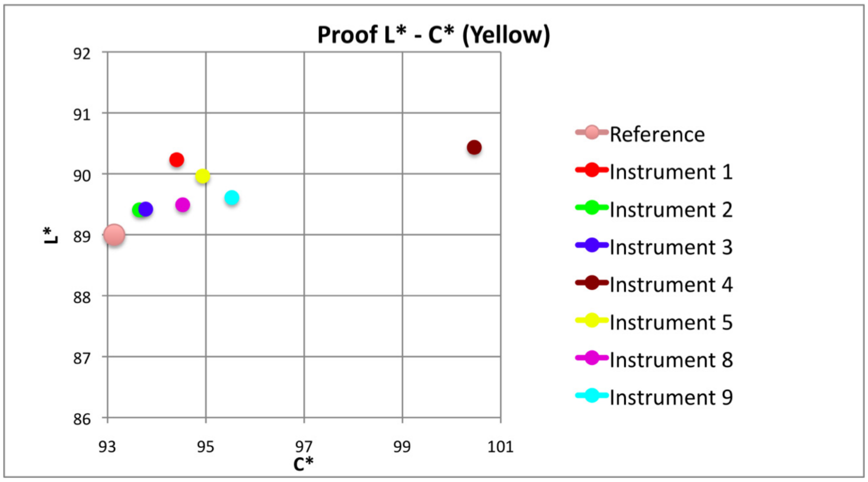


Figure 16. *Measurements of seven instruments on proof substrate primary color yellow including reference displayed on CIELAB L*, C*plane.*

Another way of assessing the measurement results on the solid primary colors is by comparing the inter-instrument performance. Table 4 shows the color differences ΔE^*_{ab} on the solid cyan and magenta between each instrument. The observation made in Figure 17 can be confirmed with the CIE ΔE^*_{ab} values in Table 4 where it can be seen that the instruments 4 and instrument 9 result in the largest color differences on cyan when compared with the other instruments (e.g., Color difference of ΔE^*_{ab} 6.12 between instrument 4 and instrument 9). The differences between instrument 4 and the other instruments range between

ΔE^*_{ab} 2.27 and 4.09. On the other hand, the performance between the instrument family B (instrument 1, instrument 2 and instrument 3) can be considered as acceptable with differences ranging between ΔE^*_{ab} 0.6 and 1.88. Looking at the results of the instrument 5 and instrument 8 the ΔE^*_{ab} is less than 0.8.

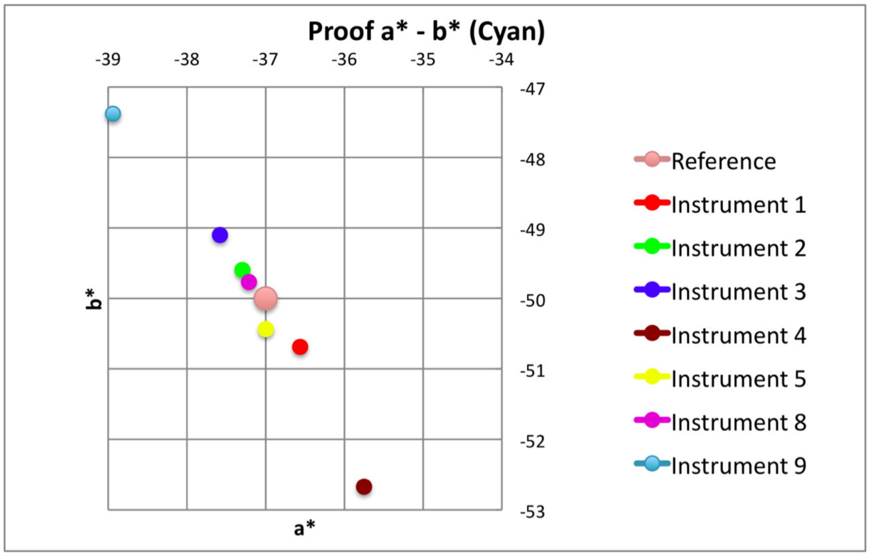


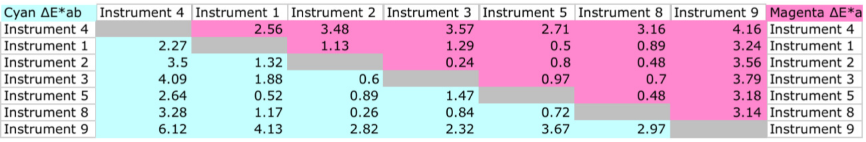
Figure 17. *Measurements of seven instruments on proof substrate primary color cyan including reference displayed on CIELAB a*, b*plane.*

The upper triangle in Table 4 shows the results on solid magenta, where again, the instrument pair instrument 4 and instrument 9 show the largest ΔE^*_{ab} of 4.16. The least color differences are not within the instrument family B (instrument 1, instrument 2 and instrument 3) itself but between instrument 8 and instrument 5 ($\Delta E^*_{ab} < 0.5$) and instrument 8 and instrument family B (ΔE^*_{ab} < 0.9).

Table 5 shows the color differences ΔE^*_{ab} on the solid yellow and black between each instrument. Regarding measurements on yellow again, the instrument 4 shows the most significant color differences compaired to the other devices with $\Delta E^*_{ab} > 5.12$ which, already has been seen on CIELAB a*, b*plane in Figure 15. On the other hand, instrument 9 shows a much better precison on yellow than what we have seen on the color cyan and magenta.

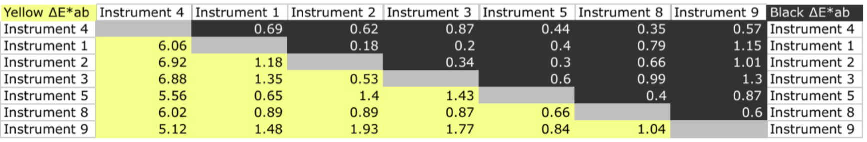
The instruments performance on solid black, however, shows measurement results, which are almost $\Delta E^*_{ab} < 1.0$ across all instrument combinations including instrument 4 and instrument 9. A very similar measurment performance on the BCRA tile black we have observed previously in Figure 4.

Hence, black seems to be the least critical color considering the precision on inter-instrument agreement.



Cyan ΔE*ab	Instrument 4	Instrument 1	Instrument 2	Instrument 3	Instrument 5	Instrument 8	Instrument 9	Magenta ΔE*a
Instrument 4		2.56	3.48	3.57	2.71	3.16	4.16	Instrument 4
Instrument 1	2.27		1.13	1.29	0.5	0.89	3.24	Instrument 1
Instrument 2	3.5	1.32		0.24	0.8	0.48	3.56	Instrument 2
Instrument 3	4.09	1.88	0.6		0.97	0.7	3.79	Instrument 3
Instrument 5	2.64	0.52	0.89	1.47		0.48	3.18	Instrument 5
Instrument 8	3.28	1.17	0.26	0.84	0.72		3.14	Instrument 8
Instrument 9	6.12	4.13	2.82	2.32	3.67	2.97		Instrument 9

Table 4. *Inter-instrument agreement on proof substrate in solid cyan (lower left half of the table) and magenta (upper right half of the table) between all instruments.*



Yellow ΔE*ab	Instrument 4	Instrument 1	Instrument 2	Instrument 3	Instrument 5	Instrument 8	Instrument 9	Black ΔE*ab
Instrument 4		0.69	0.62	0.87	0.44	0.35	0.57	Instrument 4
Instrument 1	6.06		0.18	0.2	0.4	0.79	1.15	Instrument 1
Instrument 2	6.92	1.18		0.34	0.3	0.66	1.01	Instrument 2
Instrument 3	6.88	1.35	0.53		0.6	0.99	1.3	Instrument 3
Instrument 5	5.56	0.65	1.4	1.43		0.4	0.87	Instrument 5
Instrument 8	6.02	0.89	0.89	0.87	0.66		0.6	Instrument 8
Instrument 9	5.12	1.48	1.93	1.77	0.84	1.04		Instrument 9

Table 5. *Inter-instrument agreement on proof substrate in solid yellow (lower left) and black (upper right) between all instruments.*

Below the results on substrate paper type 1 according to the ISO 12647-2 standard will be presented. The same procedure as we did follow for the proof substrate, was followed for the print substrate. The mean values (of the three measurements) have been used to calculate the color difference between the reference given by ISO 12647-2 paper type 1 (white backing) and each single instrument. The calculated color difference have been compared with the CIELAB ΔE^*_{ab} tolerances according to ISO 12647-2.

It can be seen in Table 6 that only three instruments (instrument 2, instrument 5 and instrument 8) give measurements, which are within the ISO tolerance values for all primary colors and the substrate. There is evidence of optical brighteners being present in the paper type 1 substrate which affects the CIE b* value when measuring with instrument 9. Therefore using instrument 9 will exceed the measurement value of the substrate above the tolerance value (ΔE b*±2). Instrument 1 and instrument 3 show measurement values on black, which just exceeds the color differences tolerances too, as well as instrument 4 in yellow.

Figure 18 shows the measurements of seven instruments on substrate paper type 1 on the primary color cyan including reference on CIELAB a* - b*plane. Overall, a very similar pattern considering the dispersion of the measurement as seen previously on proof can be observed. Also, the color difference in CIE b* is larger then on CIE a*.

Table 7 shows the color differences ΔE^*_{ab} on the solid cyan and magenta between each instrument on substrate paper type 1. It can be recognised that the inter-instrument agreement on substrate paper type 1 is almost identical to the inter-instrument agreement on substrate proof. The same can be stated for the inter-instrument agreement on solid yellow and black for paper type 1 as seen in Table 8.

	Substrate			Primaries			
	ΔE L*±3	ΔE a*±2	ΔE b*±2	ΔE^*_{ab} 5			
				C	M	Y	B
Instrument 1	0.3	1.25	1.41	4.24	1.2	1.86	5.24
Instrument 2	0.07	1.19	0.91	4.55	0.68	2.48	4.8
Instrument 3	0.04	1.42	1.19	4.91	1.05	2.83	5.23
Instrument 5	0.05	1.1	1.41	4.1	1.16	1.89	4.52
Instrument 8	0.15	1.3	1.2	4.16	0.57	2.41	4.02
Instrument 9	0.38	0	3.6	5.35	2.11	2.67	4.0
Instrument 4	0.5	1.79	1.35	3.89	4.07	5.01	4.37

Table 6. *Color differences on substrate paper type 1 of seven instruments including the CIELAB* ΔE^*_{ab} *tolerances according to ISO 12647-2 (Orange marked values are outside the tolerance).*

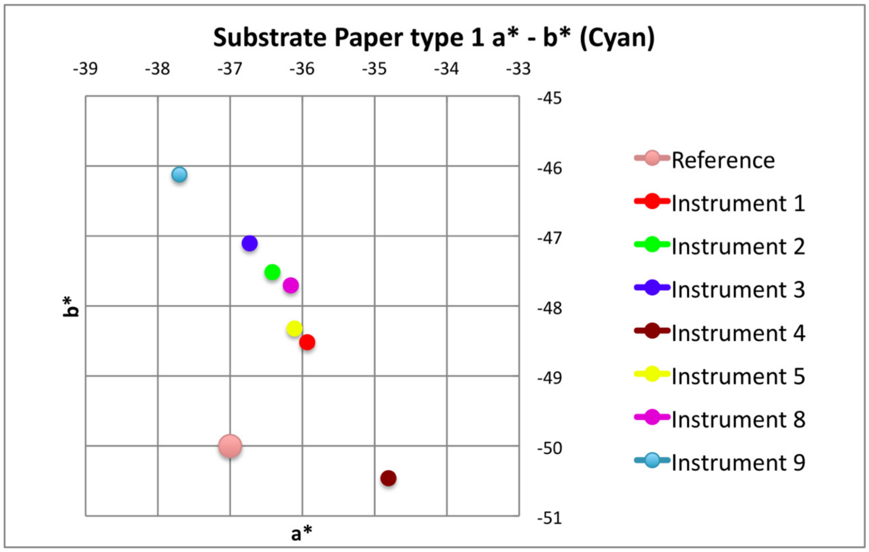
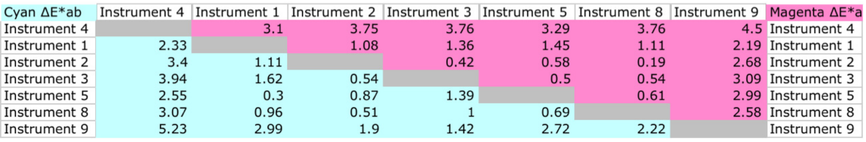


Figure 18. *Measurements of seven instruments on substrate paper type 1 primary color cyan including reference displayed on CIELAB a*, b*plane.*

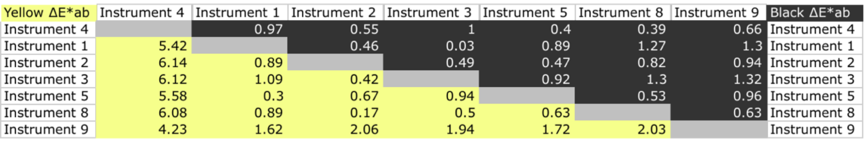
And finally the results on substrate paper type 5 according to the ISO 12647-2 standard will be presented. The identical procedure has been applied for paper type 5 as previously used for the proof substrate and paper type 1. The mean values (of the three measurements) have been used to calculate the color difference between the reference given by ISO 12647-2 paper type 5 (white backing) and each single instrument. The calculated color difference have been compared with the CIELAB ΔE^*_{ab} tolerances according to ISO 12647-2.

Table 9 shows the color differences on substrate paper type 5 of seven instruments. It can be seen that all instruments performed measurements, which are within the ISO tolerance values for the four primary colors and the substrate. Instrument 5 gives the closest readings compare to the reference. Although this paper type 5 should not contain any concentration of optical brighteners (as stated by the paper manufacturer) instrument 9 (UV cut) shows a CIE b* value (2.8) which exeeds just the given tolerance.



Cyan ΔE*ab	Instrument 4	Instrument 1	Instrument 2	Instrument 3	Instrument 5	Instrument 8	Instrument 9	Magenta ΔE*a
Instrument 4		3.1	3.75	3.76	3.29	3.76	4.5	Instrument 4
Instrument 1	2.33		1.08	1.36	1.45	1.11	2.19	Instrument 1
Instrument 2	3.4	1.11		0.42	0.58	0.19	2.68	Instrument 2
Instrument 3	3.94	1.62	0.54		0.5	0.54	3.09	Instrument 3
Instrument 5	2.55	0.3	0.87	1.39		0.61	2.99	Instrument 5
Instrument 8	3.07	0.96	0.51	1	0.69		2.58	Instrument 8
Instrument 9	5.23	2.99	1.9	1.42	2.72	2.22		Instrument 9

Table 7. *Inter-instrument agreement on substrate paper type 1 in solid cyan and magenta between all instruments.*



Yellow ΔE*ab	Instrument 4	Instrument 1	Instrument 2	Instrument 3	Instrument 5	Instrument 8	Instrument 9	Black ΔE*ab
Instrument 4		0.97	0.55	1	0.4	0.39	0.66	Instrument 4
Instrument 1	5.42		0.46	0.03	0.89	1.27	1.3	Instrument 1
Instrument 2	6.14	0.89		0.49	0.47	0.82	0.94	Instrument 2
Instrument 3	6.12	1.09	0.42		0.92	1.3	1.32	Instrument 3
Instrument 5	5.58	0.3	0.67	0.94		0.53	0.96	Instrument 5
Instrument 8	6.08	0.89	0.17	0.5	0.63		0.63	Instrument 8
Instrument 9	4.23	1.62	2.06	1.94	1.72	2.03		Instrument 9

Table 8. *Inter-instrument agreement on substrate paper type 1 in solid yellow and black between all instruments.*

	Substrate			Primaries			
	ΔE L*±3	ΔE a*±2	ΔE b*±2	ΔE^*_{ab} 5			
				C	M	Y	B
Instrument 1	0.5	0.3	1.7	2.04	3.5	1.44	2.27
Instrument 2	0.0	0.3	1.9	2.65	2.53	1.22	1.55
Instrument 3	0.0	0.4	1.8	2.78	2.18	1.47	1.55
Instrument 5	0.0	0.2	1.0	1.67	2.14	1.68	1.29
Instrument 8	0.0	0.32	2.0	2.44	3.22	1.02	1.47
Instrument 9	0.2	0.25	2.8	2.61	3.76	1.26	1.56
Instrument 4	0.2	0.12	0.8	2.33	3.51	3.72	1.28

Table 9. *Color differences on substrate paper type 5 of seven instruments including the CIELAB ΔE^*_{ab} tolerances according to ISO 12647-2 (Orange marked values are outside the tolerance).*

Finally, Figure 19 shows the measurements of seven instruments on substrate paper type 5 on the primary color cyan including reference on CIELAB a* - b* plane. The dispersion of the measurements is almost identical again with the dispersion of measurements seen on substrate proof and substrate paper type 1.

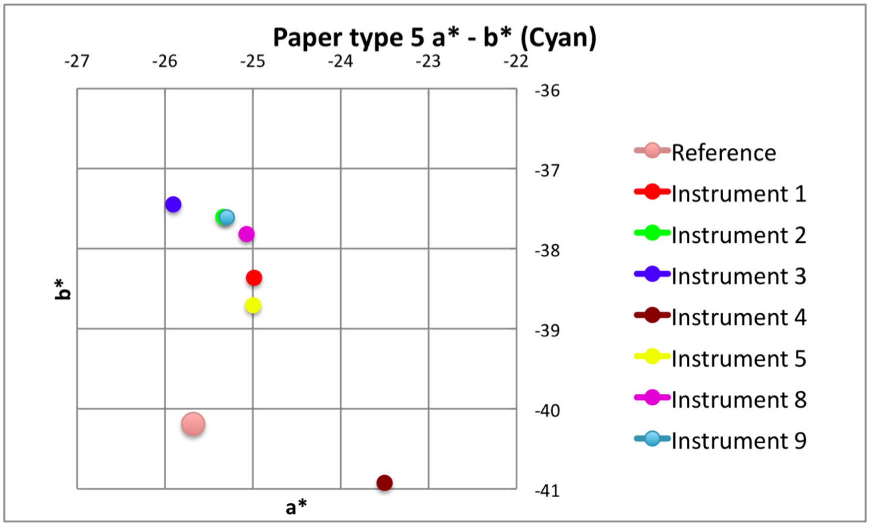


Figure 19. *Measurements of seven instruments on substrate paper type 5 primary color cyan including reference displayed on CIELAB a*, b*plane.*

The inter-instrument agreements on the solid primary colors cyan, magenta, yellow and black on substrate paper type 5 are almost identical to the inter-instrument agreement on substrate proof and paper type 1 respectively.

As seen previously accuracy describes the averaging of grouping compared to the centre of a certain target whereas precision describes the dispersion of the measurement taken by a number of instruments. In the context of a modern color managed workflow printing houses use more than one color measurement instrument to measure the same target. According to our findings the inter-instrument agreement is determining the size of the color difference compare to a given taret value. Using instruments within the same family (same model, same design of instrument from the same manufacturer with the same parameters) will result in the best inter-instrument agreement in terms of absolute colors in a controlled color managed workflow. However, to avoid color differences due to measurement uncertainities, which are outside a given standard tolerance the color difference tolerances have to be reduced inside the workflow. Furthermore, reducing the "working" color difference tolerances (e.g., from ISO ΔE^*_{ab} 5 to ΔE^*_{ab} 3.5 requires a certain definition of the inter-instrument agreement to e.g. max ΔE^*_{ab} 1.5 or 2. As seen previously is the inter-instrument agreement depending on the primary color. Hence, different inter-instrument agreement on certain colors would be required.

Conclusions and Perspectives

Nine commercial spectrophotometer instruments typically used in the graphic art industry were evaluated in terms of accuracy, repeatability and inter-instrument agreement. Considering the color difference of nine instruments according to the 12 BCRA tiles reference all instruments performd good on black with least color difference. On the other hand, almost all instruments performed poor on the Red, Orange and Yellow tile. Regarding short-term and long-term repeatability all instruments performend according to the manufacturers defined agreement except for one instrument, which did not pass the short-term repeatability test. The results of the print measurements on different substrates showed rather large variations between the instrument families. Concequently, some of the instruments performed measurements, which are outside the given ISO tolerances. The consequences will be the use of only one certain instrument family in a color managed printing workflow and to reduce the "working" color difference tolerances according to the inter-instrument agreement of that instrument family.

It can be speculated that most of the printing presses nowadays use inline high speed instruments to control the colorimetric aim values. Furthermore, distributed printing has been very common. Therefore it might be interesting to determine the inter-instrument agreement within different inline instruments and between inline instruments and laboratory hand hold instruments.

Finally, it is of interest to consider other potential directions for further work in the field color measurement uncertainities. The performance of a number of color measurement instruments (and measurement technologies), in particular for emission purposes (display) in terms of precision (repeatability, reproducibility) and accuracy could be evaluated and the possible concequences of the inter-instrument reproducibility in color managed workflow adressed. Another area within the standardization process in the graphic art industry is the appropriate set up according to ISO 3664 and ISO 12646 and the measurement of the ambient light conditions where the same instruments including a diffuse light measurement head are been used.

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