Professional paper
UDK: 655:535.65

Measurement uncertainty in colour characterization of printed textile materials

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Abstract:
The subject of uncertainty of spectrophotometric measurement of printed textile materials is one of the major unsolved technical problems in textile colourimetry today. Textile manufacturers are often trying to maintain colour difference tolerances which are within the range or even less than the uncertainty of the measurement system controlling them. In this paper, two commercial spectrophotometers with different measuring geometries (GretagMacbeth Eye-One Pro with 450/0° geometry and ChinSpec HP200 with d/8° geometry) were comparatively investigated in terms of measurement uncertainty in colour characterization of textile products. Results of the study indicate that, the despite of different measuring geometry, instruments had the similar measurement repeatability behaviour (repeatability of readings from different parts of the same sample) in the case of used digitally printed polyester materials. The important influence on measurement variability had the material preparation method (were the materials triple folded, placed on a black backing or a white backing). On the other hand, instruments showed difference concerning the inter-model agreement. Although this difference was not confirmed as significant with visual assessment, observers evaluated the measurement readings from the Eye-One Pro spectrophotometer as more accurate colour appearance characterization of textile materials.

Key words: measurement uncertainty, measurement geometry, textile printing

Introduction

During the past 40 years of growth in colour measurement, colour instrumentation in the graphic industry has experienced a tremendous advancement in technology- the instruments have become more accurate, reliable, flexible, smaller, and faster than their predecessors (Randall, 2011). Currently, there are many different models of colour measurement instruments used in the textile industry. However, in a colour managed printing workflow, the use of inappropriate instrument or more than one instrument can impair and complicate the quality control of colour reproduction processes, since different instruments may show variations in terms of measurement precision (repeatability, reproducibility) and accuracy (Nussbaum, Sole & Hardeberg, 2011).

Measurement uncertainty

Measurement uncertainty includes two categories- precision and accuracy (Berns et al., 2000). While precision represents the dispersion of the measurement readings of the same target, the accuracy describes how close is the measured result to the actual target (“refer-

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First received: 23.10.2011.
Accepted: 31.11.2011.

ence") value (Berns et al., 2000). The precision is determined with the level of repeatability and the level of reproducibility. The repeatability defines the variation between readings of the same target repeated by the same instrument over a certain period and the most common way of quantifying repeatability is with Mean Colour Difference from the Mean (Berns et al., 2000): which is the average of the colour differences calculated between the mean of the taken measurements and each individual measurement.

The reproducibility defines the variation between readings of the same target from two or more instruments. If instruments are of identical design, that kind of reproducibility is called inter-instrument agreement, while inter-model agreement represents the reproducibility of two or more instruments of different design. The reproducibility is quantified with RMS colour difference (ASTM E2214-08, 2008), obtained from pairwise colour difference assessment of a series of readings from different samples:

The most precise and accurate colour measurement instruments are spectrophotometers. However, spectrophotometers with different design have different level of measurement uncertainty. One of the design parameters, which affect measurement uncertainty, is different measuring geometry (Nussbaum, Sole & Hardeberg, 2011).

Measuring geometry

The CIE (CIE, 1986) specified four geometric arrangements for colour measurement instruments. These are bi-directional geometry types: (a) $0^0/45^0$, (b) $45^0/0^0$, and diffuse geometry types: (c) 0^0/diffuse and (d) diffuse/0^0, as shown in Figure 1.

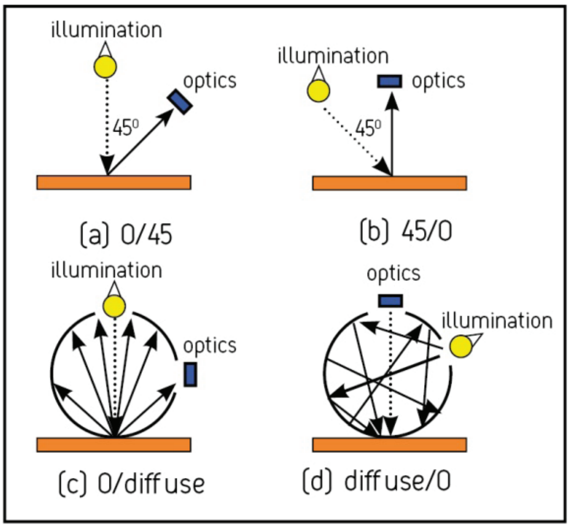


Figure 1: Recommended CIE Instrument Geometries (CIE, 1986)

The first number represents the illumination angle relative to a perpendicular drawn to the plane of the measured sample. The second angle is the measuring angle again expressed relative to the normal angle for the sample.

Figures 1a and 1b show bi-directional geometry with two types: $0^0/45^0$ or $45^0/0^0$. For example, in the case of the geometry used in a 0°/45° instrument the illumination of the sample is from 0° (90° from the sample surface), which means that the specular or gloss angle (the angle at which the light is directly reflected) is also 0°. The optics are located at 45° from the specular angle and, thus, do not detect the specular component. The term diffuse indicates that the illumination or viewing is not directional but rather diffuse, usually by the use of an integrating sphere. In diffuse geometry, illumination or viewing should be in direction normal to the sample and the remaining is diffused (collected from all direction) (Randall, 2011). Figures 1c and 1d show diffuse geometry with two types: 0^0/diffuse (0^0/d) and diffuse/0^0 (d/0^0).

In practice, d/0^0 (or 0^0/d) instruments are not truly 0-degree instruments, but rather closer to 6-8 degrees from the normal. For example, in the case of the geometry used in a 8°/d instrument, the sphere wall is covered with a highly reflective white substance, while the illuminant is located on the rear of the sphere wall. The diffuse illumination is provided by a baffle preventing the light source to directly illuminate the sample (Mouw, 1995). The sample is viewed at 8° from perpendicular which means that the specular or gloss angle is also 8° from perpendicular and this is where the specular port is located.

Using 8°/d instead of 0°/d geometry the specular component of reflectance may be excluded by allowing a portion of the gloss to escape through the specular port. That implicates that diffuse spectrophotometers can provide reflectance measurements in two different ways- the specular component included (SCI) and excluded (SCE). The measurement mode depends wheatear the specular port is opened (SCE) or closed (SCI). The SCE reading from a diffuse instrument will vary from a 0°/45° instrument's reading, since the 0°/45° geometry truly excludes all of the gloss, while the limited size of specular port may not entirely allow all of the gloss to escape.

There has been considerable debate about the relative advantages of two geometries.

If the sample is with a matte, regular surface, the amount of light reflected from that sample would be essentially constant at all angles, and nearly identical results would be obtained with both SCI and SCE mode, 0°/45° and diffuse instrument. The advantage of using instrument with diffuse geometry appears in the situations where the measured samples is with a gloss or/and an irregular surface, since the diffuse geometry averages out variations in the surface texture by the use of an integrating sphere (Mouw, 1995).

In the case of irregular or textured surface, the amount of light reflected varies greatly at differing angles. If this type of surface is measured with a 0°/45° instrument, the measurement readings can exhibit a wide variety of readings depending on measurement location (Johnston-Feller, 1983). A large variation between specular included and excluded readings would also be obtained when measuring a high gloss, regular surface, since the majority of the light is reflected at or near the specular angle. A 0°/45° instrument has an advantage in measuring regular, non textured surfaces, since it provides truly specular excluded reading (Billmeyer, Saltzman, 1981).

In general, bi-directional geometry is superior for measurement of colour and colour differences with good correlation with the visual assessment. However, for colorant formulation computation (or colour matching), the diffuse geometry is preferred as it handles specular light uniformly irrespective of surface properties (Mouw, 1995).

For these reasons, most instruments for colour formulation are diffuse since the colourist wants to measure strictly colour, especially when referent samples are not printed on the same substrate as requested for the match. In many process controls, it is necessary to verify both the geometric quality and colour, and, in these cases, a 45°/0° or 0°/45° geometry will provide the best assessment, since these instruments provide information not only about colour difference but also some appearance attributes such as surface gloss.

For textile industry, standards EN-ISO 105-J01 and 105-F10 define following conditions for colour characterizations: textile specimens should be measured using spectropthotometers with both $45^0/0^0$ ($0^0/45^0$) or $d/0^0$ ($0^0/d$) geometry, using CIE D65 illuminant and 10° CIE Standard Observer. The standards emphasize that instruments with different geometries may produce different colorimetric results on most textile materials and that the $d/0^0$ instruments are typically used. The aim of the presented work is to evaluate the measurement uncertainty performance of two measuring geometries in colour characterization of digitally printed textile products. The results of this study should contribute in defining guidance to support the proper measurement of the coloured textile samples in realistic industrial conditions.

Experimental part

Materials and instruments

Measurements were done on three textile materials (100% polyester) with characteristics presented in Table 1. Test chart consisting of 100% process colour patches was printed on these materials using Mimaki JV22-160 ink-jet printing machine with J-eco Subly nano inks.

Instruments used for textile colour characterisation were:

- GretagMacbeth Eye-One Pro ($45^0/0^0$ geometry with circumferential ring and the lightning aperture 4.5 mm) and
- ChinSpec HP200 ($d/0^0$ diffuse geometry with the lightning aperture 8mm and two measurement modes: SCI- the spectral component included and SCE-the spectral component excluded).

Both used colour measurement instruments had valid certifications.

Methods and procedures

Before conducting measurements of printed textile materials, the performance of two used instruments with different measuring geometries was firstly evaluated in terms of precision and accuracy according to standard ASTM E2214-08 (2008). As the standard preparation for measurements, the instruments were warmed up with 25 random measurements and then calibrated on their own white reference tile supplied by the manufacturer according to the manufacturer’s instructions. The measurement procedures were done according to ISO 13655 (1996).

Table 1: Specifications of used polyester (100%) materials

Material	Fabric weight (g/m^2)	Knitting density-Rows across length: p/10cm	Knitting density-Number of loops across length: p/10cm
1	110,6	170	120
2	101.5	160	100
3	141.3	260	120

Repeatability test procedure

The short –term repeatability is evaluated according to manufacturers' instruction using referent white tile and the MCDM colour differences were calculated (Berns et al., 2000).

Accuracy test procedure

The 12 colour patches, 6 chromatic (1st row) and 6 achromatic (4th row), from GretagMagbeth ColorChecker SG test chart (X-rite, 2007) were used to determine the accuracy of chosen instruments. For both instruments, single measurements (CIE Illuminant D50, 2° Standard Observer) of each colour patch had been taken in a sequence, from which the average was calculated and compared to the corresponding actual value, provided by X-Rite (X-Rite, 2009).

Measurements procedure on textile materials

In order to analyze the colour measurement variability in the case of textile materials, process colours (CMYK) were printed on three different polyester materials and then measured (CIE Illuminant D65, 10° Standard Observer) in three different manners:

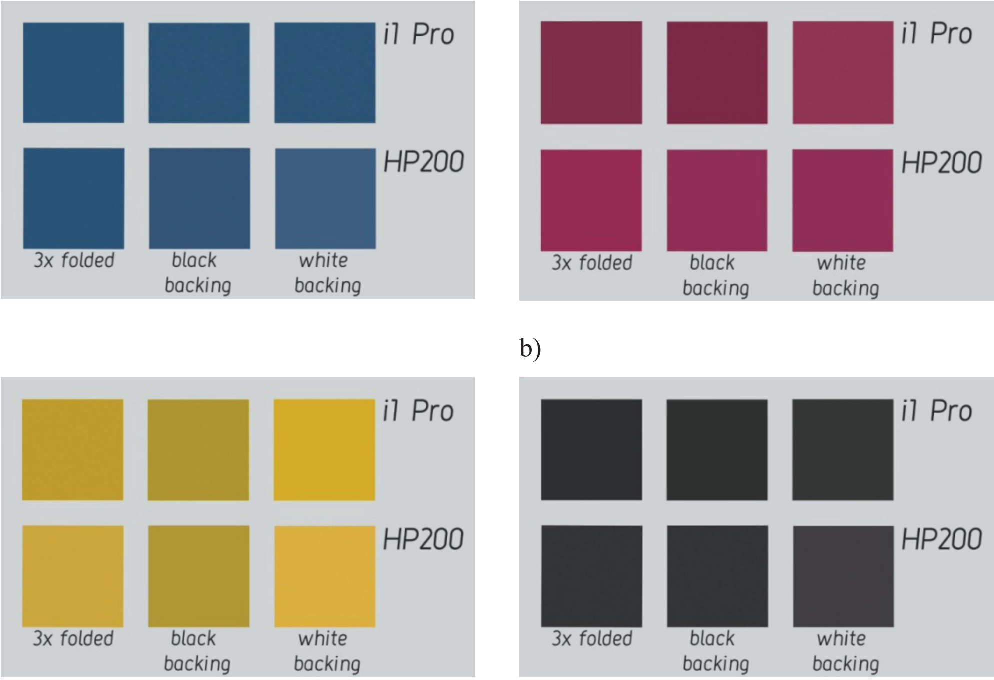
1. materials were triple folded during measurement,
2. materials were placed on a matte, black backing specified in ISO 5-3 (standard ISO 13655),
3. materials were placed on a matte, opaque white backing with L*>92 and C*<3 (standard ISO 13655).

The measurement uncertainties were obtained from 30 measurements. Although ten measurements is generally sufficient to characterise these values adequately, the uncertainty values are a little larger when a small number of replicate measurements are used due to elements of uncertainty introduced by the fewer measurements (Ladson, 2010).

Visual assessment

In visual assessment observers compared colour appearance between physical textile samples, viewed at a 45º angle in a Agile Radiant standard lightbox (illuminated with a filtered tungsten daylight simulating lamp with a correlated colour temperature of 6500±100K), and patches coloured with Lab values obtained with spectrophotometric measurements and presented on a monitor EIZO ColorEdge CG241W. A panel of 10 experienced observers (6 females and 4 males) with normal colour vision assessed each sample pair, after 2 minutes of adaptation to darkness. All extraneous light was eliminated. Figure 2 and 3 represent coloured patches, uniformly coloured and with mapped texture using LCH mapping method (Milic & Novakovic, 2011) on the scanned images of the physical samples.

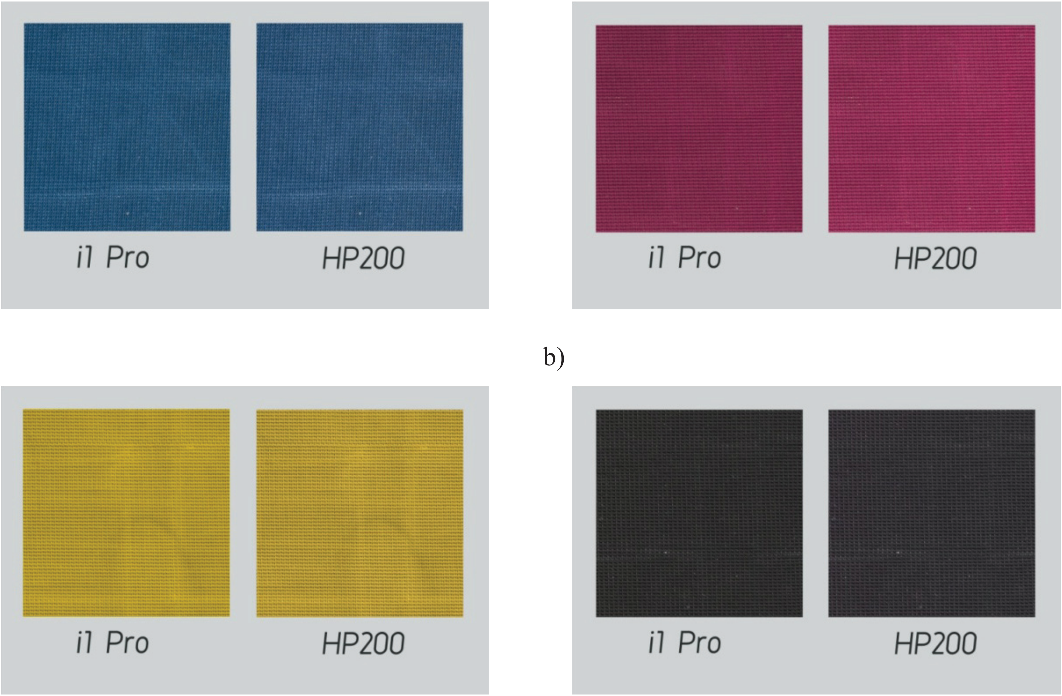
The visual assessment was conducted according to "grey scale" judgment test (Kasikovic et al., 2011), with following relation between colour difference ΔE and visual judgement presented in Table 2.



a) b)

c) d)

Figure 2: Sample patches coloured with obtained measurement readings (materials were triple folded during measurement, placed on black and white backing): a) cyan, b) magenta, c) yellow, and d) black patches.



a) b)

c) d)

Figure 3: Sample patches coloured with obtained measurement readings with mapped texture: a) cyan, b) magenta, c) yellow, and d) black patches.

*Table 2: The relation between colour difference ΔE*ab and visual judgement according to grey scale*

Colour difference interval	Visual judgement
ΔE<0.4	5
0.4<ΔE<1.25	4-5
1.25<ΔE<2.10	4
2.10<ΔE<2.95	3-4
2.95<ΔE<4.10	3
4.10<ΔE<5.80	2-3
5.80<ΔE<8.20	2
8.20<ΔE<11.60	1-2
ΔE>11.60	1

Results and discussion

Measurement repeatability and inter-instrument agreement

Table 3 shows manufacturer's agreement and the corresponding results in terms of the short-term and medium-term measurements. As can be noticed from Table 2, both instruments had satisfactory repeatability behavior in manufacturers' tolerances.

Table 3: The short-term repeatability

Model	Short term repeatability (manufacturer's agreement)	Short term repeatability (MCDM measured)
Eye-One Pro	Expected: 0.1, (ΔE94 D50, 2deg) (value of 10 measurements every 3 sec on white tabula)	0.014 (pass)
HP200	Expected standard deviation: within ΔE 0.08 – (interval test 30 times on white tabula)	0.05 (pass)

The manufacturers also have defined inter-instrument agreements within their instrument families. The inter-instrument agreement is only checked for the Eye-One Pro instrument and it is within the acceptable tolerances defined by manufacturer (average ΔE94 0.4, max ΔE94 1.0 (D50, 2°)). Another HP200 instrument was not available for the inter-instrument agreement testing during this research.

Measurement accuracy and inter-instrument agreement

Figure 4 show the colour difference between each instrument's reading on the test chart patches and the corresponding actual value.

It can be noticed that the chromatic patches give larger colour differences than the achromatic ones. The reason for these results lies in the nature of high chroma sample patches, which are difficult to measure and correct because a small variation in the steep slope of the reflectance curve causes a large ΔE error (Group of authors: Woodhead Publishing, 2010).

The accuracy of the achromatic patches is on the satisfactorily level. However, the accuracy of some chromatic patches is far outside the defined tolerances. The presented readings show significant difference between measurements from HP200 (both the SCI and the SCE mode) and Eye-One Pro instrument, especially for "dark skin", "light skin", "foliage" and "bluish green" patches, and no noticeable difference between the SCI and the SCE measurement mode of the HP200 instrument. The lowest mean accuracy showed the SCE mode of the HP200 instrument (mean ΔE 4.17), while the SCI mode of HP200 Eye-One Pro had the similar mean accuracy (mean ΔE 3.19 and mean ΔE 3.21 respectively).

Looking at the pairwise colour differences between instruments in Table 4, the inter-model agreement between two instruments can be considered as rather week for the chromatic patches and good for the achromatic patches. Since the SCE mode of diffuse instrument is "mimicking" specular excluded 45°/0° geometry, larger RMS (Eye-One Pro vs. SCE HP200) than RMS (Eye-One Pro vs. SCE HP200) value is unexpected result indicating low efficiency of the specular port in the HP200 instrument. Although the results show a rather low overall accuracy, a relatively high precision of both instruments can be considered due to the measurement dispersion.

Measurement uncertainty of printed textile materials

Figure 5 shows measurement variability of textile materials. Results from the Figure 5 indicate that both instruments had the similar measurement repeatability (repeatability of readings from different parts of the same sample) in the case of used digitally printed polyester materials. All measures of repeatability lead to the conclusion that the uncertainties involved are well below the just-perceptible colour difference. Considering its measuring geometry and smaller lightning aperture (the larger aperture leads to more averaged measuring results and, thus, to smaller measurement uncertainty) it was expected for the Eye-One Pro instrument to exhibit significantly larger measurement variability behaviour on textile materials. The reason for this good repeatability behaviour of a $45^0/0^0$ spectrophotometer, in measuring textile materials can be found in

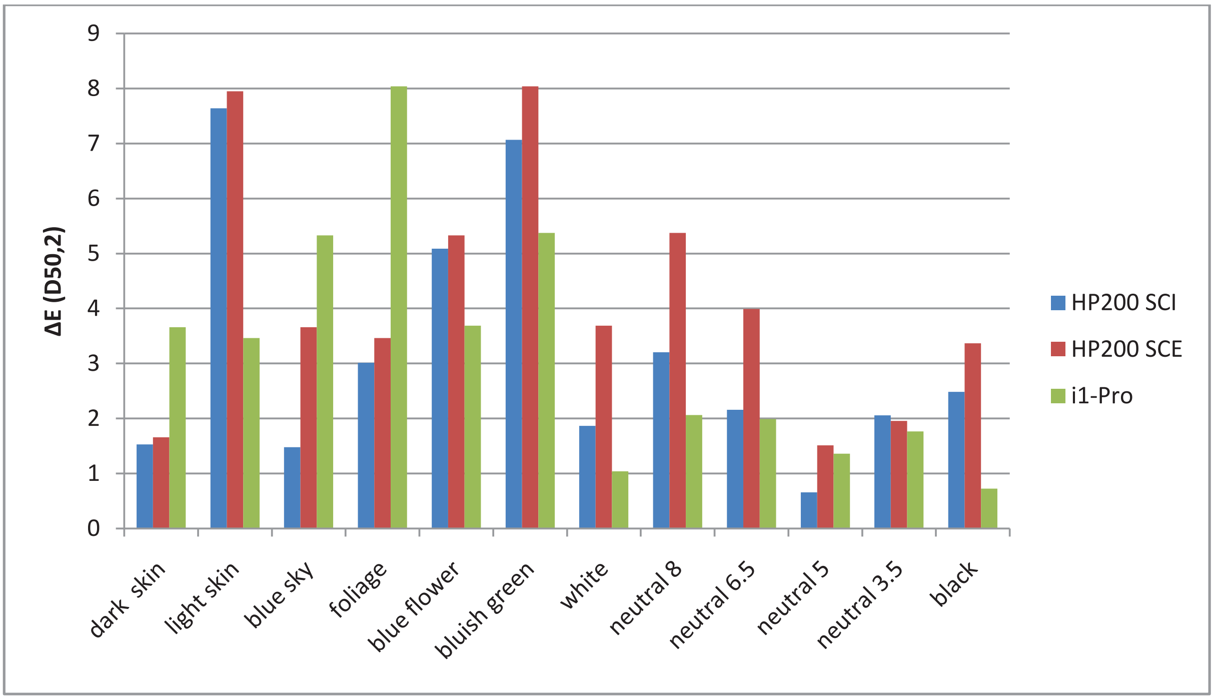


Figure 4: Colour difference of two instruments according to the 12 colour patches from GretagMagbeth ColorChecker SG test chart (CIE Illuminant D50, 2° Standard Observer)

Table 4: The inter-model agreement between two instruments

ΔE*ab	i1-Pro vs. HP200 SCI	i1-Pro vs. HP200 SCE	HP200 SCI vs. HP200 SCE
dark skin	6.98	6.10	0.92
light skin	7.39	7.60	0.50
blue sky	2.68	4.07	2.21
foliage	6.33	6.16	0.53
blue flower	4.43	4.32	0.55
bluish green	6.39	6.87	1.79
white	1.61	3.37	2.84
neutral 8	0.89	3.58	3.11
neutral 6.5	1.34	2.31	1.97
neutral 5	1.35	0.43	1.41
neutral 3.5	1.28	1.19	0.12
black	1.86	2.71	0.91
Mean ΔE error	5.70	5.86	1.08
RMS	4.31	4.60	1.69

its circumferential “ring”, which resolves problem of poor reproducibility in colour measurement of textile samples in today’s $45^0/0^0$ (or $0^0/45^0$) colorimeters and spectrophotometers (Randall, 2011). This geometry is termed circumferential $45^0/0^0$ geometry to differentiate it from the bi-directional $45^0/0^0$ geometry. The additional explanation can be found in the fine textured and regularly repeating knitting pattern of chosen polyester materials. The significant influence on measurement readings had the measurement preparation method (were the materials triple folded, placed on black backing or white backing). The lowest measurement variability for both instruments is obtained when polyester materials were triple folded and the worse by measuring with white backing. Another important conclusion deducted from Figure 5 is that there are no significant differences in terms of measurement repeatability between three polyester materials with different fabric weight and knitting density. Based on this conclusion, the visual assessment is conducted only for Material 1.

From Table 5 can be observed that instruments showed difference concerning the inter-model agreement especially in the case of yellow and magenta patches. However, the calculated colour differences CIE ΔE 2000 which defines a calculation by spectrophotometers close to the colour discrimination threshold of the human eye and the colour difference ΔE94 tex, which is specially adapted for the textile materials, show that this differences are actually less perceptible than it is obtained with CIE ΔE*ab (CIE ΔE76).

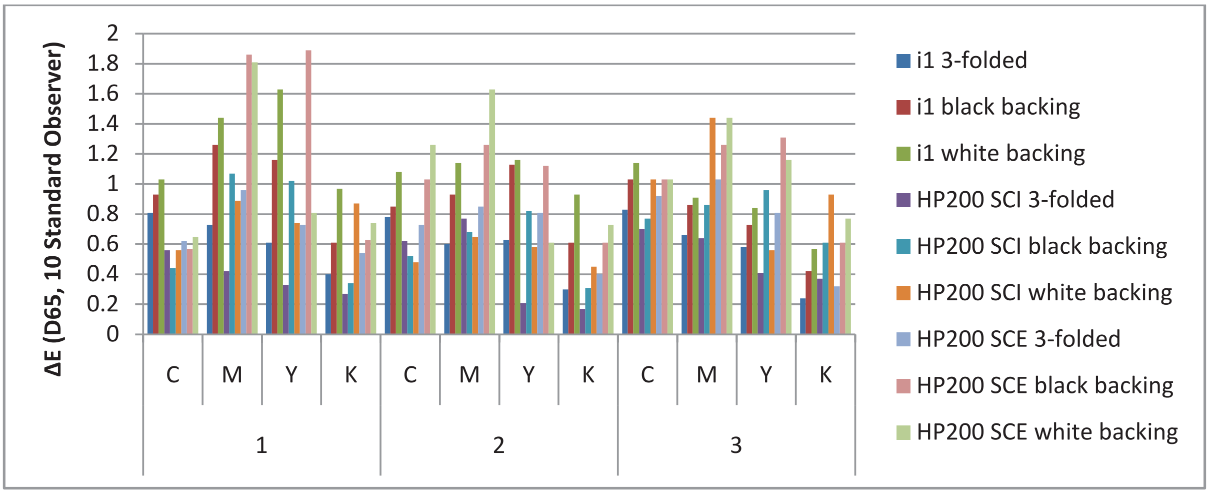


*Figure 5: Measurement repeatability of readings from different parts of the same sample (MCDM ΔE*ab) (CIE Illuminant D65, 10° Standard Observer)*

Table 5: The inter-model agreement between two instruments (CIE Illuminant D65, 10° Standard Observer)

Material 1 a		Eye-One Pro			HP200 SCI			Colour difference (Eye-One Pro vs. HP200 SCI)		
		b	L	a	b	L	ΔE*ab	ΔE94 tex	ΔE2000	
Triple folded	C	34.4	-5.9	-23.8	35.2	-4.1	-23.2	2.06	1.36	1.73
	M	32.4	39.0	3.0	35.7	46.6	3.6	8.3	3.12	3.74
	Y	65.7	7.1	70.0	69.4	7.1	57.8	12.75	3.4	4.37
	K	19.6	-0.7	-0.6	21.8	2.2	-1.4	3.73	3.14	4.50
Black background	C	33.5	-5.9	-23.2	34.9	-4.1	-23.0	2.29	1.49	1.94
	M	31.2	37.4	2.2	36.3	44.3	2.3	8.58	3.55	4.80
	Y	62.3	2.4	65.2	62.7	3.3	52.9	12.34	3.07	3.5
	K	19.5	-0.7	-0.5	21.5	1.9	-1.3	3.35	2.82	4.06
White background	C	36.5	-6.5	-24.2	39.9	-4.0	-22.7	4.48	2.48	3.71
	M	36.9	41.4	3.6	41.4	49.8	3.4	9.53	3.6	4.8
	Y	72.4	8.2	77.0	73.8	8.8	60.9	16.17	3.6	4.3
	K	22.9	-0.8	0.0	27.3	1.9	-1.4	5.35	3.71	5.20
Mean ΔE error								6.29	2.68	3.51
RMS								8.63	3.04	4.02

Visual assessment

Results of visual assessment represented on Figure 5 indicate that observers evaluated the measurement readings from the Eye-One Pro spectrophotometer as more accurate colour appearance characterization of textile materials, although this advantage is not significant according to t-test results (except for yellow colour). From Figure 6 can be deducted that best visual match is obtained when textile material is triple-folded, so that is the recommended procedure for textile colour characterisation.

The summary of t-tests significances is presented in Table 6. The conducted t-tests show significantly higher visual evaluation grades which represent better visual match between physical textile sample and coloured sample on a monitor in the case where mapping of texture is applied on coloured patch, implicating that an adequate colour mapping method should be used during soft proofing of the textile products since the standard soft proofing technique using solid colour patches does not include influence of texture on colour appearance.

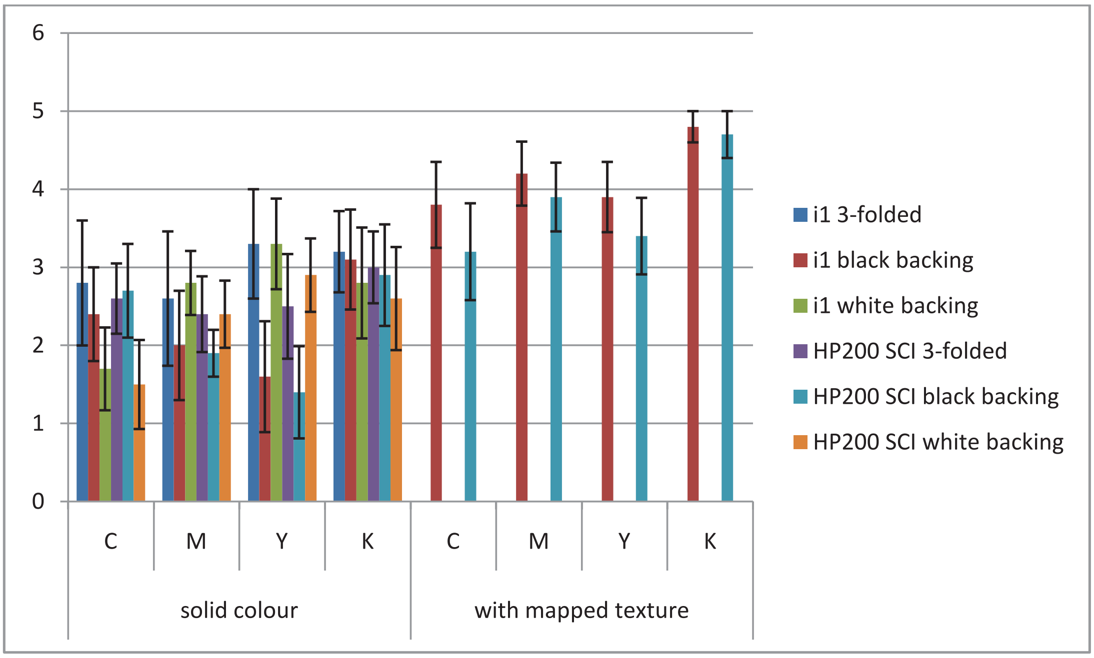


Figure 6: Visual judgment of sample pairs- mean grades and standard deviation (Material 1)

Table 6: T-test significance of visual assessment (Material 1)

T- test significance	t-tests significance between instruments (Eye-One vs HP200 SCI)			t-tests between preparation mode			
NS- not significant	3-folded	black backing	white backing	3-folded vs black backing	3-folded vs white backing	black vs white backing	solid colour vs mapped texture
C	NS ($p>0.05$)	NS ($p>0.05$)	NS ($p>0.05$)	NS ($p>0.05$)	$p<0.05$	$p<0.05$	$p<0.05$
M	NS ($p>0.05$)	NS $p<0.05$	($p>0.05$)	$p<0.05$	NS ($p>0.05$)	$p<0.05$	$p<0.05$
Y	$p<0.05$	NS ($p>0.05$)	$p<0.05$	$p<0.05$	NS ($p>0.05$)	$p<0.05$	$p<0.05$
K	NS ($p>0.05$)	NS ($p>0.05$)	NS ($p>0.05$)	NS ($p>0.05$)	$p<0.05$	$p<0.05$	$p<0.05$

Conclusion

Utilizing conveniences of digital colour communication (i.e., no sharing of physical textile samples, only sharing digital colour data for pass/fail decisions) throughout the various stages of the supply chain in the textile industry is an attractive route to increasing the product quality, shortening production times and reducing costs. However, in order for digital communication to be effective, the representation of colour patch on a monitor must correlate to visual appearance of textile materials or, in other words, the implemented colour management system must be reliable. Since the fundament of colour management system represent ICC device profiles, obtained by spectrophotometric measurements, reliability of colour management system directly depends on the spectrophotometric measurement uncertainty. The uncertainty analysis is the determination of the quality of the measurement result. Quantifying the measurement uncertainty allows textile manufacturers to add value to production process.

Considering results obtained with this study, despite of the measuring geometry, which is not recommended for textile materials, Eye-One Pro spectrophotometer could be used in colour reproduction workflow of textile industry for creating ICC profiles, which will be used for the accurate soft proof and the colour formulation. Furthermore, for optimal colour management textile material should be triple folded during measurement and a texture mapping method should be applied during soft proofing of textile materials.

The direction of further work should involve research of the measurement uncertainty in the case of different textile materials with different regular and irregular knitting patterns.

Acknowledgment

This work was supported by the Serbian Ministry of Science and Technological Development, Grant No.:35027 “The development of knowledge and production in graphic arts industry”.

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