

TEXTILE TECHNOLOGY

Instrumental and Operational Impacts on Spectrophotometer Color Measurements

J. Rodgers*, D. Thibobeaux, X. Cui, V. Martin, M. Watson, J. Knowlton

ABSTRACT

Color measurements for the classing of U.S. cottons are normally performed on the Uster® High Volume Instrument (HVI), which yields two color parameters specific to cotton—Rd (reflectance) and +b (yellowness). Since Rd and +b do not readily relate to other well known and globally recognized color systems (e.g., L*a*b* or CIELAB), a program was implemented to evaluate and validate the relationships of Rd and +b to a globally recognized color system (L*a*b*) and to investigate the impacts of key instrumental and operational variables on the color results. The tile and cotton fiber batt samples analyzed were measured on 7 color spectrophotometers (bench-top and portable). Strong L*↔Rd and b*↔+b correlations were observed on all color units, and very similar linear relationships were obtained for L*↔Rd and b*↔+b regardless of the bench-top unit used. Thus, the use of L*a*b* for relating globally recognized color parameters from a color spectrophotometer to the HVI's Rd and +b color parameters was validated. The primary variable that impacted the color agreement between units was the use of HVI glass in front of the sample. L* was the color parameter that was most impacted by the use of glass in the tile and cotton fiber color measurements. The use of glass leads to a “shift” in the sample's reflectance spectrum (%R). These shifts in %R, and the use of only 2 color filters in the HVI unit, lead to the observed differences in L*↔Rd when glass is used in the measurement.

INTRODUCTION

When a person “sees” a color, they are in reality observing with their eye and processing with their brain the light reflected off of an object that has been illuminated with a light source (e.g., the sun if outside). Thus, color is composed of 3 components and results from the interaction of a light source, an illuminated object, and the eye/observer or a “visual system” (Billmeyer and Hammond, 1996; Billmeyer and Saltzmann, 2000; HunterLab, 2000). Light is the electromagnetic radiation observed by the human eye, with the visible color spectral region consisting primarily from between 400nm (violet) and 700nm (red) (figure 1). The spectral reflectance curve obtained for a specie in this wavelength region is often called the “spectrum” for that object. In order to go from human color perception to a true color measurement, the three components for color must switch from the Light Source→Object→Eye/ Brain system to an Illuminant Spectrum→Object Spectrum→Color Matching Functions or Standard Observer Spectrum system. The mathematical combination of these three spectrums results in the total spectrum for all three components. (Billmeyer and Saltzmann, 2000; HunterLab, 2000; Hunter, 1975)

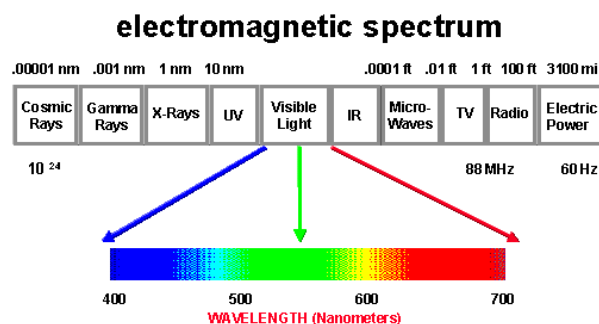


Figure 1. The electromagnetic spectrum (visible region between 400-700nm).

The true desire for color measurements is a set of numbers that will be representative of the total spectrum and indicative of the color of an object. An early color space system was that of Munsell, which is composed of three variables—lightness or value,

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hue (“color”), and chroma or saturation. (Billmeyer and Hammond, 1996; Billmeyer and Saltzman, 2000; Ohno, 2000) In addition, the color of an object can also be represented as a 3-dimensional (xyz axes) or “tristimulus” color space. Algorithms from the Commission on Illumination (CIE) can be used for the color results from a color instrument to obtain the CIE XYZ tristimulus values (often called the XYZ color space system) for an object. The need for a uniform color space that yielded improved perception of colors led to the development of a number of non-linear transformations of the CIE XYZ color space system. Several CIE color space systems have been developed using the XYZ tristimulus values as a base, and one of the most popular and globally recognized color space systems is the 3-dimensional CIELAB color space system (often denoted as $L^*a^*b^*$). In $L^*a^*b^*$, L^* represents lightness or darkness of a sample; a^* represents redness or greenness of a sample; and b^* represents the yellowness or blueness of a sample (figure 2). (Billmeyer and Saltzman, 2000; Hunter, 1975; Judd and Wyszecki, 1975) To obtain $L^*a^*b^*$, the spectrophotometer measures the diffuse reflectance of the sample, R_λ , at specific wavelength intervals over the wavelength range of the spectrophotometer (normally, a 10 nm wavelength interval). The tristimulus color coordinates XYZ, are calculated from the product of the object’s reflectance values, the spectrum for the illuminant, and the standard observer values. $L^*a^*b^*$ can then be calculated from XYZ by the equations

$$L^* = 116(Y/Y_n)^{1/3} - 16 \quad (1)$$

$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}] \quad (2)$$

$$b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}] \quad (3)$$

where X_n , Y_n , and Z_n are the values of X, Y, and Z for the illuminant that was used for the calculation of X, Y, and Z of the sample.

There are two main types of color instruments used to measure the color of textile products—colorimeters and spectrophotometers (Billmeyer and Saltzman, 2000; Hunter, 1975). Colorimeters use broad-band filters—often two or three—to obtain the tristimulus XYZ values directly (no spectrum for the object is obtained). Spectrophotometers measure the full visible spectral range to obtain a reflectance spectrum of a sample for a known illuminant, and the tristimulus XYZ values can be calculated by the product of the object’s reflectance values, the spectrum for the illuminant, and the standard observer values. Although not as all encompassing as

the spectrophotometers, colorimeters are sometimes preferred to spectrophotometers because of their low cost of manufacture and their portability. The HVI is a cotton colorimeter.

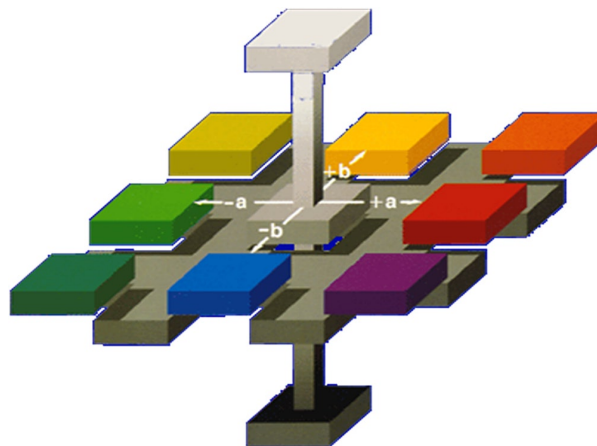


Figure 2. Example of the CIELAB or $L^*a^*b^*$ color space system.

U.S. produced cotton is classed and most of its quality parameters are determined by the Uster® High Volume Instrument (HVI), whose primary quality measurements include fiber length, length uniformity, strength, micronaire, trash content, and color. To class cotton color, the HVI measures the sample at two wavelengths/bands to obtain the parameters R_d (diffuse reflectance) and $+b$ (yellowness). The R_d and $+b$ color parameters are specific to cotton fiber, and they do not readily relate to other well known and globally recognized color systems (e.g., $L^*a^*b^*$). The standards used for the HVI units are Agricultural Marketing Service (AMS) reference ceramic tiles and cottons, which are not scientifically recognized standards such as those from NIST (National Institute of Standards and Technology). The color of the ceramic and cotton fiber batt standards are measured on a master colorimeter-HVI by AMS.

The origins of R_d and $+b$ begin as early as 1931, when Nickerson used a disk colorimeter to prepare cotton grade standards. (Nickerson, 1931) In this research, color results were given in terms of Munsell space (value and chroma). Since cotton was considered to have an almost constant hue (“white”) for the cottons studied, a 2 dimensional color space system representing Munsell value and chroma was considered sufficient. In 1948, a new color instrument was developed based on the application of the Hunter Color and Color-Difference Meter. (Nickerson, Hunter, and Powell, 1950) This

instrument measured color in terms of R_d and $+b$. From this work, the slow transition of cotton color measurements to R_d and $+b$ began.

A preliminary study with one bench-top color spectrophotometer observed a distinct linear relationship between $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ on Agricultural Marketing Service (AMS) standard tiles and standard cotton fiber batts. (Thibodeaux, et. al., 2005) Rodgers, et. al. (2006) examined the potential for “traceable” color standards for cotton color measurements (color tiles, AMS standard tiles, AMS standard cotton batts) and $L^*a^*b^*$ inter-instrument agreement on a small set of color spectrophotometers. Shofner, et. al. (2006) also examined the potential for “traceable” color standards on one color spectrophotometer and an ACTS/IsoTester color unit. Both studies indicated a significant impact on the color results when glass is used in the color measurement [HVI glass (approximately 6 mm thickness) placed between the sample and the instrument measurement port].

In order for “traceable” standards to be developed for color measurements of cotton, it is desirable for the standards employed to yield reproducible and similar color results ($DE^* < 1.0$) between different color spectrophotometers and other color units and in some manner be related back to NIST-traceable color units and standards. DE^* indicates the degree of color difference and can be expressed as the square root of the sum of the square of the differences in L^* (DL^*), in a^* (Da^*), and in b^* (Db^*), where D is the color parameter difference between the instrument being compared and the reference instrument for that specific color parameter of interest (L^* , a^* , or b^*). A $DE^* > 1.0$ is generally recognized as a significant color difference. (Berger-Schunn, 1994) A program was implemented to perform comparative color analyses with multiple color units (bench-top and portables) from several vendors to study the “universality” of the previously observed relationship(s) of R_d and $+b$ to $L^*a^*b^*$ and to study the influence of various instrumental and sampling/procedural variabilities on the color result. In this investigation, the comparative program was expanded to 7 color spectrophotometers (bench-top and portable instruments) from four vendors. In addition, the relationships of $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ between the multiple spectrophotometers and the HVI unit were studied. Spectral analyses were performed, and the results used to study the $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ relationships and the impact of instrumental and sampling/operational variabilities on the color result. The program was a joint project

between the Southern Regional Research Center (SRRC) of the Agricultural Research Service (ARS), Cotton Incorporated, and AMS.

MATERIALS AND METHODS

The samples analyzed were Macbeth color tiles (13 tiles, wide color range), AMS standard tiles (2 sets of 5 tiles per set), and AMS standard cotton fiber batts (2 boxes, 12 fiber batts per set). An example of the AMS ceramic tiles and cotton batts are given in Figures 3 and 4. All samples were measured at the Materials Testing Laboratory of the Cotton Structure & Quality Research Unit, Southern Regional Research Center-Agricultural Research Service-United States Department of Agriculture (CSQ, SRRC-ARS-USDA).

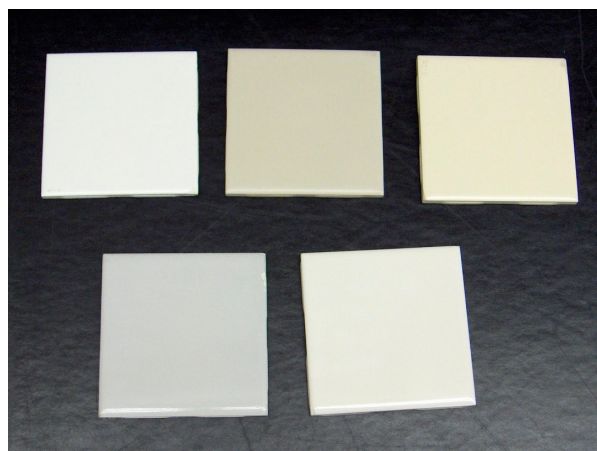


Figure 3. Representative set of 5 AMS ceramic tiles



Figure 4. Representative set of 12 AMS cotton batts.

The samples were measured on 7 color spectrophotometers from four color instrument manufacturers (bench-top and portable instruments). The bench-top color spectrophotometers were the Macbeth CE7000A (reference), X-Rite 8400, Minolta CM7000, and Hunter-Lab UltraPro. The portable spectrophotometers were the Macbeth XTH, X-Rite SP64, and Minolta CM2600d.

Each sample was measured 5 times (5 replicates) on each color instrument, and the instrumental settings were illuminant D65, 10° observer, large area of view, and both specular component excluded (SCE) and included (SCI), where possible. The SCE results are reported in this paper. Similar results were obtained for SCI (with normally higher L* and slightly lower b* results).

The illuminant is the instrumental “light source,” and D65 represents average daylight (daylight with a correlated color temperature of 6500 K). The “10° observer” refers to a 10° field of view for the sample and the type of standard observer or color matching functions. The area of view is the size of the sampling/measuring port for the instruments evaluated. SCE and SCI denote the inclusion or exclusion of the specular component of reflected light from the sample’s surface. When light strikes the surface of a sample, two main types of reflectance can result—specular and diffuse reflectance. Specular reflectance is a mirror-light reflection in which light is reflected off the object’s surface in an equal but opposite direction. Diffuse reflection is the scattered or diffused reflected light from the sample. Often, SCE is used to measure the sample’s color (diffuse reflectance only), while SCI is used to demote the sample’s appearance (diffuse and specular reflectance). Thus, more total reflected light is present for SCI compared to SCE, which often results in higher L* and slightly lower b* results. (Billmeyer and Saltzmann, 2000; Billmeyer and Hammond, 1996; HunterLab, 2000; Hunter, 1975)

All tile samples were measured “without glass” (“as is”; tile samples placed directly against the spectrophotometer port) and “with glass” (a portion of a glass plate from a HVI unit was placed between the sample and the spectrophotometer port). The cotton samples were measured with glass only. The same 6mm thick HVI glass was used for all “glass” measurements.

Each unit was compared for the impact of instrumental and operational/sampling variables on the color results. The color results were compared by L*, a*, b*, and DE*, with the Macbeth CE7000A spectrophotometer as the reference/“standard” unit. DE* is often used to denote the total color difference for all 3 dimensions of color space (L*, a*, and b*). DE* can be expressed as the square root of the sum of the square of the differences in L* (DL*), in a*(Da*), and in b*(Db*), as shown in equation 1.

$$DE^* = \sqrt{(DL^*)^2 + (Da^*)^2 + (Db^*)^2} \quad (1)$$

“D” is the difference in color result between the instrument being compared and the reference instrument (e.g., Macbeth CE7000A) for the color parameters L*, a*, and b*. A DE* > 1.0 is generally recognized as a significant color difference. (Berger-Schunn, 1994)

RESULTS AND DISCUSSION

As noted above, a program was implemented to perform comparative color analyses with multiple color units (bench-top and portables) from several vendors to study the “universality” of the previously observed relationship(s) to Rd and +b to L*a*b* and to study the influence of various instrumental and sampling/procedural variabilities on the color result. In this investigation, the comparative program was composed of 7 color spectrophotometers (bench-top and portable instruments) from four vendors.

Tables 1 to 4 compared the DE* color agreement between bench-top and portable units on the color tiles and AMS tiles, both with and without glass (SRRC’s Macbeth CE7000A bench-top spectrophotometer was the reference unit). When glass is not used in the color measurement with bench-top units, DE* was < 1.0 for most color tiles and all AMS tiles. However, the color unit agreement was much lower when glass is used in the color measurement (DE* > 1.0 for most measurements), with the worst color unit agreement occurring with the portable units (highest DE*s). Tables 5 and 6 and figures 5-8 indicate the comparative agreement for L*, a*, and b* between the various bench-top spectrophotometers on AMS tiles, both with and without glass. L* is the color parameter that is most impacted by the use of glass in the color measurement, followed by b* and a*. For L*, |DL*| between spectrophotometers was often > 1.0 when glass was used in the color measurement, but |DL*| between spectrophotometers was < 1.0 when glass was not used in the color measurement. For b* and a*, the comparative agreement between the various bench-top and portable spectrophotometers on AMS tiles, both with and without glass, often yielded |Db*| and |Da*| results that were < 1.0, with the least glass impact observed for a*. These results indicate that the development and use of “traceable” standards for HVI cotton color measurements is feasible, with the most promising standard system being the use of ceramic or metal tiles on a research-grade bench-top spectrophotometer with no glass between the sample and spectrophotometer port.

Table 1. Comparison of DE* between spectrophotometers, Macbeth color tiles, without glass. MB=Macbeth, XR=X-Rite, MIN=Minolta, HL=HunterLab, second B=Bench-top, P=Portable

Sample	DE*, without glass						
	MBB	XRB	MINB	HLB	MBP	XRP	MINP
White	REF	0.22	0.10	0.39	0.18	0.46	0.63
Off white	REF	0.19	0.08	0.50	0.21	0.44	0.69
Lt. gray	REF	0.18	0.09	0.64	0.32	0.39	0.82
Dk gray	REF	0.15	0.41	0.59	0.19	0.33	0.70
Charcoal	REF	0.11	0.02	0.96	0.22	0.69	1.21
Mauve	REF	0.26	0.23	1.05	0.21	0.58	1.21
Red-orange	REF	0.67	0.47	1.67	0.46	0.80	1.90
Orange	REF	0.74	0.99	1.75	0.25	1.46	2.29
Yellow	REF	0.64	0.23	1.29	0.46	1.36	1.93
Med green	REF	0.50	0.29	0.96	0.30	0.93	1.37
Lt green	REF	0.52	0.23	1.23	0.32	1.24	1.78
Blue	REF	0.34	0.26	0.90	0.10	0.48	1.02
Purple	REF	0.24	0.44	0.64	0.24	1.50	1.65

Table 2. Comparison of DE* between spectrophotometers, AMS standard tiles, without glass. MB=Macbeth, XR=X-Rite, MIN=Minolta, HL=HunterLab, second B=Bench-top, P=Portable

Sample	DE*, without glass						
	MBB	XRB	MINB	HLB	MBP	XRP	MINP
<i>BOX 1</i>							
P101	REF	0.22	0.47	0.32	0.22	0.18	0.29
P102	REF	0.19	0.30	0.52	0.30	0.21	0.86
P103	REF	0.22	0.22	0.32	0.18	0.21	0.45
P104	REF	0.18	0.29	0.49	0.30	0.64	0.68
P105	REF	0.50	0.08	0.43	0.21	0.63	0.50
<i>BOX 2</i>							
P201	REF	0.22	0.15	0.35	0.17	0.25	0.38
P202	REF	0.21	0.77	0.54	0.35	0.34	0.65
P203	REF	0.22	0.28	0.30	0.24	0.32	0.54
P204	REF	0.17	0.09	0.51	0.35	0.49	0.79
P205	REF	0.23	0.08	0.43	0.13	0.54	0.62

The primary variable that impacted the color agreement between units was the use of HVI glass in front of the sample being measured (with glass measurements). The glass impact was severe for the portable units' agreement to the reference bench-top unit, but less so for the bench-top units. The severe impact of glass use on the color results with the portable color units, compared to the impact of glass use on the bench-top color units, is most likely due to the differences in

instrument geometry between the portable and bench-top color units. All of the bench-top and portable color units contained integrating sphere geometry. However, the integrating spheres for the bench-top units were much larger than those on the small, hand-held portable units, and the impact of a 6mm glass plate placed at the sampling/measurement port on the color results would be expected to be much more severe on units with smaller integrating spheres.

Table 3. Comparison of DE* between spectrophotometers, Macbeth color tiles, with glass. MB=Macbeth, XR=X-Rite, MIN=Minolta, HL=HunterLab, second B=Bench-top, P=Portable

Sample	DE*, with glass						
	MBB	XRB	MINB	HLB	MBP	XRP	MINP
White	REF	1.28	2.24	1.56	10.16	5.44	1.87
Off white	REF	1.12	1.99	1.45	8.30	4.49	2.04
Lt. gray	REF	0.84	1.52	1.23	6.38	2.79	1.83
Dk gray	REF	0.84	1.51	1.28	6.17	2.70	1.62
Charcoal	REF	1.10	1.13	1.39	2.72	2.78	2.82
Mauve	REF	0.81	1.27	1.17	5.37	3.58	1.82
Red-orange	REF	0.99	1.35	0.74	10.02	8.58	1.87
Orange	REF	1.16	2.15	1.40	13.77	11.76	1.82
Yellow	REF	1.17	2.39	1.79	13.52	10.80	2.07
Med green	REF	0.86	1.73	1.34	7.66	5.33	1.93
Lt green	REF	0.84	1.64	1.69	7.55	5.30	1.99
Blue	REF	0.85	1.56	1.56	6.89	5.02	1.51
Purple	REF	3.21	2.15	3.53	6.83	13.86	1.38

Table 4. Comparison of DE* between spectrophotometers, AMS standard tiles, with glass. MB=Macbeth, XR=X-Rite, MIN=Minolta, HL=HunterLab, second B=Bench-top, P=Portable

Sample	DE*, with glass						
	MBB	XRB	MINB	HLB	MBP	XRP	MINP
<i>BOX 1</i>							
P101	REF	2.03	1.76	1.54	9.62	5.42	2.64
P102	REF	1.50	2.25	1.81	8.20	4.25	2.18
P103	REF	1.05	1.97	1.43	9.26	5.16	1.17
P104	REF	0.44	2.92	2.00	10.07	5.06	1.09
P105	REF	1.24	2.12	1.44	9.85	5.12	1.27
<i>BOX 2</i>							
P201	REF	1.16	2.11	1.58	9.81	5.53	2.07
P202	REF	1.00	1.30	0.88	8.70	4.68	1.51
P203	REF	1.18	2.51	1.77	9.61	5.49	1.15
P204	REF	1.06	1.96	1.40	8.37	4.25	0.54
P205	REF	1.14	2.26	1.66	9.90	5.08	1.20

Next, the color parameter relationship between $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ was studied in detail and validated. The two sets of AMS tiles were measured on the SRRC MacBeth CE77000A bench-top spectrophotometer, with 6mm HVI glass (same glass used in both studies). This is a repeat of a previous study that indicated strong $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ correlations (Thibodeaux, et. al., 2005), and the purpose of this investigation was to verify the previous correlation results on the same spectrophotometer

prior to expanding the investigations to multiple color spectrophotometers. Very similar $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ correlations were obtained between the previous and new investigation. As observed in the previous Thibodeaux study, the $L^* \leftrightarrow R_d$ agreement in the new investigation was linear with a slope of near 2.0 and a large offset, and the $b^* \leftrightarrow +b$ agreement yielded a linear relationship with a slope of near 1.0 and a small offset. (figures 9 and 10)

Table 5. Comparison of DE* components (DL*, Da*, Db*) between spectrophotometers, AMS standard tiles, without glass. MB=Macbeth, XR=X-Rite, MIN=Minolta, HL=HunterLab, second B=Bench-top, P=Portable

sample	DE* components, without glass						
	MBB	XRB	MINB	HLB	MBP	XRP	MINP
<i>DL*</i>							
P101	REF	0.06	-0.44	0.10	-0.19	0.05	-0.25
P102	REF	-0.04	-0.26	0.01	-0.24	0.03	-0.85
P103	REF	0.00	-0.12	-0.04	-0.15	0.08	-0.03
P104	REF	0.09	0.23	0.37	0.28	0.62	0.62
P105	REF	0.46	0.06	0.24	0.14	0.57	0.49
<i>Da*</i>							
P101	REF	-0.17	0.15	-0.05	-0.08	-0.17	0.15
P102	REF	-0.14	0.07	-0.13	-0.10	-0.19	0.12
P103	REF	-0.15	0.08	-0.09	-0.08	-0.17	0.13
P104	REF	-0.13	0.07	-0.04	-0.04	-0.15	0.10
P105	REF	-0.19	-0.02	-0.10	-0.09	-0.26	-0.01
<i>Db*</i>							
P101	REF	0.13	-0.02	-0.30	-0.07	-0.04	0.05
P102	REF	0.12	0.12	-0.50	-0.14	-0.08	0.06
P103	REF	0.15	0.16	-0.30	-0.06	0.09	0.43
P104	REF	0.08	0.16	-0.32	-0.10	0.05	0.24
P105	REF	0.04	0.05	-0.35	-0.12	-0.09	0.06

Table 6. Comparison of DE* components (DL*, Da*, Db*) between spectrophotometers, AMS standard tiles, with glass. MB=Macbeth, XR=X-Rite, MIN=Minolta, HL=HunterLab, second B=Bench-top, P=Portable

Sample	DE* components, with glass						
	MBB	XRB	MINB	HLB	MBP	XRP	MINP
<i>DL*</i>							
P101	REF	1.85	1.73	1.54	-9.60	-5.41	-2.59
P102	REF	1.48	2.22	1.80	-8.09	-4.23	-2.02
P103	REF	1.02	1.92	1.43	-9.13	-5.12	-0.78
P104	REF	0.43	2.91	1.99	-10.06	-5.03	-1.03
P105	REF	1.23	2.11	1.44	-9.81	-5.12	-1.15
<i>Da*</i>							
P101	REF	0.13	0.29	0.02	0.26	0.18	0.37
P102	REF	-0.09	0.23	-0.04	0.14	0.06	0.25
P103	REF	-0.09	0.26	0.02	0.08	0.07	0.30
P104	REF	-0.09	0.16	0.01	0.37	0.24	0.36
P105	REF	-0.12	0.16	0.01	0.20	0.06	0.25
<i>Db*</i>							
P101	REF	0.81	0.05	-0.09	-0.54	0.05	-0.34
P102	REF	0.23	0.30	-0.08	-1.33	-0.42	-0.78
P103	REF	0.21	0.35	-0.01	-1.60	-0.64	-0.81
P104	REF	-0.01	0.16	-0.10	-0.16	0.51	0.00
P105	REF	0.13	0.19	0.00	-0.87	-0.11	-0.49

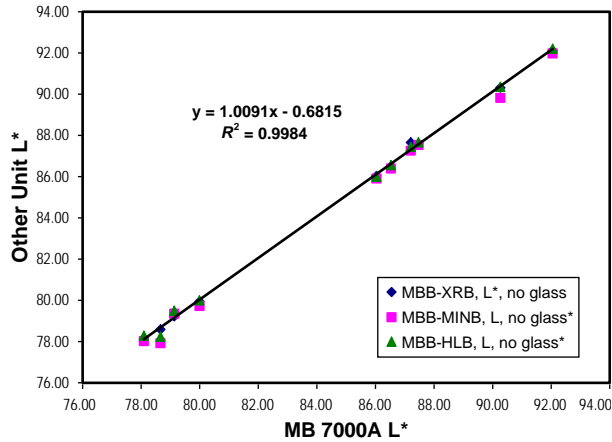


Figure 5. Comparison of L* between bench-top spectrophotometers, AMS tiles, without glass. Correlation line is the comparison of the Macbeth CE7000A (MBB) and HunterLab UltraPro (HLB) bench-top spectrophotometers.

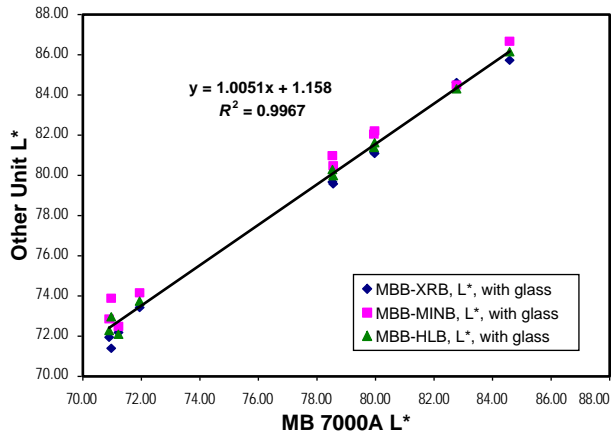


Figure 6. Comparison of L* between bench-top spectrophotometers, AMS tiles, with glass. Correlation line is the comparison of the Macbeth CE7000A (MBB) and HunterLab UltraPro (HLB) bench-top spectrophotometers.

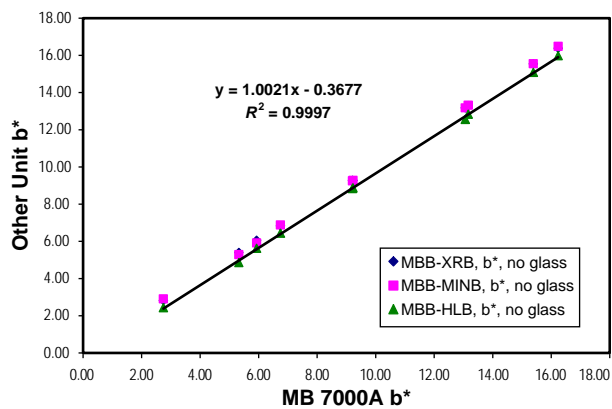


Figure 7. Comparison of b* between bench-top spectrophotometers, AMS tiles, without glass. Correlation line is the comparison of the Macbeth CE7000A (MBB) and HunterLab UltraPro (HLB) bench-top spectrophotometers.

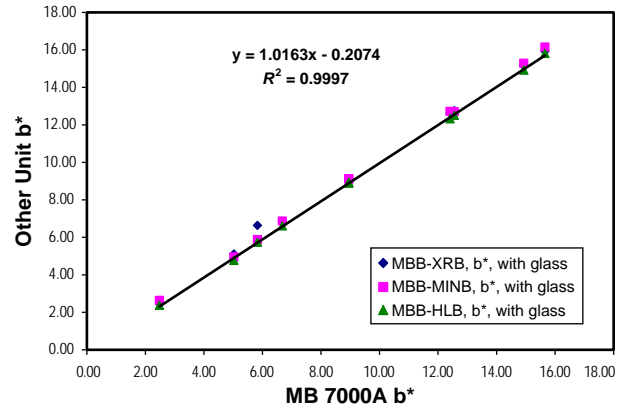


Figure 8. Comparison of b* between bench-top spectrophotometers, AMS tiles, with glass. Correlation line is the comparison of the Macbeth CE7000A (MBB) and HunterLab UltraPro (HLB) bench-top spectrophotometers.

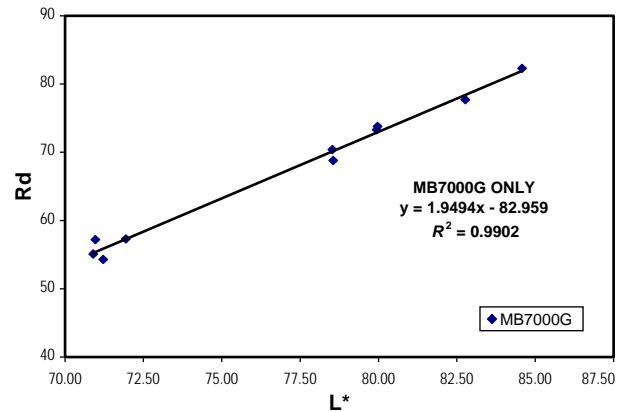


Figure 9. Validation of L*↔Rd for the Macbeth CE7000A bench-top spectrophotometer, AMS tiles, with glass.

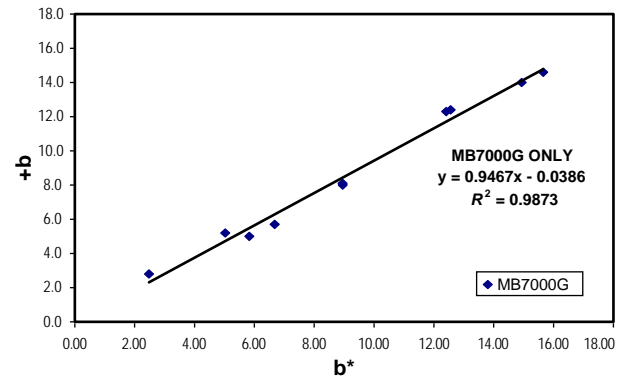


Figure 10. Validation of b*↔+b for the Macbeth CE7000A bench-top spectrophotometer, AMS tiles, with glass.

The strength of the L*↔Rd and b*↔+b relationships were determined by comparing L*↔Rd and b*↔+b for each unit, both with and without glass. The between-unit color agreement was very good for L*, b*, and DE* for the AMS tiles when external

glass is not placed in front of the tile sample at the measurement port ($DL^*/Da^*/DE^* < 1.0$ normally). As demonstrated in figures 11-14, linear relationships were obtained for all $L^* \leftrightarrow Rd$ and $b^* \leftrightarrow +b$ comparisons. In all cases and with each spectrophotometer, the $L^* \leftrightarrow Rd$ relationship yielded a slope of near 2.0 and a large offset, while the $b^* \leftrightarrow +b$ relationship yielded a slope of near 1.0 and a small offset. Therefore, similar (almost identical) linear relationships were obtained for $L^* \leftrightarrow Rd$ and $b^* \leftrightarrow +b$, regardless of the bench-top unit used. These results validated the use of $L^*a^*b^*$ for relating globally recognized color parameters from a color spectrophotometer to the HVI's Rd and $+b$ color parameters. Similar Rd , $+b$ and $L^*a^*b^*$ responses with glass use were observed for cotton batt measurements, in which glass was used at all times.

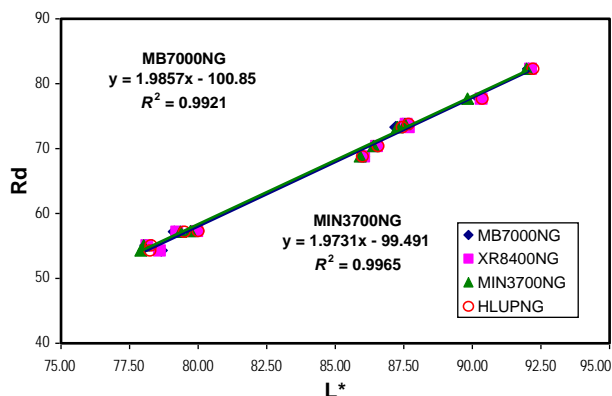


Figure 11. $L^* \leftrightarrow Rd$ for relationships for bench-top spectrophotometer, AMS tiles, without glass.

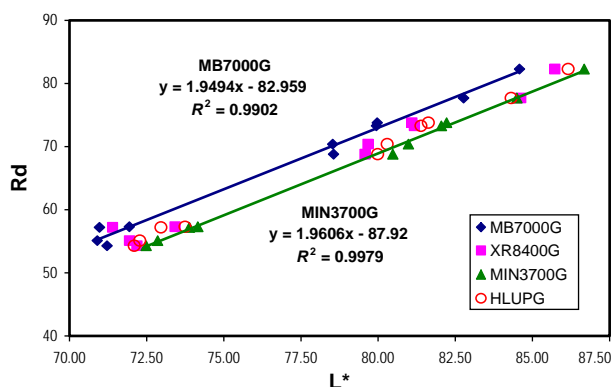


Figure 12. $L^* \leftrightarrow Rd$ for relationships for bench-top spectrophotometer, AMS tiles, with glass.

In addition, figures 11-14 also indicate the impact of glass on the color results of tiles. Distinct differences were observed between the different spectrophotometers for $L^* \leftrightarrow Rd$ when glass is used in front of the spectrophotometer measurement port,

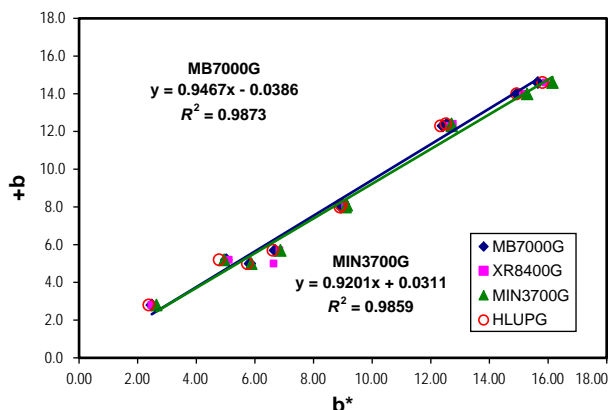


Figure 13. $b^* \leftrightarrow +b$ for relationships for bench-top spectrophotometer, AMS tiles, without glass.

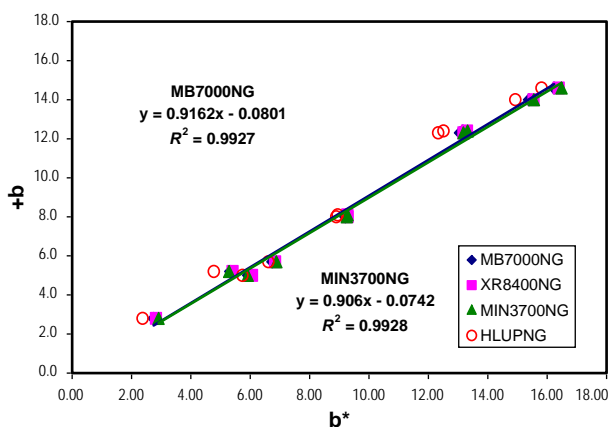


Figure 14. $b^* \leftrightarrow +b$ for relationships for bench-top spectrophotometer, AMS tiles, with glass.

but the $L^* \leftrightarrow Rd$ differences for each tile were small when no glass is used (the tile only is placed against the spectrophotometer measuring port). The differences in $b^* \leftrightarrow +b$ were overall similar whether or not the glass was used in the color measurement. These results support the earlier observation that the major impact of glass on color results is for L^* , which in turn leads to major impacts on DE^* .

In order to better understand the source of the $L^* \leftrightarrow Rd$ and $b^* \leftrightarrow +b$ responses and the impact of glass on L^* but not b^* , analyses were performed on the sample's reflectance (%R) curves. Typical reflectance curves for an AMS tile set are given in figure 15. In figure 16, the reflectance curves for AMS tiles (white and brown for this example) are displayed, both with glass and without glass. The curves for each tile are similar in shape, but the without glass curves are higher in %R. The use of glass has resulted in a "shift" in %R, and the magnitude of the shift is not linear from 400-700nm for a given spectrophotometer and not the same for

different spectrophotometers, due to the differences in the sphere sizes and geometry between the different color spectrophotometers. Both R_d and L^* are *directly related* to the total diffuse reflectance from the sample (%R). Thus, the increased %R observed when glass is not used in the color measurement leads to higher L^* results for “no glass” measurements (compared to the L^* results for “with glass” measurements) with all spectrophotometers.

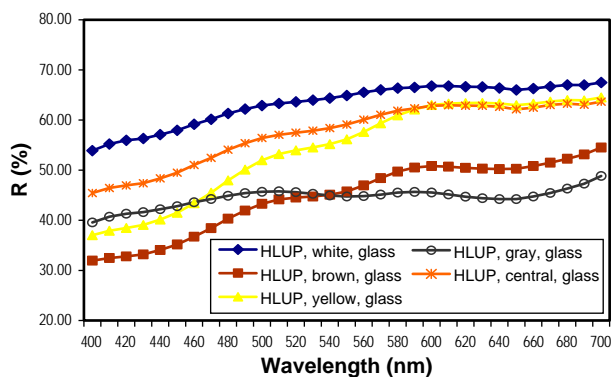


Figure 15. Typical reflectance curves for AMS tiles, bench-top spectrophotometer, with glass.

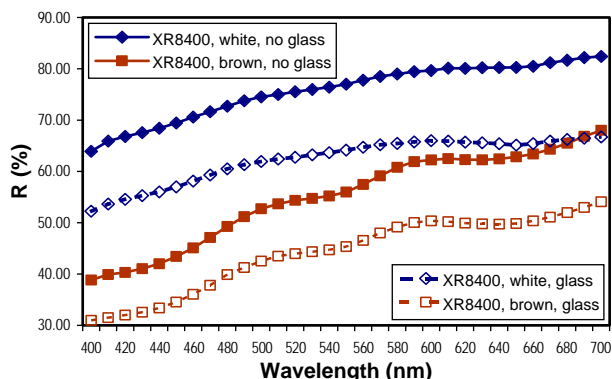


Figure 16. %R for white and brown AMS tiles, X-Rite bench-top spectrophotometer, with & without glass.

As noted previously, the difference between the without and with glass %R curves are not the same across the *entire* spectrum (400-700nm) for spectrophotometers. Further, R_d is calculated from the sample's reflectance (“%R”) at only two spectral regions (two filters in the HVI colorimeter, the “blue” and “yellow” spectral regions), while L^* is calculated from the sample's reflectance across the entire spectral region (400-700nm). As the color spectrophotometer uses the entire 300nm spectral region for color measurements while the HVI uses only two tight wavelength regions for color measurements, L^* contains a greater contribution of %R and from different spectral regions compared

to R_d . This increased %R for L^* normally results in higher L^* values compared to R_d for a given sample. The higher L^* results and differences in algorithms for calculating L^* and R_d result in the $L^* \leftrightarrow R_d$ relationship yielding a slope significantly > 1.0 (figures 11, 12, and 16).

However, both b^* and $+b$ are calculated as the *difference* in %R between two regions of the %R curve (“blue” vs. “yellow” spectral regions). This “%R difference” is very similar for a given sample with both the HVI colorimeter and the spectrophotometer, as the shifts in the %R curves between color units result in very similar differences between the two spectral regions. In addition, for these two spectral regions, differences between color units due to %R shifts with glass use are normally small. Thus, differences in b^* between different color spectrophotometers were observed to be small, both with and without glass use ($|Db^*| < 1.0$ in most cases). Since b^* and $+b$ are both “%R difference” calculations and since the impact of glass use is significantly minimized with a difference calculation, the $b^* \leftrightarrow +b$ relationship is linear and near unity (figures 13, 14, 16).

One overall summary of these results is that the development and use of “traceable” standards for HVI cotton color measurements is feasible. The most promising standard system is the use of ceramic or metal tiles on a research-grade bench-top spectrophotometer with no glass at the measurement port. Not using the glass in the standard tile measurements will minimize the “shift” in %R, which will minimize the observed differences in $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ linearity and correlations, and remove the need to use a glass correction algorithm to correct for the glass effect.

CONCLUSIONS

The strong $L^* \leftrightarrow R_d$ and $b^* \leftrightarrow +b$ correlations observed on one color unit were verified and validated on all color units. The between-unit color agreement was very good for L^* , b^* , and DE^* for the AMS tiles when external glass is not placed in front of the tile sample at the measurement port. Very similar linear relationships were obtained for $L^* \leftrightarrow R_d$ (slope ~ 2) and $b^* \leftrightarrow +b$ (slope ~ 1), regardless of the bench-top unit used. Thus, the use of $L^*a^*b^*$ for relating globally recognized color parameters from a color spectrophotometer to the HVI's R_d and $+b$ color parameters was validated.

The primary variable that impacted the color agreement between units was the use of HVI glass in front of the sample. The use of glass, which is often necessary for the measurement of cotton fiber, often resulted in large DE^* differences in color results between the different color instruments, especially for the portable color units. L^* was the color parameter that was most impacted by the use of glass in the tile and cotton fiber color measurements. Distinct differences were observed between the different spectrophotometers for L^* and $L^* \leftrightarrow Rd$ correlation agreements when glass is used (tiles and cottons), but the L^* differences and $L^* \leftrightarrow Rd$ correlation agreements for tiles were usually small when no glass is used. The differences in $b^* \leftrightarrow +b$ were often similar overall for bench-top color units whether or not the glass was used in the color measurement, even for cotton batts. The use of glass leads to a “shift” in the sample’s reflectance spectrum (%R), and the magnitude of the shift was not linear over the entire spectrum. These shifts in %R with glass use, and the use of only two color filters in the HVI unit, lead to the observed differences in $L^* \leftrightarrow Rd$ and the observed $b^* \leftrightarrow +b$ linearity and correlations.

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DISCLAIMER

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