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The Analysis of Metameric Blue Fibers and Their Forensic Significance

ABSTRACT: Metamerism is a phenomenon where two or more colored items with different colorant chemistries appear to the observer to be the same color. Those differences should result in different UV-visible spectra. Additionally, the literature on color science states that metameric samples will have spectra that intersect at three or more loci. Metameric samples of blue textile fibers, which were created using different coloring agents or different relative concentrations of the coloring agents, were studied to demonstrate that they could be differentiated by obtaining their spectra between 350 and 800 nm using UV-visible microspectrophotometry. However, while some of the metameric samples tested did intersect at three or more loci, others did not intersect at all. In the spectra that did intersect, no correlation was found between either the dye chemistries or the relative component concentrations.

KEYWORDS: forensic science, fibers, color comparison, metamerism, metameric fibers, UV-visible spectrophotometry

In their daily lives, people may be confronted with the problem of color matching. The dye that will impart color to a polyester fiber may not be taken up by a wool fiber, resulting in the use of different compounds and mixtures to try to create the same color. Therefore, an apparent match between a polyester garment and a wool garment in a store may no longer look like a match after leaving the store. Dyes used on textiles are different from the colorants used in paints. A paint color that has been created in a store to match a pillow fabric may not appear to be the perfect match at home. These color variation problems are examples of metamerism.

Metamerism is the phenomenon of two or more colored items (produced using different dyes, pigments, or coloring agents) appearing to be the same color under specific lighting conditions. If a change in lighting conditions results in the items looking different, this phenomenon is called illuminant metamerism. If a change in the observer results in the items looking different, this phenomenon is called observer metamerism (1,2).

In forensic science, the concern is whether or not metameric samples (samples that were created with the express intent of appearing to be the same color) can be differentiated through their UV-visible spectra (3,4). Because different coloring agents are used, the UV-visible spectra of the colored items should be different (5). And, according to the literature on color science, metameric samples will have spectra that intersect at three or more loci (1,6). Berger-Schunn does cite exceptions where metameric pairs have spectra that intersect at only two loci. However, there are few documented results to demonstrate just how different the spectra might look, nor do these results confirm that the spectra intersect at three or more loci. Additionally, there are also metameric samples that are created using the same coloring agents, but in different proportions (1,2). There is very little documentation regarding this scenario in the forensic science literature. Thus, this study was undertaken in order to help fill that void.

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Materials and Methods

Blue fabric swatches of the following fiber types and dye combinations were tested (see Table 1). The dye combinations and concentrations were chosen to achieve metamerism between the fabric swatches under Illuminant D65 (daylight) lighting conditions. The dye types were chosen based upon their suitability for the fiber type.

The cotton and polyester swatches are examples of metameric pairs created using different coloring agents. The nylon, silk, and wool swatches are examples of metameric pairs created using the same coloring agents, but in different proportions.

The fabric swatches were examined visually under different lighting conditions—daylight, incandescent light, fluorescent light—to determine the quality of the metameric match between the samples. Under daylight illumination, all of the fabric swatches appeared to be the same shade of blue. Under incandescent light, the nylon, silk, and wool swatches appeared to be the same shade of blue. The cotton and polyester swatches appeared to be different shades of blue. Under fluorescent light, the nylon and polyester swatches appeared to be the same shade of blue. The wool swatch appeared to be a slightly darker shade of blue than the nylon and polyester. The cotton and silk swatches appeared to be different shades of blue.

Single fibers from each fabric swatch were mounted between a quartz slide and quartz cover slip, using glycerol as a mounting medium. The mounted fibers were then analyzed in absorbance mode using the CRAIC Technologies (San Dimas, CA) QDI 2000 UV-visible microspectrophotometer with a 15× objective. Ten samples from each swatch were analyzed to observe the range of variation of absorbance within each sample and to demonstrate the consistency of results. Absorbance spectra from 350 to 800 nm were obtained. Absorbance spectra of colorless fibers of the same fiber types were also obtained to confirm that spectral differences were because of the dyes, and not from the chemistry of the fiber types.

TABLE 1—*Fiber types, dyes, and formulations used on each sample for this study.*

Fiber Type	Dye	Dye Strength
Cotton	Reactive dye Levafix Blue EGRN	Full strength
	Reactive dye Levafix Yellow EG150	Full strength
Polyester	Disperse dye Blue CVS 300	0.366%
	Disperse dye Red CVS 300	0.042%
	Disperse dye Yellow CVS300	0.037%
Nylon	Acid dye Telon Blue AFN	1.769%
	Acid dye Telon Red AFG	0.108%
	Acid dye Telon Yellow FG	0.059%
Wool	Acid dye Telon Blue AFN	1.503%
	Acid dye Telon Red AFG	0.090%
	Acid dye Telon Yellow FG	0.040%
Silk	Acid dye Telon Blue AFN	1.879%
	Acid dye Telon Red AFG	0.148%
	Acid dye Telon Yellow FG	0.087%

Results

The blue cotton fabric swatch was created using blue and yellow dyes. No red dye was used to create this swatch. An examination of the spectrum of the cotton fiber (Fig. 1) shows maximum absorbance in the red wavelengths (620–750 nm); this is represented by the peak at 625 nm in the spectrum. There is a noticeable difference in the absorbance between the wavelengths in the red region and those in the yellow (570–590 nm), as represented by a shoulder on the slope of the 625 nm peak. The blue color of the fiber is seen in the low absorbance in the blue wavelengths (450–495 nm), as manifested by the valley in the spectrum in the blue wavelengths. Low absorbance translates to high transmittance and oftentimes, high reflectance, resulting in the perception of color of the corresponding wavelength.

The blue polyester fabric swatch was created using blue dye and low concentrations of red and yellow dyes. The proportions of red to yellow dyes are similar. The dye formulation is seen in the spectrum of the polyester fiber (Fig. 2). Because the proportions of red and yellow dyes are similar, there is no distinct peak or valley representing absorbance by the red or yellow dyes. Instead, the maximum absorbance in the orange wavelengths (590–620 nm) was because of the blue dye. There is weaker absorbance in the blue region of the spectrum, which results in the polyester fabric's blue color.

The spectra for the nylon, wool, and silk fibers (Figs. 3–5, respectively) show distinct peaks in the red and yellow regions, reflecting the highest concentrations of blue dyes and slightly higher concentrations of red dyes in their formulations. Each spectrum has a distinct valley, representing little absorbance in the blue region and therefore, the blue color.

Discussion

Because dye uptake by the fibers comprising each sample may not have been equal, multiple fibers were analyzed. A range of variation in absorbance within each sample was observed. However, an overlay of the 10 spectra for each sample showed them to have identical spectral shapes (7). An average spectrum of the 10 spectra for each sample was therefore plotted.

The shapes of the spectra for the cotton and polyester fibers were noticeably different from each other and from the spectra for the nylon, silk, and wool fibers. As shown in Table 1, the dyes used on the cotton and polyester fibers are different from each other and from the dyes used on the nylon, silk, and wool fibers.

Because the same colorants (dyes) were used in the making of the nylon, wool, and silk fabric swatches, the samples are not typically considered metameric samples within the forensic community. However, because the formulations used to create each swatch are different, the samples are metameric. These specimens are of forensic interest because they answer the question as to the degree of variation needed to differentiate two similarly colored samples from different sources.

It was expected that the spectra for the nylon, silk, and wool fibers would be similar in shape. General similarities in spectral shape were observed. They did, however, show differences in relative absorbance at the different wavelengths, resulting in small, but significant, differences in spectral shape between the nylon, wool, and silk samples.

An examination and comparison of the spectra for the nylon, silk, and wool fibers shows a correlation between peak height ratios and dye ratios (see Table 2 and Fig. 6).

Comparing the nylon, wool, and silk spectra, an examination of the difference between the valleys representing absorbance of blue light and the peaks representing absorbance of yellow light shows a correlation to the amount of blue dye used versus the

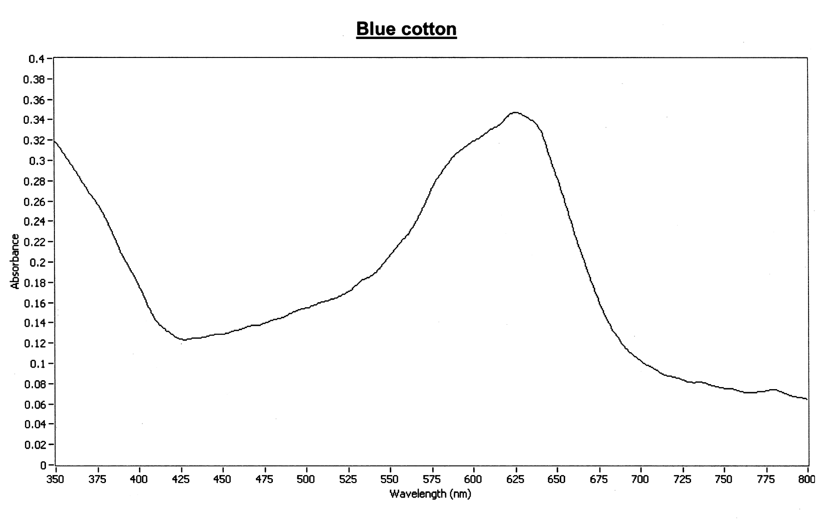

FIG. 1—*UV-visible spectrum of a blue cotton fiber.*

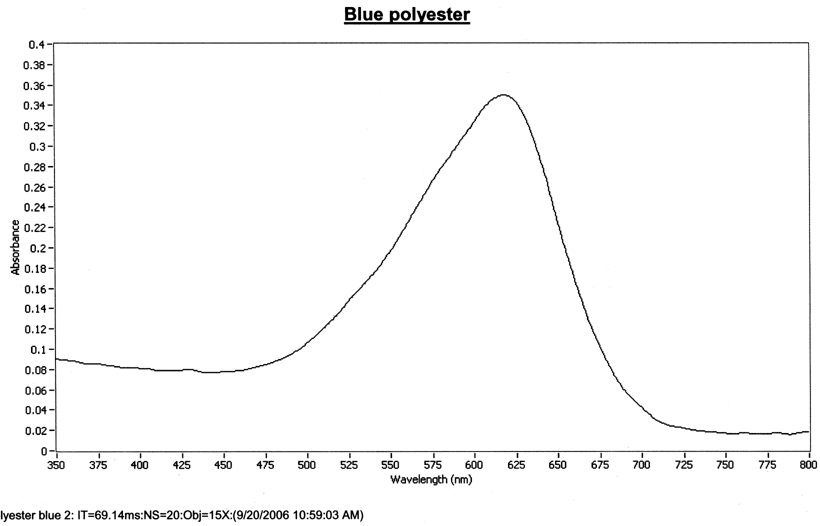

FIG. 2—*UV-visible spectrum of a blue polyester fiber.*

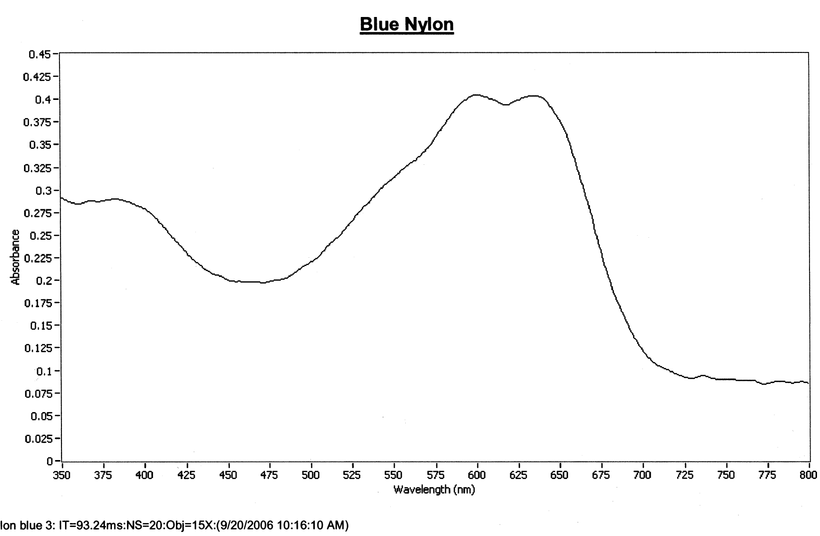

FIG. 3—*UV-visible spectrum of a blue nylon fiber.*

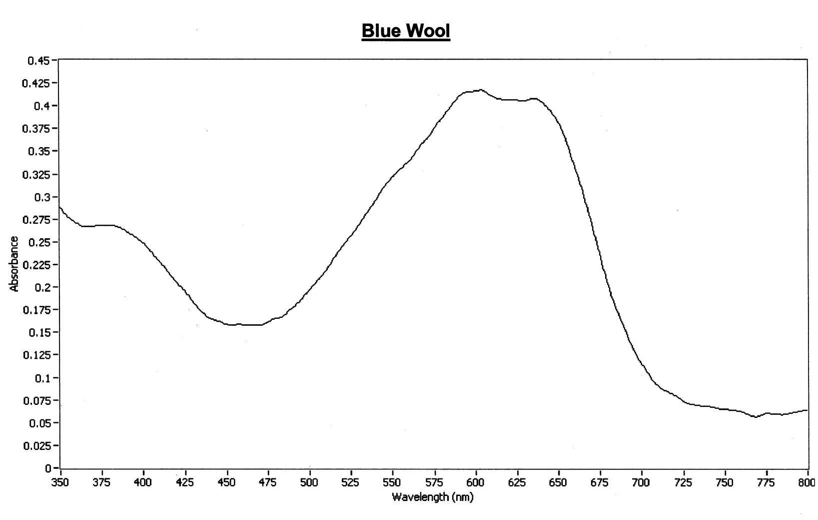

FIG. 4—*UV-visible spectrum of a blue wool fiber.*

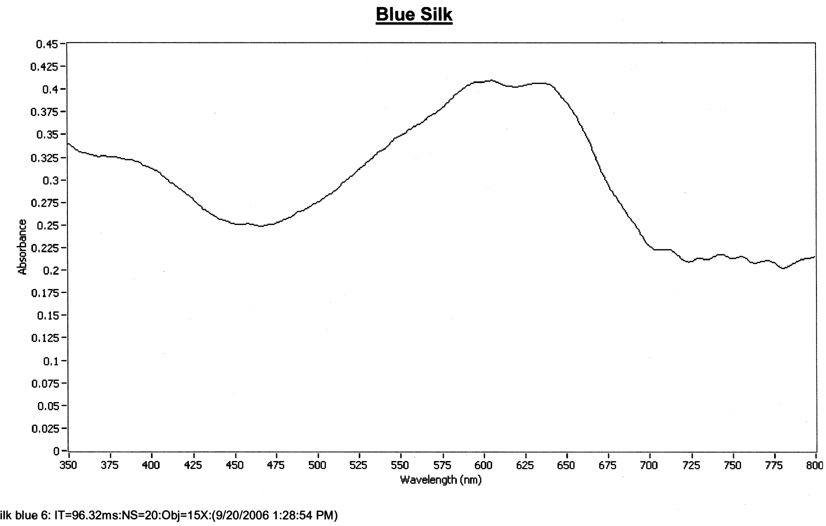

FIG. 5—*UV-visible spectrum of a blue silk fiber.*

TABLE 2—*Nylon, silk, and wool fabric samples created using the same trio of dyes. The table shows the proportions of blue to red dye, blue to yellow dye, and red to yellow dye used within each sample.*

Fiber Type	Ratio of Blue: Red Dye	Ratio of Blue: Yellow Dye	Ratio of Red: Yellow Dye
Nylon	16.38	29.98	1.83
Wool	16.70	37.58	2.25
Silk	12.70	21.60	1.70

amount of yellow dye used. Similar correlations exist between the blues and reds and the reds and yellows. An examination of the average spectra from these three fiber types highlights the differences in relative absorbance between the nylon, wool, and silk samples and demonstrates the correlation between relative absorbance and the proportions between the dyes used to make each sample (see Table 3).

Comparisons of the spectra of each sample to the spectra of the other four samples show some of the spectra intersect each other at one or more loci while others do not intersect each other at all. These differences are due to the range of variation in absorbance within each sample. For example, one of the spectra of the silk fibers was greater in absorbance than all of the spectra of the wool fibers. Therefore, there was no intersection at any loci. Alternatively, most of the spectra of the silk fibers were within the range of absorbance exhibited by the wool fibers, resulting in intersections at one or more loci.

Conclusions

Metameric samples created using different coloring agents are easily differentiated through their UV-visible-NIR absorbance spectra. The absorbance spectra will have different shapes, representing differences in absorbance at different wavelengths. In this scenario,

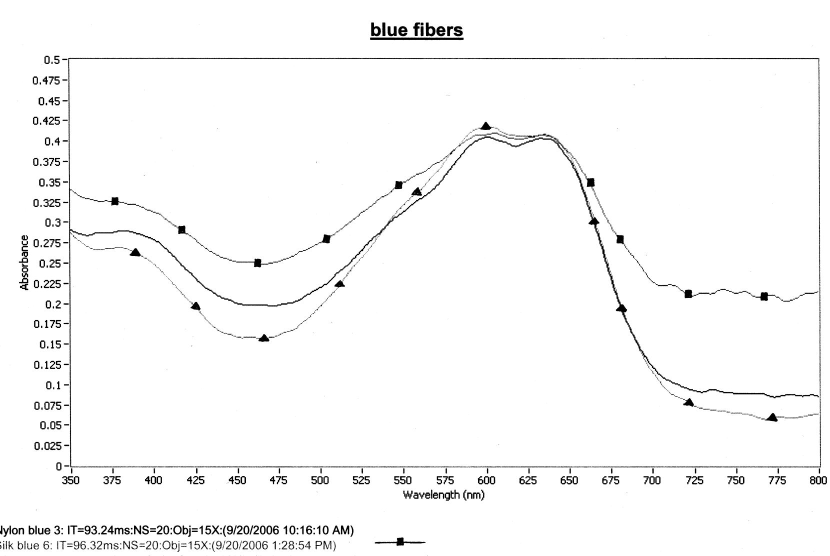

FIG. 6—*Overlaid spectra of blue nylon, blue wool, and blue silk fibers. Note the similarities in spectral shape between the three samples. The differences between the valleys at the blue wavelengths and the peaks at the yellow and red wavelengths correlate to the ratios of dyes blue to yellow and blue to red.*

TABLE 3—*Correlation between the proportions of blue, red, and yellow dyes and the relative absorbances in the regions of the blue, red, and yellow wavelengths. The more dye used, the more light of the corresponding color is transmitted.*

Fiber Type	Proportions Between Dyes Blue/Red/Yellow	Relative Absorbance at Blue/Red/Yellow Wavelengths
Nylon	1.769/0.108/0.059	0.234/0.418/0.422
Wool	1.503/0.090/0.040	0.171/0.344/0.356
Silk	1.879/0.148/0.087	0.212/0.322/0.326

it would be easy to discern that the samples are from different sources.

Metameric samples created using the same coloring agents in different proportions can be differentiated through their UV-visible absorbance spectra if there are significant differences in the formulations. The absorbance spectra will have similar, although not identical shapes, because of different relative peak heights. The differences in peak heights correspond to the differences in dye stuff concentrations. In this scenario, the samples can be determined to be from different sources if there are significant differences in the proportions of the coloring agents. A close examination of the peak heights may be necessary to discern differences in spectral shape. If the differences in formulary proportions are slight, it may not be possible to differentiate the samples as originating from different sources. A forensic examiner would have to consider other experimental methods, or more sophisticated data analysis techniques, in order to differentiate the samples.

Contrary to published literature, the spectra of metameric samples do not necessarily intersect at three or more loci. As demonstrated with the polyester spectrum compared against the nylon, wool, and silk spectra presented in Figs. 2–5, some spectra do not intersect at all.

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References

1. Nassau K, editor. Color for science, art and technology. New York, NY: Elsevier Science BV, 1998;22–4,48.
2. Berns RS. Billmeyer and Saltzman's principles of color technology, 3rd ed. New York, NY: John Wiley & Sons, Inc., 2000;14,27–9.
3. Scientific Working Group for Materials Analysis. Forensic fiber examination guidelines. Forensic Sci Commun 1999;1(1), http://www.fbi.gov/hq/lab/fsc/backissu/april1999/houcktoc.htm.
4. Adolf F-P, Dunlop J. Microspectrophotometry/colour measurement. In: Robertson J, Grieve M, editors. Forensic examination of fibres, 2nd ed. Philadelphia, PA: Taylor & Francis, 1999;251–89.
5. Causin V, Casamassima R, Marega C, Maida P, Schiavone S, Marigo A, et al. The discrimination potential of ultraviolet-visible spectrophotometry, thin-layer chromatography, and Fourier transform infrared spectroscopy for the forensic analysis of black and blue ballpoint inks. J Forensic Sci 2008;53(6):1468–73.
6. Berger-Schunn A. Practical color measurement: a primer for the beginner, a reminder for the expert. New York, NY: John Wiley & Sons, Inc., 1994;59.
7. Scientific Working Group for Materials Analysis. Standard guide for microspectrophotometry and color measurement in forensic paint analysis. Forensic Sci Commun 2007;9(4), http://www.fbi.gov/hq/lab/fsc/backissu/oct2007/standards/2007_10_standards01.htm.

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