An Investigation of how the Texture Surface of a Fabric Influences its Instrumental Color

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Abstract: In this article, the influence of texture surface of a fabric on its instrumental color is investigated. While former studies have found it is difficult to establish a quantitative relationships between texture of fabric and its instrumental color (color difference and color attributes, such as lightness, chroma, and hue), this article investigates from a theoretical and empirical perspective the interaction between texture and color. Eighty four knitted cotton yarn dyed fabric samples in four color centers and 21 texture structures were used in this study. It is revealed that fabric samples with different texture surfaces define a set of lines with identical direction in the reflectance space, and thus the normalized reflectance curves of these samples are identical. In the CIEXYZ space, tristimulus values of these fabric samples define a line, and thus their chromaticity coordinates are constant. In the CIELAB space, however, linearity is lost due to the non-linear transformation from the CIEXYZ space to the CIELAB space. The finding of this article has the potential to discount the influence of texture of a fabric on its color. Experiments show that the influence of texture on color for samples in the four color centers can be reduced by 79, 55, 71, and 57%, respectively comparing to the real measured color difference. © 2014 Wiley Periodicals, Inc. Col Res Appl, 40, 472-482, 2015; Published Online 9 October 2014 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/col.21923

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INTRODUCTION

Color is one of the most important factors affecting the quality of a fabric. However, the color of a fabric is influenced by its texture.¹⁻⁴ While fabric samples normally have different texture structures, the underlying assumption is these samples are flat when their colors are measured by a spectrophotometer,⁵ which is a popular instrument to assess colors of fabrics in textile and garment industries. Normally, a spectrophotometer can be considered as a combination of two subsystems: the optical subsystem and the detection subsystem. The optical subsystem generates light to illuminate a sample. It is composed of light source, integrating sphere, and lenses. The detection subsystem measures the radiant flux of the light reflected by a sample. It consists of detector array and spectral analyzer. In the optical subsystem the light beam is often divided into to parts: a reference beam and a sampling beam. The ratio of the reflected radiant flux of the sample to that of the reference beam is defined as the spectral reflectance of the sample. However, the reflected radiant flux of a sample changes with its texture structure. Thus, the texture structures of fabrics have an impact on both their instrumental and perceived colors.

A number of studies have been conducted to investigate how the texture surface of a fabric affects its color. These studies can be categorized into three

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Fig. 1. The basic optics within a spectrophotometer when it is used to measure the color of a fabric.

directions: the influence of texture on color difference,⁶⁻¹³ the influence of texture on color attributes,^{4,14} and the relationship between texture descriptors and colors.^{1–3}

Kuehni and Marcus⁶ were the pioneers in studying the effect of texture structures of fabrics on their visual color difference. They found the minimum value to perceive a color difference between different texture structures of fabrics was one CIELAB unit. Xin et al.⁷ and Han et al.⁸ investigated the effect of texture structures on visual color difference. Xin et al. found the texture of fabric samples can significantly influence the visual color difference evaluation. Han et al. compared the visual color difference of CRT-displaying textured and non-textured fabric samples. It was found that nontextured samples agree with physical samples worse than textured samples in terms of color difference. Kandi and Tehran⁹ found the texture structures had a significant influence on the performance of color difference formulae. Montag and Berns¹⁰ explored the influence of texture on the suprathreshold lightness tolerances. They found texture increased the lightness tolerance thresh-olds. Huertas *et al.*^{11–13} studied the influence of texture structures on the visual suprathreshold color tolerances of lightness, chroma, and hue. They found textures increase the lightness tolerance more than the chroma and hue ones.

Shao *et al.*⁴ investigated the influence of texture structures of knitted fabrics on instrumental and visual colors. They concluded that texture structures of fabrics had an impact on their lightness, chroma and hue values. Luo *et al.*¹⁴ investigated how the surface texture of a fabric influences its luminance and chromaticity values. They concluded that color difference between fabrics with different texture structures mainly stems from their luminance rather than chromaticity difference.

Some researchers focused on studying the relationships between texture descriptors of fabrics and their instrumental and visual colors. Xin *et al.*¹ employed the half-width of histogram as the texture descriptor and found there was high correlation between visual color difference and the texture feature from this descriptor. Kandi *et al.*² investigated the relationship between the instrumental and visual color difference of fabrics and their texture parameters described by Gabor functions. They found there was some correlation between the visual color difference and Gabor function values but the relationships between the instrumental color and the Gabor function values were not reported. Kitaguchi *et al.*³ found that there was good relationship between visual assessment results and features from co-occurrence and gray level difference.

While the impact of texture on color has been studied for more than three decades, quantitative relationships, such as linearity or correlation between texture and instrumental color (color difference and color attributes, such as lightness, chroma, and hue) are found difficult to be established. Although Luo *et al.*¹⁴ concluded that the texture surface of a fabric influences its luminance rather than chromaticity values, how the texture structure of a fabric influences its luminance is still unknown. In contrast to focusing on studying how texture structures of fabrics influence color difference, lightness, chroma, and hue, this article investigates from a theoretical and empirical perspective how texture surfaces of fabrics influence their reflectance and tristimulus values.

How the Texture Surface of a Fabric Affects its Instrumental Color

How the Surface Texture of a Fabric Affects its Measured Reflectance. Figure 1 shows the basic optics of the optical subsystem within a spectrophotometer. The optical flux at the detector array changes with fabrics since the reflected radiance values by the surfaces of these fabrics are different when they have different texture structures. Given the area of the detector A_d , the optical system efficiency τ , the maximum aperture diameter of the lens system F, the contribution of the sample at the position (p,q) to the flux at the detector $\Phi(\lambda, p, q)$ is given by^{15,16}

$$\Phi(\lambda, p, q) = \pi \frac{A_d \tau}{4F^2} L(\lambda, p, q) \tag{1}$$

where $L(\lambda, p, q)$ denotes the radiance of the surface of a fabric sample at the position (p, q). λ is the wavelength.

For a texture surface with only diffuse reflection, its radiance at position (p,q) is the product of a geometry term $m_b(p,q)$ and a reflectance term $E(\lambda, p, q)R(\lambda)$.

$$L(\lambda, p, q) = m_b(p, q) E(\lambda, p, q) R(\lambda)$$
(2)

where $E(\lambda, p, q)$ denotes the irradiance at the position (p, q). $R(\lambda)$ denotes the nominal reflectance of the components of a fabric sample. For example, it refers to the nominal reflectance of yarns for yarn dyed fabrics.

The lights that reach the position (p,q) compose of two parts¹⁷: lights from the direct illuminant $E_D(\lambda, p, q)$ (light source of the spectrophotometer) and lights from

ambient illuminant $E_A(\lambda, p, q)$ (lights reflected by neighbors).

The lights from the direct illuminant would be masked and shadowed by neighbors. An occluded term $H(p,q) \in [0,1]$ is used to indicate the percent masked and shadowed. H(p,q)=0 expresses the light is completely occluded, such as valleys of a surface. H(p,q)=1 refers to the situation where no occlusion, such as peaks of a surface.

$$E_D(\lambda, p, q) = H(p, q)E(\lambda) \tag{3}$$

where $E(\lambda)$ denotes the spectrum of the direct illuminant.

The light reflected by neighboring positions results in an ambient illuminant for the measured point (p,q). The lights from the ambient illuminant are integrated over the entire hemisphere $\Omega(p,q)$.

$$E_A(\lambda, p, q) = \oint_{\Omega(p,q)} m_b(\overrightarrow{i}) E(\lambda, \overrightarrow{i}) R(\lambda) d\overrightarrow{i}$$
(4)

where \vec{i} denotes the incident angle of ambient light at hemisphere $\Omega(p,q)$. $m_b(\vec{i})$ and $E(\lambda, \vec{i})$ express the geometry term and the total illuminant of the lights reflected by its neighbor from the direction $\vec{i} \cdot E(\lambda, \vec{i})$ is also composed by two parts: lights from the direct illuminant $H(\vec{i})E(\lambda)$ and lights from ambient illuminant $E_{AA}(\lambda, \vec{i})$.

$$E_{A}(\lambda, p, q) = E(\lambda)R(\lambda) \oint_{\Omega(p,q)} m_{b}(\overrightarrow{i})H(\overrightarrow{i})d\overrightarrow{i} + \oint_{\Omega(p,q)} m_{b}(\overrightarrow{i})E_{AA}(\lambda, \overrightarrow{i})R(\lambda)d\overrightarrow{i}$$
(5)

Substitute Eq. (3) and Eq. (5) into Eq. (2), we get

$$L(\lambda, p, q) = m_b(p, q)H(p, q)E(\lambda)R(\lambda) + m_b(p, q)E(\lambda)R^2(\lambda) \oint_{\Omega(p,q)} m_b(\overrightarrow{i})H(\overrightarrow{i})d\overrightarrow{i} + m_b(p, q)E(\lambda)R^2(\lambda) \oint_{\Omega(p,q)} m_b(\overrightarrow{i})E_{AA}(\lambda, \overrightarrow{i})R(\lambda)d\overrightarrow{i}$$
(6)

According to the one-bounce model of mutual illumination,¹⁸ inter-reflection diminishes dramatically with each bounce. The last term of Eq. (6) can be assumed to be negligible as it represents the two bounces of interreflection. If we represent the ambient integral in the second term of Eq. (6) as an ambient coefficient A(p,q), we get

$$L(\lambda, p, q) = m_b(p, q)H(p, q)E(\lambda)R(\lambda) + m_b(p, q)A(p, q)E(\lambda)R^2(\lambda)$$
(7)

The total radiant flux at the detector is

$$\Phi_{S}(\lambda) = \iint_{p,q} \Phi(\lambda, p, q) dp dq$$

$$= \pi \frac{A_{d}\tau}{4F^{2}} E(\lambda)R(\lambda) \iint_{p,q} m_{b}(p,q)H(p,q)dp dq$$

$$+ \pi \frac{A_{d}\tau}{4F^{2}} E(\lambda)R^{2}(\lambda) \iint_{p,q} m_{b}(p,q)A(p,q)dp dq$$

$$= \left(1 + \frac{\iint_{p,q} m_{b}(p,q)A(p,q)dp dq}{\iint_{p,q} m_{b}(p,q)H(p,q)dp dq} R(\lambda) \right) \pi \frac{A_{d}\tau}{4F^{2}} E(\lambda)R(\lambda)$$

$$\iint_{p,q} m_{b}(p,q)H(p,q)dp dq$$
(8)

The radiant flux of a fabric sample at the detector of a spectrophotometer is determined by three parameters: the geometric term $m_b(p,q)$, the occlusion coefficient H(p,q)and the ambient coefficient A(p,q). These three parameters change with positions of the surface of a fabric sample. According to the Oren-Nayar reflectance model,¹⁹ geometric variable can be specified the as $m_b(p,q) = \cos(\theta)$, where θ is the angle of incidence. At the positions near to peaks of the surface, the contribution of $m_b(p,q)A(p,q)$ to the total radiant flux is insignificant compared to $m_b(p,q)H(p,q)$ as the occlusion coefficient and the geometric variable are close to 1 but the ambient coefficient is near to 0. At the positions near to the valleves of the surface, the contribution of $m_b(p,q)A(p,q)$ to the total flux is also slight as the incident angles of position at the valleys are large $(m_b(p,q))$ is close to 0). However, the possibility of light reaching peaks is much larger than valley areas because the real yarn crosssectional shape of fabrics approximates race-track,²⁰ lens,²¹ or shoulder squareness²² rather than ideal circle, as shown in Fig. 2. In addition, the integrating sphere of a spectrophotometer would cause the intensity of light from the direct illuminant larger than light from the ambi-Thus, ent illuminant. the ratio term $\int \int m_b(p,q)A(p,q)dpdq / \int \int m_b(p,q)H(p,q)dpdq \quad \text{can} \quad \text{be}$

assumed to be negligible for a fabric sample measured by a spectrophotometer.

$$\Phi_{S}(\lambda) = \pi \frac{A_{d}\tau}{4F^{2}} E(\lambda) R(\lambda) \iint_{p,q} m_{b}(p,q) H(p,q) dp dq \qquad (9)$$

The reference subsystems within a spectrophotometer measure the beam reflected by the sphere wall, which gives a measurement of the light incident on the fabric sample.²³ The flux at the detector of the reference subsystem is,



Fig. 2. The ideal and real yarn cross-sectional shapes of fabrics: (a) ideal yarn cross-sectional shape: circle; (b) real yarn cross-sectional shape: race-track; (c) real yarn cross-sectional shape: lens; (d) real yarn cross-sectional shape: shoulder squareness. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary. com.]

$$\Phi_R(\lambda) = \pi \frac{A_d \tau}{4F^2} E(\lambda) A_r \tag{10}$$

where A_r denotes the area of the aperture of a spectrophotometer.

The reflectance response of a spectrophotometer (measured reflectance) to a fabric can be modeled as,

$$R_{b}(\lambda) = \frac{\Phi_{S}(\lambda)}{\Phi_{R}(\lambda)}$$

$$= \frac{\iint_{p,q} m_{b}(p,q)H(p,q)dpdq}{A_{r}}R(\lambda)$$

$$= \left(\frac{\iint_{p,q} m_{b}(p,q)H(p,q)dpdq}{A_{r}}|R(\lambda)|\right)\bar{R}(\lambda)$$
(11)

)

$$\iint_{A_r} m_b(p,q)H(p,q)dpdq$$

where $\frac{p,q}{A_r} |R(\lambda)|$ is termed as the magnitude of the measured reflectance, $\bar{R}(\lambda)$ denotes the normalized nominal reflectance.

The expression in Eq. (11) defines a set of lines with identical direction but different magnitude in the reflectance space. The direction of the set of lines is determined by the nominal reflectance of components of fabric samples $R(\lambda)$. Their magnitude depends on the geometric terms $m_b(p,q)$ and the occlusion coefficients H(p,q) which, change with textured surfaces.

The normalized reflectance of a fabric sample is

$$\bar{R}_{b}(\lambda) = \frac{R_{b}(\lambda)}{\int_{\lambda}^{R_{b}(\lambda)d\lambda}} = \frac{\int_{\lambda}^{p,q} m_{b}(p,q)H(p,q)dpdq}{\int_{\frac{p,q}{A_{r}}} R(\lambda)} = \frac{R(\lambda)}{\int_{\lambda}^{R(\lambda)d\lambda}} = \frac{R(\lambda)}{\int_{\lambda}^{R(\lambda)d\lambda}}$$
(12)

The Eq. (12) expresses the normalized reflectance curves of fabrics with different texture surfaces are the same line in the normalized reflectance space, which depend on the nominal reflectance $R(\lambda)$.

How the Texture Surface of a Fabric Affects its Tristimulus Values. Given the CIE color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, the color of a fabric sample can be specified in CIEXYZ color space.

$$\begin{cases} X = \int_{\lambda} R_{b}(\lambda)E(\lambda)\bar{x}(\lambda)d\lambda = \frac{\int_{p,q} m_{b}(p,q)H(p,q)dpdq}{A_{r}} \int_{\lambda} E(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \\ Y = \int_{\lambda} R_{b}(\lambda)E(\lambda)\bar{y}(\lambda)d\lambda = \frac{\int_{p,q} m_{b}(p,q)H(p,q)dpdq}{A_{r}} \int_{\lambda} E(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \\ Z = \int_{\lambda} R_{b}(\lambda)E(\lambda)\bar{z}(\lambda)d\lambda = \frac{\int_{p,q} m_{b}(p,q)H(p,q)dpdq}{A_{r}} \int_{\lambda} E(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda \end{cases}$$
(13)

The expression in Eq. (13) reveals that fabric samples with different texture structures define a line in the CIEXYZ color space. The direction of the line is

$$\left[\int_{\lambda} E(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \int_{\lambda} E(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \int_{\lambda} E(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda\right]^{T}.$$

The chromaticity coordinates of the fabric sample is computed as following.

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Fig. 3. The prepared physical samples of knitted yarn dyed fabrics. (a) the samples are in 4 color centers: green, gray, red, and blue. (b) the 21 texture structures of green samples.

$$\begin{cases} x = \frac{X}{X+Y+Z} = \frac{\int_{\lambda} E(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda}{\int_{\lambda} E(\lambda)R(\lambda)(\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda))d\lambda} \\ y = \frac{Y}{X+Y+Z} = \frac{\int_{\lambda} E(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda}{\int_{\lambda} E(\lambda)R(\lambda)(\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda))d\lambda} \end{cases} (14) \\ z = \frac{Z}{X+Y+Z} = \frac{\int_{\lambda} E(\lambda)R(\lambda)(\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda))d\lambda}{\int_{\lambda} E(\lambda)R(\lambda)(\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda))d\lambda} \end{cases}$$

Equation (14) reveals that the chromaticity coordinates of fabric samples with different texture structures are constant.

How the Texture Surface of a Fabric Affects its Color in CIELAB Space. The color of a fabric sample in CIE-LAB space can be transformed from its color specified in CIEXYZ space.

$$\begin{cases} L * = 116f(Y/Y_n) - 16\\ a * = 500[f(X/X_n) - f(Y/Y_n)]\\ b * = 200[f(Y/Y_n) - f(Z/Z_n)] \end{cases}$$
(15)

where

$$f(t) = \begin{cases} t^{1/3} & t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3} \left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{otherwise} \end{cases}$$
(16)

Equations (15) and (16) show the transformation of color from the CIEXYZ to CIELAB space is nonlinear. The linearity of fabric samples with different texture structures in the reflectance space [Eq. (11)] and CIEXYZ space [Eq. (13)] is lost in the CIELAB space. Assuming linear dependence of spectral reflectance with texture, therefore, it is messy to estimate the influence of texture structures of fabric samples on their colors in the CIELAB space.

EXPERIMENTAL AND DISCUSS

Preparation of Samples

84 samples of knitted yarn dyed cotton fabrics were prepared for experiment. These samples were in four color centers recommended by the CIE^{24} : green, gray, red, and blue [Fig. 3(a)]. In each color center, the single jersey

COLOR research and application



Fig. 4. The reflectance and normalized reflectance curves of all samples. (a) the reflectance curves of samples in green, gray, red and blue color centers (from top to bottom). (b) the normalized reflectance curves of samples in green, gray, red, and blue color centers (from top to bottom). Noted that all the curves in (a) and (b) are drawn with the same scale.

structure, i.e., the plain structure, was defined as the standard texture structure [Fig. 3(b)–Std.]. The batch texture structures in each color center included 20 different textures widely used in knitwears [Fig. $3(b)-2\sim21$]. The standard and batch samples in each color center were knitted by one same colored yarn using a Shima Seiki Knitting Machine.

The MACBETH Color-Eye 7000A Spectrophotometer was used to measure the colors of these samples. The specular component excluded (SCE) and UV excluded modes were applied to eliminate the influence of specular light and UV on samples.

Reflectance Space

We first analyzed how the texture structures of the samples affect their measured reflectance values. Equation (11) shows fabric samples with different texture surfaces define a set of lines with identical direction but different magnitude in the reflectance space and their normalized reflectance is identical [Eq. (12)]. Figure 4 shows the reflectance and normalized reflectance curves of all the samples. As shown in Fig. 4(a), the reflectance curves of samples in each color center have the same shape but slightly different magnitude. Figure 4(b) shows that the normalized reflectance curves of samples in each color center are approximately constant.

To check the degree of similarity among the normalized reflectance curves of samples in each color center, the angle between the normalized reflectance curves of batch samples and the standard sample in each color center is calculated.²⁵

$$\theta = \cos^{-1} \left(\frac{\bar{R}_{b}^{B}(\lambda) \bullet \bar{R}_{b}^{S}(\lambda)}{\|\bar{R}_{b}^{B}(\lambda)\| \|\bar{R}_{b}^{S}(\lambda)\|} \right)$$
(17)
$$= \cos^{-1} (\bar{R}_{b}^{B}(\lambda) \bullet \bar{R}_{b}^{S}(\lambda))$$

TABLE I. The angles between the normalized reflectance curves of the batch and standard samples in green, gray, red, and blue.

	Green samples	Gray samples	Red samples	Blue samples	Mean of samples with different color
Texture No 2	0.51°	0.20°	0.65°	0.90°	0.56°
Texture No. 3	0.57	0.20	0.00	0.00	0.50
Texture No /	0.52	0.36°	0.42	1 130	0.50
Texture No.5	0.61	0.30	0.72	0.60°	0.70
Texture No.6	0.04	0.10	0.44	0.09	0.48
Texture No.7	0.75	0.41	1.010	0.94	0.00
	0.75	0.77	1.01	0.93	0.60
	0.44	0.27	1.12	0.70	0.05
Texture No.9	0.26	0.17	0.35	0.92	0.43
Texture No.10	0.46°	0.11°	0.62	0.67°	0.46°
Texture No.11	0.57°	0.10°	0.45°	0.79°	0.48°
Texture No.12	0.27°	0.35°	0.23°	0.40°	0.31°
Texture No.13	0.52°	0.23°	0.50°	0.63°	0.47°
Texture No.14	0.70°	0.66°	1.09°	0.91°	0.84°
Texture No.15	0.46°	0.49°	0.99°	0.50°	0.61°
Texture No.16	0.35°	0.14°	0.51°	0.82°	0.46°
Texture No.17	0.27°	0.40°	0.23°	0.77°	0.42°
Texture No.18	0.83°	0.43°	1.69°	1.09°	1.01°
Texture No.19	0.69°	1.12°	0.60°	0.95°	0.84°
Texture No 20	0.16°	0.16°	0.08°	0.40°	0.20°
Texture No 21	0.44°	1.32°	0.00	0.78°	0.86°
Mean of samples with	0.51°	0.41°	0.66°	0.80°	0.00

TABLE II. The magnitude of reflectance of samples in green, gray, red, and blue.

	Orregen	0	Ded	DL
	Green	Gray	Red	Blue
	samples	samples	samples	samples
Texture Std.	1.09	1.79	1.64	0.71
Texture No.2	1.09	1.76	1.65	0.70
Texture No. 3	1.09	1.76	1.62	0.70
Texture No.4	1.11	1.81	1.63	0.73
Texture No.5	1.08	1.78	1.63	0.70
Texture No.6	1.05	1.74	1.60	0.68
Texture No.7	1.06	1.77	1.60	0.68
Texture No.8	1.09	1.79	1.64	0.71
Texture No.9	1.08	1.78	1.61	0.70
Texture No.10	1.10	1.81	1.65	0.73
Texture No.11	1.10	1.77	1.64	0.72
Texture No.12	1.09	1.77	1.62	0.73
Texture No.13	1.06	1.73	1.60	0.69
Texture No.14	1.03	1.72	1.59	0.69
Texture No.15	1.09	1.78	1.63	0.70
Texture No.16	1.11	1.78	1.64	0.70
Texture No.17	1.01	1.76	1.57	0.64
Texture No.18	1.10	1.66	1.66	0.72
Texture No.19	1.08	1.79	1.65	0.71
Texture No.20	1.11	1.76	1.64	0.72
Texture No.21	1.07	1.70	1.59	0.67

where $\bar{R}^B_{\ b}(\lambda)$ and $\bar{R}^S_{\ b}(\lambda)$ denote the normalized reflectance of the batch and standard samples in each color center. The normalized reflectance curves between the batch and standard samples are identical when the angle is equal to 0°. The difference of their normalized reflectance curves is larger with increasing angles.

Table I shows the angles between the normalized reflectance curves of the batch and standard samples in

each color center. The angles of samples with texture No. 20 are smallest, i.e., 0.16° , 0.16° , 0.08° , and 0.40° for the green, gray, red, and blue samples. This stems from that texture Std and texture No. 20 are visually similar, as shown in Fig. 3(b). Samples with texture No. 18, No. 7, and No. 21 produce the largest, second largest and third largest angle differences for all of the samples, i.e., 1.01° , 0.86° , and 0.86° . These results highly agree



Fig. 5. The color histograms of all samples in the CIEXYZ space. (a-d) the color histograms of green, gray, red, and blue samples.



Fig. 6. The chromaticity and tristimulus values of all samples: (a), (c), (e), (g): the chromaticity values of green, gray, red and blue samples. (b), (d), (f), (h): the tristimulus values of green, gray, red, and blue samples.

with the large perceived differences between texture Std and texture No. 18, No. 7, and No. 21. The average angles are 0.51° , 0.41° , 0.66° , and 0.80° for the samples in green, gray, red, and blue. The small angles between the normalized reflectance curves of the batch and standard samples in each color center demonstrate that their normalized reflectance curves resemble in the normalized reflectance space, which echoes the results shown in Fig. 4(b).

Given a measured reflectance of a sample $R = [r_1, r_2, \dots r_n]$, the magnitude of the reflectance is defined as²⁶:

$$|R| = \sqrt{\sum_{i=1}^{n} r_i^2}$$
(18)

where n denotes the number of spectral bands.

Table II shows the magnitude of measured reflectance of samples in each color center. The reflectance magnitude is in the ranges [1.01, 1.11], [1.66, 1.81], [1.57, 1.66], and [0.64, 0.73] for the samples in green, gray, red, and blue. It can be observed that the texture structure of a fabric would cause its reflectance magnitude fluctuation, which coheres the results shown in Fig. 4(a).

When considering a reflectance curve as a vector, reflectance can be expressed as a combination of direction (normalized reflectance) and magnitude. With Fig. 4(b) showing that fabrics with different texture structures have approximately identical normalized reflectance, whereas Fig. 4(a) showing that their reflectance magnitude values vary with texture structures, it can be concluded that the texture surface of a fabric sample dominantly influences the magnitude of reflectance rather than its direction.

CIEXYZ Color Space

Figure 5 plots all of the color samples in the CIEXYZ space. For samples in the green, gray, green, and blue color centers, their colors form a straight line in the CIEXYZ space. Least squares regress method²⁷ was used to fit the tristimulus values of these samples. The correlation values between the colors and the regressed lines are 0.994, 0.997, 0.913, and 0.997 for the green, gray, red and blue samples. The high correlation values demonstrate that colors of fabric samples with different texture structures approximately define a line in the CIEXYZ color space.

Figure 6 shows the chromaticity and tristimulus values of samples in green, gray, red, and blue. The chromaticity coordinates of samples in each color center are approximately identical. However, their tristimulus values dramatically vary with texture structures. The standard deviations²⁸ of samples in each color center are used to quantify the chromaticity and tristimulus difference between samples with different textures, as shown in Table III. The standard deviations of chromaticity values are <0.0012 for all samples. However, the standard deviations of tristimulus values of these samples are more than 0.2.

CIELAB Color Space

The third experiment analyzed the colors of the samples in CIELAB color space. Figure 7 shows the color

TABLE III. The standard deviation (std) of chromaticity and tristimulus values of all samples.

	std of x	std of y	std of X	std of Y	std of Z
Green samples	0.0007	0.0009	0.3750	0.5175	0.5952
Gray samples	0.0000	0.0004	0.6305	0.6644	0.6770
Red samples	0.0022	0.0002	0.4410	0.3427	0.2209
Blue samples	0.0008	0.0012	0.2578	0.2645	0.6128



Fig. 7. The color histograms of all samples in the CIELAB space. (a-d) the color histograms of green, gray, red, and blue samples.

distributions of samples in CIELAB color space. Least squares regress method²⁴ was used to fit the colors. The correlation values between the colors and the regressed lines are 0.081, 0.161, 0.044, and 0.372 for the samples in green, gray, red, and blue. Comparing Fig. 7 with Fig. 5, we can conclude that the color distributions of the samples in CIELAB space are much less linear than those in CIEXYZ space.

Removing the Effect of Texture on Color

The linear relationship between the measured reflectance of fabrics with different textures can be utilized to estimate a theoretical reflectance for each fabric which discounts the influence of texture on color. For a fabric sample with j-th texture in the color center C_i , its theoretical reflectance $R_{\tau_i}^j(\lambda)$ can be expressed as

$$R_{T,i}^{j}(\lambda) = |R_{T,i}^{j}(\lambda)|\bar{R}_{T,i}^{j}(\lambda)$$
(19)

where $|R_{T,i}^{j}(\lambda)|$ and $\bar{R}_{T,i}^{j}(\lambda)$ denote the magnitude and the normalized reflectance of $R_{T,i}^{j}(\lambda)$. As shown in Eq. (11), the magnitude of measured

As shown in Eq. (11), the magnitude of measured reflectance of the sample with j-th texture in color center C_i ($|R_{b_i}^j(\lambda)|$) is determined by the texture surface variable $(\int \int_{p,q} m_b(p,q)H(p,q)dpdq)$, the size of aperture A_r and



Fig. 8. The multiple relationships of textured samples in terms of reflectance magnitude. In each color center, the samples with the plain texture are chosen as the standard.



Fig. 9. The color difference before and after removing texture effect between samples with different texture structures and the stand texture structure (a-d) the green, gray, red and blue samples.

the nominal reflectance magnitude $|R_i(\lambda)|$. A reasonable assumption is that the texture surface variables are approximately identical for two samples $(R_{h,1}^{l}(\lambda))$ and $R_{h2}^{j}(\lambda)$ with the same texture but in different color centers C_1 and C_2 . Comparing to the corresponding samples $(R_{b,1}^{s}(\lambda) \text{ and } R_{b,2}^{s}(\lambda))$ with standard texture in C_1 and C_2 , as a consequence, the multiple relationships $|R_{h,1}(\lambda)|/|$ $R_{b,1}^{s}(\lambda)$ and $|R_{b,2}(\lambda)|/|R_{b,2}^{s}(\lambda)|$ can be approximated to be identical. For the sample $R_{h,i}^{j}(\lambda)$, we can estimate its multiple relationship of reflectance magnitude $(M_j = |R_{b,i}^j(\lambda)| / |R_{b,i}^s(\lambda)|)$ compared to the sample of the standard texture $(R_{bi}^{s}(\lambda))$ as the mean value of multiple relationship of reflectance magnitude among samples with the jth texture in all the color centers:

$$M_{j} = \frac{1}{N} \sum_{i=1}^{N} \frac{|R_{b,i}^{i}(\lambda)|}{|R_{b,i}^{s}(\lambda)|}$$
(20)

where N denotes the number of color centers, here, N=4.

Given the measured reflectance $R_{b,i}^{j}(\lambda)$ for the sample with jth texture in the color center C_i , its magnitude of theoretical reflectance $|R_{\tau_i}^{j}(\lambda)|$ can be estimated as

$$|R_{T,i}^{j}(\lambda)| = \frac{|R_{b,i}^{j}(\lambda)|}{M_{j}}$$

$$(21)$$

The normalized reflectance $\bar{R}^{j}_{\tau,i}(\lambda)$ can be estimated as $\bar{R}^{j}_{b,i}(\lambda)$ since samples with different texture structures in a

color center have the same normalized reflectance [Eq. (12) and Fig. 4(b)].

Figure 8 shows the multiple relationships of reflectance magnitude for the green, gray, red and blue samples. For each color center, the sample with single jersey was chosen as the standard texture. It can be observed that samples with same texture in different color centers have approximately identical multiple relationship in terms of reflectance magnitude when compared to the samples with standard texture. Some outliers exist in Fig. 8 such as the samples with No. 17 texture structure, yet the deviation is high, which could be due to the non-uniformity of the sample preparation. The color differences between batch and standard samples before and after removing texture effect were calculated by the CMC (2:1) formula, which is one of the color difference formulas widely adopted in textile. The standard sample in each color center is the one with the standard texture. As shown in Fig. 9, the color difference after removing texture effect is much smaller for the samples in the four color centers. The average color difference values before texture effect removal for samples in green, gray, red and blue are 0.39, 0.30, 0.31, 0.32 CMC(2:1) units. The average color difference values after removing texture effect are 0.08, 0.13, 0.09, and 0.14 CMC (2:1) units for these samples. The influence of texture on color is reduced by 79%, 55%, 71%, and 57% for the green, gray, red, and blue samples, respectively.

CONCLUSION

The influence of texture surface of a fabric on its instrumental color is studied in this article using 84 physical knitted cotton yarn dyed fabric samples in four color centers and 21 texture structures. In the reflectance space, fabrics with different texture surfaces define a set of lines with identical direction and their normalized reflectance curves are constant. In the CIEXYZ space, fabric samples with different texture surfaces define a line and their chromaticity coordinates are identical. In the CIELAB space, however, linearity does not held due to the non-linear transformation from the CIEXYZ space to the CIELAB space. Experimental results show fabric samples with different texture structures are more linear in the reflectance and CIEXYZ spaces than the CIELAB space. The finding of this article has the potential to remove the influence of texture of a fabric on its color when it is measured by a spectrophotometer. Experiments show that the influence of texture on color can be reduced by 79%, 55%, 71%, and 57% for the samples in the four color centers. This study implies that the color of a fabric sample specified in the CIELAB space is not suitable for analyzing the influence of texture surface of a fabric sample on its instrumental color, while the CIELAB color space approximates human vision. Instead, the reflectance and CIExyY spaces are recommended.

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