Effect of Texture on Visual Perception of Color Lightness in Inkjet Printed Woven Textiles

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Abstract

Colored textiles are influenced by a wide range of parameters due to highly diverse textile structures and the resulting textures. In practice, variation in color appearance due to changes in surface characteristics is a serious management problem.

The goal of this study is to understand the effect of texture on visual perception of color in inkjet printed woven textiles. Cotton woven samples were constructed with nine different weave structures. The surface characteristics of the samples were determined using the KES-F and profiling instruments. Each sample was digitally printed with identical squares of primary colors of cyan, magenta, and yellow and secondary colors of red, green, and blue. The amount of ink applied was controlled consistently with an image editing software. CIE L values were calculated from the measured reflectance. For visual assessment, the rank order method was applied and 25 observers ranked the perceived texture and color lightness of each sample.*

By employing the rank order method, a perceived visual texture scale was obtained statistically from the specified rankings. The scale of visual texture shows high correlation with the friction coefficient (MIU) and the mean deviation of the MIU (MMD). The roughness (SMD) was not correlated with the scale of visual texture. The surface measurements from the profiling instrument (Pa) are also correlated with the scale of visual texture. The scale of the perceived color lightness was estimated from the assessed rankings. The measured CIE L values and the scale of perceived lightness have a linear relationship for the primary and secondary colors. The scale of the perceived texture and the CIE L* values showed a relatively good correlation, but the surface characteristics of the weave structure, such as highly oriented yarn on the surface, can affect the light reflectance differently.*

Introduction

It has been a challenge to accurately reproduce a given hue with a range of substrate and ink combinations with digital textile printing [1]. In digital color reproduction, generation of color in a printing system is dependent upon many variables including the colorants, the print engine, the medium and the interrelations among them (See Figure 1). The number of parameters highly affects the accuracy of color matching operations [2].

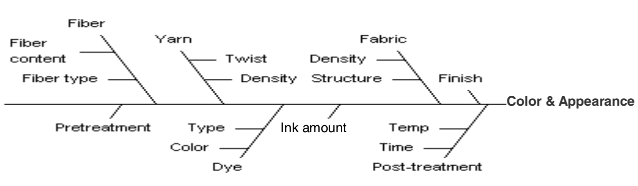

Figure 1 *Variables in inkjet printing on textiles*

The printing process for textiles is different from paper printing. The surface of textile materials is very highly textured, commonly in non-uniform ways and is rougher and more porous than paper. In printing, this can cause dot deformation, physical dot gain and influence ink penetration. Inkjet printing systems consistently eject drops of inks as specified by the CAD software, regardless of the substrate. In addition, in the inkjet printing process colorants do not penetrate into the fibers like in the dyeing process. Hence, most of the inks react with the surface of the fibers. So, the surface topology might affect how much of the ink reacts with the fiber and how much will be washed out. The surface characteristics of woven textiles, such as fiber cross-sectional shape in micro-scale or yarn and fabric structure in macro-scale dramatically influence light interaction with the surface and hence color. The goal of this study is to understand the effect of texture on visual perception of color in inkjet printed woven textiles.

Background

Color results from the interaction of a light source with an object, and with the observer's eye and brain. Any light source can be described in terms of the relative power emitted by each wavelength. Plotting this power as a function of the wavelength gives the spectral power distribution curve of the light source. A number of spectral power distributions, known as illuminants, have been defined by the Commission Internationale de l'Eclairage (CIE) for use in describing color. Industries such as paints, plastics, and textiles have adopted D65, representing average daylight, as the standard illuminant [3].

The chromatic properties of an object along with its geometric surface attributes may affect the reaction to light and influence the perceived color. To evaluate color, the CIE specified that opaque samples should either be illuminated at 45° from the normal (perpendicular to the specimen surface) and viewed at an angle close to the normal (45/0), or be illuminated at an angle close to the normal and viewed at an angel 45° to the normal (0/45). Two alternative viewing geometries are known as diffuse/normal and normal/diffuse and refer to the use of spectrophotometers with integrating spheres that collect all the light reflected in a sphere from the surface of a sample placed against an opening [3].

In 1931, CIE established the standard RGB color matching function, and developed convenient standard imaginary primaries, X, Y, and Z by linear transformation of the real primaries. These transformed functions are called the *CIE 1931 XYZ color matching functions*. The ideal observer whose color matching conditions correspond to the color matching functions $\overline{x}(\lambda)$, $\overline{y}(\lambda)$, and $\overline{z}(\lambda)$ with the 2° field of view is called the *CIE 1931 standard colorimetric observer* [3], [4]. By using the color matching function, light stimuli expressed by a spectral power distribution can be specified by three values, known as the *tristimulus values* of light stimuli. Hunt [5] declared that if two color stimuli have the same tristimulus values, they will look alike when viewed under the same photopic conditions by an observer whose color vision is not significantly different from that of the CIE 1931 Standard Colorimetric Observer. Conversely, if the tristimulus values are different, the colors may be expected to look different in these circumstances. In practice, it is difficult to relate the tristimulus values of an object to its appearance because the *XYZ* values have very little real meaning to most observers [6]. For more accurate specification of object colors and color differences, CIE recommended three-dimensional color spaces, CIELAB and CIELUV in 1976. When dealing with surface color such as paint and textiles, the CIELAB color space is most widely used. In the CIELAB system, the L^* value means lightness of a color from 0 to 100. The chromatic axes, indicated with a^* and b^*, show the red-green and blue-yellow characteristics of color, C^*_{ab} indicates chroma and h_{ab} shows hue [4].

There are two methods used to assess color: instrumental measurement and perceptual assessment. Both methods can be used for the examination of color differences. Spectrophotometers can be used to measure the ratio of reflected to incident light (the reflectance) from a sample at many points across the visible spectrum. *XYZ* or L^* a^* b^* coordinates can then be calculated for a particular illuminant [6]. When obtaining spectral data, the standard illuminants and light sources along with the standard reference whites, plus the geometry and the viewing angles of measuring devices should be defined.

When an object is observed, its characteristics are influenced by how light is reflected from the surface. Different surface features create varying directional distributions of light, allowing the surface to be analyzed on the basis of geometrical optics [7]. With a smooth surface, the angle of reflection equals the angle of incidence. If the surface is microscopically rough, the light rays will reflect and diffuse in many different directions. Several reflectance models have been developed based on rough surfaces including Kirchhoff theory, the Torrance-Sparrow model and the Lambertian reflection model [8], [9], [10], [11], [12].

Woven textiles are constructed from yarns which can have different diameter and twist. The yarns are made from fibers with various structural properties such as cross-sectional shape, diameter and longitudinal shape. In a woven textile, reflection occurs between two media, between air and a fiber or air and a pigment particle. Figure 2 (a) shows light striking a simplified fiber circular cross section. When a light beam strikes normal to the surface and is passed back from the media, reflection occurs. The amount of the surface-reflected light from many textiles normally falls somewhere between 0 and 4 % [7], [13]. When many fibers are grouped in a yarn, as in Figure 2 (b) which shows several fibers in cross section, some of the reflected light from the surface becomes trapped and lost by absorption [7], [14]. Figure 2 (c) presents pile fabrics, such as velvets, corduroys, and carpets, which have more opportunity for the incident light to be trapped between the fibers or yarns.

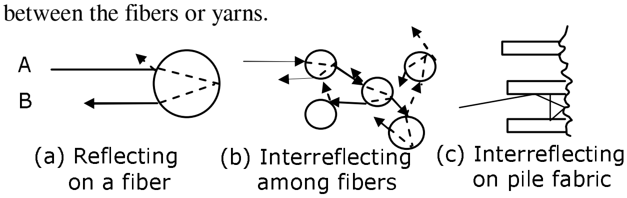

***Figure** 2 Diagram of light reflection on a fiber, yarn, and pile fabric [7],[14],[15]*

When textiles of different structures are dyed or printed with the same colorants, and under the same conditions, the color appearance can vary according to the configuration of the fabric, fibers or yarns. The micro-scale structure of the fiber, the yarn, the textile and finishing may affect color appearance [16]. Kim and Lewis [15] investigated the color differences among identically dyed woven fabrics, flock surfaced fabrics and flock fibers. When light entered a flocked surface, it was partially reflected and absorbed back and forth among the dyed flock fibers, so the color appeared purer, more saturated, and lower in chroma value than a plain fabric. Lee and Sato [17], [18] examined the reflected light characteristics of different weave constructions using a goniospectrophotometer and a goniophotometer [19], [20] concluding that light reflection should be influenced by the weave direction of the fabric. They found that the surface color of fabrics varied with the warp and weft yarns on the surface, and that the perceived texture could be anticipated by the characteristics of the reflected light. A commercial damask design uses this surface reflection effect to make one area appear darker than the other, depending on the angles of illumination and viewing [7].

In inkjet printing systems, surface roughness is likely to influence image formation in the physical printing, as well as in color perception. Print density and color may be affected by substrate roughness through variations in ink distribution, and ink thickness. Oittinen and Saarelma [21] determined that in non-contact printing spreading tends to cause ink to flow sideways from smooth points perhaps resulting in depletion of ink from initial contact points.

Describing the surface topography of textile substrates in measurable, quantitative terms is difficult because of its many visual and tactile attributes. Surface texture roughness has been traditionally measured using the stylus profiling method by a surface height variation (SHV) trace that characterizes thickness variations. Several calculated profile parameters have been standardized through ASME B47.1-2002 and ISO 4287. ASME B47.1-2002 defines roughness average, R_a, value as the arithmetic average of the absolute value of the profile height deviation. Root-mean square roughness R_q, is also defined in terms of surface-height deviations from the mean surface. In practice, the two representative surface heights, R_a and R_q are usually very similar. The Kawabata Evaluation System for Fabric (KES-F) measures surface height variation using a steel wire 0.5 mm in diameter moved across a surface at a constant rate of 0.1 cm/sec acquiring SMD, the mean deviation of surface roughness. Surface friction is measured with a contact force of 50gf, and MIU (mean value of coefficient of friction) and MMD (mean deviation of coefficient of friction) are calculated. The measure of surface friction indicates the fabric resistance to the probe moving across the surface, while the surface roughness is a measure of the contour of fabric surface.

Visual assessment for purposes of color control and specification requires careful and consistent control of several factors [3], [22]. The illuminating conditions should be stable over time, implying the use of a light booth. Once the background and surround are defined and the light sources selected, the spectral power distributions and levels of illumination must be measured. Specimens should be placed on the floor of the booth so that the illumination is centered perpendicular to the plane of the specimens. The observation angle is 45° from normal where normal is considered to be perpendicular to the specimen. When observing samples of different sizes, different areas of the retina are used and the colors appear different [22]. Therefore, sample size should be consistent. The observer should be about 6-12 inches from the opening of the booth.

The assessment of an object's color appearance can vary among individuals and the same individual can make varied judgments on different days or at different times. Color perception abilities depend on an individual's cone sensitivities, degree of color blindness, age, general health, and even attitude [23]. Observers are also influenced by adjoining or background color, the relative sizes of areas of contrasting color, and gloss and texture of a surface. Therefore, in addition to a standard environment, a color vision test for observers should be conducted to qualify observers prior to visual perception assessment. For color confusion-evaluation, the Ishihara color test is most widely used [6]. The newer Neitz test of color vision readily identifies the type and severity of color vision deficiency [24]. The Farnsworth-Munsell 100 hue test is widely used for assessing color discrimination, and is relatively quick and simple to use [6].

Gustav Teodor Fechner, a German philosopher and scientist, initially determined three approaches for measuring perceptual experiences [25]. *Detection* deals with how much of a stimulus change is necessary for an individual to see, hear, or otherwise sense. The study of *discrimination* focuses on how much two stimuli must differ in order to be recognized as not the same. *Scaling* attempts to determine how much of a change exists in the psychological experience or in the quality of a stimulus scaling experiments attempt to derive relationships between the physical measurements and perceptual magnitudes of stimulus intensity. A variety of scaling techniques have been devised to generate these relationships, such as rank ordering, category scaling, paired comparison, and magnitude estimation [25], [26].

Lo et al. [27], Fairchild and Braun [28], Fairchild and Johnson [29], and Tsukada et al. [30] published color appearance models to describe how the human visual system perceives the color of an object under different lighting conditions and with different backgrounds. By applying such a model, an image that is viewed under one lighting condition can be adjusted to appear the same if viewed under different lighting condition. Such models have not attempted to incorporate textile surface textures.

This investigation focused on the relationship between the perceived and measured surface texture, and perceived and measured color, using woven fabrics. The differences between the measured color lightness (CIE L* values) and the perceived color lightness with inkjet printed colored samples were investigated in terms of the surface texture change. Rank order methods were employed to determine the relative perceived lightness and texture of the given set of samples and to establish the differences in perceived lightness and texture.

Method

Sample Preparation

A 16 harness double Rapier Picanol GTM loom was used to construct nine woven fabrics with diverse weave structures (see Table 1). To minimize variability, a 20 Ne, open-end spun cotton yarn provided by Cotton Inc. was used for the weft with a warp of 20 Ne cotton yarns. Warp ends were threaded with a straight draw configuration and four ends per dent.

Table 1 Weave structures, unit repeat size and geometric properties of nine woven fabrics

Fabric No	Weave structure	Repeat	Density Count/inch)	
			Warp	Weft
1	Honeycomb	8x8	122	85
2	Monk leno	8x8	126	85
3	Bedford cord	16x4	123	82
4	Herringbone	16x8	114	77
5	Entwining Twill	16x16	114	78
6	Crepe	8x8	121	80
7	Hopsack	8x8	111	81
8	Brighton Honeycomb	16x16	134	80
9	Whipcord	8x16	127	78

Following construction, all woven fabrics were desized, scoured, and bleached. A pre-treatment solution was prepared following a commercial pre-treatment formula from Ciba Specialty Chemicals (Irgapadel MP (150 g/l), sodium chloride (100 g/l), sodium carbonate (40 g/l), and urea (100 g/l) to 1000 l of water). The woven fabrics were soaked in the solution for 12 hours, then were passed through a padding machine and dried under tension to minimize wrinkles and assure uniform pretreatment distribution.

Pretreated fabrics were digitally printed with 100 % ink level of cyan, magenta, yellow, red, green and blue. Red, green and blue were created by mixing the primaries, and the ink level was controlled using off-the-shelf software and determined by the percentage of cyan, magenta, and yellow. A Mimaki TX2-1600 digital textile printer with a piezo DOD (Drop-on-Demand) printhead was used with reactive dye-based inks from Ciba Specialty Chemicals. All printed samples were steamed at 280˚F for 1 hour in a Jacquard Vertical Fabric Steamer from Jacquard Inkjet Fabric System, and were then pre-washed twice in cold water for 5 minutes, washed with soap in hot water for 20 minutes, and rinsed. Mock-printed samples were also prepared. Mock-printed samples were pre-treated, post-treated and exposed to all of the same chemicals and temperatures as the printed samples except for printing [7].

For the perceived texture evaluation, nine fabric stimuli with different weave structures were prepared from the mock printed fabrics. The stimuli had a physical size of 1.5 inches square. A clear plastic mounting was cut to 1.5 by 2.0 inches and attached to each stimulus. Samples were oriented so the warp direction aligned with the extra mounting length so that observers could view and arrange stimuli in a consistent way. The printed fabric samples were also cut to 1.5 inches square, and attached onto the clear mounting in the same way as the first set of stimuli. (See Figure 3) Printed Stimuli sets for nine different weave structures were prepared.

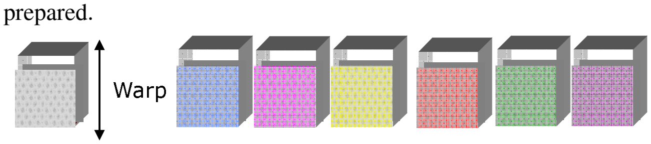

***Figure** 3 Prepared stimuli*

Fabric Characterization

The nine mock-printed fabrics were conditioned 24 hours following the procedures specified in ASTM D1776, then were used to measure the surface texture characteristics. First, the Kawabata Evaluation System for Fabric was used to measure the surface geometry and the friction coefficient, using a sample size of 20 cm by 20 cm. Each sample was measured three times in different locations and the measurements averaged. The overall friction coefficient (MIU), mean deviation of friction coefficient (MMD), and surface roughness (SMD) are reported in Table 2.

Second, the surface profile of each sample was measured with a stylus profilometer, specifically, the Somicronic Surfascan instrument with a ST204 stylus with 10 μm radius. This instrument measures the 2-dimensional primary profile of the surface and calculates standard surface texture parameters (ASME 2002). Each sample was measured in both warp and weft directions four times and averaged. From the total profile of each sample, the roughness average, R_a and waviness average, W_a, were calculated. Averages of warp and weft values were used to represent the overall surface roughness.

Table 2 Tightness factors and surface texture parameters for each fabric

No	Kawabata Surface values			Profilometry		
	MIU	MMD	SMD	P_a	W_a	R_a
1	0.9187	0.0798	12.586	110.4	68.71	24.68
2	0.83	0.0485	17.696	81.45	43.49	20.20
3	0.8022	0.0546	15.568	66.53	35.63	19.31
4	0.7847	0.028	4.6245	59.71	26.98	15.90
5	0.7791	0.0387	5.4083	79.27	27.21	21.61
6	0.8657	0.0414	14.895	60.33	36.36	21.65
7	0.8310	0.0409	8.4004	60.45	29.85	18.95
8	1.1321	0.1297	13.564	227.2	192.3	26.23
9	0.9767	0.0518	6.6289	120.5	87.05	25.26

Lightness of all mock-printed and printed fabrics was measured using the Spectraflash SF600X spectrophotometer and the specular included mode. CIE L*, a*, b*, C_{ab}, and h values were determined for mock-printed and printed samples.

Visual Assessment

As previously discussed, rank ordering is one of the accepted methods for scaling a set of stimuli or samples on a given perceptual attribute. In this study, observers were instructed to arrange the mock printed woven stimuli in order from least to most textured according to their perception of the visual texture. Observers wore a glove to avoid the influence of tangible texture. Then, six colors of digitally printed stimuli with nine different weave structures were ranked according to the perceived lightness of the colors, one color set at a time. All stimuli, including mock-printed and printed, were assessed inside a Datacolor viewing cabinet under a D65 simulator. An illuminating /viewing geometry of approximately 45/0 was used. The mounted samples were viewed against a neutral gray background.

The sets of stimuli were evaluated by 25 observers who had normal color vision according to the Neitz test. Before ranking the samples, each observer was acclimated to the light box illumination for 60 seconds. Observers assessed the color samples while standing in front of the light box. Samples were assessed through side by side comparison in one specified orientation as indicated by the mounting. This procedure was repeated one more time at least 24 hours later for a total of 50 observations for each set of samples. The rank orders assigned during each observation were recorded and analyzed using statistical methods.

Analysis Methodology

The recorded rank order data from each observer was converted to the ranking frequency. The mean ranks (M_R) were calculated by multiplying the ranks and frequencies, summing, and dividing by the number of samples [31]. After ordering M_R values sequentially, successive integers were assigned as the overall rank for each sample (R). If the rank number increases as the stimulus has less of the attribute scaled, as in color lightness, mean choice *Mc* values are often computed in which the Mc value increases as the attribute scaled increases. The mean choice is defined as $M_C=n - M_R$, where *n* is the number of samples. Then, *Mc* values can be ordered, and successive integers (*R'*) assigned again. *Mc* values of lightness rank order for each color and successive integers (*R'*) of lightness were calculated.

The concordance between two observed ranks for the same subjectively judged series of samples was specified by Spearman's rank order correlation coefficient (r_s). Spearman's correlation coefficient (r_s) was the earliest statistical technique based on ranks to be developed, and is perhaps the best known today [32]. If two variables are completely independent, (r_s) is equal to zero, while +1 and -1 represent complete identity or complete inversion, respectively [33].

Results and Discussion

The perceived texture and texture measurement from two different types of methods were analyzed. For the KES-F measurements, the mean deviation of the friction coefficient (MMD) was most strongly associated with visual texture estimation. Profilometry measures P_a and W_a were also associated with estimation of visual texture. Other instrumental texture measures were not associated with visual texture.

A regression analysis of the CIE L* values of each color against the estimation of visual lightness showed the coefficient of determination (R^2) values for cyan, magenta, yellow, and green were over 0.9. For the red and blue samples, R^2 values were slightly lower, but, were still indicative of a positive relationship.

The Spearman rank-order correlation coefficients were computed for the visual mean rankings and the instrumentally measured rankings of texture and lightness. The Spearman rank-order correlations are listed in Table 3. As shown in the table, the perceived visual texture rank and the mean deviation of friction coefficient (MMD), W_a, MIU, and P_a are positively correlated. The visual texture rank is not associated with SMD and R_a.

Table 3 Spearman's rank order correlation for texture

Spearman's rank order coefficient (r_s) between measured and perceived texture					
MIU**	MMD*	SMD	P_a*	W_a*	R_a
0.7167	**0.8333**	**0.2667**	**0.7833**	**0.83**	**0.58**
*α=0.05, **α=0.1					

Table 4 shows the perceptual and measured lightness rank

Spearman rank-order correlation coefficient for each color. The visual lightness ranking is highly positively correlated with CIE L* at the level of α = 0.05.

Table 4 Spearman's rank order correlation for color lightness

Spearman's rank order coefficient (r_s) between measured and perceived ranking of lightness					
Cyan	Magenta	Yellow	Red	Green	Blue
0.9333	0.95	0.9	0.9	1	0.933

Measured surface texture is not represented by a single absolute value, since surface texture is subjective and can be characterized by many different predominant dimensional changes. Hence, for analysis of human perception of lightness variation due to texture, the perceptual texture ranks determined by the observers were assumed to be the true surface texture rank. The estimated rank scale was considered to represent the texture differences among the given samples. Based on these assumptions, the correlation between the perceived visual texture ranking and the measured color lightness among the nine mock-printed samples was analyzed. The Spearman rank correlation coefficient r_s was -0.49, suggesting an inverse relationship but the correlation was not significant at α = 0.05 level.

To clarify the relationship, CIE L* was plotted against the z value of visual texture. The scatter plot showed an outlier, a whipcord weave structure, which has a dominant ridged twill line on the surface. This strong, linearly patterned surface was assessed as strongly textured by observers, but a relatively high lightness value was measured since the highly oriented yarns reflected light. Hence, in contrast to other samples, the whipcord weave sample has relatively higher lightness than expected for its texture level. The Spearman rank-order correlation coefficient without a whipcord weave sample was -1 which means the ranking of the perceived texture and the ranking based on measured lightness were inversely related. That is, the greater the perceived texture the lower the perceived lightness.

An ANOVA test for differences among samples in perception of color due to texture variation showed that there was at least one significant difference in mean ranking of color lightness perception among the fabric texture. The interaction between color and texture was significant, $F(40, 2646) = 33.87$, $P<0.0001$. This result verifies that the effect of texture on perceived color varies among colors and textures as can be seen in Figure 4.

The rank of visual lightness of each color is plotted against the visual texture ranking in Figure 4. This graph shows that, in general, as the visual texture rank increases, samples are perceived as darker. Highly textured samples showed the most consistent ranks. This analysis also shows that the lightness of sample 9, the outlier in the previous analysis, was inconsistently ranked. It could be that the observers had a difficulty judging the lightness of sample 9 because it had both a highly textured surface and higher surface reflection caused by the highly oriented yarn.

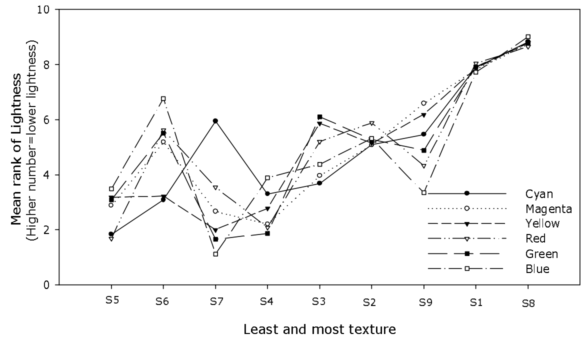

***Figure** 4 Plot of visual lightness rank against visual texture rank*

Conclusion

This study showed that the visually perceived texture estimation of the woven fabric samples was highly correlated with the instrumentally measured surface texture values MIU, MMD, P_a, and W_a. The visually perceived color lightness estimation also showed high correlation with instrumentally measured color lightness (CIE L*) values. In general, results showed that as the visual texture rank increased, inkjet printed samples were perceived as darker but the effect of texture is not consistent across colors as demonstrated by the ANOVA results. So lightness of color was a function of perceived visual texture, but surface characteristics, such as highly oriented yarns or long floats that affect the light reflection, could mediate this affect. In future work, the strong surface orientation of diverse types of fabric can be characterized using pattern recognition and their interaction with color perception investigated to enhance color prediction for textiles. In addition, further work should attempt to relate measurable color differences to perceptual color differences in order to understand how the effect of texture on textile color might impact practical application.

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