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Visual Color Difference between Colored-Yarn Mixed Woven Fabrics and Their Instrumentally Measured Colors: the Effects of Individual Yarn Colors and Texture

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Abstract: The study investigated the differences between perceived and instrumentally measured colors of woven fabrics in which different colored yarns are woven together such that they are perceived as solid colors. Cyan, magenta, and yellow yarns were woven together to produce 63 fabrics in a wide range of colors, the values of which were measured spectrophotometrically. The measured colors were generated as solid color images on a calibrated cathode ray tube (CRT) monitor. Then the fabrics were scanned and their scanned images were displayed beside their corresponding solid color images on the CRT monitor to evaluate the visual color difference between them. The results showed that the individual yarn colors and their interlacement on the fabric surface influenced the overall color appearance. Although the woven and solid colors in each pair had identical CIELAB color values, the perceived color difference was as large as 5.68 $\Delta E^{*}_{ab,10}$ on average. Fabrics composed of various colors of yarn were found to have larger visual color differences from their measured colors than those composed of single colors of yarn. The visual color difference varied according to texture, but texture strength, which has been widely reported as a strong parametric factor in visual color difference evaluation, was not shown to have had a consistent effect. This study also examined how the overall color attributes, including the lightness, chroma, and hue, of fabrics affected the visual color difference and developed a predictive model of those effects.

Keywords: Visual color difference, Woven fabric, Yarn color, Texture, Solid color

Introduction

Instrumental color measurement systems have been widely used in industries heavily relying on color such as textiles, plastics, paper, and graphic arts. One of the most important applications is color quality control which evaluates the color variations between the standard and batch samples quantitatively by means of color difference formulas [1]. Conventionally, this task was conducted by experienced experts subjectively, but recently the visual methods were completely or mostly replaced by instrumental methods in order to achieve higher levels of accuracy in color evaluations. Instrumental color measurements provide the superior colorimetric accuracy required not only for quantitative color evaluation, but also for color specification and communication. However, there are many visual phenomena in the world that cannot be described solely with the colorimetric values determined instrumentally. For example, two objects with different CIELAB coordinates can match in color appearance under a certain illuminant, although they usually do not match under others. Color appearance also depends on the size, shape, surface characteristics, background, and surround of the colored object [2].

Textile fabrics are rarely flat and have three-dimensional surface textures. The surface texture is regarded as one of the most important parameters which affect the overall color appearance of fabrics [3]. Several experiments [3-7] have been carried out to analyze the texture effect quantitatively using colored fabrics with different textures. In the work of Xin *et al.* [4], 15 differently textured woven fabrics, which were color-mapped and displayed on a cathode ray tube (CRT) monitor, were used. It was found that an increase of 10 units of texture strength, represented by the half-width of histogram of texture images, in luminance channel causes a decrease of 0.25 CIELAB units in visual color difference. In another study by Shao *et al.* [5], the effect of surface texture on instrumental and visual color difference evaluations was investigated using seven differently textured knitted fabrics. A high degree of inconsistency was found between spectrophotometric measurement and visual assessment results with high *PF*/3 (performance factor, a measure of variability) values, which indicate the strong texture effect on color perception. Kandi *et al.* [6] also found that surface texture has a significant effect on the measured and perceived colors of textiles and different colored textiles have different magnitudes of the texture effect.

The previous works focused mainly on the texture type and texture strength of fabrics. They used a limited number of colors for fabric samples, and the colors used were solid colors which were obtained by using single colored yarns or a color-mapping technique. However, in the case of the fabrics composed of various colored yarns, not only the surface texture but the individual yarn colors influence the overall color appearance. The way the individual yarn colors work follows one type of color mixing principle, optical

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color mixing [8,9]. There are three typical color mixing principles: the additive color mixing of lights, the subtractive color mixing of colorants, and the optical color mixing [10]. Essentially, the additive and subtractive color mixings are physical phenomena. However, the optical color mixing is a psychophysiological phenomenon, i.e. it is a color illusion in which two or more colors are perceptually mixed and create a new color. In woven fabrics, when the different colored yarns juxtaposed on the textured surface are observed from some distance away, the colors and texture are all optically mixed and perceived as a non-textured solid color overall (e.g. the woven fabric composed of red and blue yarns in the same proportion will be perceived as solid purple). There have been some efforts to derive theoretical models to predict the spectrophotometric measurements of multicolored woven fabrics, by assuming them as solid colors, from the measured colors of individual yarns and the structural parameters of the fabrics [8,11-16]. However, those individual parameters affect not only the measured color of the fabrics, but also the subjectively perceived color appearance. We still can see the individual yarn colors and texture on the fabric surface which produce obviously different color appearance from that of the solid color having the same colorimetric values. This optical mixing phenomenon should be studied quantitatively in terms of its effect on color appearance as well.

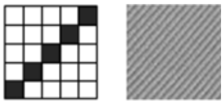
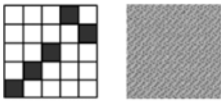
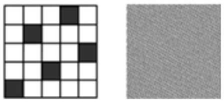
This study investigated the effects of individual yarn colors and texture of woven fabrics on the perception of the overall fabric colors. Sixty-three woven fabrics with three different textures and 21 different colors, which were obtained by mixing cyan, magenta, and yellow yarns in different proportions, were used. For the quantitative investigation, the visual color difference between the fabrics and their instrumentally measured colors, which were visually generated as solid color images, was evaluated using the gray scale method on a CRT monitor. The specific objectives of the study were to: 1) demonstrate a discrepancy in color appearance between woven fabrics and their measured colors, 2) investigate the effects of the number of yarn colors and the texture shown on the fabric surface on this discrepancy, 3) examine how these effects vary with the overall physical color attributes, i.e. lightness, chroma, and hue, of fabrics, and finally 4) develop a visual color difference prediction model for colored-yarn mixed woven fabrics with textures.

Experimental

Preparation of Woven Fabric Samples and Scanned Images

Sixty-three woven fabrics were produced by a Staubli LX 3202 jacquard machine with the following specifications: yarn type: non-lustrous polyester filament; yarn diameter: 0.125 mm (measured by Mitutoyo Digimatic IDC/IDS Thickness Gage); yarn colors: white (L^*_{10}=92.97; a^*_{10}= -0.46; b^*_{10}=1.58) yarns for warp and cyan (L^*_{10}=50.48; a^*_{10}= -19.76; b^*_{10}=-38.14), magenta (L^*_{10}=51.20; a^*_{10}=62.45; b^*_{10}=0.86), and yellow (L^*_{10}=84.87; a^*_{10}= -0.60; b^*_{10}=88.37) yarns for weft; weave structures: 1/4 twill, broken-twill, and sateen; and yarn densities (warp×weft/cm^2): 47×40/cm^2. The sateen fabrics (a total of 21 fabrics) and their experimental data were derived from the previous part of this research series on the optical mixing effect of colored yarns without texture [17]. The physical color attributes of yarns were obtained from spectrophotometric measurements (Datacolor 650 spectrophotometer, USA) in which yarns were

Table 1. Designs of woven fabric samples

Weaves^a			Colors^b			
Structures		Density	Warp	Weft color arrangements		
T		47×40/cm^2 (warp×weft)	W	1. CCCCC	8. MCMCY	15. YYCYY
				2. CCMCC	9. MCYCY	16. MMMMM
BT				3. CCYCC	10. YCYCY	17. MMYMM
				4. CMCMC	11. MMCMM	18. MYMYM
S				5. CMCYC	12. MCMYM	19. YMYMY
				6. CYCYC	13. MYCMY	20. YYMYY
				7. MCMCM	14. YCYMY	21. YYYYY
Number			3 weaves (textures)×21 colors=63 samples			

^{a}Weaves: T: 1/4 twill; BT: 1/4 broken-twill; S: 1/4 sateen, ^{b}colors: twenty-one colors obtained by mixing cyan, magenta, and yellow yarns in various proportions. W: white yarn; C: cyan yarn; M: magenta yarn; Y: yellow yarn. In weft color arrangements, each letter C, M, or Y represents one pick of the color.

measured in the form of being evenly wound in eight layers onto nonfluorescent cardboard. The reason for using eight layers of yarn was to prevent any appearance of background through the gap between the yarns (nonfluorescent cardboard was used as background to minimize the effect of light reflection from the surface, although the background was hidden). To make fabric samples in a wide range of colors, 21 weft color combinations, which included three combinations with one yarn color, 12 combinations with two yarn colors, and six combinations with three yarn colors, were used. Table 1 shows the color and weave designs of fabric samples.

The physical fabric samples were scanned using a HP K209a-z color scanner to be displayed on a CRT monitor for visual assessments. In the scanning process, the image enhancement and automatic color adjustment functions of the scanner were disabled. The scanning resolution was 1200 ppi with which the scanned images were visually equivalent to their corresponding physical fabric samples at a viewing distance of 50 cm, where their textures and individual yarn colors are clearly seen. In the case of twill and broken-twill fabrics, the scanned images were displayed in their original orientation where the lines of grain run from the top-right hand-corner of the fabrics towards the bottom-left hand-corner. It was confirmed by three color specialists that all 63 scanned images faithfully represent the physical fabric samples under standard viewing conditions (this process was conducted under the illuminant D65 of a Verivide CAC 120 light cabinet).

Instrumental Color Measurement

The spectral reflectance values of 63 physical woven fabric samples were measured using a Datacolor 650 spectrophotometer (USA) with the following specifications: specular component included (SCI; this mode, which includes both the specular and diffused reflected light, is commonly used to measure the true colors of colored objects), ultraviolet excluded, and a large aperture (26 mm). The values were obtained from 400 nm to 700 nm of the visible spectrum with 10 nm intervals. From the reflectance values, the CIE lightness (L^*_{10}), redness-greenness (a^*_{10}), yellowness-blueness (b^*_{10}), chroma ($C^*_{ab,10}$), and hue ($h_{ab,10}$) values were calculated based on the CIE standard illuminant D65 and the CIE 10° standard observer. The measured colors of fabric samples were then visually generated as solid color images using Datacolor TOOLS color analysis and visualization software (Datacolor, USA) to be compared with scanned fabric images. Table 2 provides some examples

Table 2. Examples of woven and solid color pairs with their colorimetric values

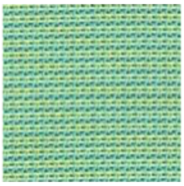
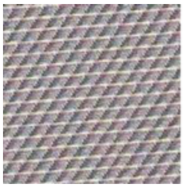
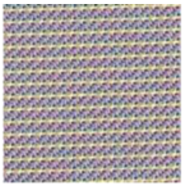
T sample pairs[a]		BT sample pairs		S sample pairs	
Woven color	Solid color	Woven color	Solid color	Woven color	Solid color
	🟦		🟦		🟦
L^*_{10}	57.28	L^*_{10}	58.18	L^*_{10}	57.96
a^*_{10}	-19.83	a^*_{10}	-18.89	a^*_{10}	-19.19
b^*_{10}	-36.71	b^*_{10}	-36.03	b^*_{10}	-36.47
$C^*_{ab,10}$	41.72	$C^*_{ab,10}$	40.68	$C^*_{ab,10}$	41.21
$h_{ab,10}$	241.62	$h_{ab,10}$	242.33	$h_{ab,10}$	242.25
	🟩		🟩		🟩
L^*_{10}	65.48	L^*_{10}	67.32	L^*_{10}	67.04
a^*_{10}	-23.33	a^*_{10}	-20.36	a^*_{10}	-20.79
b^*_{10}	6.71	b^*_{10}	6.47	b^*_{10}	6.08
$C^*_{ab,10}$	24.28	$C^*_{ab,10}$	21.37	$C^*_{ab,10}$	21.66
$h_{ab,10}$	163.95	$h_{ab,10}$	162.38	$h_{ab,10}$	163.70

Table 2. Continued

T sample pairs[a]		BT sample pairs		S sample pairs	
Woven color	Solid color	Woven color	Solid color	Woven color	Solid color
	🟪		🟪		🟪
L^*_{10}	58.27	L^*_{10}	60.00	L^*_{10}	59.94
a^*_{10}	11.2	a^*_{10}	11.25	a^*_{10}	11.65
b^*_{10}	-4.11	b^*_{10}	-3.74	b^*_{10}	-3.51
$C^*_{ab,10}$	11.93	$C^*_{ab,10}$	11.86	$C^*_{ab,10}$	12.17
$h_{ab,10}$	339.83	$h_{ab,10}$	341.62	$h_{ab,10}$	343.24
	🟧		🟧		🟧
L^*_{10}	65.9	L^*_{10}	67.55	L^*_{10}	67.41
a^*_{10}	36.85	a^*_{10}	33.60	a^*_{10}	34.20
b^*_{10}	29.4	b^*_{10}	29.21	b^*_{10}	29.06
$C^*_{ab,10}$	47.14	$C^*_{ab,10}$	44.52	$C^*_{ab,10}$	44.88
$h_{ab,10}$	38.58	$h_{ab,10}$	41.01	$h_{ab,10}$	40.36
	🟨		🟨		🟨
L^*_{10}	87.3	L^*_{10}	87.92	L^*_{10}	87.55
a^*_{10}	-4.95	a^*_{10}	-5.04	a^*_{10}	-4.98
b^*_{10}	79.8	b^*_{10}	76.84	b^*_{10}	77.05
$C^*_{ab,10}$	79.96	$C^*_{ab,10}$	77.01	$C^*_{ab,10}$	77.21
$h_{ab,10}$	93.55	$h_{ab,10}$	93.75	$h_{ab,10}$	93.70

[a] Sample pairs: T: 1/4 twill; BT: 1/4 broken-twill; S: 1/4 sateen. Color (weft color arrangement) no.: 1 (top), 6, 8, 18, and 21 (bottom) in Table 1. Note that the fabric images have been enlarged here to show their surface textures and thus they might not faithfully represent the real colors assessed in the experiment.

of the woven and solid color pairs visually evaluated in this study (the CIELAB coordinates were obtained from spectrophotometric measurements).

Visual Color Difference Evaluation

The gray scale method [18-20] is a standard method to quantify the magnitude of color difference perception. In the textile industry, the AATCC and ISO Gray Scale for Color Change [21,22] have been widely used as standard scales for assessing the color changes of various textile materials. The Gray Scale for Color Change consists of nine pairs of neutral gray standards, which illustrate the perceived color differences. These give a rating of 5 (no color difference, best rating), 4-5, 4, 3-4, 3, 2-3, 2, 1-2, and 1 (a large color difference, worst rating). In this study, a pilot experiment (with 35 woven-solid color pairs and five observers) was conducted using the standard AATCC gray scale to evaluate its suitability for woven-solid color pairs. The results were rated relatively widely from Grade 1 to Grade 4, which indicate that the standard gray scale is suitable to distinguish the effect of individual yarn colors and texture of woven fabrics on color difference perception and thus used in the main experiment. Actually, these results are quite different from those of related studies on the fabric texture effect on visual color difference evaluation [3,7]. In these studies, differently textured fabrics, composed of single colored yarns, were compared to each other, not to solid colors, and the perceived color differences were narrowly rated between Grades 4 and 5 (about 0-1.7 $\Delta E^*_{ab,10}$). The different results imply that visual color differences are affected more by the presence of texture than by its type and strength, and not only texture but the individual yarn colors mixed affect the overall color appearance of fabrics. The AATCC gray scales, i.e. nine pairs of gray patches, were visually generated on a CRT monitor based on their spectrophotometrically measured color values using Datacolor TOOLS color analysis and visualization software for visual assessments. Table 3 provides the CIELAB color difference, $\Delta E^*_{ab,10}$, for each gray scale grade under the CIE standard illuminant D65 and 10° standard observer. The gray scale grade G can be transformed into visual color difference ΔV using equation (1). The coefficients in the equation were obtained by fitting a third-order polynomial function between G and $\Delta E^*_{ab,10}$ presented in Table 3. The R^2 value of this fitting is 0.9998, indicating an excellent fitting.

$$\Delta V = -0.2815G^3 + 3.371G^2 - 14.906G + 25.382 \qquad (1)$$

The visual assessments were performed by 12 observers in a dark room (temperature: 20±2 °C; relative humidity: 65±2 %) and the influence of extraneous illumination was eliminated. All the observers had normal color vision according to the Ishihara and Farnsworth-Munsell 100-hue tests [23,24]. These tests have been widely reported to be standardized measures of color-blindness and chromatic discrimination which are used for both adults and children [25,26]. Before the main experiment, on a separate day, observers had a training session to become familiar with the gray scale method for assessing visual color differences. The same experimental display was used for the training and main experiment. Figure 1 shows the arrangement of a woven-solid color pair and gray scales on a mid-gray background (with L^*_{10} of 50) on a Samsung SyncMaster 21 inch CRT monitor for visual color difference evaluation. The monitor was calibrated before each use using Datacolor Spyder5Elite display calibration system (Datacolor, USA). The monitor was set to a gamma of 2.2, a white point of 6500 K, and a luminance of 90 cd/m^2. The size of the displayed samples, including gray scales, was 7 cm^2, and there was no black frame for the individual samples and no dividing line for the pairs. The viewing distance was 50 cm, and the viewing angle was 0° to the normal of the samples.

Table 3. $\Delta E^*_{ab,10}$ (CIE standard illuminant D65, 10° standard observer) for each grade of the AATCC gray scale for color change

Grade (G)	$\Delta E^*_{ab,10}$
5	0
4.5	0.8
4	1.7
3.5	2.5
3	3.4
2.5	4.8
2	6.8
1.5	9.6
1	13.6

Each observer commenced an experiment session by adapting to a mid-gray background for three minutes. Then, observers rated the visual color difference of each woven-solid color pair using the displayed gray scales. The following instruction was given to each observer:

> You will be shown a series of woven-solid color pairs. Your task will be to assign one of the nine gray scale grades displayed below to describe the visual color difference between woven color and solid color in each pair (Grade 1: largest difference~Grade 5: no difference). If the grade of a woven-solid color pair is not equal to the grade of the closest gray scale, you are encouraged to give an intermediate grade, such as 3.2 for visual color difference which is greater than Grade 3.5 but smaller than Grade 3.

At the beginning of each assessment, the right and left patches of the gray scale pair were the same (Grade 5 was given). The right gray patch was fixed as standard, and the left gray patch changed to one of nine gray patches on bottom which the observer clicked. All 12 observers assessed the 63 woven-solid color pairs twice under the same experimental conditions on separate days. After the visual assessments, the gray scale grades G obtained for each woven-solid color pair were transformed into visual color difference values ΔV using equation (1).

To assess inter- and intra-observer variability, the standardized residual sum of squares (*STRESS*) index was employed. The *STRESS* index has been widely employed in color difference experiments to determine not only the performance of color-difference formulas with respect to visual data, but also observer variability [27]. The computation of *STRESS* index is given by equation (2) where ΔV_i are the visually perceived color differences for a given set of color pairs (i=1, …, N), ΔE_i are the color differences computed by a color-difference formula, and F is a scaling factor. When the *STRESS* index is used to determine observer variability, specifically inter-observer variability (observer accuracy),

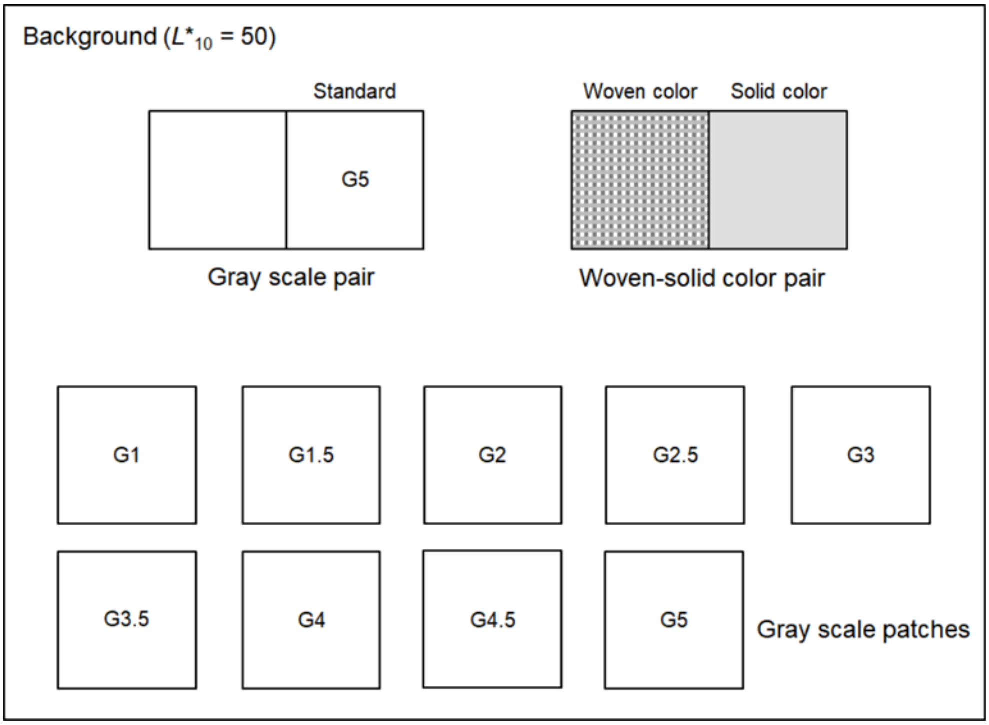


Figure 1. Schematic of experimental display for visual color difference evaluation (size of all samples: 7 cm^2; viewing distance: 50 cm; viewing angle: 0 $^\circ$).

ΔV_i and ΔE_i should be replaced by the mean visual responses of a given observer and the mean responses of all observers. For the assessment of intra-observer variability (observer repeatability), ΔV_i and ΔE_i should be replaced by the responses of a given observer in two different visual assessment sessions. For a perfect agreement between the two data sets, ΔV_i and ΔE_i, the *STRESS* index is equal to zero (0 % error), which is desired in practical applications. In this study, the mean inter- and intra-observer variability was 30.41 and 31.83, respectively, which were considered satisfactory in comparison with those of a previous study involving visual color difference assessments [27].

$$STRESS = 100\left(\frac{\Sigma(\Delta E_i - F\Delta V_i)^2}{\Sigma F^2 \Delta V_i^2}\right)^{1/2} \text{ with } F = \frac{\Sigma \Delta E_i^2}{\Sigma \Delta E_i \Delta V_i} \qquad (2)$$

Data Analysis

To demonstrate a discrepancy in color appearance between woven fabrics and their instrumentally measured colors, the visual color differences ΔV of 63 woven-solid color pairs were numerically analyzed. Then, to investigate the influence of individual yarn colors, that is, the number of yarn colors shown on the fabric surface, and texture on this discrepancy, the ΔV data for woven fabric samples with three different textures, in which one, two, or three colors of yarn are mixed, were statically analyzed. The one-way ANOVA (analysis of variance) and two-way ANOVA with the Scheffé's HSD (Honestly Significant Difference) post-hoc test were conducted to investigate the respective and combined effects of individual yarn colors and texture. Then, to examine how these effects vary with the overall physical color attributes of woven fabrics, the ΔV of woven-solid color pairs were plotted against their lightness, chroma, and hue values, respectively, with the best-fitting curves derived by using the least-squares method. Finally, the multiple regression analysis was carried out to develop a predictive model of the visual color differences of woven fabrics from their instrumentally measured colors, in which the number of yarn colors, texture, and the overall physical color attributes of the fabrics were predictors.

Results and Discussion

Discrepancy in Color Appearance between Woven Fabrics and Their Instrumentally Measured Colors

The visual color differences of 63 woven-solid color pairs, that is, woven fabric samples and their instrumentally measured colors visually generated as solid color images, and the corresponding ranges and standard deviations are given in Table 4. From Table 4, it can be found that the mean visual color difference of the pairs is 5.68 ΔV units with the variation from 2.20 to 9.82, which is not small. As a related study, Montag and Berns [28] found that the supra-threshold lightness tolerances of textured colors are approximately twice as large as those of solid colors. Xin and Shen [7] also found that people cannot perceive the difference between two textured fabrics when the measured color difference is smaller than 1.3 $\Delta E^*_{ab,10}$. In this study, even though the woven (textured) and solid colors in each pair are of physically identical color in terms of CIELAB values (thus the measured color difference is 0 $\Delta E^*_{ab,10}$), the visual color difference is larger than those of the textured pairs in previous studies [3,4,7,28] which have actual color differences of up to 5.0 $\Delta E^*_{ab,10}$ units due to different strengths of the textures. All these results indicate that perceived color is affected more by the presence of texture than by its strength. It can also be seen from Table 4 that different fabrics with different numbers of yarn colors have different magnitudes of visual difference from their measured colors.

Effects of Individual Yarn Colors and Texture

The one-way ANOVA with the Scheffé's HSD post-hoc test was conducted to determine whether there are any statistically significant differences in ΔV between woven fabric samples depending on the number of yarn colors and texture shown on the fabric surface. Figure 2 and Figure 3 show the effects of individual yarn colors and texture, respectively.

As the effect of individual yarn colors, there was a statistically significant difference in ΔV between the samples composed of a single color of yarn and those composed of two or three colors of yarn (F=17.15, p<0.001). From Figure 2, it can be found that the samples composed of two or three colors of yarn have larger ΔV than those composed of a single color of yarn (mean ΔV of the samples composed of a single, two, and three colors of yarn were 4.21, 5.79, and 6.17, respectively). This finding indicates that the interlacement of different colors of yarn makes observers perceive the fabrics more differently from their actual measured colors. Meanwhile, there was no significant difference in ΔV between the samples composed of two colors of yarn and those composed of three colors of yarn.

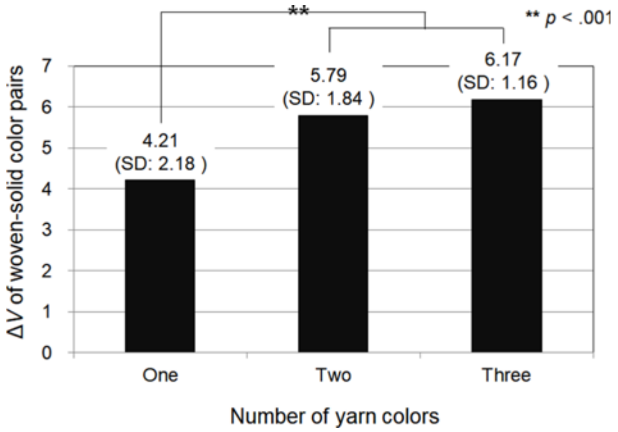


Figure 2. Visual color difference ΔV ($\Delta E^*_{ab,10}$ units) of woven fabric samples (woven colors) from their instrumentally measured colors (solid colors) depending on the number of yarn colors.

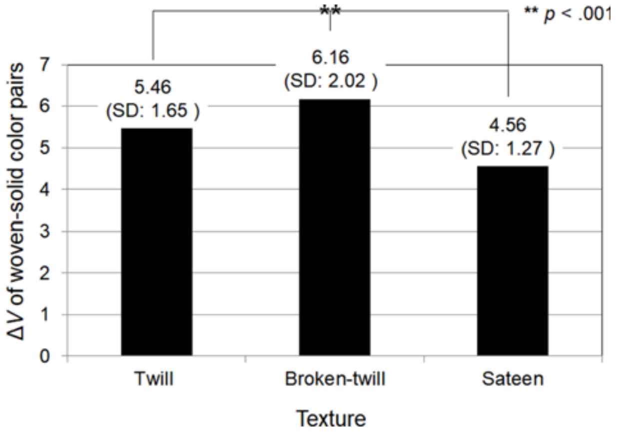


Figure 3. Visual color difference ΔV ($\Delta E^*_{ab,10}$ units) of woven fabric samples (woven colors) from their instrumentally measured colors (solid colors) depending on the texture.

As the effect of texture, the twill, broken-twill, and sateen fabric samples had significantly different ΔV values (F=21.23, p<0.001). Figure 3 shows that broken-twill samples had the largest ΔV, followed by twill and then sateen (mean ΔV of twill, broken-twill, and sateen samples were 5.46, 6.16, and 4.56, respectively). It can be seen in Table 2

Table 4. Visual color differences ΔV ($\Delta E^*_{ab,10}$ units) between woven fabric samples and their instrumentally measured colors

ΔV	Woven fabric samples[a] with												Total
	One yarn color				Two yarn colors				Three yarn colors				
	T	BT	S	Total	T	BT	S	Total	T	BT	S	Total	
Mean	4.39	4.71	3.52	4.21	5.82	6.62	4.95	5.79	6.16	7.16	5.20	6.17	5.68
Minimum	2.41	2.73	2.20	2.20	3.64	3.56	2.62	2.62	5.00	5.26	3.81	3.81	2.20
Maximum	7.42	8.12	4.97	8.12	7.65	9.82	7.44	9.82	7.17	8.02	6.21	8.02	9.82
SD	2.66	2.97	1.39	2.18	1.51	2.07	1.65	1.84	0.78	1.01	0.78	1.16	1.81

[a] Woven fabric samples: fabrics composed of one, two, or three yarn colors. T: 1/4 twill; BT: 1/4 broken-twill; S: 1/4 sateen. See Table 1 for the color and weave designs.

that twill samples had the visually strongest texture, followed by broken-twill and then sateen, which had a nearly invisible texture. The texture strength can be described by its coarseness index [4]. The coarseness index determines the way light reflects off the surface, in the sense that the diffused reflection occurs when light falls on coarse surfaces (with strong textures) while the specular reflection occurs on smooth surfaces (with no or weak textures). Since in diffused reflection, the light incident on the surface is scattered away in many different directions, rather than concentrated in one direction as in the case of specular reflection, the quantity of light observed in a specific direction is relatively small. This luminous quantity, also known as photometric quantity, can be deduced from the spectral distribution of the surface. As an example, Figure 4 shows the spectral distributions (distributions of the spectral reflectance multiplied by the CIE luminosity function) of three magenta-colored fabric samples with different surface textures. The three curves almost overlap each other because the difference between the three texture strengths used in this study was not tremendously large. For the precise comparison of the texture strengths, they should be quantified by calculating numerical values for the photometric quantities represented by the areas below the curves. The underlying theory in the calculation of texture strength, that is, surface texture determines light reflection is the same as that derived in the previous studies [3,4] on the texture effect on visual color difference evaluation. The photometric quantities of magenta-colored twill, broken-twill, and sateen samples calculated were 24.70, 26.13, and 25.92, respectively, indicating that twill was the photometrically strongest texture, followed by sateen and then broken-twill. It is important to note that photometrically measured (and calculated) texture strength does not consist with visually observed texture strength. While twill was the strongest texture both visually and photometrically, broken-twill and sateen were inconsistent (although there was a very small difference between broken-twill and sateen in photometrically measured strength). More importantly, while twill was the photometrically strongest texture for all fabric samples, a small number of samples had inconsistent results of broken-twill and sateen with others. Again, this is thought to be due to the small differences between the texture strengths studied. Thus texture strength should not be judged solely by visual observation, but rather it should be photometrically calculated on each surface especially when its effect should be quantitatively analyzed. Since readers might be confused about the term texture strength, it was replaced by photometrical strength of texture in the remaining sections of this paper.

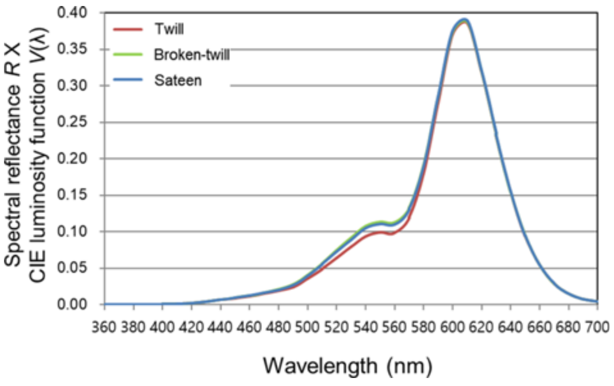


Figure 4. Spectral distributions of three magenta-colored fabric samples with different textures.

In this study, the photometrically weakest texture, which was mostly broken-twill, caused the largest visual color difference, but the strongest texture, twill, did not cause the smallest difference. This was inconsistent, to some extent, with previous works done by Tsang [3] and Xin *et al.* [4], who found that texture strength was negatively correlated with visual color differences. These inconsistent findings indicate that the photometrical strength of texture may not the only texture feature that affects human color perception. It is thought that the grain lines observed on twill and broken-twill samples, which were produced due to successive warp floats, might have led to the nonlinear effect of texture on color difference perception. The texture effect needs to be explored further by using more varied types of textures. Meanwhile, a two-way ANOVA test revealed that there was no statistically significant effect of the combinations of individual yarn colors and textures (F=0.27, p>0.05).

Visual Color Difference Depending on the Overall Color Attributes

To examine how the visual color differences ΔV between woven fabric samples and their instrumentally measured colors vary depending on their overall physical color attributes, the ΔV of 63 woven-solid color pairs were plotted against their lightness L^*_{10}, chroma $C^*_{ab,10}$, and hue $h_{ab,10}$ values, respectively. The least-squares method was used to derive the best-fitting curves. This method is the simplest and most commonly applied form of regression and determines the best-fitting line or curve through a set of data points by minimizing the sum of squares [29,30]. Figures 5-7 show the plots of ΔV with the best-fitting curves, third-order polynomial curves.

It can be seen from Figure 5, in which ΔV are plotted against L^*_{10} values, that the visual color difference increases with the lightness of the fabric up to a certain point (where L^*_{10} is around 80), after which the visual color difference decreases rapidly. This indicates that the textural features of lighter fabrics, except too light fabrics with L^*_{10}>80, generally make the fabrics appear more different from their measured colors than those of darker fabrics do. In particular, the relatively consistent appearance (with small ΔV) of highly light colors has also been reported in the

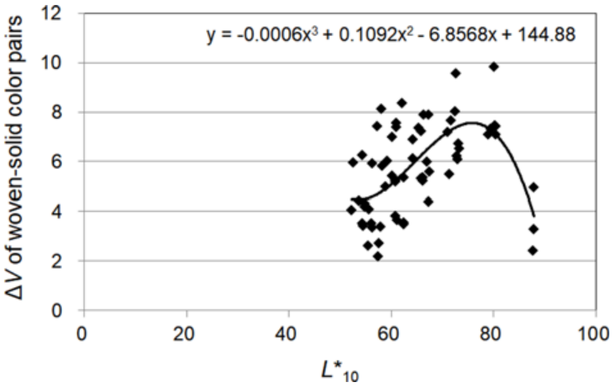


Figure 5. Visual color difference ΔV ($\Delta E^*_{\mathrm{ab,10}}$ units) of woven fabric samples (woven colors) from their instrumentally measured colors (solid colors) depending on their lightness L^*_{10}.

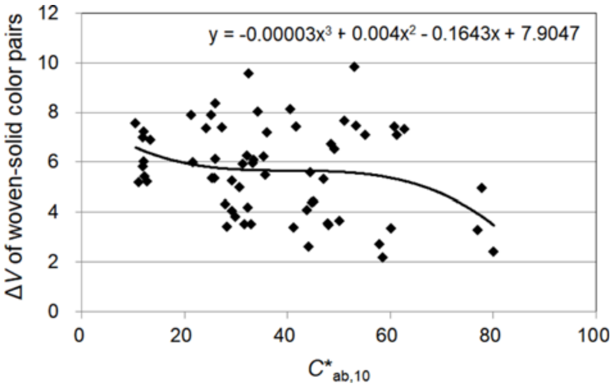


Figure 6. Visual color difference ΔV ($\Delta E^*_{\mathrm{ab,10}}$ units) of woven fabric samples (woven colors) from their instrumentally measured colors (solid colors) depending on their chroma $C^*_{\mathrm{ab,10}}$.

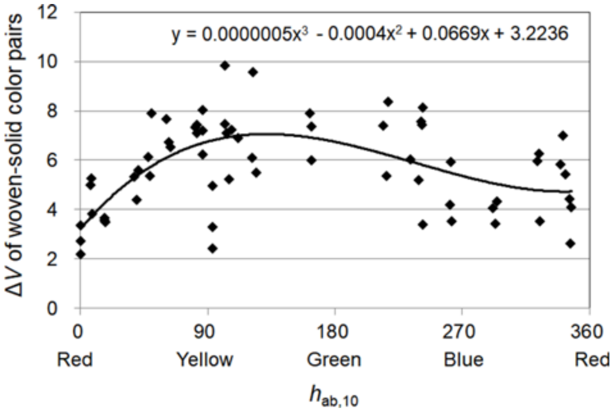


Figure 7. Visual color difference ΔV ($\Delta E^*_{\mathrm{ab,10}}$ units) of woven fabric samples (woven colors) from their instrumentally measured colors (solid colors) depending on their hue $h_{\mathrm{ab,10}}$.

vision and color science literature [2,9]. This indicates that the overall appearance of highly light colors tends not to be easily affected by various physical parameters. As the effect of chroma, a gradual downward slope of the curve in Figure 6, where ΔV are plotted against $C^*_{\mathrm{ab,10}}$ values, indicates that desaturated fabrics have larger visual color difference than saturated fabrics from their measured colors in general. From the steep and gentle slopes of fitting curves in Figures 5 and 6, respectively, it is reasonable to say that humans are more sensitive to lightness changes compared with chroma changes when they perceive the overall colors of objects with different surface properties. As the effect of hue, it is seen from the curve for the plots of ΔV against $h_{\mathrm{ab,10}}$ values in Figure 7 that fabrics have the largest visual color difference from their measured colors when their hues are close to yellow-green (where $h_{\mathrm{ab,10}}$ is between 90 and 180), and the difference gradually decreases as the hues become close to red (where $h_{\mathrm{ab,10}}$ is around 0 or 360). This general trend gives the prediction of ΔV for successive hues from 0 to 360, which has not been given in many previous studies conducted with a small number of hues.

Visual Color Difference Prediction Model

A predictive model of the visual color differences of woven fabrics from their instrumentally measured colors was developed by employing a multiple regression (enter method). The parameters discussed in the previous sections, that is, the number of yarn colors, the photometrical strength of texture, and the overall physical color attributes of the fabrics, were used as predictors for the modeling. First-, second-, and third-degree polynomial equations were derived. Among them, the first-degree polynomial was found to produce the smallest error values on average and thus selected as a final visual color difference prediction model. The model is given in equation (3), where $\Delta V_{\mathrm{fabric}}$ refers to the visual color difference, which corresponds to the CIELAB color difference $\Delta E^*_{\mathrm{ab,10}}$ or lightness difference ΔL^*_{10} (since this study investigated the visual color difference in the lightness direction using the gray scale method), of the fabric from its measured color, N refers to the number of yarn colors mixed in the fabric, TS refers to the photometrical strength of texture, and $L^*_{\mathrm{10,fabric}}$, $C^*_{\mathrm{ab,10,fabric}}$, and $h_{\mathrm{ab,10,fabric}}$ refer to the measured lightness, chroma, and hue values of the fabric, respectively. Note that the positive coefficient of $C^*_{\mathrm{ab,10,fabric}}$ in equation (3) was inconsistent with the negative slope in Figure 6, in which $\Delta V_{\mathrm{fabric}}$ was plotted against $C^*_{\mathrm{ab,10,fabric}}$. This inconsistent trend of $C^*_{\mathrm{ab,10,fabric}}$ in equation (3) resulted from the combined effect of multiple variables used in the model.

$$\begin{aligned}\Delta V_{\mathrm{fabric}} = {} & 1.07\,N - 0.387\,TS + 0.755\,L^*_{\mathrm{10,fabric}} \\ & + 0.011\,C^*_{\mathrm{ab,10,fabric}} + 0.005\,h_{\mathrm{ab,10,fabric}} - 31.903 \quad (3)\end{aligned}$$

The errors in visual color difference predictions were calculated by subtracting the visually assessed ΔV of 63 fabric samples from the predicted ΔV by the model. The mean error value was 1.04 (SD: 0.73), which is thought to make reasonable predictions. It has been reported by Montag and Berns [28] that 3 units of color difference in the lightness direction, which is higher than the mean error value produced by the model, can hardly be perceived. Thus it can be said that the error is acceptable. To further evaluate the accuracy of the model, STRESS values were calculated for the 63 pairs of visual and predicted results. The STRESS index was adopted by CIE [31] not only to measure observers' variability, but also to quantify the predictions of visual results made by color-difference formulas. If a STRESS value for a color-difference formula is below observers' variability, the formula is considered useful. The mean STRESS value calculated for the 63 pairs was 18.37, which was lower than both inter- and intra-observer variability (30.41 and 31.83, respectively). Thus the visual color difference prediction model developed in this study is considered reasonably accurate. Now that ΔV is available from the model, it is possible to predict the degree of discrepancy between the instrumentally measured colors and the actually perceived color appearances of fabrics accurately. Therefore, the visual color difference prediction model suggested in this study can be thought of as useful in designing various colored-yarn mixed woven fabrics with desired color appearances.

Conclusion

The visual color difference between colored-yarn mixed woven fabrics and their instrumentally measured colors was investigated. For the visual color difference evaluation, the instrumentally measured colors, which were numerical color values, were converted into solid color images. Although the woven and solid colors were physically identical in terms of CIELAB values, the perceived color differences were as large as 5.68 $\Delta E^*_{ab,10}$ on average. Woven fabrics composed of two or three colors of yarn were found to have larger visual color differences than those composed of a single color of yarn, indicating that mixing different colors of yarns had a significant optical effect. In other words, different colored yarns that were placed near one another became optically mixed to create the appearance of a new color. This visual color difference between woven fabrics and their measured colors varied with different types of woven textures. However, the photometrical strength of textures, which has been widely reported as a strong parametric factor in visual color difference evaluation, was not shown to have had a linear effect. The weakest texture, which was mostly broken-twill in this study, caused the largest visual color difference, but the strongest texture, twill, did not cause the smallest difference as found in previous studies. These inconsistent findings indicate that the photometrical strength of texture may not the only texture feature that affects human color perception and thus suggest the need for further investigation with more types of textures. It was also examined how the lightness, chroma, and hue of fabrics affect their visual difference from measured colors. As a result, less saturated and lighter fabrics, except too light fabrics with L^*_{10}>80, were found to have larger visual differences than more saturated and darker fabrics in general. As the effect of hue, it was found that when the hues of fabrics are close to yellow-green ($90<h_{ab,10}<180$), the largest visual color difference is caused, and the difference gradually decreases as the hues become close to red ($h_{ab,10}=0$ or 360). Lastly, by considering these parameters, a visual color difference prediction model was derived and its predictive performance was evaluated.

It is envisaged that the findings of this study will be a useful guideline for textile designers when designing colored-yarn mixed woven fabrics by allowing them to predict the color appearances of fabrics actually perceived by consumers. In addition, the findings will be the foundation for further developing color difference equations for textile applications by introducing the significant parameters of fabrics. Since this study only investigated visual color differences in the lightness direction, further investigation of the effects on colorfulness and hue differences would also be useful for color quality control in the textile industry.

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