Color Reproduction of Digitally Printed Silk Fabrics

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Abstract

The benefits and beauty of printing on textile are apparent. With developments in digital large-format printing technologies, digital textile printing usage continues to grow. I.T. Strategies' Research on Emerging Print Markets predicts that the value of the printed output from digital textile printers will grow from $1.9 billion in 2007 to $6.1 billion in 2012. Short-run, on-demand textile printing is pushing creative professionals to market their designs in a cost-effective way. Short-run sampling and customized production with digital textile printing is an option. Hence, the accuracy of color reproduction on the digitally printed textile is crucial for designers. The color must be a near-perfect match. The main objective of this study is to evaluate color reproduction capability of digitally printed silk fabrics. A set of specific colors was selected from the Pantone for fashion and home color guide, which contains spot colors widely used in fashion design. The spot color test chart was printed on silk fabrics with acid dye inks. Three different silk fabrics—silk chiffon (8 momme), silk crepe de chine (23 momme), and spun silk taffeta—were tested and compared. Color management with ICC profiles was used to investigate the reproduction of specific spot colors. The CIE L*a*b* color values of printed color patch were measured using an X-Rite i1iO spectrophotometer. The color reproduction capability of digitally printed silk fabrics was evaluated in terms of color difference (ΔECMC 2:1), which was calculated from the difference in shade between the target spot color and color patches on the printed silk fabrics. It was found that crepe de chine is capable of yielding a wider color gamut and higher optical densities, resulting in better color reproduction capability. About 60% of Pantone colors can be reproduced by crepe de chine with ΔECMC2:1 values lower than 4.0. Chiffon has a relatively small color gamut and only can reproduce lighter colors. Only about 34% of Pantone colors can be reproduced by chiffon with ΔECMC 2:1 lower than 4.0. It was also found that crepe de chine and chiffon tended to have better fade resistance than taffeta. For the acid dye inks, yellow ink had better lightfastness, while cyan ink had poorer fade resistance.

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1. Introduction

The majority of all textiles are printed using rotary screen print machines (around 69% of the market). While this technology offers high speed and inexpensive output, there are some drawbacks. Rotary print process requires a lengthy setup time between patterns and needs to deal with registration problems. Facing to the demand of short-run and just-in-time delivery of fashion items in the textile industry, rotary screen technology apparently is not the best choice for providing economical short-run production. In order to reduce sampling costs, the inkjet printing technology is penetrating into textile printing. Digital textile printing, based on inkjet technology, empowers designers and retailers with digital design. Digital printing serves as a sampling tool, offering immediate results. It also acts as a production tool, providing the ability of mass customization (Cahill, 1999; Eckman, 2004; Stefanini & Dunand, 1999; Tippett, 2001; Tse and Briggs, 1999; Ujiie, 2006).

Although today's textile inkjet printing market is still extremely small, and generally confined to sampling and for some short-run length production, the market continues to grow. According to I.T. Strategies' Research on Emerging Print Markets, the value of the printed output from digital textile printers will grow from $1.9 billion in 2007 to $6.1 billion in 2012 (Crowley, 2009). A projection for the digital wide-format printing market also predicts that inkjet printing will expand its share of textile printing market (Romano, 2009). Further developments in hardware/ink chemistry and higher throughput will provide the solution for extending digital textile printing technology.

Today, the majority of digital textile printing technologies operate with water-based dye based on the paper inkjet print systems. Since fabric is a three-dimensional structure, the ink and colorant requirements vary from substrate to substrate, such as acid dyes for silk, nylon, and wool; disperse dyes for polyester; and reactive dyes for cotton and rayon. Table 1 summarizes comparisons of ink chemistry used in the inkjet textile printing.

Table 1. *Comparisons of ink chemistry.*

Ink type	Fiber Type	Pre-treatment	Post-treatment
Acid	Silk, nylon, wool	Acid donor	Steam and wash
Disperse	Polyester	Thickener	High-temperature steam and wash
Reactive	Cotton, rayon	Alkali	Steam and wash
Pigment	All, best on cotton, polyblends	Not required	Dry heat

Silk is a fine, strong, continuous filament produced by the larva of certain insects. It is a natural protein fiber composed of fibroin. Filament silk fibers are smooth and produce a cool sensation when placed on the skin. Today, most silk fibers are converted to apparel fabrics (Humphries, 2009; Hatch, 1993). For silk fabrics, acid dyes are the common choice. They are water-soluble anionic dyes and do not react with the fiber to form covalent bonds, but instead are attracted to positively charged dye sites on the fiber. Since dyes are not fixed 100% to a textile substrate in such systems, printing with acid dye inks generally involves pre-treatment and post-treatment (steaming-washing-drying) in order for the dyestuff to fix onto the fabric. (Cook, 1995; King, 2002; Ujiie, 2006).

Pre-treatment

Fabric substrates are three-dimensional structures. Once the ink droplet is ejected through the nozzle orifice onto the fabric surface, its low-viscosity liquid is liable to spread laterally by capillary effects (either wick into macro-capillaries between yarns and fibers or diffuse into the micro-capillaries in fibers). The subsequent interactions in the form of wicking and diffusion determine dot quality, line quality, inter-color bleeding, and mottle. In order to produce high-quality printed goods, dye molecules in the ink droplets must be fixed on or near the surface of the textile fiber substrate for sharp and brilliant color images. Therefore, pre-treatment of textiles in preparation for inkjet printing is carried out to prevent wicking of the ink on the fabric. The pre-treatment for acid dyes on silk usually includes three main constituents: thickener, urea, and an acid or latent acid. The preferred thickening agents for printing with acid dyes are of the mannogalactan type. These are stable to the acidic conditions, which are required at the fixation stage (Chang, 2000; Eckman, 2004; Ujiie, 2006; Weiser, Raulfs, and Siemensmeyer, 2000).

Post-treatment

A post-treatment usually involves steaming, washing, and drying processes. Steaming is the process normally used to fix printed textiles. Acid dyes are steamed under atmospheric pressure at just over 100 degree Celsius. During the process, steam condenses on the fabric and is absorbed by the thickener and hygroscopic agents in the printed areas. Dyes and chemicals dissolve and form extremely concentrated dye baths within the thickener film. A following wash-off process is applied to ensure removal of unfixed dye. The washing-off process takes place in several stages, the first of which is a cold rinse. The reason for this is that thickener, auxiliaries, and loose dye should be removed under conditions where the dye is unlikely to stain white or unprinted ground shade areas. The risk of this happening may be reduced further by the inclusion of reagents that hold the unfixed dye in the bath (Ujiie, 2006).

Print quality in inkjet printing is strong dependent on the printing hardware/software and interactions between the ink and the substrate. In inkjet printing on paper, the significance of ink-media interactions is well recognized. Inkjet printing on textiles, however, is a quite different matter (Ahmed, 1992; Chang, 2000; Tse and Briggs, 1999). Fabric pre-treatment, steaming, and other finishing processes are all variables that affect color reproduction. Serving as sampling and short-run production tool, the accuracy of color reproduction on the digitally printed textile and the ability to consistently control output are essential. This study evaluated color reproduction capability of digitally printed silk fabrics in terms of color gamut and color match. Color matching was evaluated based on the color difference (ΔE_{CMC} values). The ΔE_{CMC} has been adopted by the textiles industry since 1984. The formula for ΔE_{CMC} is as follows (Delta E, 2009):

$$\Delta E_{CMC} = \left[\left(\frac{\Delta L^*}{lS_L} \right)^2 + \left(\frac{\Delta C^*}{cS_C} \right)^2 + \left(\frac{\Delta H^*}{S_H} \right)^2 \right]^{1/2}$$

Equation 1 Where

$$\Delta C = C_1 - C_2$$

$$C_1 = \sqrt{a_1^2 + b_1^2}$$

$$C_2 = \sqrt{a_2^2 + b_2^2}$$

$$\Delta H = \sqrt{\Delta a^2 + \Delta b^2 - \Delta C^2}$$

$$\Delta L = L_1 - L_2$$

$$\Delta a = a_1 - a_2$$

$$\Delta b = b_1 - b_2$$

$$S_L = \begin{cases} 0.511 & L_1 < 16 \\ \dfrac{0.040975 L_1}{1 + 0.01765 L_1} & L_1 \geq 16 \end{cases}$$

$$S_C = \frac{0.0638 C_1}{1 + 0.0131 C_1} + 0.638$$

$$S_H = S_C\left(FT + 1 - F\right)$$

$$T = \begin{cases} 0.56 + \left|0.2\cos(H_1 + 168)\right| & 164 \leq H_1 \leq 345 \\ 0.36 + \left|0.4\cos(H_1 + 35)\right| & otherwise \end{cases}$$

$$F = \sqrt{C_1^4 / (C_1^4 + 1900)}$$

$$H_1 = \tan^{-1}(b_1 / a_1)$$

2. Methodology

In order to evaluate color reproduction capability of digitally printed silk fabrics, color management with ICC profiles was used to investigate the reproduction of specific spot colors. The digital printer, an Epson Stylus Pro 9800 with acid dye ink set, was tested on three different kinds of silk fabrics.

2.1. Spot Color Test Chart

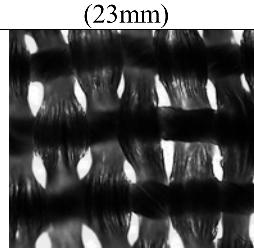
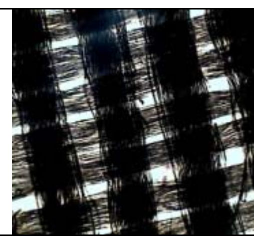
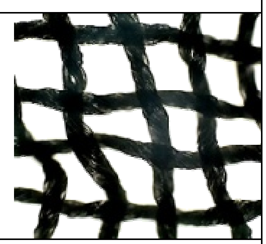
Spot colors from the Pantone for fashion and home color guide were used to design the spot color test chart (Figure 1) for this study. The Pantone for fashion and home color guide contains spot colors widely used in the fashion design. $L^*a^*b^*$ values of Pantone for fashion and home color swatches were used as target values. Adobe Photoshop CS3 was employed to generate the spot color test chart in digital form.

Figure 1. *Spot color test chart.*

2.2. Equipment and Materials

In this study an Epson Stylus Pro 9800 printer was used with acid dye inks (Huntsman Lanaset® SI HS acid inks). Three silk fabrics were tested and compared. These pretreated fabrics were paper-backed for digital textile printing. Table 2 shows characteristics of tested silk fabrics. As shown in Table 2, the tested silk fabrics are all made with plain weave; however, their texture and porosity differ a great deal one from another. Chiffon is the most porous and thin fabric, while crepe de chine is a less porous and heavier fabric.

Table 2. *Characteristics of tested silk fabrics.*

Silk Fabrics	Crepe De Chine (23mm)	Taffeta	Chiffon (8mm)
Microscope images (@100X magnification)			
Characteristics	A fine, lightweight, plain weave silk fabric wove. The fabric has a fine crepe effect and is very soft to touch.	Fabrics made w/plain weave. The fabric usually has a fine cross rib produced by employing a heavier filling yarn than wrap.	Extremely thin flat plain weave. The holes are 4.5 momme (mm) to 8 momme. The fabric is delicate but relatively strong.
Applications	It is used for ladies' dress material, the lining of ladies' coats and decorative ladies' handkerchief material	It is used for ladies' dress material, western dress lining and day umbrella material.	It is mainly used for veils, shawls, ladies' cap decoration, summer wear decoration, etc.

2.3. Digital Textile Printing

ICC profiles were generated for tested silk fabrics by using the TC 9.18 target, which was printed without color management via Epson Stylus Pro 9800 print driver. Once the silk fabrics have been printed and dried, steaming was used to fix printed textiles. Acid dyes were steamed under atmospheric pressure at around 100°C for one hour, followed by washing and drying to ensure removal of unfixed dye. The washing-off process occurs in several stages, including hand wash with cold water, washing with Inkjet Fabrics Acid Wash agent, and a couple of cold rinse cycles. After wash, the silk fabrics were patted dry with towels. When dry, printed silk fabrics were then measured with an X-Rite i1iO spectrophotometer (D65/10° measuring geometry), operated by GretagMacbeth Measure Tool 5.0.9 software. The measurement files were used to generate profiles using GretagMacbeth ProfileMaker Pro 5.0.9.

2.4. Evaluation of Color Reproduction

The digital spot color test chart (Figure 1) was printed via the Epson Stylus Pro 9800 print driver, whereas the ICC profiles were assigned in relevant functions. Once the silk fabrics have been printed and dried, the post-treatment (steaming-washing-drying) was applied again to set the dye and remove the loose colorant. L*a*b* values for each color patch of the chart were measured using the X-Rite i1iO spectrophotometer. The quality of color reproduction was evaluated in terms of color difference (ΔE_{CMC}). The color gamuts of tested silk fabrics were compared using ColorThink Pro 3.0 software.

3. Results and Discussion

Table 3 lists color-related attributes of tested silk fabrics, including optical densities and color gamut. Among three tested silk fabrics, crepe de chine yielded higher optical densities and produced a wider color gamut. The overall average of optical density of crepe de chine were 1.60 for cyan (C), 1.58 for magenta (M), 1.09 for yellow (Y), and 1.59 for black (K). Compared to crepe de chine, taffeta produced lower optical densities and a smaller gamut volume. The optical densities of cyan, magenta, and black for taffeta were in the range of 1.34 to 1.39. Chiffon has a quite open textile structure, resulting in poorer ink holdout. The overall averages of optical density of chiffon were 0.74 for cyan, 0.73 for magenta, 0.57 for yellow, and 0.71 for black. The color gamut of chiffon was in the range of 51,000 to 61,000, which corresponds to the density measurements.

Table 3. *Color-related attributes of tested silk fabrics.*

Silk fabrics	Optical Density				Color Gamut
	Cyan (C)	Magenta (M)	Yellow (Y)	Black (K)	
Crepe De Chine	1.59–1.61	1.57–1.59	1.08–1.11	1.59–1.60	242,000–245,000
Taffeta	1.38–1.39	1.35–1.36	0.95–0.96	1.34–1.39	211,000–221,000
Chiffon	0.73–0.77	0.72–0.75	0.56–0.58	0.70–0.72	51,000–61,000

The gamut comparison for the tested silk fabrics is shown in Figure 2. The largest color gamut was found in crepe de chine, followed by the silk taffeta. Chiffon yielded the smallest color gamut. The color gamut of crepe de chine (wire frame) is slightly larger than that of taffeta (red color). However, the silk taffeta yielded a wider color gamut in magenta and purple regions. The silk crepe de chine gamut is larger in the lower L^* values area, while taffeta gamut is larger in the higher L* values area. The silk chiffon has a relatively small color gamut and only can reproduce lighter colors.

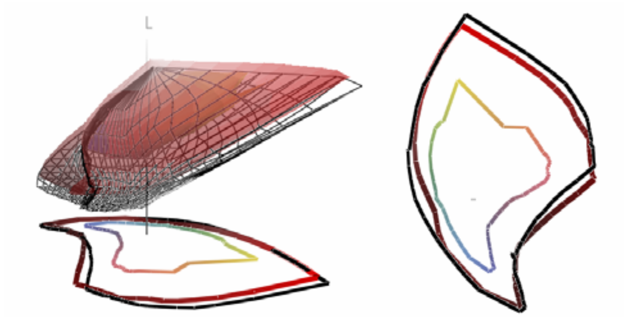


Figure 2. *Gamut comparison for the tested silk fabrics.*
(Crepe De Chine: wire frame; Taffeta: red; Chiffon: true color)

The graphs of color gamut with L*a*b* values of target spot color data for crepe de chine, taffeta, and chiffon are shown in Figure 3, Figure 4, and Figure 5, respectively. There are some spot colors in the test charts that are out of color gamut of the test silk fabrics. In other words, those high-saturated colors are difficult to be duplicated on those silk fabrics.

Figure 3. *Color gamut of crepe de chine.*

Figure 4. *Color gamut of taffeta.*

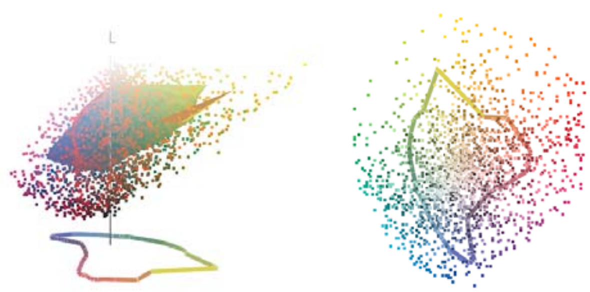


Figure 5. *Color gamut of chiffon.*

Table 4 summarizes ΔE_{CMC} comparison for tested silk fabrics. As expected, crepe de chine has better reproduction capabilities in terms of lower average ΔE_{CMC} value (3.75). The average ΔE_{CMC} value of taffeta is 4.23, while chiffon has a larger ΔE_{CMC} value of 6.79. Figure 6 shows color reproduction capability of tested silk fabrics. Crepe de chine can reproduce about 60% of Pantone colors with $\Delta E_{CMC\ 2:1}$ lower than 4.0, while about 97.3% of Pantone colors can be reproduced with $\Delta E_{CMC\ 2:1}$ lower than 8.0. For the silk Chiffon, there are only about 33.5% of Pantone colors can be reproduced with $\Delta E_{CMC\ 2:1}$ lower than 4.0.

Table 4. *Summary of ΔE_{CMC} comparison for tested silk fabrics.*

Silk fabrics	Average $\Delta E_{CMC\ 2:1}$	Best 90%	Worst 10%
Crepe De Chine	3.75	3.14	6.93
Taffeta	4.23	3.48	9.04
Chiffon	6.79	5.65	16.12

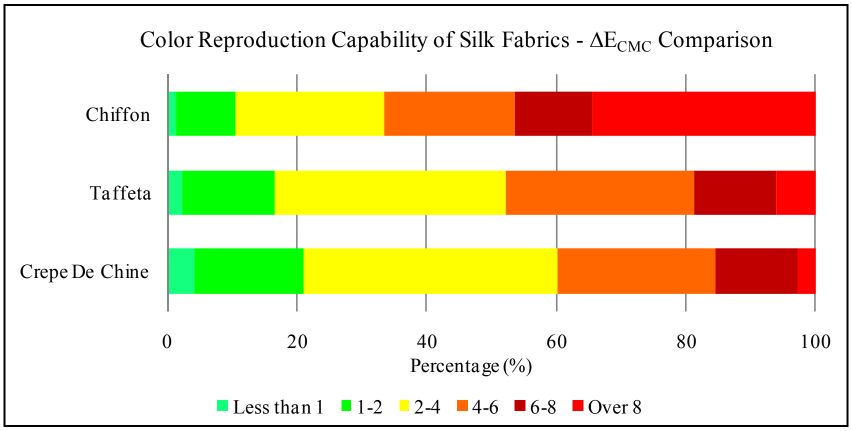


Figure 6. *Color reproduction capability of tested silk fabrics.*

The lightfastness of textiles has been a concern for many years. In order to examine lightfastness of tested silk fabrics, silk fabrics were exposed to artificial sunlight for 50, 100, 150, 200, 250, 300, 350, 400, 450, and 500 hours with a Q-Sun Xenon lamp equipped with a Daylight-Q filter. Test chamber was used at irradiance settings of 0.68 $W/m^2/nm$ at 340nm (noon summer sunlight) and 63°C for black standard temperature (BST). Figure 7 illustrates color changes in silk fabrics after light exposure for 500 hours. As shown in Figure 4, the silk chiffon was the most stable chromophore, whereas the silk taffeta was the least stable. After 500 hours exposure, the gamut volume of taffeta drops 85.62%, followed by the crepe de chine (77.69%) and chiffon (77.18%).

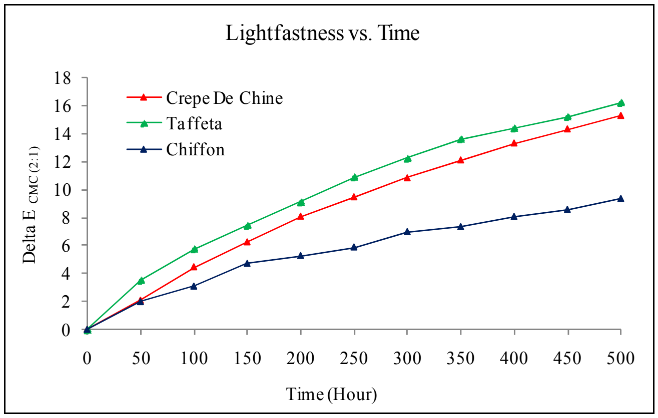


Figure 7. *Color changes in silk fabrics after light exposure for 500 hours.*

Table 5 lists the color changes of primary colors (cyan, magenta, and yellow) before and after 500 hours exposure. For the acid dye inks, yellow ink had better lightfastness, while cyan ink had poor fade resistance (with ΔE_{CMC} values of over 13). Figures 8 to 10 illustrate ink color changes (in the a*, b* chroma diagram) with fading for cyan, magenta, and yellow inks, respectively. For the cyan acid dye ink (as shown in Table 5 and Figure 8), most of the average ΔE resulted from the Δb* shift. For magenta acid dye ink, on the other hand, most of the average ΔE resulted from the Δa* shift, as well as from the ΔL* shift. Yellow acid dye ink provided better fade resistance, compared to cyan and magenta inks. Figure 10 indicates that increasing exposure resulted in a trend to less b* values for the yellow.

Table 5. *Summary of primary color changes before and after exposure.*

Colors	Silk fabrics	L*a*b* value before exposure			L*a*b* value after 500 hours exposure			ΔE_{CMC}
		L*	a*	b*	L*	a*	b*	
Cyan	Crepe De Chine	25.5	11.8	–52.0	29.8	–5.1	–15.1	17.9
	Taffeta	33.0	7.3	–52.5	41.0	–6.1	–13.2	18.5
	Chiffon	48.6	3.4	–32.9	51.1	–4.0	–9.5	13.2
Magenta	Crepe De Chine	35.7	57.1	14.4	49.7	34.3	8.6	11.6
	Taffeta	41.2	56.4	8.1	58.7	28.0	6.2	13.8
	Chiffon	52.8	32.7	6.3	59.9	25.1	4.6	4.9
Yellow	Crepe De Chine	79.5	8.0	98.1	76.1	10.9	77.8	6.5
	Taffeta	84.0	5.2	93.5	81.8	6.7	65.4	8.6
	Chiffon	83.3	2.2	60.7	80.6	3.6	46.9	5.2

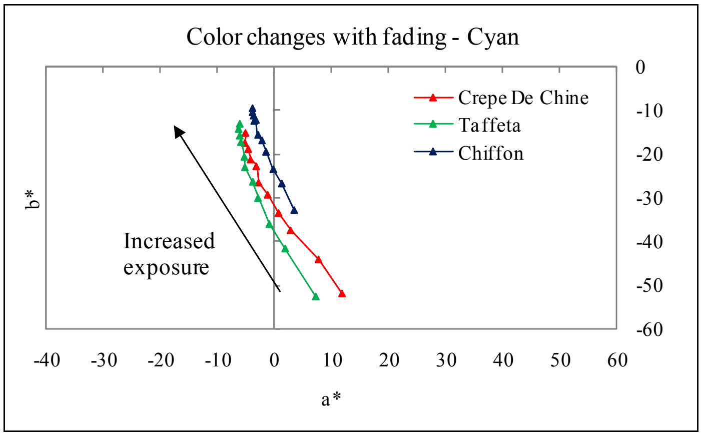


Figure 8. *Color changes with fading for the cyan ink.*

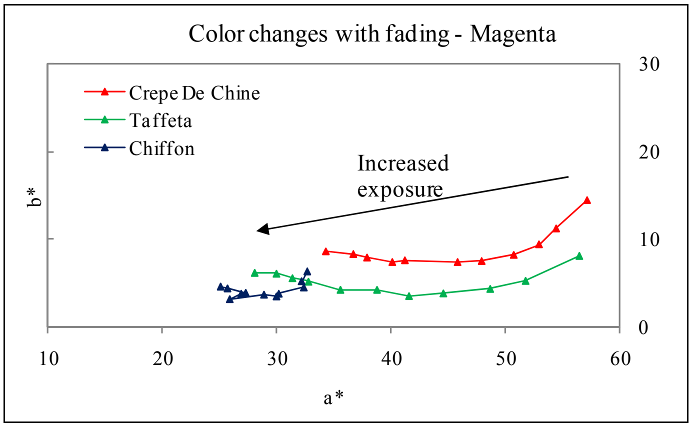


Figure 9.*Color changes with fading for the magenta ink.*

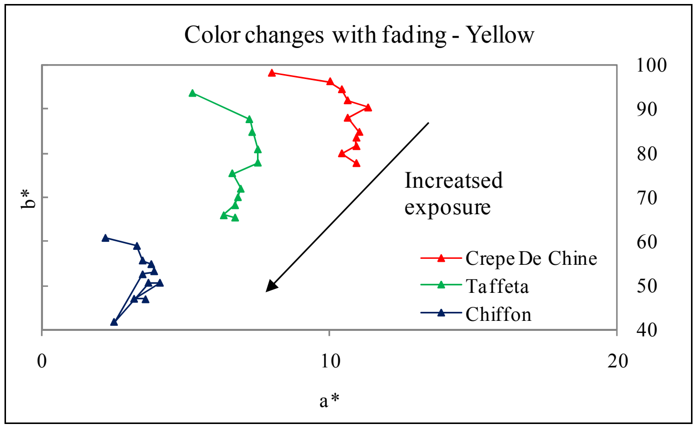


Figure 10. *Color changes with fading for the yellow ink.*

4. Conclusions

The ability to accurately reproduce a given color using digital inkjet textile printing is crucial for sampling as well as for mass customization. Understanding which colors are attainable within the limits of specific fabrics and ink sets is especially beneficial for designers. This study conducted color reproduction tests on three different silk fabrics. The choice of textile substrate significantly influences image quality. It shows crepe de chine is capable of yielding a wider color gamut and higher optical densities, resulting in better color reproduction capability. About 60% of Pantone colors can be reproduced by crepe de chine with $\Delta E_{CMC\ 2:1}$ values lower than 4.0. Taffeta has a smaller color gamut, compared to crepe de chine. However, it yielded a wider color gamut in magenta and purple regions, as well as in the higher L* values area. Taffeta also can reproduce about 52% of Pantone colors (with $\Delta E_{CMC\ 2:1}$ lower than 4.0). Compared to crepe de chine and taffeta, chiffon has a quite open textile structure, resulting in poorer ink holdout. Therefore, ink control for chiffon is very important to avoid bleeding. Chiffon has a relatively small color gamut and only can reproduce lighter colors. About 34% of Pantone colors can be reproduced by chiffon with $\Delta E_{CMC\ 2:1}$ lower than 4.0.

Tested digital printer Epson Stylus Pro 9800 with acid dye technology provides only CMYK process color, which limits the volume of color gamut. By using basic color management techniques, nearly 90% of Pantone colors can be reproduced by the chosen silk fabrics with $\Delta E_{CMC\ 2:1}$ values lower than 8.0, with exception of chiffon. To pursue accurate color matching, incorporating color management solutions and the advanced wide-format textile digital printers equipped with extended ink sets are necessary.

The choice of textile substrate also influences light fastness. Printed with acid dye inks, crepe de chine and chiffon tended to have better fade resistance than taffeta. For the acid dye inks, yellow ink had better lightfastness, while cyan ink had poorer fade resistance. Further developments in ink formulation are needed to improve the light fastness of digital printing on silk fabrics.

The digital textile printing process is more complicated than the inkjet paper printing process. There are many variables that can have an impact on color quality. Fabric pre-treatment, steaming, and other finishing processes are all variables that affect color reproduction for a customization scenario. The ability to consistently control output is essential. The development of innovative colorants to eliminate the need for post-treatment, such as use of pigment-based inks, could be an important advancement.

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