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Digital Textile Ink-Jet Printing Innovation: Development and Evaluation of Digital Denim Technology

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Abstract. *This research explored the potential for ink-jet printing to replicate the coloration and finishing techniques of traditional denim fabric and standardized the reproduction and evaluation procedure. Although denim fabric is widely consumed and very popular, one drawback to denim is that the finishing and manufacturing processes are energy and water intensive and can cause environmental hazards as well as generation of pollution through water waste, particularly at the finishing stage. Textile ink-jet printing has the potential to replicate some of the coloration and finishing techniques of traditional denim fabric without negative environmental impacts. A two-phase research project was conducted. In Phase I (P1), an optimal standard production workflow for digital denim reproduction (including color and finishing effects) was established, and six different denim samples were reproduced based on the workflow. In Phase II, an expert visual assessment protocol was developed to evaluate the acceptance of the replicated digital denim. Twelve ink-jet printing, color science, and denim industry experts finished the assessment.* © *2021 Society for Imaging Science and Technology.*
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1. INTRODUCTION

Denim, a woven cotton fabric, is a trend driven substrate used throughout the world in multiple consumer markets. As a profitable fashion fabric, denim can be classified according to texture, weight, finishing method, and surface effects [1, 2]. The consumer demand for novel and different denim surface appearance resulted in extensive research and development efforts in finishing application by several major apparel companies [3]. Digital denim, first researched and recorded by Carly Spano of Cotton Incorporated, USA, is a process of replicating traditional denim manufacturing and finishing effects by textile digital ink-jet printing. This research builds upon Cotton Incorporated and seeks, produces, or replicates a denim-like fabric through digital printing by printing onto a non-dyed twill fabric [4].

Digital denim has the potential to use less water, energy, and colorant when compared to traditional denim manufacturing. In addition, denim fabric, replicated by ink-jet printing, would enable textile and apparel designers to create various novel finishing effects onto jeans, jackets, or other denim type garments, with reduction in cost, labor, and time [5–7]. This innovative process would also provide opportunities for design and manufacturing to be more centralized, thereby allowing designers to work closely with producers and retailers to deliver quick response to customers [4, 8]. Because denim trends change rapidly, a quick response model would enable the denim industry to meet the growing demands of fast fashion and regional trends. Consumer data base analysis can also be established to make the company more competitive [9].

Although digital denim is still a new concept without any standard production workflow or testing standards, it is still an attractive idea because of the potential benefits such as lowering or eliminating the environmental impact, increasing customization, as well as reducing the cost of labor, material, and energy [4, 10]. However, further research efforts are required to increase the printing quality of denim fabric through color management and computer-aided design (CAD) work. In addition, production procedures and evaluation standards need to be established and standardized.

2. RESEARCH OBJECTIVES

Current digital denim production relies mainly on the designer's design skills and creativity rather than a clear production workflow, which limits the mass production of digital denim. In addition, there is currently no reliable assessment of the criteria to assess whether digital denim fabric can replace traditional denim fabric. To explore

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Table I. Technical information of tradition denim samples.

Label	Warp yarns	Filling yarns	Weight (oz/yd^2)	Thread count	Finish effect
Sample 1	9/1 Ne. TM 4.6	7/1 Ne. TM 3.8	13.0	68 ends/in × 48 picks/in	Enzyme washed
Sample 2	10/1 Ne., TM 4.0	7/1 Ne. TM 3.5	13.0	78 ends/in × 48 picks/in	Enzyme washed
Sample 3	9/1 Ne. TM 4.6	7/1 Ne. TM 3.8	13.1	68 ends/in × 49 picks/in	Bleached down
Sample 4	10/1 Ne., TM 4.0	7/1 Ne. TM 3.5	12.9	76 ends/in × 49 picks/in	Bleached down
Sample 5	10/1 Ne. TM 4.0	7/1 Ne. TM 3.5	13.0	76 ends/in × 48 picks/in	Permanganate washed
Sample 6	9/1 Ne. TM 4.6	7/1 Ne. TM 3.8	13.3	70 ends/in × 50 picks/in	Permanganate washed

the potential for ink-jet printing replicating the coloration and finishing techniques of traditional denim fabric and standardizing the reproduction and evaluation procedure, a two-phase research study was conducted. The objectives of these two stages were to:

(1) Establish an optimal standard production workflow for digital denim reproduction (including color and finishing effects);
(2) Develop a standard visual assessment protocol of replicated denim fabric, and evaluate the acceptance of the replicated denim via an expert visual assessment.

3. EXPERIMENTAL STAGE ONE

3.1 *Material*

Six traditional denim fabrics with washing effects were provided by a research-based textile company (Table I). All of the samples were made of 3/1 right-hand twill with 100% cotton content. Both the warp yarns and filling yarns used to weave the denim were open end. In keeping with the traditional denim process, the warp yarns were dyed using indigo and the filling yarns were kept in the greige state. The raw fiber for all of the yarns were purchased from American cotton growers. All the denim samples obtained were hand-abraded in garment form, washed in a garment washing machine with different washing effects, and subsequently softened in a garment washing machine with Cotton Soft 200. The six traditional denim samples were labeled as Sample A1, Sample A2, Sample A3, Sample A4, Sample A5, and Sample A6. As shown in Table I, the warp yarns and filling yarns information, weight and thread count, and the finishing effect were different between the six samples.

3.2 *File Preparation*

Denim fabric samples (A1–A6) were scanned and turned into ready for printing digital files. The sample that needed to be scanned was placed on the flatbed of Epson E11000XL scanner with the technical face side down. Then the cover was put down to prevent any other light source. After that, a preview was conducted using EPSON Scan software (Figure 1). Since the maximum resolution for the HP Latex 365 Printer is 1200 × 1200 dpi, the 1200 dpi scan setting was used and kept consistent for all six scans. The scanning process for each piece of denim fabric took five to six minutes.

Figure 1. Original denim (left) and digital scan image (right).

The whole scanning process for all six samples took about thirty to thirty-five minutes.

All the scanned images were saved in a TIFF format. In contrast to other graphic formats such as JPEG, TIFF has an alpha channel which, in addition to the color information, can also store the transparency of individual pixels. The advantage of this method is the simple, and therefore fast compression and decompression of such files with lossless quality. Therefore, TIFF format is primarily used to provide high-quality graphics for printing without loss. The much higher amount of data of a TIFF file, when compared to the JPEG format, is preferred in the graphics and printing industry [11–13].

All the scanned files were edited using Adobe Photoshop CC 2018 (19.0) for Windows version 10. Each file was cropped to a 7 × 12 inch rectangle that captured the main part of the fabric without including any pockets or selvedge area. After cropping, each file was rotated 90 degrees to ensure that the twill direction matched the original denim fabric. After editing, all the files were re-saved as TIFF files with 1200 resolution to keep as much detail for printing as possible.

3.3 *Digital Printing Fabric*

The fabric used for digital printing was provided by Duravibe and pre-treated for latex ink printing (Table II). The fabric

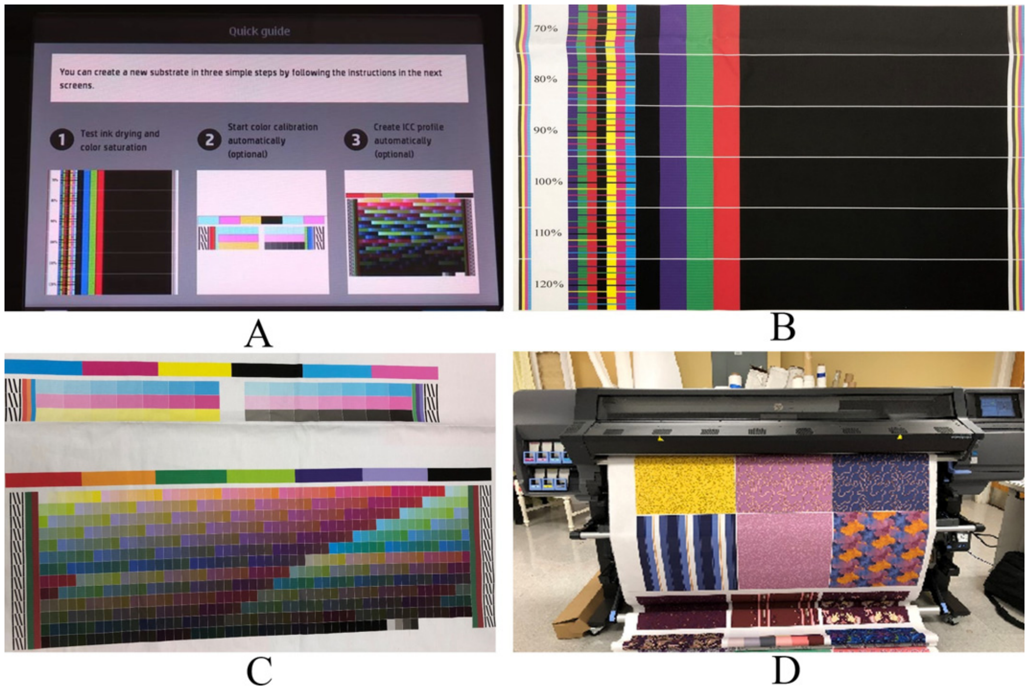

Figure 2. Facilities and process for conducting ink-jet printed sample (A) Color calibration steps, (B) Ink drying and color saturation test, (C) Part of ICC profile creation color chart, (D) HP Latex 365 Printer.

Table II. Visual assessment instrument.

Visual assessment instrument	
Part I Demographics information	Identify expertise & Visual assessment experience
Part II Visual appearance Assessment	Evaluate the digital and traditional denim samples

type was twill optic, 3/1 right hand with a weight of 6.28 oz/yd^2. The fabric was bleached and then pre-treated with pigment printing. Pre-treatment was deemed necessary for the digital textile printing process as it significantly improves the print quality, especially line quality and clarity [14–17].

3.4 *Color Calibration and Profiling*

Color calibration was conducted before printing to ensure color accuracy and consistency [18, 19]. The color calibration process, which included three steps were (1) Ink drying and color saturation test; (2) Automatic color calibration; and (3) ICC profile creation (Figure 2). The first two steps were conducted through the HP latex printer, and the last step was conducted using Wasatch RIP software and an X-Rite i1iO spectrophotometer. The ink limitation was set at 110% ink for the color charts creation within Wasatch RIP software printed using the HP latex 365 printer and then read into the software using an X-Rite i1iO spectrophotometer.

3.5 *Conduct Ink-jet Textile Printing Trial*

All the samples were printed using an HP Latex 365 printer, with a thermal printhead, and color profile calibrated for 100% pre-treated cotton twill fabric. Compared to reactive dyes, pigment-based ink produces less waste during the production procedure, and have certain environmental benefits [10, 20, 21]. Latex ink is an eco-conscious and versatile pigment-based ink, but unlike solvent inks, the latex ink has low-VOC emissions, without losing the vibrant color and high color reproducibility of solvent inks. Resins contained in the latex ink are dissolved by heat and form a membrane to firmly fix pigments to the surface of the media [19, 22].

The inkset used for this study was cyan, magenta, yellow, black, light magenta, and light cyan with a latex optimizer. The total ink limitation was 360%. All the fabric was pre-treated and post-treated. The pre-treatment, DP-300 (45% solids) for cotton, was developed for pigment-based inkjet printing on textiles. The main components in the pre-treatment reagents were multivalent metal salts as ink coagulants, acrylic resin for ink anchoring to the substrate, and additives for wetting and surface tension control such as isopropyl alcohol, propylene glycol, and silicone-based compounds. For the post-treatment, all print samples were heat fixed with the Practix Mfg heat calendar. The temperature setting was 300 Fahrenheit and the dwell time was 80 seconds. The facility, temperature, and dwell time setting were consistent for all the print samples.

In total, six digital samples were printed with one for each denim sample. The digitally reproduced samples were labeled as B1, B2, B3, B4, B5, and B6 associated with the corresponding traditional denim fabric (A1, A2, A3, A4, A5, and A6).

4. EXPERIMENTAL STAGE TWO

4.1 *Determination of Variables*

Variables were determined for the assessment protocol and survey instrument before conducting the visual assessment comparison between the traditional denim (Sample A1–A6) and digital denim samples (Sample B1–B6). Five variables were controlled consistently during the visual assessment: illumination, viewing environment, observers, frequency and interval, and viewing order. Seven variables were chosen to evaluate the perceived difference between the two samples: color, line quality, visual texture, scale, overall appearance, lightness, and overall matching [14, 15].

Color difference was used to determine how close the color is matched between digital denim and traditional denim samples. Line quality was used to evaluate how well the weight, clarity, and uniformity of the stripes in the digital denim is compared to the traditional denim sample. Visual texture was used to evaluate the ability of digital denim samples replicating the woven structure appearance of the traditional denim samples. Scale was used to evaluate how accurate the size proportion of the digital denim samples is matched to the traditional denim samples. Overall appearance was used to evaluate how well the color, scale, line quality, and visual texture appeared to interact in the digital denim samples, and therefore closely match the traditional denim samples. Lightness included comparisons of the brightness between the traditional denim and the digital denim samples [15, 20, 23].

4.2 *Development of Visual Assessment Instrument*

After the determination of the variables and review of previous work, an instrument was developed [15]. The instrument was approved by North Carolina State University's Institutional Review Board (IRB) before starting the assessment.

The instrument included two parts, which can be seen in Table II. Part I collected the demographic information of each participant, which was used for determining the expertise area and visual assessment experience of the participant. Part II consisted of the visual appearance assessment, which included questions for color, line quality, visual texture, scale, overall appearance, lightness, and overall matching.

4.3 *Scale Description*

For color matching, the AATCC gray scale was used to evaluate the perceived color matching between two samples. Participants assigned a value of 1 to 5 after comparing colors, with 5 representing no color difference between samples, and 1 representing the highest color difference between samples. When analyzing results, the closer the mean was to 5 for each sample set compared, it indicated a more closely perceived color match.

Regarding line quality, visual texture, scale, and overall appearance, five options were given to participants to describe the matching level between two samples which were: not at all (1), slightly (2), somewhat (3), mostly (4), and exactly (5). Each option was given a number for statistical analysis purposes. Lightness is the most direct color visual effect and a very important quality index for a textile product. For the lightness comparison, participants were asked to choose one of five options that best described the lightness relationship between the two samples: A is obviously brighter than B ($A \gg B$), A is slightly brighter than B ($A > B$), A is as same brightness as B ($A = B$), B is slightly brighter than A ($A < B$), and B is obviously brighter the A ($A \ll B$).

4.4 *Expert Visual Assessment Protocol Development*

An expert visual assessment was conducted to evaluate the replication of the traditional denim samples via ink-jet digital textile printing. The visual assessment protocol and instrument were developed based on previous research [3, 15]. The gray scale for evaluating change in color (ISO International Standard 105/A02) was used for evaluating color. The visual assessments focused on appearance (including line quality, visual texture, scale, and overall appearance), lightness matching, and overall matching and were conducted without using any instruments. All the participants were experts from either the textile industry or doctoral students whose area of focus was color science. Experienced participants were recommended for visual assessment rather than inexperienced participants to increase the accuracy and shorten the total experiment time [14]. Therefore, all the participants had experience in conducting visual assessments.

4.5 *Illuminant and Viewing Environment*

The visual assessments were carried out in the Color Science Lab in the Wilson College of Textiles at North Carolina State University. To minimize variability, the principal investigator (PI) arranged carefully controlled viewing conditions, which were kept the same throughout the test trials. A Macbeth Spectra Light III viewing booth with a filtered tungsten daylight-simulating lamp (D65) was switched on during the experiment. This light source was the only illumination in the lab, with all other sources of light turned off. The lamp of the viewing booth had a color temperature of 6500 ± 200 K and constant illumination of approximately 1400 lx [14].

4.6 *Visual Assessment Sample Set-up*

The traditional denim and the digital reproduced samples were identified by labels on the back of the 15×15 inch medium gray-colored PVC easel (one for each sample) to maintain consistency during the experiment. The samples were placed in the viewing booth on the easel with a two inch gap between each sample. Only the assessment parts of the fabric were accessible, and the rest of the part was covered by a white board. The size of the selected part of the traditional denim sample was 7×12 inch, which avoided stitched edges, pocket area, and selvage. Each participant repeated the assessment three times for each pair of samples. In total, six pairs of samples were assessed.

4.7 *Expert Visual Assessment Protocol*

Each pair of samples (in total, six pairs of samples) were compared three times using the same evaluation instrument,

Figure 3. Expert visual assessment.

and all the answers were recorded. Each participant viewed the samples by the numeric order from sample 1 to sample 6 three times for each sample using the same evaluation instrument, visual assessment protocol, and assessment environment, and all the answers were recorded by the PI.

4.7.1 *Step 1*

The participants wore a pair of gray gloves to minimize color variability, as well as to prevent damaging the samples and the AATCC gray scales. The participants sat in front of the Macbeth Spectra Light III viewing booth, and the filtered tungsten daylight-simulating lamp (D65) was turned on by the PI. While the participants adapted to the light source by sitting in the viewing booth for two minutes, the PI introduced the steps of the experimental process to them. After the participants adapted to the viewing conditions in the lab, they were shown the informed consent form. Once they gave their consent, the participants were asked to complete Part I of the visual assessment, which asked for demographic information.

4.7.2 *Step 2*

After finishing Part I, participant was asked to conduct Part II of the visual assessment (Figure 3 PART I). The first question in Part II consisted of assessing the color of the digital and traditional samples. Participants sat in front of the viewing booth after wearing gray gloves and were told that they could use the AATCC gray scale freely to identify the color difference for each pair of samples. The participants were free to move the AATCC gray scale to identify the color difference between the pair of samples, but they were not allowed to move or change the display of samples.

4.7.3 *Step 3*

Next, participants were asked to perform the visual assessment focused on appearance (Fig. 3 PART II), which includes line quality, visual texture, scale, and overall appearance, and overall matching. After identifying the appearance difference, participants compared the lightness of the pair of sample. Participants chose one option from five that best described the relationship between two samples.

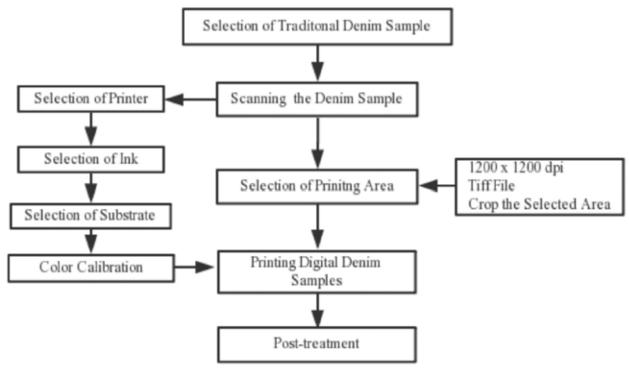

Figure 4. Reproduction workflow of denim.

5. RESULTS AND DISCUSSION

5.1 *Stage One Result: Reproduction Workflow*

A reproduction workflow was developed, and six digital denim samples were printed using the developed workflow (Figure 4). The traditional denim samples for reproduction were selected and scanned using the photo scanner. After scanning, the printing area was selected using CAD software and the digital file was saved as tiff file using 1200 × 1200 dpi to obtain the maximum image quality. HP Latex 365 printer, six color (CMYK+LC+LM) latex ink with optimizer, and 100% pre-treated right-hand cotton twill were selected for printing. A color calibration was conducted before printing to ensure the color accuracy. After printing, a post-treatment was applied for the printed digital denim fabric samples. This workflow can be used for future research or industry purpose.

5.2 *Stage Two Result: Expert Visual Assessment*

5.2.1 *Visual Assessment Part I: Demographics Information*

The questions in Part I focused on the demographics information, which included four questions that identified the expertise and visual assessment experience for the participants (Table III). As shown in Tables III and IV, all of the participants were industry professionals working in textile areas, or PhD students, focus on color science or digital textile printing research. All the participants selected

Table III. Demographics information of visual assessment participants.

	Profession	Experience (years)	Visual assessment experience (years)	Visual assessment frequency
1	Denim manufacturing	Greater than eighteen	Fifteen to eighteen	Three or four times a week
2	Ink-jet textile printing; Colorist/Color management; Color science/ Color matching	Six to nine	Six to nine	Three or four times a week
3	Ink-jet textile printing; Denim manufacturing; Sourcing/ Consulting;	Fifteen to eighteen	Fifteen to eighteen	Once or twice a week
4	Colorist/Color management; Color Science/ Color matching	One to three	One to three	Once or twice every two months
5	Colorist/Color management; Sourcing/ Consulting Color science/ Color matching	Six to nine	Six to nine	Once or twice a week
6	Colorist/Color management; Color science/ Color matching	Three to six	One to three	Once or twice every two months
7	Color science/ Color matching	Six to nine	One to three	Once or twice every two months
8	Denim manufacturing; Dyeing manufacturing/Chemist; Colorist/Color management; Color science/ Color matching	Six to nine	Three to six	Once or twice a month
9	Ink-jet textile printing; Colorist/Color management; Color science/ Color matching	Three to six	One to three	Once or twice every two weeks
10	Colorist/Color management; Color science/ Color matching	Three to six	One to three	Once or twice every four months
11	Color science/ Color matching	Three to six	One to three	Once or twice every two weeks
12	Ink-jet textile printing; Dyeing manufacturing/Chemist	Three to six	One to three	Once or twice half year

Table IV. Other text answers for expertise.

Expert number	Other answers for expertise
1	Weaving
2	Dyeing
3	Woven product development

up to three options for their specialization. In addition, visual assessment experience and frequency were used to identify the expertise. All the selected experts have experience in visual assessment.

5.2.2 *Visual Assessment Part II: Visual Assessment Results*
A total of six sets of samples of traditional denim and digitally printed denim were visually compared, and digital scan of traditional denim samples and corresponding digital reproduced samples can be seen in Table V. The data were recorded and analyzed in JMP software.

5.3 *Color and Appearance Assessment Results*

Figure 5 shows the comparison of different samples and aspects. Sample pair 5 was rated significantly different than the other samples, while scale and color matching received a significantly high match for all three trials, the line quality, visual texture, and overall appearance were rated low with means between 2.3 and 2.8. The line quality, specifically, was rated significantly lower by the experts than the other samples.

For the Sample 1 pair (Sample A1 and Sample B1), scale and line quality had the highest mean ratings for all three trials, where line quality received 3.6 for all three trials, and scale scores were between 4.4 and 4.6. The color matching, visual texture, and overall appearance were rated as the second strongest group, with all means above 3. However, the overall matching received the lowest rating which was slightly below 3. For the Sample 2 pair (Sample A2 and Sample B2), overall participants rated scale higher than any of the other samples. Color matching, line quality, visual texture, overall appearance were in the second strongest group. Overall appearance and overall matching were rated slightly lower than the other aspects. All of the mean ratings were above 3. For the Sample 3 pair (Sample A3 and Sample B3), color matching and scale received the strongest match for all three trials. Line quality, visual texture, overall appearance, and overall matching were in the second strongest matching group. For pair of Sample 4 (Sample A4 and Sample B4), scale received the strongest match for all three trials. Color matching, line quality, visual texture

Table V. Traditional denim sample (A) and corresponding digital reproduced sample (B).

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
A						
B						

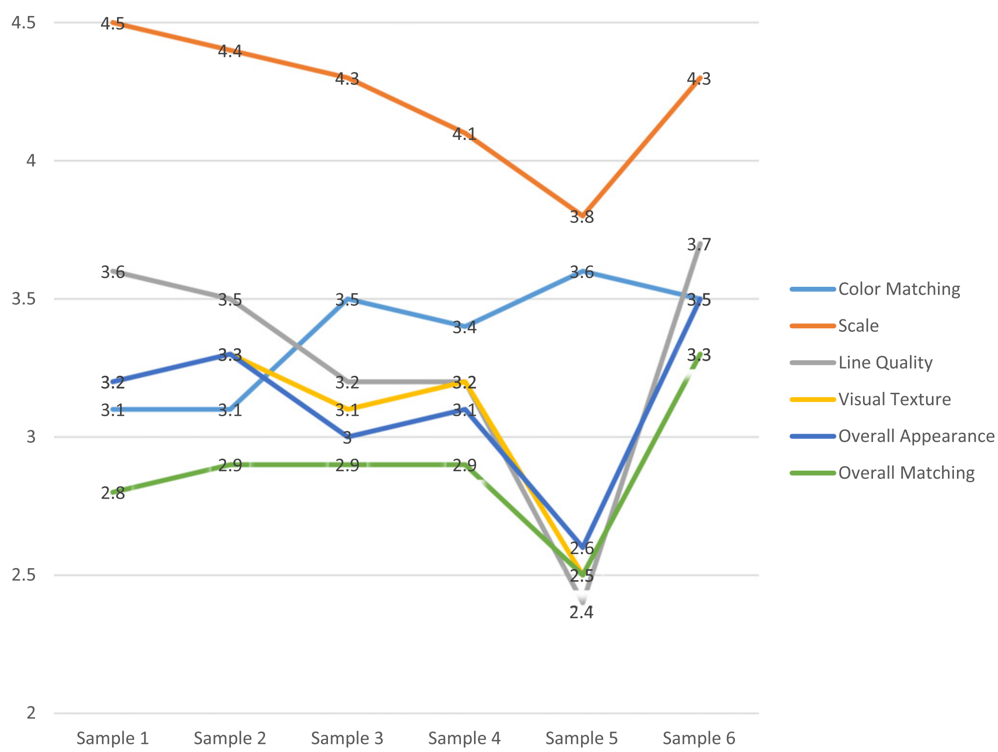

Figure 5. Mean response results of color and appearance.

are in the second strongest matching group. However, the mean scores of overall appearance and overall matching are slightly lower than the other aspects. All of the mean scores are close or above 3. For pair of Sample 5 (Sample A5 and Sample B5), color matching and scale received the strongest match for all three trials. However, line quality, visual texture, overall appearance, and overall matching received significantly lower scores for all three trials, which are between 2.3 and 2.8. For pair of Sample 6 (Sample A6 and Sample B6), all of the aspects which includes color matching, line quality, visual texture, and overall appearance are well matched with high mean matching scores. Overall matching received a 3.3 mean matching score for all three trials, which is also a high matching score but slightly lower than other aspects. All of the mean scores are above 3.3.

5.4 *Perceived Lightness Difference Assessment Results*

According to the results, the lightness of the traditional and digitally reproduced samples is different (Table VI). For samples 1, 3, and 4, none of the participants believed that

Table VI. Perceived lightness difference.

Lightness		Trial 1 (%)	Trial 2 (%)	Trial 3 (%)
	A ≫ B	58.0	75.0	46.0
	A > B	17.0	31.0	23.0
Sample 1	A = B	0.0	0.0	0.0
	A < B	8.0	15.0	16.0
	A ≪ B	17.0	15.0	15.0
	A ≫ B	59.0	59.0	59.0
	A > B	8.0	8.0	8.0
Sample 2	A = B	8.0	8.0	8.0
	A < B	9.0	8.0	17.0
	A ≪ B	17.0	17.0	8.0
	A ≫ B	33.0	33.0	25.0
	A > B	25.0	25.0	33.0
Sample 3	A = B	0.0	0.0	8.0
	A < B	25.0	25.0	17.0
	A ≪ B	17.0	17.0	17.0
	A ≫ B	25.0	25.0	25.0
	A > B	33.0	34.0	25.0
Sample 4	A = B	0.0	0.0	0.0
	A < B	25.0	33.0	42.0
	A ≪ B	17.0	8.0	8.0
	A ≫ B	41.0	41.0	41.0
	A > B	42.0	42.0	42.0
Sample 5	A = B	17.0	17.0	17.0
	A < B	0.0	0.0	0.0
	A ≪ B	0.0	0.0	0.0
	A ≫ B	9.0	8.0	8.0
	A > B	25.0	25.0	25.0
Sample 6	A = B	8.0	0.0	0.0
	A < B	50.0	50.0	59.0
	A ≪ B	8.0	17.0	8.0

the lightness of sample A matches the lightness of sample B. Few of the participants thought the lightness of sample 2 (one participant), sample 5 (two participants), and sample 6 (one participant in trial 1) matches for traditional and digitally reproduced samples.

5.5 *Reliability Statistics*

The reliability of data is the key to whether the data is meaningful [24]. Although the variables in the experiment process and environmental conditions were effectively controlled, the psychological state of the experimental participants, such as the degree of tension, mood, and exhaustion, may still make the experimental results unsustainable [14]. Therefore, the PI used analysis of variance (ANOVA) and Pearson correlation to analyze the reliability of the data between the three trials and between the six pairs of samples.

Table VII. Summary of Pearson correlation results between three trials.

		T1&T2	T1&T3	T2&T3
	Pearson correlation	0.898	0.803	0.8940
Sample 1	Sig. (2-tailed)	<0.0001*	<0.0001*	<0.0001*
	N	84	84	84
	Pearson correlation	0.869	0.838	0.896
Sample 2	Sig. (2-tailed)	<0.0001*	<0.0001*	<0.0001*
	N	84	84	84
	Pearson correlation	0.884	0.877	0.906
Sample 3	Sig. (2-tailed)	<0.0001*	<0.0001*	<0.0001*
	N	84	84	84
	Pearson correlation	0.910	0.868	0.859
Sample 4	Sig. (2-tailed)	<0.0001*	<0.0001*	<0.0001*
	N	84	84	84
	Pearson correlation	0.890	0.889	0.908
Sample 5	Sig. (2-tailed)	<0.0001*	<0.0001*	<0.0001*
	N	84	84	84
	Pearson correlation	0.853	0.853	0.887
Sample 6	Sig. (2-tailed)	<0.0001*	<0.0001*	<0.0001*
	N	84	84	84

5.6 *Variance and Correlation Between Three Trials*

5.6.1 *Pearson Correlation – Between Three Trials*

According to the Pearson correlation results for the three trials, there was a strong significant positive correlation between trial one and trial two, trial one and trial three, and trial two and trial three, which indicated these three trials were consistent (Table VII). Recall that the experiment process and environmental conditions variables were controlled during the assessments.

5.6.2 *Analysis of Variance (ANOVA) – Between Three Trials*

An ANOVA was conducted to compare the results of the trials for every visual assessment property (color matching, visual texture, lightness matching, line quality, overall appearance, and overall matching) (Table VIII). There was not a significant difference between the trials for any property ($p > 0.05$). The data collected from three trials were consistent. Again, recall that the experiment process and environmental conditions variables were controlled during the assessments.

According to the statistical analyses, all three trials were consistent. The experiment process and environmental conditions variables were controlled during the assessments.

5.7 *Variance Between Samples*

5.7.1 *Analysis of Variance (ANOVA) – Between Samples*

An ANOVA was conducted to compare the results of the six samples, within each trial, for every visual assessment property (color matching, visual texture, lightness matching, line quality, overall appearance, and overall matching). There

Table VIII. Summary of ANOVA test between three trials.

		DF	SS	MS	F ratio	*P*-value
Color matching	Trial	2	0.64583	0.322917	0.4610	0.6313
	Error	213	149.18750	0.700411		
	C. Total	215	149.83333			
Line quality	Trial	2	0.00694	0.003472	0.0047	0.9953
	Error	213	157.98264	0.741703		
	C. Total	215	157.98958			
Visual texture	Trial	2	0.28704	0.143519	0.2257	0.7982
	Error	213	135.47222	0.636020		
	C. Total	215	135.75926			
Scale	Trial	2	0.17593	0.087963	0.1304	0.8778
	Error	213	143.70833	0.674687		
	C. Total	215	143.88426			
Overall appearance	Trial	2	0.17593	0.087963	0.1824	0.8334
	Error	213	102.69444	0.482134		
	C. Total	215	102.87037			
Lightness matching	Trial	2	0.02778	0.01389	0.0067	0.9933
	Error	213	441.59722	2.07323		
	C. Total	215	441.62500			
Overall matching	Trial	2	0.583333	0.291667	0.6291	0.5341
	Error	213	98.750000	0.463615		
	C. Total	215	99.333333			

was not a significant difference between the samples for any trials for color matching, visual texture scale, and lightness matching ($p > 0.05$). See Table IX.

However, there was a significant difference between the six pairs of samples by trial for line quality, overall appearance, and overall matching. For line quality matching between the six samples (Table X), the p-values were <0.001, 0.0048, and 0.0031 for trial 1, trial 2, and trial 3, respectively.

To locate which samples were significantly different, a Tukey HSD test was conducted. As seen in the ordered differences report (Table XI), in trial 1 there were significant differences ($p < 0.05$) between sample 5 and sample 1, sample 5 and sample 2, sample 5 and sample 4, and sample 5 and sample 6. In trial 2, there were significant differences ($p < 0.05$) between sample 5 and sample 1, sample 5 and sample 2, and sample 5 and sample 6. In trial 3, there were significant differences ($p < 0.05$) between sample 5 and sample 1, sample 5 and sample 2, and sample 5 and sample 6.

For overall appearance matching between the six samples (Table XII), the p-values were 0.0058, 0.0065, and 0.3959 for trial 1, trial 2, and trial 3, respectively. There were significant differences between the six samples for trial 1 and trial 2, but not trial 3.

To locate which samples were significantly different, a Tukey HSD test was conducted. As seen in the ordered differences report (Table XIII), in trial 1 there was a

Table IX. ANOVA results between samples for color, visual texture, and lightness matching.

Color matching	Source	SS	DF	MS	F	Sig
Trial 1	Sample	4.323	5	0.865	1.223	0.308
	Error	46.646	66	0.707		
	C. Total	50.969	71			
Trial 2	Sample	3.167	5	0.633	0.883	0.498
	Error	47.333	66	0.717		
	C. Total	50.500	71			
Trial 3	Sample	3.073	5	0.615	0.909	0.481
	Error	44.646	66	0.676		
	C. Total	47.719	71			
Visual texture	Source	SS	DF	MS	F	Sig
Trial 1	Sample	7.569	5	1.514	2.216	0.063
	Error	45.083	66	0.683		
	C. Total	52.653	71			
Trial 2	Sample	6.833	5	1.367	2.333	0.052
	Error	38.667	66	0.586		
	C. Total	45.500	71			
Trial 3	Sample	4.736	5	0.947	1.919	0.103
	Error	32.583	66	0.494		
	C. Total	37.319	71			
Scale	Source	SS	DF	MS	F	Sig
Trial 1	Sample	3.278	5	0.656	0.958	0.450
	Error	45.167	66	0.684		
	C. Total	48.444	71			
Trial 2	Sample	5.569	5	1.114	2.136	0.072
	Error	34.417	66	0.521		
	C. Total	39.986	71			
Trial 3	Sample	2.778	5	0.556	0.699	0.627
	Error	52.500	66	0.795		
	C. Total	55.278	71			
Lightness	Source	SS	DF	MS	F	Sig
Trial 1	Sample	17.778	5	3.556	1.726	0.141
	Error	136.000	66	2.061		
	C. Total	153.778	71			
Trial 2	Sample	20.111	5	4.022	2.077	0.079
	Error	127.833	66	1.937		
	C. Total	147.944	71			
Trial 3	Sample	20.792	5	4.158	2.305	0.054
	Error	119.083	66	1.804		
	C. Total	139.875	71			

significant difference ($p < 0.05$) between sample 5 and sample 6. In trial 2, there were significant differences ($p < 0.05$) between sample 5 and sample 2, and sample 5 and sample 6.

Table X. ANOVA results between samples for line quality matching.

Line quality	Source	SS	DF	MS	F	Sig
Trial 1	Sample	15.069	5	3.014	6.232	**<0.0001***
	Error	31.917	66	0.484		
	C. Total	49.986	71			
Trial 2	Sample	11.267	5	2.253	3.744	**0.0048***
	Error	39.729	66	0.602		
	C. Total	50.997	71			
Trial 3	Sample	13.958	5	2.792	4.002	**0.0031***
	Error	46.042	66	0.698		
	C. Total	60.000	71			

For overall matching between the six samples (Table XIV), the p-values were 0.0481, 0.1460, and 0.0830 for trial 1, trial 2, and trial 3, respectively. There were significant differences between the six samples for trial 1, but not for trials 2 and 3.

To locate which samples were significantly different, a Tukey HSD test was conducted. As seen in the ordered differences report (Table XV), in trial 1 there was a significant difference ($p < 0.05$) between sample 5 and sample 6.

According to the statistical analyses, sample 5 was significantly different from samples 1, 2, 4, and 6 for line quality. Sample 5 was also significantly different from other samples in overall appearance and overall matching. In overall matching, sample 5 was significantly different mainly due to the influence by the line quality difference between digital and traditional denim samples.

6. CONCLUSIONS

The ability to effectively replicate the traditional denim by digital printing varied according to the visual appearance or finishing effect of the traditional denim fabric. For example, Sample pair 5 was rated significantly different than the other samples according to the statistical analysis. While scale and color matching received a significantly high match for all three trials, the line quality, visual texture, and overall appearance were rated low with means between 2.3 and 2.8. The line quality, specifically, was scored significantly lower by the experts than the other samples. This shows to a certain extent that, compared to color, texture and line quality are more difficult to achieve with digital printing.

Matching scores above three indicates a good matching between two samples [14, 20]. For overall matching, all of the mean scores are above or close to 3. Sample 6 received the highest score (3.3) for all three trials with high scores (above 3.3) for other aspects as well. Sample 5 received the lowest score (2.5) for all three trials. Overall, sample A6 and sample B6 are the best matching.

This response from the experts could be due to the fact that the lightness of the traditional and digitally reproduced samples differed from each other because the digital printing technology cannot provide the same ink penetration as the traditional denim dyeing process. The lightness difference may have significantly influenced the overall matching between digital denim and traditional denim. For example, the overall matching scores are slightly lower than other aspects (color matching, line quality, visual texture, scale, overall matching) for samples 1, 2, 3, 4, 6. Different lightness between digital denim and traditional denim samples could be the reason. The results indicate that digital printing cannot fully reproduce the lightness of traditional denim, which may be caused by different ink saturation. Traditional denim industry has higher ink saturation than digital printing technology.

Table XI. Ordered differences report between samples for line quality matching.

	Level			Mean
Trial 1	S6	A		3.6666667
	S1	A		3.5833333
	S2	A		3.5000000
	S4	A		3.3333333
	S3	A	B	3.0000000
	S5		B	**2.3333333**
	Level	- Level		*p*-value
	S6	S5		***0.0002****
	S1	S5		***0.0006****
	S2	S5		***0.0015****
	S4	S5		***0.0097****
	Level			Mean
Trial 2	S1	A		3.5833333
	S6	A		3.5833333
	S2	A		3.5000000
	S3	A	B	3.2500000
	S4	A	B	3.0833333
	S5		B	**2.4583333**
	Level	- Level		*p*-value
	S1	S5		***0.0089****
	S6	S5		***0.0089****
	S2	S5		**0.0193***
	Level			Mean
Trial 3	S6	A		3.7500000
	S1	A		3.5833333
	S2	A		3.4166667
	S3	A	B	3.2083333
	S4	A	B	3.1666667
	S5		B	**2.3750000**
	Level	- Level		*p*-value
	S6	S5		***0.0019****
	S1	S5		***0.0091****
	S2	S5		**0.0366***

Table XII. ANOVA results between samples for overall appearance.

Overall appearance	Source	SS	DF	MS	F	Sig
Trial 1	Sample	7.667	5	1.533	3.636	**0.0058***
	Error	27.833	66	0.422		
	C. Total	35.500	71			
Trial 2	Sample	6.236	5	1.247	3.566	**0.0065***
	Error	23.083	66	0.350		
	C. Total	29.319	71			
Trial 3	Sample	2.792	5	0.558	1.050	0.3959
	Error	35.083	66	0.532		
	C. Total	37.875	71			

Table XIII. Ordered differences report between samples for overall appearance.

	Level			Mean
Trial 1	S6	A		3.5833333
	S2	A	B	3.2500000
	S1	A	B	3.1666667
	S3	A	B	3.0000000
	S4	A	B	3.0000000
	S5		B	2.5000000
	Level		- Level	*p*-value
	S6	S5		***0.0016****
Trial 2	Level			Mean
	S6	A		3.5000000
	S2	A		3.3333333
	S1	A	B	3.2500000
	S4	A	B	3.2500000
	S3	A	B	3.0000000
	S5		B	2.5833333
	Level		- Level	*p*-value
	S6	S5		***0.0042****
	S2	S5		**0.0319***

Table XIV. ANOVA results between samples for overall matching.

Overall matching	Source	SS	DF	MS	F	Sig
Trial 1	Sample	5.236	5	1.047	2.377	**0.0481***
	Error	29.083	66	0.441		
	C. Total	34.319	71			
Trial 2	Sample	3.736	5	0.747	1.706	0.146
	Error	28.917	66	0.438		
	C. Total	32.653	71			
Trial 3	Sample	4.278	5	0.856	2.053	0.083
	Error	27.500	66	0.417		
	C. Total	31.778	71			

Table XV. Ordered differences report between samples for overall matching.

	Level			Mean
Trial 1	S6	A		3.3333333
	S2	A	B	3.0833333
	S3	A	B	2.9166667
	S4	A	B	2.9166667
	S1	A	B	2.6666667
	S5		B	2.5000000
	Level		- Level	*p*-value
	S6	S5		**0.0347***

The majority of the matching mean scores were above three and the rest were close to three, which indicates the digitally reproduced denim samples could replicate the traditional denim samples to some extent. The benefits of textile ink-jet printing, such as the quick response, ability for customization, and relatively low pollution, water, and energy usage, may make this a viable production process for novel denim fabrics.

7. LIMITATIONS AND FUTURE RESEARCH

This article explored the application of digital printing technology in the field of traditional denim through color reproduction and statistical analysis of textile experts' evaluation of printed samples. However, due to time limitation, data on dry and wet crock fastness, washing fastness, and light fastness are not collected, which could be good topic for further research. In addition, fabric hand and mass production potential analysis are all potential directions for future research.

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