# ABSTRACT

MING WANG. Replication of Screen Printing Fabric via Ink-jet Textile Printing. (Under the direction of Committee Chair Dr. Lisa Parrillo-Chapman).

In textile industry, screen printing is a traditional printing technology that has been used for years. In the past few years, ink-jet digital printing has rapidly increased each year in the textile industry. Ink-jet digital printing is fast, flexible, relatively inexpensive for sample printing and can be applied quickly in response to consumer demand. For these reasons, replicating the relatively slow and inflexible screen printing process by using ink-jet digital printing is gaining interest in the fashion, apparel, and textile industry.

The aim of this research is to replicate a screen-printed sample provided by a textile corporation via ink-jet digital printing, and from this case, to analyze the potential of ink-jet digital printing to replace traditional screen printing. Two stages involving three main objectives was established to achieve this target: In stage one, first, an optimal workflow was explored for replicating a screen-printed fabric using ink-jet textile digital printing, and second. In stage two, a visual assessment instrument and protocol was established to evaluate the acceptance of the replicated ink-jet printed fabric. Then, a visual assessment by 12 expert participants was conducted to determine if the digitally printed sample was a suitable substitute for screen printed sample, and to explore the potential for digital ink-jet printing to replace traditional screen printing. The instrument used in this pilot test was created and then presented to participants. Data gathered from the visual assessment was then analyzed and compared by using SPSS statistics software.

Replication of Screen Printing via Ink-jet Textile Printing

by
Ming Wang

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## DEDICATION

This work is dedicated to my parents for their loving and financial support. I would like to thank doctoral students Xingyu Li, Yi Ding, Sajeesh Kulappurath, and Jihye Lim. To faculty of College of Textiles, Tri Vu and Jeffrey Krauss for their help. Jack Daniels, president of American Association of Textile Chemists and Colorists (AATCC) and his assistantance helped greatly, as did Garry Atkinson and Malinda Keever, technical Associate of AATCC and their assistant. To all the experienced textile industry expert Steve Smith, David Clark, Mark Sawchak, Harold Mull and Kerry King are due my thanks for their knowledge and support. Thank you to all who participated in my assessment. My professors and committee members Dr. Marguerite Moore and Dr. Minyoung Suh have my deep gratitude for their assistance and teachings. And to my Committee Chair Dr. Lisa Parrillo-Chapman, I give my highest appreciation for all her teachings and support, without her guidance, this research would not have been possible.

## BIOGRAPHY

Ming Wang was born July 15, 1992 in Tengzhou, Shandong, China. He is the only child of Xingyin Wang and Ying Li. Ming Wang finished his primary and high school education in Shandong Province. Ming Wang come to Shanghai, China alone in September 2011 and attended Donghua University. In August 2014, Ming Wang passed the interview, TOEFL and GRE test and then come to North Carolina State University via “3+X” program for two years and was accepted in to the College of Textiles.

In August of 2014, Ming Wang began attending North Carolina State University to pursue a Master’s degree and enrolled in the Masters of Science program in Department of Textile Apparel, Technology and Management. Under the persuasion and encouragement of his instructor, Dr. Lisa Parrillo-Chapman, Ming Wang adapted to life in America and studied hard. While pursuing his Master’s degree, he was awarded a research assistantship with Dr. Lisa Parrillo-Chapman and manages the College’s Digital Design lab and aids in the research on ink-jet textile printing.

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## GLOSSARY

**Appearance** - in psychological studies, perception in which the spectral and geometric aspects of a visual stimulus are integrated with its illuminating and viewing environment (ASTM E 1499, 2008)

**Brightness -** attribute of visual sensation according to which an area appears to emit more or less light (Fairchild, 2005)

**Color Change** - a change in color of any kind whether in lightness, hue or chroma, or any combination of these, discernable by comparing the test specimen with a corresponding untested specimen (AATCC Procedure 1, 2012)

**Chroma** - the proportion of the spectrally pure color that expresses the degree of departure from the gray of the same lightness; i.e., brighter or duller (AATCC Procedure 9) In order for a stimulus to have chroma, it must be judged in relation to other colors (Fairchild, 2005)

**Raster Image Processor (RIP) -** The hardware/software product that converts vector based images to a raster graphic format suitable for a specific printer

**Gamut** - the range of colors that can be produced by a color-imaging device (; i.e., computer display or printer) as specified in some appropriate three or more dimensional color space (Fairchild, 2005)

**Gray Scale -** a scale consisting of pairs of standard gray chips, the pairs representing progressive differences in color or contrast corresponding to numerical colorfastness grades (AATCC Procedure 1, 2012)

**Hue** - the attribute of color perception by means of which an object is judged to be red, orange, yellow, green, blue, violet, or combination of these (AATCC Procedure 9, 2010)

**Illuminates -** are standardized tables of value that represent a spectral power distribution typical of some particular light source; i.e., CIE illuminants A, D65, and F2 are standardizations of incandescent, daylight and florescent sources respectfully (Fairchild, 2005)

**Lightness** - the amount of light reflected from a non-self-luminous textile material or the attribute of color perception by which such a surface is judged to reflect more or less light than another surface; i.e., darker or lighter (AATCC Procedure 9, 2010)

**Line Quality** - describes the appearance of a line. A characteristic of a line that is determined by its weight, direction and uniformity (Pipes, 2008)

**Metamerism** - the attribute of two colored materials, which match under one illuminant and to one observer, but do not match when exposed to a different illuminant (having a different spectral power distribution) or when viewed by another observer (AATCC Procedure 9, 2010)

**Munsell Color System -** a system of specifying colors illuminated by daylight and viewed by an observer adapted to daylight, in terms of three attributes: hue, value and chroma, using scales that are approximately uniform (Long, Luke, 2001)

**Observer** - in psychological studies, one who judges visually, qualitatively or quantitatively, the content of one or more appearance attributes in each member in a set of objects and stimuli (ASTM E 1499, 2008)

**Saturation –** the colorfulness of an area judged in proportion to its brightness, seen completely in isolation from other colors; i.e., a traffic light appears saturated on a dark night when compared to the appearance of oncoming white traffic lights whose saturation is very nearly zero (Fairchild, 2005)

**Scale** - in psychological studies, is used to assess the content of one or more appearance attributes in the members of a set of stimuli (ASTM E 1499, 2008)

**Texture** - the surface character of a material, which can be experienced through touch; i.e., rougher or smoother (Pipes, 2008)

**Value -** is that quality by which a light color is distinguished from a dark one. Color values are often referred to tints and shades (Long, Luke, 2001)

**Visual Texture** - the surface character of a material, which can be experienced through the illusion of touch; i.e., rougher or smoother (Pipes, 2008)

# 1. CHAPTER 1: INTRODUCTION

## 1.1. Research Objectives

The aim of this research is to replicate a screen-printed sample (A) that was provided by a textile corporation via ink-jet digital printing, and to explore the potential for digital ink-jet printing to replace traditional screen printing. Therefore, two stages which involved three main objectives were established to achieve this target:

[1] To develop a workflow for the fabric replication of a screen-printed fabric using ink-jet textile digital printing.

[2] To develop a visual assessment instrument and protocol to evaluate the acceptance of the replicated ink-jet printed fabric;

[3] To determine if the ink-jet digital printed sample was a suitable substitute for screen printed sample via an expert visual assessment.

## 1.2. Significance of Research

Ink-jet digital printing doesn't require screens (stencil) or setups. Once the files are formatted they are loaded onto the press and the job is ready to run. And instead of carrying boxes of labels in inventory, some of which might never be used, which traditional printing requires, digital printing can print exactly what is needed without these items. With no plates and setups required, the cost also is reduced compared to the cost of traditional printing. Additionally, ink-jet digital printing technology allows printing on a broad range of substrates (materials). This capacity allows the use of unique materials, and a unique material is an excellent way to make a design stand out. Last but not least, digital ink-jet printing does not use screen (stencil) or energy-intensive drying stations, which allows for a more environmentally-friendly operation.  Digital ink-jet printing also does not exhaust any fumes or create waste for the landfill.

If ink-jet digital printing technology can replace traditional screen printing in most applications, then the textile printing industry will incur less cost, invest less time in the product development and manufacturing process and be a more environmentally friendly alternative to traditional screen printing. This research attempts to replicate a screen-printed sample via ink-jet digital printing, and to explore the potential for digital ink-jet printing to replace traditional screen printing.

# 2. CHAPTER 2: LITERATURE REVIEW

## 2.1. Digital Textile Printing

### 2.1.1. Introduction

As Dawson and Hawkyard (2000) said: “The art of textile printing is probably as old as civilization itself”. Digital printing technology is a new product combined with digital technology and traditional textile dyeing technology products, which is a revolutionary breakthrough in the development path of the textile printing industry. As the digital world and technology are creating new possibilities, digital ink-jet printing represents the future direction of technology development in the textile printing and dyeing industry (Dehghani, Jahanshah, Borman, Dennis, & Wang, 2004). This technology has already become a popular tool in textile & clothing industry. It took decades for people to realize its superiority for the textile industry, but now more industry practitioners are calling ink-jet printing technology "a textile printing technology revolution" or "a universal printing technology". Therefore, the industry has grand expectations for this technology (Treadaway, 2004).

Data gathered from many other articles show that during 2012 the global textile printing industry output is about 30 billion square meters per year, and the annual production is about 165 billion dollars (Kan & Yuen, 2012, Abe, 2012, Parsons, 2015). According to the latest research report “Digital Printing 2017 Outlook" presentation (Smithers, Pira 2012), digital printing increased 23% from 2009 to 2012, trending toward accelerated future growth (Figure 1).

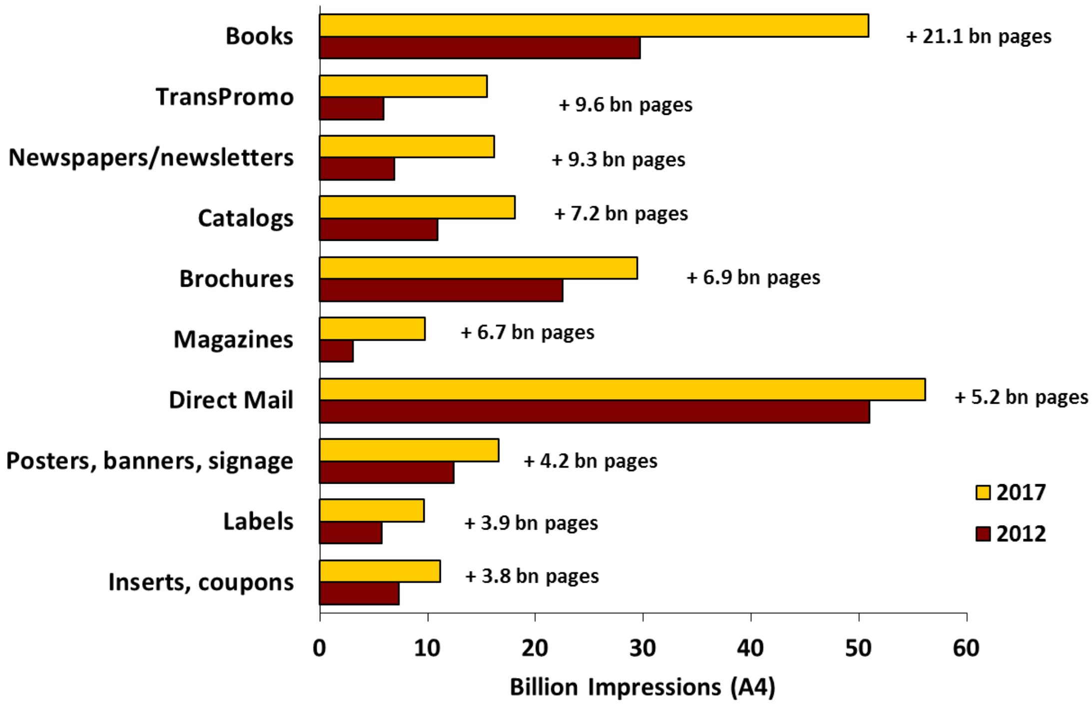



**Figure 1:** Top Production Digital Print Applications (Smithers, Pira 2012). Retrieved from: http://blog.infotrends.com/?tag=forecast

By 2015, digital printing fabric output will reach 25 to 30 billion square meters per year, of which the fastest-growing is European digital printing. Digital printing output in 2013 accounted for 40% of total printing output. Europe and America have the highest production rate in global textile printing market; for example, one of Europe's largest printing companies, the KBC German company, has more than 20 sets of high-speed digital printing machines, providing digital printing and processing capability second to none in Europe. Meanwhile, Asian and Africa still have a highly traditional textile printing industry.

As depicted in Figure 2, digital textile printed products globally are expected to reach 29.8 billion square meters by 2020. During this period, Asia-Pacific is expected to become the largest and fastest growing market, with a projected 4.4% CAGR (Compound Annual Growth Rate). This dramatic growth is projected based on the use of innovative technology and a growing population. Open system ink-jet print heads can allow different suppliers to adopt digital printing technology by lowering the cost of switching to the innovative technology. Countries with low labor costs, such as China and South East Asian nations, also are helping to reduce costs.

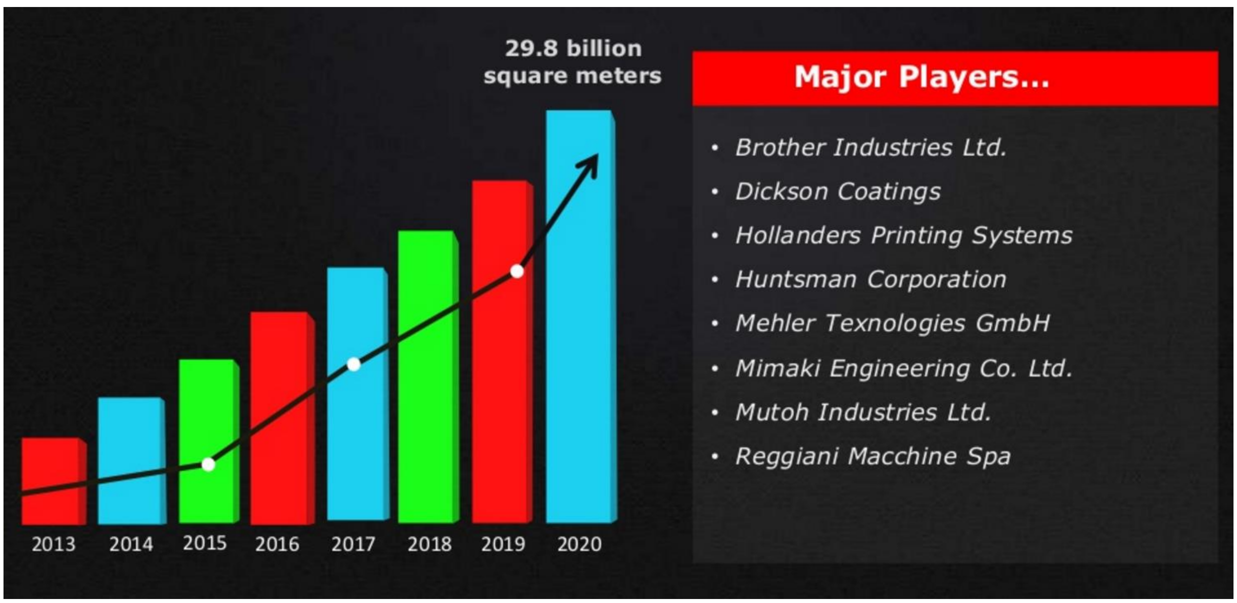
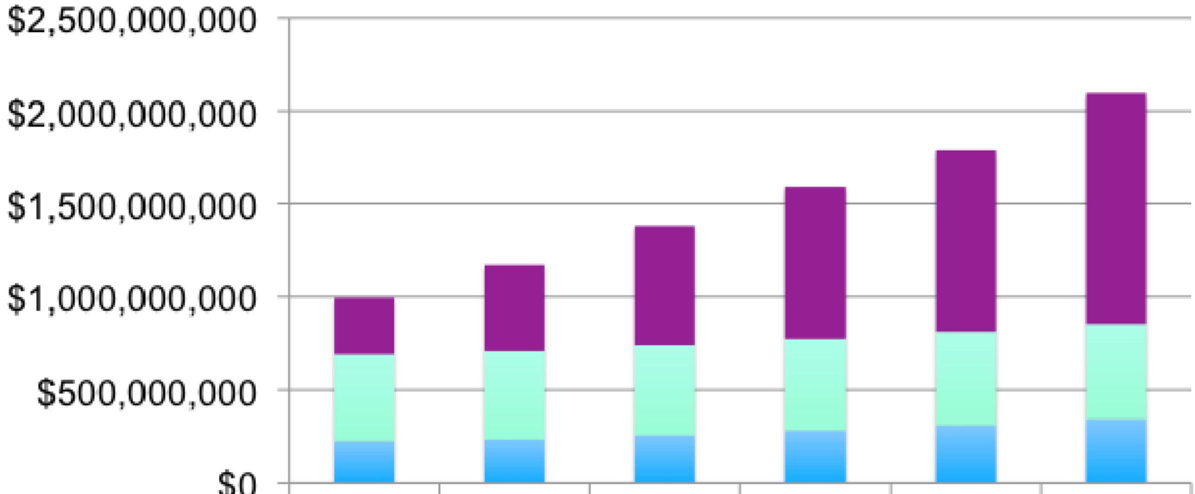



**Figure 2:** Global Production of Printed Textiles.

Rederived from: http://www.slideshare.net/GlobalIndustryAnalystsInc/textile-printing-a-global-strategic-business-report

The Ink Jet Textile Printing Forecast (2014) also pointed out that projected ink jet textile printer hardware and ink revenues will grow rapidly in the period from 2013 to 2018 (Figure 3). The total revenues are expected to rise from $500 million to $2.5 billion.




| | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|
| >$200,000 R-2-R | $304,056,470 | $466,068,085 | $642,238,636 | $816,429,592 | $974,335,402 | $1,240,070,111 |
| <$200,000 R-2-R | $466,691,676 | $475,246,053 | $484,005,865 | $492,976,795 | $502,164,690 | $511,575,568 |
| DTG | $223,767,531 | $232,419,163 | $255,192,860 | $281,013,810 | $310,105,417 | $342,954,243 |

**Figure 3:** Projected Ink Jet Textile Printer Hardware and Ink Revenues, 2013-2018 (Ink Jet Textile Printing Forecast 2014).

### 2.1.2. Development Path

Ink-jet digital printing technology is a new product combining digital technology and traditional textile dyeing technology products, which is a revolutionary breakthrough in the development path of the textile printing industry (Savvidis, George, et al, 2014). As the digital and networking technology increase, digital printing represents the future direction of technology development of textile printing and dyeing industry. In the following section, the development path of textile digital printing, which is included digital printing system and digital printing machine, is introduced.

#### 2.1.2.1.Digital Printing System

Textile digital printing began in the 1970s, with the aim of developing a non-contact printing system and producing a multicolored pattern in digital form (Ross, 2000). In the 1990s, textile digital printing achieved rapid development and moved from changes in the technical model into production and application. At the Paris International Textile Machinery Exhibition in 1999, the digital ink-jet printing system received wide attention in the industry. At the time, most production system design resolution was very low, which prevented application of ink-jet technology for carpet and velvet furniture cloth printing. In addition, the dyes used for printing required special selection, and that process posed an obstacle limiting the popularization and application of this technology (Parrillo-Chapman, 2008).

The Millitron printing system from the Milliken textile printing company of America and the Austrian company Zimmer's Chromo Jet system began to use the electromagnetic valve system, and also to use computer-controlled ink-jet and air jet to print patterns required to meet designers' needs (Singh, 2010, Grudier, 1999). At that time, printing accuracy (resolution) was low, only around 20 dpi, and the maximum was only 40 dpi, which is not suitable for clothing and other textile printing, and can be used only for carpet printing (Kan & Yuen, 2012). By the 1980s and 1990s, the improvement of the piezoelectric nozzle and the use of heated air bubbles had improved the resolution of fine digital printing. These improvements also set off a digital printing boom (Malik, Kadian & Kumar, 2005; Rekaby, 2013). For example, in 1987, the Japanese company Seiren engaged in research in piezoelectric ink-jet printing CAD technology. Viscotex system was also developed that time and began to be used in mass production in 1990. In 1993, Japan's Spinning and Canon company developed a digital printing system called the "wonderful printing" system (bubble printing system). About the same time, Japan's Konica and Sumitomo company developed the Nassenger system (piezoelectric type) for ink-jet printing (Savvidis, George, et al, 2014).

As the computer technology continued to progress, now it can automatically read out the original pattern (or scanning input or direct input pattern of digital photography software) and put it to digital processing, directly ink-jet printing on the fabric, which is digital textile ink-jet printing technology (Abe, 2012). Japanese company Siren's Viscotex system produced textiles reported to equal 10 million square meters and sales of 12 billion yen in 1998. The Sirsen company sell all kinds of fabric such as cotton, wool, silk, polyester, nylon and elastic fiber, plus weaving, knitting, artificial fur, and wide range of finished products. All over the world, ink-jet printing is growing rapidly: in Germany, the Netherlands, France, the United States and also in developing countries (Malik, Kadian & Kumar, 2005).

#### 2.1.2.2.Digital Printing Machine

Textile digital printing machine models have not yet perfected the prototypes. There are hundreds of digital printing machines from the paper printing industry, but not as many ink-jet printers specifically for textile printing (Parsons & Campbell, 2004).

In 1999, the Stork company in The Netherlands first launched the Amber digital printing machine. The company improved its print system, enabling it to use acid dyes for real silk and nylon / elastic silk printing, and also to use pigment or disperse dye transfer printing, and for any high-quality printing on the fabric. In addition, Stork also developed the Zircon polyester printing machine and the Amethyst printing machine, which is suitable for high-volume packaging printing. The Amethyst can also be used for proofing and small batch production (Fletcher, 2013), especially for printing factory test products and bulk custom product production. The Amethyst printing machine can print on cotton, silk, and viscose while using eight-color continuous ink-jet technology. In addition, it can print photographic true color and can accurately reflect the high-quality color of profiling (Dunkerley, 1981). Digital files from the camera can be directly loaded into the printer, and the maximum width of fabric is 1650 mm. Printing capacity is up to 350 m per day, it can accommodate an installed roll up to 250 m, and has an ink storage capacity for up to 16 hours of uninterrupted printing. Amethyst uses the Windows platform Stork / Lectra software and is compatible with Stork, Lectra, and other CAD design software (Singh, 2010, Grudier, 1999).

In most developing Asian countries, such as China, India, and Pakistan, textile ink-jet printing is still an emerging technology, but rapidly progressing. In China, the Honghua Digital Company started about 1997 to study the development of digital textile ink-jet printing technology and progressed quickly (Abe, 2012). By July 2000, except for some imported nozzles, the company had designed and manufactured its own piezoelectric printing equipment and computer software.

### 2.2. Screen printing

Screen printing is the most widely used printing method in textile industry today. It involves three methods, rotary screen printing, flat (bed) screen printing and conventional screen printing. Rotary screen printing is the most popular method worldwide, producing 58% of printed fabric product. Flat screen printing produces 28% of worldwide output. Rotary screen printing is so named because it uses a cylindrical screen that rotates in a fixed position rather than a flat screen that is raised and lowered over the same print location. The other printing method such as handheld screen printing (6%), intaglio printing (3%) and transfer printing (5%) also contribute to traditional printing industry (Figure 4, Kan, C. W., & Yuen, C. W. M, 2012). The basic principle for screen printing involves squeezing the dye across the screen with a blade (squeegee) to fill the open mesh apertures with ink and transfer them onto the surface of fabric.

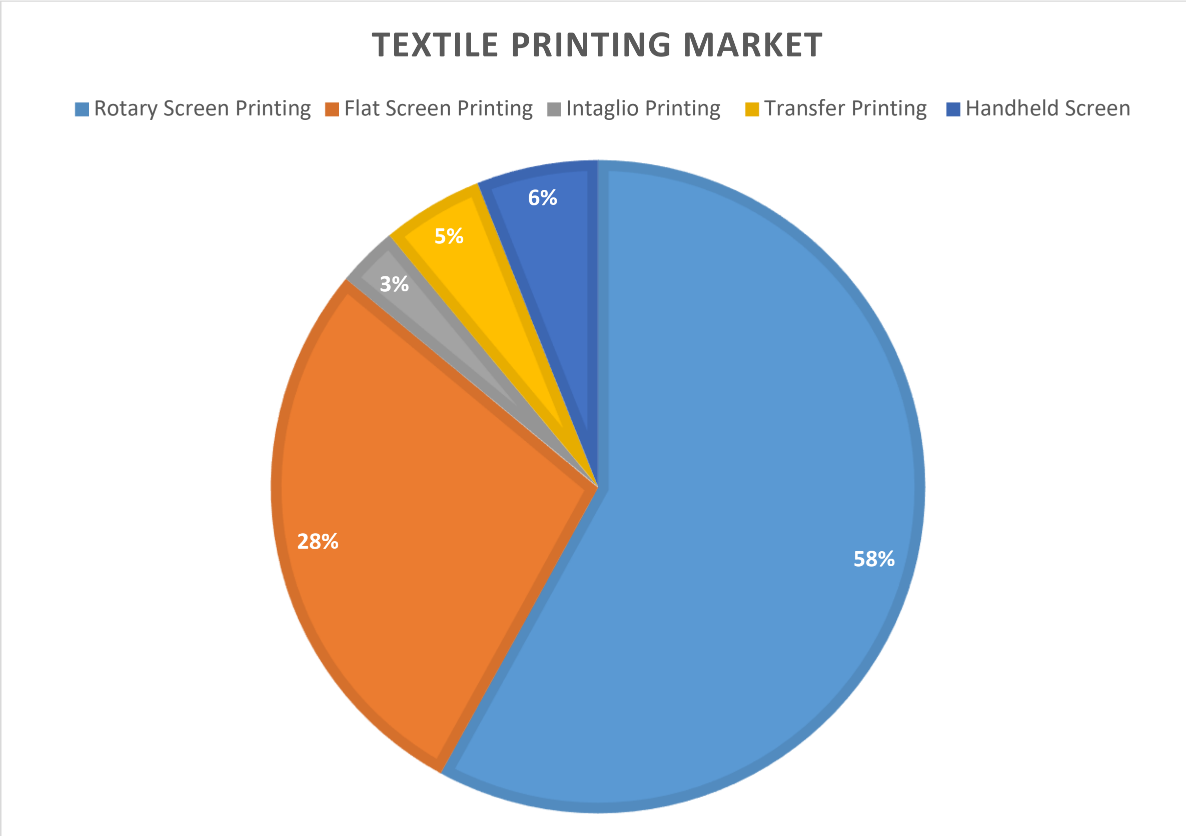



**Figure 4:** Screen Printing Methods (Kan, C. W., & Yuen, C. W. M, 2012)

Despite its productivity, the dominant rotary screen printing method has several limitations (Deghani, Jahanshah, Borman, Dennis and Wang, 2004). One limitation is that color and pattern changes are slow and expensive because rotary screen printing requires a long time to set up (up to 6-8 weeks). Screen printing machines are not as durable as digital printing machines, and in addition, screen printing machines require more space for storage and operation than digital printing machines do. As the textile industry continues to mature, and consumers' demand for fast style change increases, the need for a new fabric printing technology capable of fast and frequent style and color changes intensifies. The potential answer to meet these challenges for the printing industry is the revolutionary printing technique called ink-jet printing.

### 2.2.1. Contrastive Study

Compared to the conventional screen printing process, digital ink-jet printing is a process that enables direct transfer of a design onto the fabric from a computer file, without the need for production of screens or for running heavy-duty machinery (Cie , 2015). This technology evolved from digital proofing technology from Kodak, 3M, and other major manufacturers, with artists and other printers trying to adapt these dedicated prepress machines to fine-art printing. However, the trend now is shorter deliveries and runs because fashion changes frequently and in some cases, there can be as many as five to six design changes in a year. Printing smaller collections and unique textile products, which is called sampling process, requires the higher flexibility of printers and, consequently, faster prepress and printing of color designs (Malik, et al., 2005). One way to minimize costs associated with sampling is to remove the screens (strike-off) from the sampling stage altogether. As a result, newly changing market requirements are challenging textile printers to make a broader use of design software, and to meet the higher expectations of textile and fashion designers, as well as of managers. The advantages that digital ink-jet printing has over screen printing help textile printers to meet these challenges of developing textile market. These advantages are summarized as follows.

### 2.2.2. Advantages

The first advantage of ink-jet printing is individualization through quick response.

Digital printing eliminates the complex screen making process of traditional printing (Table 1). Computer design uses digital printing technology to print directly on the printing substrate, allowing shorter fabric runs or batches. Especially for requests for small amounts of fabric, digital printing enables production of multi-species of small quantities of products with superior performance, significantly shortening response time for meeting the customers' needs. Sample production, the selection process and the purchasing cycle also become more efficient.

**Table 1:** Comparison of Technical Details of Conventional Printing Methods with Digital Ink-Jet Printing (Choi et al., 2003)

| Printing Operation | Flat screen printing | Roller printing | Rotary screen printing | Heat transfer printing | Digital ink-jet printing |
|---|---|---|---|---|---|
| Squeegee | Moving to and fro | No squeegee system | Continuous rotating | No squeegee system | No squeegee system |
| Fabric motion | Intermittent motion | Continuous | Continuous | Intermittent or continuous | Intermittent or continuous |
| Screen movement | Lifting and lowering | No screen system | Rotary | No Screen system | No screen system |
| Colour supply | By hand | By hand | Automatic | No colour supply | Automatic |
| Design and effect | Fine design, no half tone effect and continuous strip | Very fine design, half tone effect, no horizontal line and no large design repeat | No fine design, has half tone effect and continuous strip possible | Varied | Varied |
| Types of fabric suitable | Not for knitted fabric | Not for knitted fabric | Knitted and woven fabric | Mainly for polyester | Mainly for woven fabric, cotton and polyester |
| Sampling | Easy | Difficult | Difficult | Easy | Easy |
| Engraving cost | Relative lower | Expensive | Expensive | Varied | Low |

Another advantage of digital printing is lower storage costs because the equipment usually needs less space than traditional equipment.

A third advantage of digital printing is lower labor costs because the complex screen-making process is eliminated.

These advantages combine to make investments in time, money, space, and labor lower for digital printing than for traditional printing, while simultaneously allowing fast-track investment projects suitable for small companies and for technological innovation. And additional advantages can be gained.

One additional advantage is that digital printing allows rapid response to fashion changes, including the ability to move more quickly from design to production. Without the screen-making process, design proofing has become very convenient, allowing a consumer to obtain products within a relatively short waiting time.

What’s more, original designs can be copied, which makes transposition faster and speeds the realization of potential profit.

As global business continues to grow, digital printing can help enable global synergies that must be used to remain competitive. Ideas and patterning need to be interchanged, while flexible locations close to the market need to be utilized. And digital printing enables printing on unusual textiles, creating new products that in turn can expand consumer demand.

For color performance, computer color palette of textile ink jet printing is more accurate than traditional printing. Textile ink-jet printing heads can achieve micro-spray, which overcomes the screen printing technology network defects. Because of that capacity, the color performance is more delicate, making the transition color performance more natural. Wider color gamut and invisible pattern performance can be achieved. Linear patterns are clearer. Delicate color reduction and separation are more convenient. Last but not least, digital printing equipment is more environmentally friendly in wear properties and production processes. Digital printing equipment requires little energy consumption, and sewage production approaches “zero” (Kan, Yuen, 2012).

### 2.2.3. Weaknesses

The main advantages of digital printing technology, summarized, are its technology, design capacity and environmental sustainability. However, several weaknesses exist, mainly product price and capacity problems. In addition, technical shortcomings, such as the relative simplicity of printing effect, make it difficult to express thick levels of pattern or text.

Regarding pricing, digital ink-jet printing has relatively high production costs compared to the conventional rotary screen printing method for a large amount of fabric.

Capacity is another weakness. The relatively more popular ink-jet printer in the market has an average production speed of 7-17 m/h. Ink-jet printer prices range usually from $6000 to $20,000. The high-speed printer production capacity is about 300 m / h, but its price is very expensive. Meanwhile, the traditional flat screen printing machine production speed is about 1000 m/h with lower price from $5000 to $10000.

Regarding color performance, digital printing technology at this stage cannot express the thick layering pattern effect that can be produced by traditional printing technology. And digital printing ink penetration (referring to whiteness) is less than the penetration achieved with traditional printing. Also, the performance of black color concentration in various dyes and pigment inks is slightly lower for digital printing. Digital printing technology cannot show some of the specific colors, such as the mix of gold and silver, part of the fluorescent color, water blue, green, gouache, beige and so on. Innovative technology will be needed to overcome these weaknesses.

### 2.2.4. Comparison

Treadaway's (2004) study found that there are many distinct advantages of digital printing. Especially for short runs, sampling or proofing is easy and economical and there is no screen. As shown in Figure 5, ink-jet printing clearly has a shorter production cycle compared to screen printing (Choi et al., 2003). As ink-jet printing eliminates the need for screen engraving, paste making, and strike-offs, it is less time-consuming and costly. Also, digital ink- jet printing provides unlimited design space, allowing designers to fully reveal their personalities and imaginations.

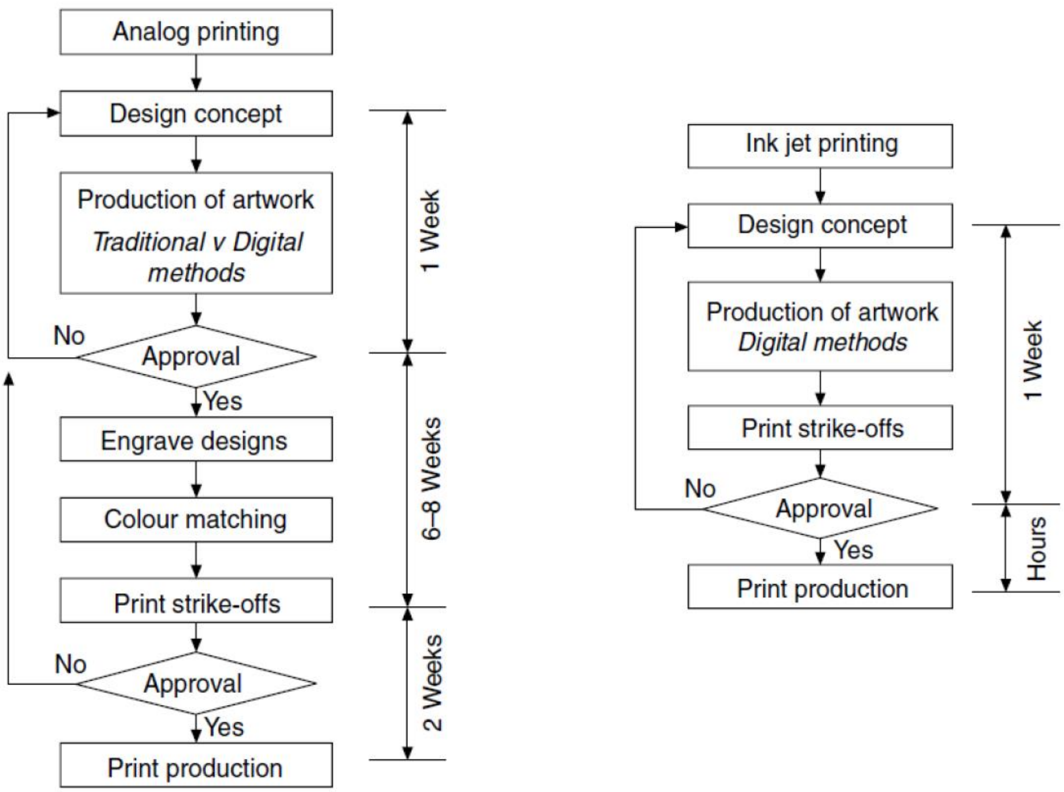



**Figure 5:** Production Process of Conventional Printing (left) vs. Digital Ink-jet Printing (right) (Choi et al., 2003)

Regarding environmental aspects, all the dye goes onto the fabric, which keeps the use of water and energy relatively low (Treadaway, 2004).

For short runs, ink jet printing has obvious advantages (Choi et al., 2003). Since rotary screen printing is the most common printing method in the textile industry worldwide, it is important to understand the difference between rotary screen printing and ink-jet printing. It is obvious from Table 2 that fabric lengths are a crucial factor. For long runs, rotary screen printing is fast (30 – 70 m/minute) and economical. With no pre-treatment, rotary screen printing can achieve a wide color gamut and high efficacy, as well as decent quality. For short runs, though, ink-jet printing is more efficient because of its short downtime and almost "zero" waste of fabric and ink. (Kan, Yuen, 2012).

**Table 2 :** Comparison of Rotary Screen with Digital Ink-jet Printing (Choi et al., 2003)

| Rotary screen printing | Digital ink-jet printing |
|---|---|
| Aqueous pastes made up on site in large batches | Special inks in small containers from the machine maker |
| 30-70m/min | 1m/min |
| No fabric pre-treatment | Fabric pre-treatment required |
| Usually up to 100 dpi, but 255 max. | 1440 dpi |
| Digitised design information to laser engraver | Fully integrated with CAD |
| Restrictions on repeat distance | No restrictions on repeat |
| Screen cost, engraving, washing, storage | No screens |
| Contact with fabric | Non-contact |
| Half-tones not straightforward | Half-tones no problem |
| Usually designs mis-registration at set-up | Instant registration |
| Strike-offs on proofer may be different from bulk | Strike-offs on bulk machine |

## 2.3. Technological Aspects of Ink-jet Digital Printing

Ink-jet printing involves the ejection of ink droplets through microjets onto various kinds of substrate to make a surface pattern at a specific location without contact between the print head and the substrate (Kan, Yuen, 2012). Its functional principle is that the pattern is drafted or transferred from any digital model or by scanner from standard photographic models or drawings to the fabric via an ink-jet printer (Malik et al., 2005). The hardware and software that comprise the ink jet printing system, plus its colorants and auxiliary equipment for fabric preparation and finishing process, are also important aspects (King, 2009).

### 2.3.1. Hardware

In textile digital printing technology, hardware includes mainly printers and print heads, which have a critical influence on the printing speed, printing quality, substrate types and print life. Choosing suitable hardware for the printing process is imperative. Figure 5 compares the print resolution of the two main kinds of textile printers available in the market. One printer is the coarse resolution printer, and the other one is the fine resolution printer (Kan, Yuen, 2012). Since the coarse resolution printer has a maximum resolution up to 40 lines per inch (which is low), it has been accepted only by the carpet industry in the field of textile printing (Malik et al., 2005).

#### 2.3.1.1. Fine Resolution Digital Ink-jet Printer

Most printers in the textile industry are fine resolution digital printing ink-jet printers because they can offer a resolution of up to 300 lines per inch, which provides richer color and more vivid design, including details (Kan & Yuen, 2012; Treadaway, 2004; Malik, Kadian, Kumar, 2005). Fine resolution digital ink-jet printers can be divided into two kinds according to ink drop methods, drop-on-demand (DOD) or continuous ink-jet (CIJ) printing system (Figure 6).

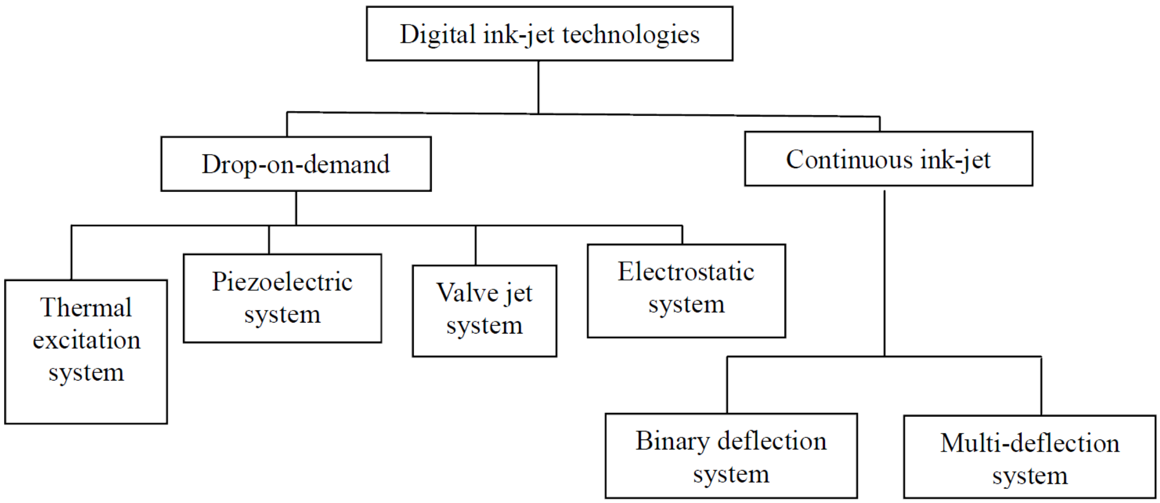



**Figure 6:** Development of Fine Resolution Digital Ink-jet Printer (Kan, Yuen, 2012)

#### 2.3.1.1.1. Drop-on-Demand (DOD) Printer

The most prominent method of ink-jet printing today is drop-on-demand (DOD), which produces an ink droplet that will be fired onto the fabric only when triggered by the computer. In this system, every individual droplet is ejected in response to electrical impulses so that ink can be accurately controlled and the waste can be reduced (Figure 7).

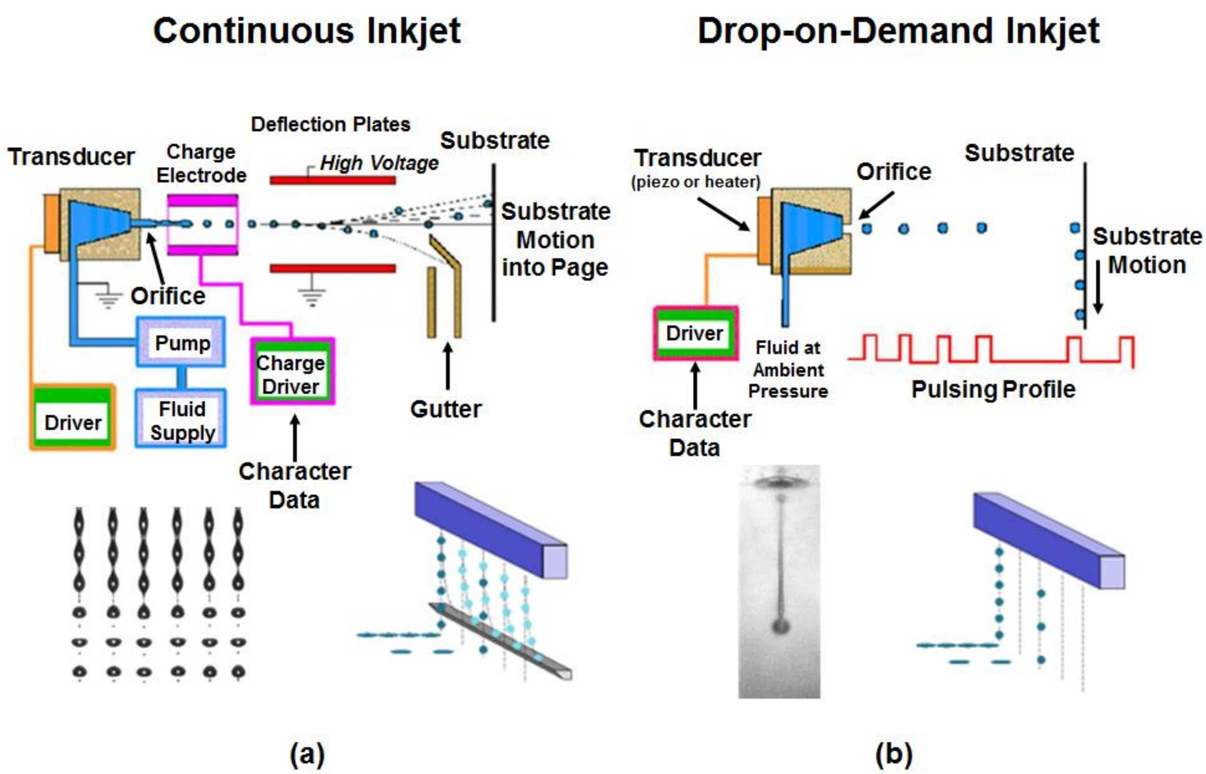



**Figure 7:** Drop-on-Demand (DOD) (b) and Continuous Ink-jet (CIJ) (a) Printing System (Furlani, 2016)

For the DOD printers employed the thermal excitation principle to generate the ink drop, the signal given by the computer heats a resistor to a hot temperature (>350°C), which causes the volatile component of ink to form a vapor bubble, and ultimately a drop of ink is ejected from the nozzle. Approximately 10,000 drops are produced in one second, and the volume of a single ink droplet is about 150-200 picolitres. The biggest advantage of this system is the low cost of nozzle fabrication. This system, also has disadvantages, such as a high failure rate for the nozzle. Another disadvantage is the decomposition of ink components on the resistor due to the hot temperature required for ejection of the drop. This decomposition of ink components leads to poor heat transfer and resistor failure due to rapid heating. In spite of this problem, thermal excitation is still the most used system due to its low cost and relatively high efficiency (Kan, Yuen, 2012).

The second most used system in textile ink-jet printing is the piezoelectric system, in which a droplet of ink is produced by using a piezoelectric transducer (Figure 8). This system has a higher drop cycle time, but produces a smaller volume per drop of ink, which is around 14,000 drops on fabric every second and 150 picolitres. Higher print resolution (1440 dpi) can be achieved by this printing system, which makes it the right choice for high-quality design printing.

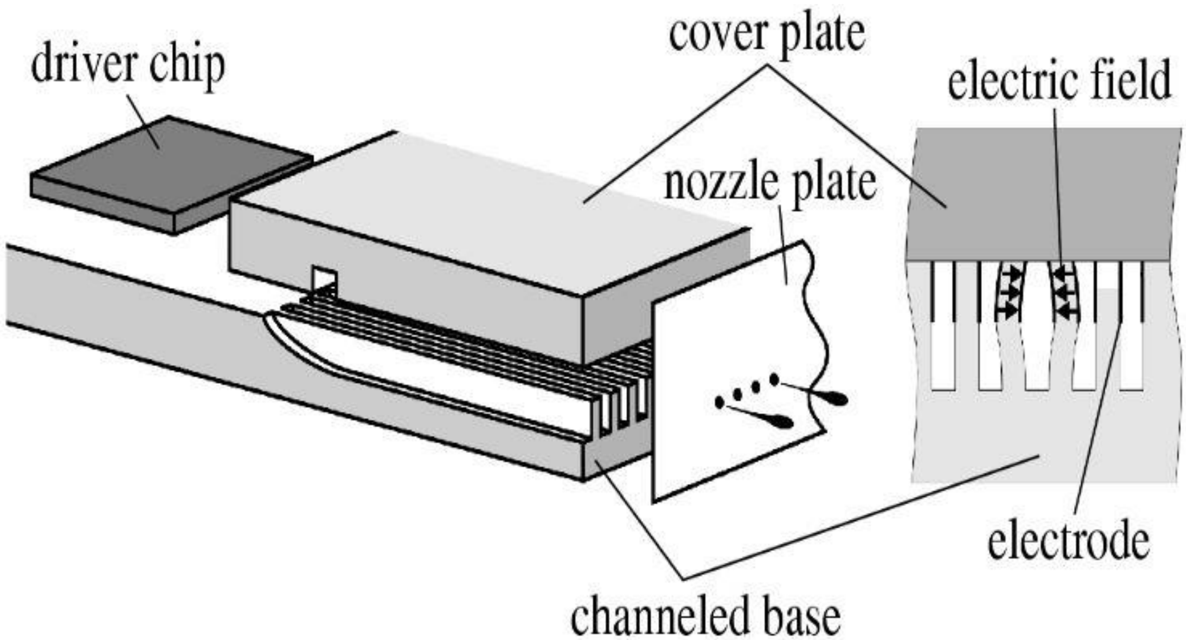



**Figure 8:** Piezoelectric System of Drop-on-Demand (DOD) (Chen, Ding &Wu, 2015)

The other three systems in the market, but that are not very popular in textile printing, are the electrostatic jet system, the ultrasonic droplet generation (Figure 9), and the valve jet system.

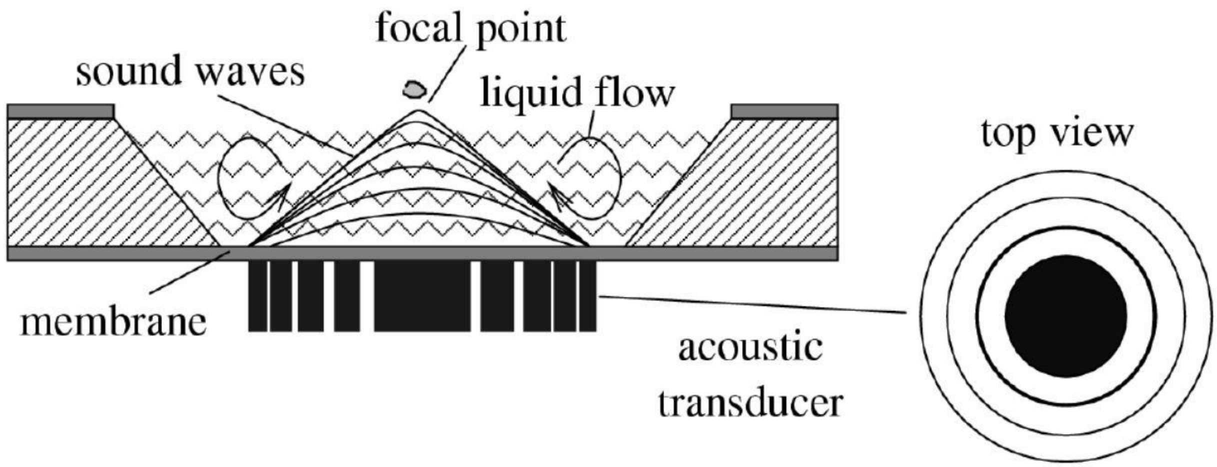



**Figure 9:** Ultrasonic droplet generation (Chen, Ding & Wu, 2015)

#### 2.3.1.1.2. Continuous Ink-jet (CIJ) Printers

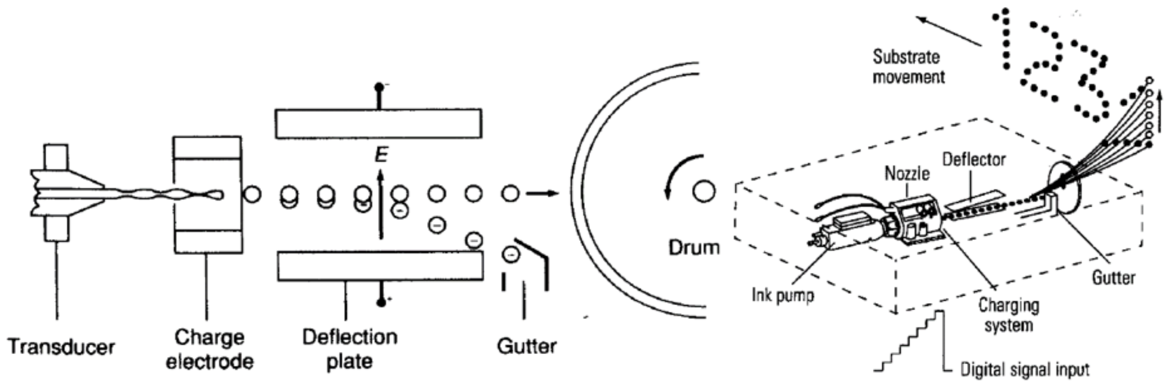
Another kind of printer is the continuous ink-jet (CIJ) printer. The difference between this printer and the drop-on-demand system is that ink is forced at high pressure through a small nozzle. The emerging stream of ink is broken into small droplets which can be selectively charged and deflected while passing through high voltage deflection plates. There are three main types of continuous ink-jet printers.

The most popular continuous ink-jet printer is a binary continuous ink-jet system. This is a relatively expensive and complex print head technology which has had some problems in adapting to the use of process colors, but can run well and at high speeds in industrial applications with little tendency to clog. Unlike DOD print heads, binary continuous print heads generate a constant stream of droplets, which are electrostatically deflected and recycled if not required immediately for printing.

The second most used continuous ink-jet system in the market uses multi-deflection continuous ink-jet print heads. This is also a complex technology, but has proven more reliable and less expensive to manufacture and maintain than the binary continuous system. The print heads can be used with a wide range of inks, produce larger drop sizes and cover more pixels with fewer print heads. In this version of continuous ink-jet technology, it is the un-deflected drops which are recycled while the electrostatically deflected drops hit the fabric. These heads are generally considered well- suited to textile printing at higher speeds and are attracting an increasing amount of interest and development effort. However, they are suited for use only with relatively low viscosity inks.

Air jet deflection is a method seldom used in the textile industry. This system uses a variation of the ink-jet principle in which droplets are deflected by an airstream has been in commercial use for a number of years; one example is the Milliken. It has proved well suited to applications requiring both relatively low definition (20-30 dpi) and high ink volume, such as carpet printing. The ability to use much higher viscosity inks than other print heads helps to prevent wicking by long carpet fibers and allows cheaper dye chemistry to be used. Running speeds 50 times or higher than other existing textile head designs can be achieved. However, as this technology is probably not adaptable to the needs of the mainstream textile printer, it is not considered further here.

In CIJ printers, ink is forced at a high pressure through a small nozzle. The emerging stream of ink is broken into small droplets which can be selectively charged and deflected while passing through high voltage deflection plates (Figure 10). The design can be produced by two techniques, i.e. (i) binary deflection system, and (ii) multi-deflection system (Kan, Yuen, 2012).




(1) (2)

**Figure 10:** (1) CIJ Binary Deflection System (Provost & Kool, 1996)
(2) CIJ Multi-Defection System (Choi et at., 2003)

In the binary deflection system, droplets are either charged or uncharged by charging plates. Uncharged droplets are unaffected by deflection plates, which carry a charge opposite to that of the charging plates. The un-deflected droplets then strike the substrate to form the image. Droplets carrying a charge are deflected to a catcher or gutter by the deflection plates for recycling (Patra, 2005).

### 2.3.2. CAD and Software

In 1980, CAD was introduced in textile printing. The adoption of CAD has led to better quality and flexibility in textile design development. At present, textile printing covers a huge market proportion, as I motioned before, worldwide each year (Malik et al., 2005).

As a non-contact printing system, the digital ink-jet printing textile design can be translated into high resolution data through different software and storage formats (Kan, Yuen, 2012). The main file format that is commonly used in digital ink-jet printing is shown in Table 3. The most popular one in industry is TIFF format.

**Table 3:** File Format that Commonly Used in Digital Ink-jet Printing (Kan et al., 2012)

| File Format | Explanation |
|---|---|
| BMP | Bitmap: Format for digital images which is the basis for all Windows-based graphic display; 24-bit BMP data files for high definition images are very large. |
| TIFF | Tag(ged) image file format: One of the most common types of files used in textile design systems; compared to BMP the data size is usually smaller. |
| GIF | Graphic interchange format: Compact image format (compression of 5-10 times) but limited to 256 colours; wide Internet usage; colour limitations overcome by the more recent introduction of PNG. |
| PNG | Portable network graphics: Format which supports 24- or 48-bit colour; capable of a greater degree of lossless compression than TIFF |
| JPEG | Joint picture experts group: Very compact picture file compression system (degree of compression typically ca. 5-10 times smaller than corresponding BMP files); loss of detail when compressed more than 10-20 times; best system for photographic images. |
| PDF | Portable document format (Adobe): Commonly used file compression system for both graphics and text on the internet, which also uses HTML. |
| HTML | Hypertext markup language. |
| EPS | Encapsulated postscript: Common format for text, graphics and desktop publishing systems and for printer drivers (e.g. the Shiraz CMS). |

Textile CAD has given the textile industry a breakthrough, saving a lot of time and labor cost. In digital printing technology, designers can either make design through CAD software or through the input computer image (by scanning digital camera images). The information is directly transferred to the digital ink-jet printing printer, allowing ink-jet printing of the pattern directly on a variety of textiles substrates. The number of colors is unlimited. Chromatography accuracy is guaranteed by the printing equipment. Through ink-jet digital printing, the complex traditional printing process is greatly simplified. For these reasons, textile ink-jet digital printing is known as a revolutionary achievement in the industry, based on its capacity to print in small quantities, with high-quality, and with almost no pollution.

Many advantages in various aspects of the textile industry are provided by this textile CAD tool. It is widely used in traditional products, such as footwear and bag design, as well as in the fashion industry. CAD technology also allows the rapid response needed to meet consumers' demands. Through its flexibility and quick responsiveness, zero inventory production can also be achieved. Software exists that can be used in almost every textile-related product, enabling the industry to ride the trend of mass customization to meet the individual requirements.

#### 2.3.2.1.Textile CAD Advantages

There are two main kinds of CAD software in used, which are proprietary and off-the shelf. For the proprietary, it is owned by an individual or a company (the one that developed it) and almost always major restrictions on its use (Ex. Lectra Kaledo). While for the off-the-shelf CAD software, they are ready-made and available for sale to the public (Ex. Adobe Photoshop CS6.1). The use of digital printing technology allows designers to check designs and patterns easily, without causing any significant delays or additional costs. Design files can be easily stored and delivered with high-resolution and accurate color data. Designers can work anywhere they want and send their design files through the internet. In addition, design files can be saved to floppy disks, zip disks, CD-ROM or hard drives to save space (Figure 11). In addition, simulation can also be done by computer, allowing designers to see their fabrics or garments without needing any swatches.

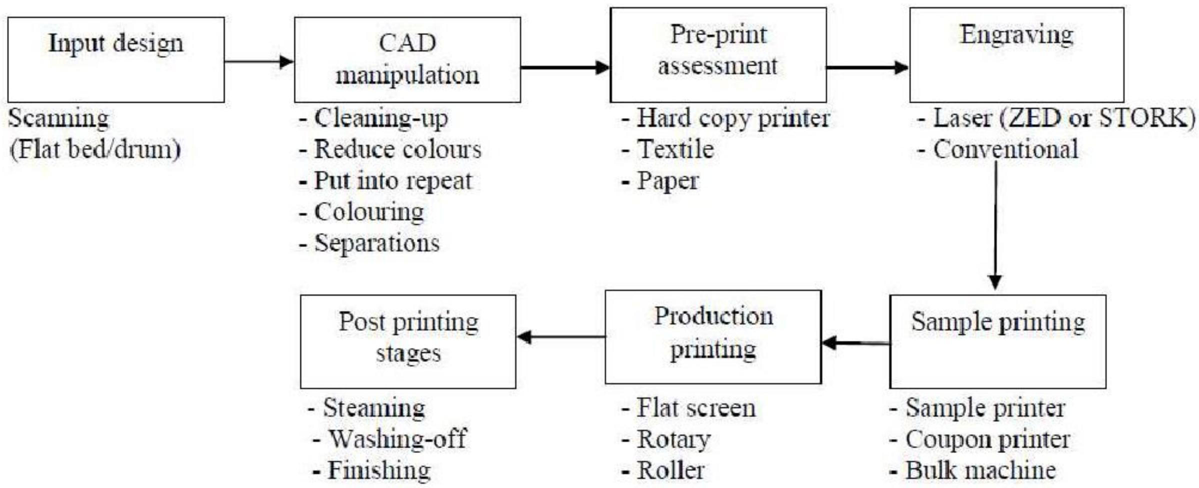



**Figure 11:** Integration of CAD Systems into Print Production (Chavan, 1996)

However, correct use of CAD software requires careful attention. Most software must be connected to a specific kind of hardware to achieve its function, and updates must sometimes be made through the hardware provider. In addition, training the operator is also important to ensure that the CAD system works smoothly and achieves maximum capacity.

**2.3.2.2.RIP Software**

RIP software is a decision-making system connected to ink-jet printer, which can ensure the printing results meet the consumer's requirement. The printing options are stored in the RIP system, and operators choose suitable fabric, ink and color calibration options to ensure the desired result and printing quality. The operational windows are easy to understand (Figure 12), which provides a good way for ink-jet printing beginners to learn it.

RIP software is a bridge between the input design files (vector art or raster image) and the output hardware (printer). For each person who uses it, the software adapts print file and the printing options, such as substrate, ink and resolution, to that individual's chosen options. Choosing the correct setting and color calibration file is the key to producing the desired output.

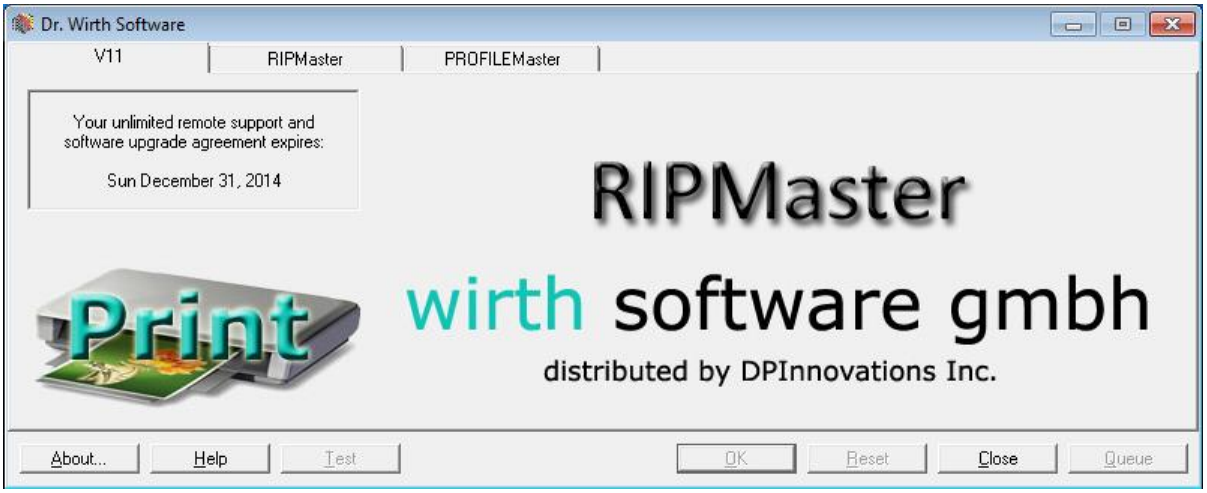



**Figure 12:** RIP Master Software (Capture from Digital Design Lab, COT, NCSU)

## 2.4. Colorants

Ink is the core of textile digital printing system because not all ink is compatible with the given fabric and printer. At the beginning, the Swiss company Ciba proposed three kinds of inks (i.e., reactive dyes, acid dyes and disperse dyes) from the late 1990s and began to develop them. Disperse dye particles were found to have drawbacks, often clogging the print machine nozzle, and requiring a high quality of adhesive. In addition, post-processing temperature conditions affected color, color fastness, and the softness of the product.

From today's point of view, manufacturers are promoting a variety of ink brands in their products, but no one manufacturer's products have achieved 100% praise in practical application. As we all know that a dye/ink system (4 colors, 6 colors, 8 colors) in the printing process will have its own color matching software. The software must be specific, which means that when it is applied to different machine models, the color profile will be different for each different machine.  This connection means that when each ink manufacturer launches its own ink, the color software also needs to be provided at the same time. The need to produce the inks and color software simultaneously leads to more complex and difficult engineering systems, and this complexity has a significant impact on the color vividness, fullness and other qualities of the printed product. As shown in Table 4, four main kinds of ink are used in textile ink-jet printing.

**Table 4: Textile Substrates and Ink Combination**

| | Pre-treatment | Post-treatment | Cotton | Silk | Polyester | Nylon | Wool |
|---|---|---|---|---|---|---|---|
| Reactive Dye | Required | Steam | × | × | | | |
| Acid Dye | Required | Steam | | × | | × | × |
| Disperse Dye | Required | Heat setting | | | × | | |
| Pigment | Not required | Heat Setting | × | × | × | × | × |

Retrieved from: http://pigmentinc.com/au/about-digital-textile-printing/

### 2.4.1. Reactive Dye Based Ink

Inks based on reactive dyes can be used for printing cotton, viscose or cellulosic fibers. An elevated level of color fastness is provided by covalent bonds, which are formed through chemical reactions between dyes and cellulose. Both pre-treatment and post-treatment are required to achieve firm chemical bonds. In the pre-treatment process, the alkali is used on the fabric, as it interferes with reactive dyes and the nozzle components if put in the ink itself. Heat is applied after printing, by a steam or hot air fixation process. A separate washing process is needed to wash off any unfixed reactive dye and to ensure optimum fastness (Kanik & Hauser, 2003; Yuen et al., 2005).

### 2.4.2. Acid Dye Based Ink

Acid dyes can be applied on nylon, silk, wool or polyamide fibers. Although acid dyes account for only a small proportion of all dyes, they are still quite important for digital ink-jet printing as many high-quality designs to be printed on luxurious fabrics such as wool and silk require acid dyes. Wider color gamut and a good color fastness can be obtained through acid dye ink jet printing. A pretreatment is generally necessary to prevent wicking of the ink on the fabric as well as a steaming post-treatment. (Chen et al., 2002; Yang & Li, 2003). Usually, dye inks can be used for both screen printing and digital printing for the same application because of its wide color gamut and good wash fastness (Savvidis, Karanikas, Nikolaidis, Eleftheriadis& Tsatsaroni2014).

### 2.4.3. Dispersed Dye Based Ink

Dispersed dyes are used mainly for man-made fiber, such as polyester, lycra and spandex, which are suitable materials for making banners or flags, soft signage and sportswear. Depending on the specific kind/ of dispersed dye, transfer inks can be used to print on paper and then transferred to fabric or directly printed on fabric (Lamminmäki, Kettle & Gane, 2011). There are also dispersed dye-based inks which have particular fastness properties that can be applied directly to the substrate. Heat fixation (>200ºC) is required once dye is transferred from paper or direct print to the fabric, where the gaseous dye transfers to polyester fibers under this temperature. Color is brighter after fixation and color fastness and UV stability also increase (Clark, 2003; Fan et al., 2006).

### 2.4.4. Pigmented Ink

Application of pigmented ink is mainly for soft furnishings, interior decoration and fashion clothing. There are small spaces in woven or knitted fabric because of the weaving or knitting manufacturing process. Pigmented particles can be locked into these voids through the binder to form a bond. After heat fixation, color pigment is bound to the fabric. No chemical reaction happens during this process; instead, only physical bonding occurs (Ervine et al., 2000).

Compared to the other inks mentioned previously, the color gamut for pigmented ink is not as wide as it is with dispersed dye or acid dye, but it is good enough for most printing situations. However, pigment ink has several advantages over other inks. First, pigment ink can be applied to a wide range of fabrics, such as cotton, silk, rayon, cotton/poly blends, and 100% polyester in a variety of weights. In addition, fabric used for pigment printing is not required to be pretreated because no chemical reaction occurs. Pre-treatment is optional, as it can increase the color gamut. Also, no post-treatment process is needed, which reduces time and labor costs. Finally, pigment inks are environment friendly as there is no steaming, fixation or washing process, which is extremely important for future textile industry (Ervine et al., 2000; Sayed & Khobian, 2003).

## 2.5. Pre-Treatment of Textile Fabric

Not all fabrics are ready for the printing process at the beginning because most of them contain impurities. These impurities are either natural impurities or are acquired from manufacturing processes such as spinning, knitting or weaving. The purpose of fabric preparation is to remove all the impurities to ensure the fabric is ready for the next step. The three primary steps include de-sizing, scouring and bleaching. Inadequate preparation may cause uneven dyeing or uneven printing in the continuous finishing process (Clark, 2003; Fan et al., 2006). In addition to fabric preparation, substrates for ink jet printing typically have to be pre-treated as well. The pre-treatment process for cellulosic, synthetic and protein fibers is different and substrates prepared for printing require a pre-treatment to increase the color gamut and improve print quality and fastness properties

### 2.5.1. Pre-Treatment of Cellulosic Fiber

Cotton is the dominating cellulosic used in the world. Due to its relatively good strength, good moisture absorption and wicking properties, it is the leading material that used for the apparel industry.

As a natural cellulosic fiber, cotton must be properly prepared to remove all the natural and manufacturing impurities (Menezes & Choudhari, 2011). Depending on the different inks applied on the fabric, different pre-treatment is required. For reactive dye, printing paste formed by alkali and other additional chemicals is used for pre-treatment. After printing, the fabric is steamed and washed to fix color and remove unreacted dye (Kan & Yuen, 2012).

### 2.5.2. Pre-Treatment of Protein fibers

Silk and wool represent the protein fabrics, which are usually used for luxurious products because of its smooth surface, bright color effect and high strength properties. Pre-treatment makes sure protein fabric is ready for printing. As Bendak and Raslan (2011) said, an acid-releasing agent, such as ammonium sulphate $(NH_4)_2SO_4$, and a moisture-absorbing agent, such as urea, should be included with some thickeners in the pre-treatment solution, which can be padded or coated on the fabric. A receiving layer on the surface of the fabric then forms, which cannot only prevent spreading of ink jets on fabric, but can also improve moisture regain from steaming, help the fibers swell and make the dye penetrate into the fibers more rapidly (Bendak & Raslan, 2011).

## 2.6. Color Management for Textile

### 2.6.1. Color Definition

Color is a property that distinguishes among various kinds of light, which is defined wholly in terms of human perception. If two instances of light appear to a viewer to be the same color, they are the same color. Color science is a technical science which involve not only materials science, such as physics and chemistry, but also biological science, such as physiology and psychology. Color science is now widely used in textile, dyeing, painting, and architecture, as well as engineering. According to the estimation of Hunt and Pointer (2011), there are ten million assorted colors all over the world. However, on one hand, color is not only determined by itself; environment light and objects illuminated can also influence the effect of color. On the other hand, different observers may have their unique judgments on the same color. A specific observer's mood, energy level, alertness and other mental factors may also affect color judgment. In addition, comments or leading opinions from other observers or research can also affect judgement (Hunt, Pointer, 2011).

### 2.6.2. Color Models

Color model is an abstract mathematical model describing the way colors can be represented as multiples of numbers, typically as three (RGB, Lab) or four values (CMYK) or color components. When this model is associated with a precise description of how the components are to be interpreted (viewing conditions, etc.), the resulting set of colors is called color space. Color models are used to verify whether the colors of an image fall within the color range of the print process by equipment used for image output (Cochrane, 2014). Two commonly referenced color models in the textile industry are the Munsell Color System and the CIELAB Color Model. Both color models are applied to a wide range of industries, including the textile and apparel industry.

#### 2.6.2.1.CIE Color Model

The CIE (Commission International de l'Eclairage) color model is used to ensure color accuracy in ink jet printing (Figure 13). As color accuracy can be influenced by humans themselves or by different devices, the CIE model defines color by using a specific location in a three-dimensions color space, which can be represented as three unique numbers, such as an RGB or Lab value. In addition, color can also be described graphically in two dimensions or as a planar projection. There are three commonly used color spaces, as follows:

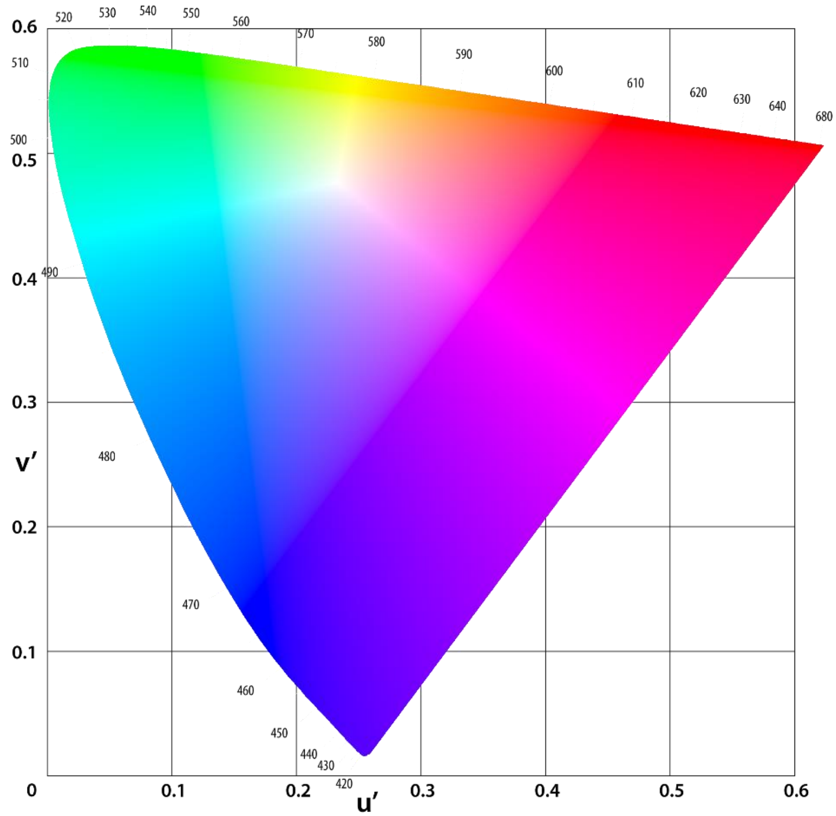



**Figure 13:** CIExy Color Coordinates**.**

Retrieved from: https://en.wikipedia.org/wiki/Chromaticity

(1) CIExy color coordinates: XYZ or xyY (usual depicted as a 2-D, x/y plot) (Figure 11).

(2) CIELAB color coordinates: L*a*b*, a visually more uniform color space usually displayed as a 2-D, a*/b* plot (Figure 14).

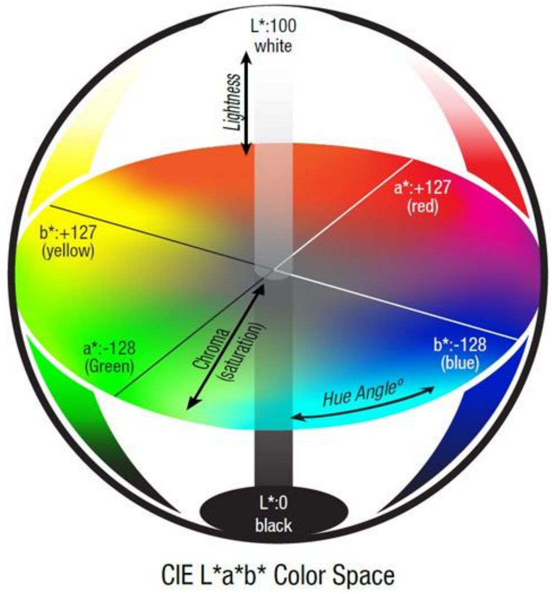



**Figure 14:** CIELAB Color Coordinates.
Retrieved from:
http://www.packnet.co.kr/news/n_read.html?newsid=9638&kind=menu_code&keys=3&listpage=n_list.html

(3) CIELCH color coordinates: LCH (lightness, chroma, hue), which is sometimes used as an L/C plot to show the chromatic build-up of a particular color (p.166) (Ujiie, 2006).

**2.6.2.2.Munsell Color System**

The Munsell Color System has a big influence in today's color science. Color systems and color atlases have existed for a long time, but no uniform system existed until the artist Albert Henry Munsell created the Munsell color system based on previous human psychological experience in the early twentieth century. According to Cochrane (2014), the primary two parts of the Munsell Color System are the color charts (or "atlases") and theoretical system. Color charts provides purchasable samples of color. The theoretical system, which is also called "color space," describes the human experience of color (Cochrane, 2014). As described in theoretical system, any color can be identified by a specific three-digit number that represents hue, value and chroma respectively. As shown in Figure 15, hue represents different degrees of red, green or blue color, which is represented by the middle cylindrical section (hue of value 5 in Figure 15). Value is represented by the cylindrical pillar in the center, with the lightest value at the top and the darkest value at the bottom (from 10 to 0). Value also known as lightness or tone, is a representation of variation in the perception of a color or color space ‘s brightness. Chroma represents the difference from neutral gray (value of Chroma is 6 in Figure 15), which can be used to measure the purity of color (Fairchild, 2005).

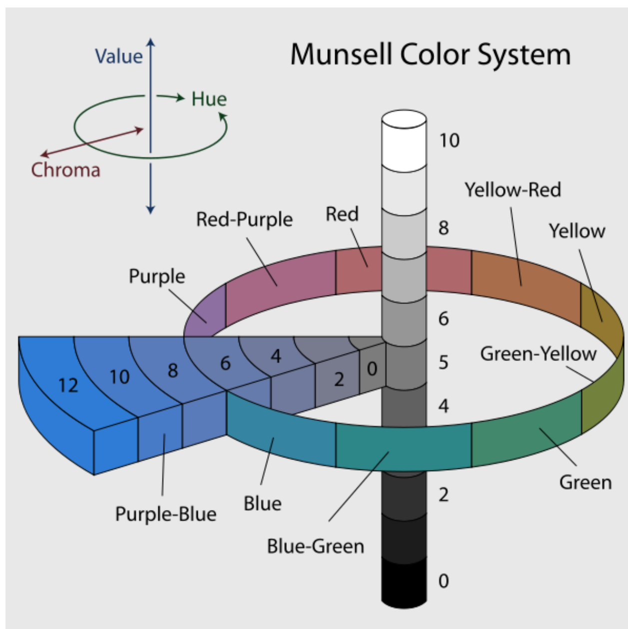



**Figure 15:** Munsell Color System (Cochrane, 2014).

Retrieved from**:** https://en.wikipedia.org/wiki/Munsell_color_system

Munsell’s system is developed based on extremely large human visual assessment response data according to color, which is still being enriched and completed today (Cochrane, 2014).

### 2.6.3. Color Management for Digital Ink-jet Printing

In the actual digital printing process, the designer's original document, which provides the color (source color), needs to be identified by the color conversion system. Then it needs to be converted to the output device (as the destination color), and printed on the fabric. In this process, ensuring that the color remains accurate during conversion to the digital printing process is a critical issue. Therefore, color management in digital printing is essential. According to Kan and Yuen (2012), in an ideal color management system, CAD color management software (such as RIP) should be able to cooperate with the printer and convey information accurately. The color system mobilizes the color information within the database and integrates it with the fabric information to ensure that the color distribution system operates correctly and efficiently. Of course, prior to printing, color calibration appropriate for the specific printing environment is essential to ensure that a combination of specific dyes and digital printing machines can produce rich, accurate, high quality products.

For example, as shown in Figure16, the original design is input by scan to the CAD system, where the designer can modify the file by using CAD software. The CMS color manipulation system and color match prediction system ensure the input color (source color) matches the color that appears on the fabric (output color). Finally, the system records the color information and the printing data to ensure the reproducibility and to monitor quality.

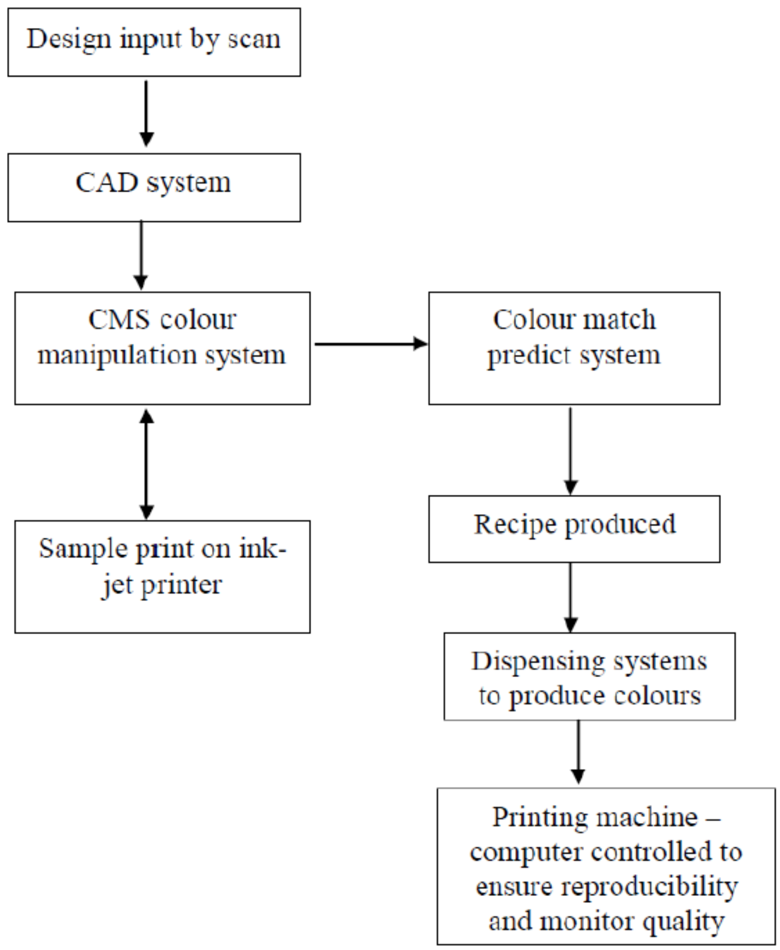



**Figure 16:** Ideal Integration Color Print Production System (Kan & Yuen, 2012)

Today, color calibration systems (like the RIP system) are installed with ink-jet printing technology when the printer is purchased. During the calibration process, printable color is scanned and saved to predict the color gamut. The process is repeatable until the right color gamut is obtained (Outlon & Young, 2004). The colorants are the most expensive part in the whole printing process, so great control of ink drop is also very important. According to Zhu and Wang (2010), “It is found that light ink leads to low ratio of coloration in digital textile printing process. So, it is important to control the total amount of light ink”

(Zhu &Wang, 2010). According to the research conducted by Zhu and Wang (2010), light ink limitation control methods can reduce the amount of ink. Through this new color management technology, the use of unnecessary light ink during the printing process can be eliminated (Zhu &Wang, 2010).

### 2.6.4. Color Visual Assessment

People's observation of color given the meaning of color existed (Hunt, Pointer, 2011). Visual experiment is one of the important methods of color assessment, and it usually comes in two forms. The first is a physical way that applies spectrophotometers for testing or color evaluation to subjectively test colors. The second is a psychophysical measure that is measured by a trained observer to identify the perceived color difference. In general, physical methods are believed to be more reliable than psychophysical measurements because the careful experiment preparation, the design of experimental variables, the controlled experimental environment, and the tools (AATCC gray scale) that help reduce experimental uncertainty (Fairchild, 2005).

#### 2.6.4.1.Experimental Variables

There are many experimental factors in conducting color visual assessment. All the factors are shown in Table 5 and can be classified into three categories: observer, observation environment, and procedural design of the experiment (Fairchild, 2005).

**Table 5:** Experimental Variables (Fairchild, 2005)

| | |
|---|---|
| Observer age | Control and history of eye movements |
| Observer experience | Adaptive state |
| Number of observers | Complexity of observer task |
| Screening for color vision deficiencies | Controls |
| Observer acuity | Repetition rate |
| Instructions | Range effects |
| Context | Regression effects |
| Feedback | Image content |
| Rewards | Number of images |
| Illumination level | Duration of observation sessions |
| Illumination color | Number of observation sessions |
| Illumination geometry | Observer motivation |
| Background conditions | Cognitive Factors |
| Surround conditions | Statistical significance of results |

For the variables of observers, there are four factors that are relatively important. The first one is mood, fatigue and stress level, which may vary according to the experiment process, influence by the researchers and the experimental environment. The other variable of observers is variability of the ability to discriminate between small color differences (ASTM E 1499). The observers must have been properly trained and pass the normal color vision tests. The judgments of even the most highly trained observers can change or exhibit some variability, so an observer's color vision should be tested periodically (Fairchild, 2005, ASTM D 1729). In addition, observer experience level is another important aspect, according to the research conducted by Shamey and his team (2010).  The judgments made by expert subjects scored 43% higher on average visual difference ratings than novice subjects' judgments (Shamey, Cardenas, Hinks, and Woodard, 2010). Last but not least, the willingness of the participant may dramatically influence the participant's experimental performance.

Regarding the observation environment, any changes of viewing conditions, such as the size of test specimens, proximity of the observer to the sample, level of illumination or distraction during the experimental process, may significantly change the results. Regarding the procedural design of the experiment, differences in rewards, sessions lengths, and number of observations, as well as the design of instruments, can influence the results.

**2.6.4.2.Solution to Control for Variables**

To moderate variability among observers, sessions should be limited both in the length of time and number of observations. Experienced participants are recommended rather than inexperienced participants to increase the accuracy and shorten the total experiment time. In addition, rewards given to participants after they finish experiments is a great way to encourage willingness (ASTM E 1499). To ensure the participant meets the requirement for color assessments, the participant should take a standard color vision test before starting the experiment.

Color testing methods are used to determine whether one has normal or abnormal vision, including the Ishihara, Farnsworth-Munsell 100-Hue, and the Nietz tests. The Ishihara test is used to test for red and green color blindness. The observer is asked to identify a distinct colored number within a group of colored dots to pass the test (Figure 17). For the Farnsworth-Munsell 100-Hue test, the observer organizes four sets of color chips by their constant lightness and chroma in order to test what hue(s) the observer is deficient in. The Nietz test is to determine whether one has any red-green and or blue-yellow color deficiencies and also classifies the severity of the color deficiency (Fairchild, 2005, ASTM E 1499). The Nietz test is similar to the Ishihara test but can be as short as five minutes.

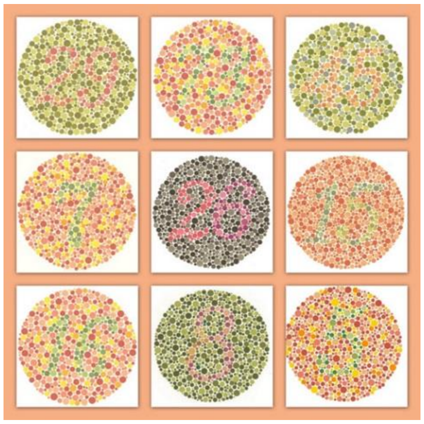


**Figure 17:** The Ishihara Test.

Retrieved from http://salvatorepuglia.info/2009/12/12/communication-the-ishihara-pseudo-isochromatic-test-and-its-variant-by-s-puglia/

The observation environment should include consistent viewing conditions, including a consistent size of test specimen, proximity of the observer to the sample, and level of illumination, which should all be the same throughout the whole experiment process. Distraction should also be highly controlled and minimized to avoid the variability that affects the participants' judgements (ASTM E 1499, Hinks et al., 2007). Moreover, samples being assessed for color differences should be viewed at a distance of 18 to 24 inches and the edges of the samples should come in contact with the Munsell color associated with the interior of the viewing booth. The same gloss and texture should be used for the paired samples. In addition, sample size should be no smaller than 3.5 x 6.5 inches; otherwise, the precision of perceptual color differences may be reduced (ASTM D 1729).

#### 2.6.4.3.Psychophysical Method

The psychophysical method applied for this study is the AATCC Gray Scale for Color Change. The physical instrumental measurements can be used in conjunction with subjective measurements collected through visual assessment to reinforce the findings (ASTM E 1499, ASTM D 1729). The AATCC Gray Scale for Color Change can be used to conduct quantitative measurements between samples, which consist of pairs of standard gray chips representing varying differences in color or contrast. According to research (Fairchild, 2005), scaling analyses can be applied to identify the attitudes of observers toward perceptual attributes, such as lightness, hue and chroma. The color change represented by the AACTT Gray Scale can be used to identify differences in lightness, hue and chroma. One-dimensional psychophysical scales such as paired, rank order, and category comparisons are common scaling techniques used for measurement (Fairchild, 2005). The Scale of AATCC consists of 9 color difference half steps from 5 to 1, with 5 representing no color difference between samples and 1 representing the highest color difference between samples (AATCC 1-2012). The recommended CIE illuminant to use in conjunction with the ATTCC gray scale is D65, which is the standardization of daylight.

## 2.7. Summary

This literature review introduces background knowledge about ink-jet digital textile printing development and screen printing. The introduction addresses fundamental principles for digital ink-jet textile printing, a comparison between ink-jet digital textile printing and screen printing, color management and color evaluation processes, and visual assessment development. All the literature cited indicates a significant potential to save time and money during the product development process if ink-jet textile printing can replace screen printing fabric. However, the threshold standard for this replacement is not yet clearly established, and further research are needed to create a standard for building a whole digital ink-jet printing system capable of ensuring color accuracy and digital printing quality.

# 3. CHAPTER 3: METHODOLOGY

## 3.1. Research Purpose

The aim of this research is to replicate a screen-printed sample provided by a textile corporation via ink-jet digital printing, and to explore the potential for of digital ink-jet printing to replace the traditional screen printing. To achieve this target, a protocol which involved two stages was established (Figure 18).

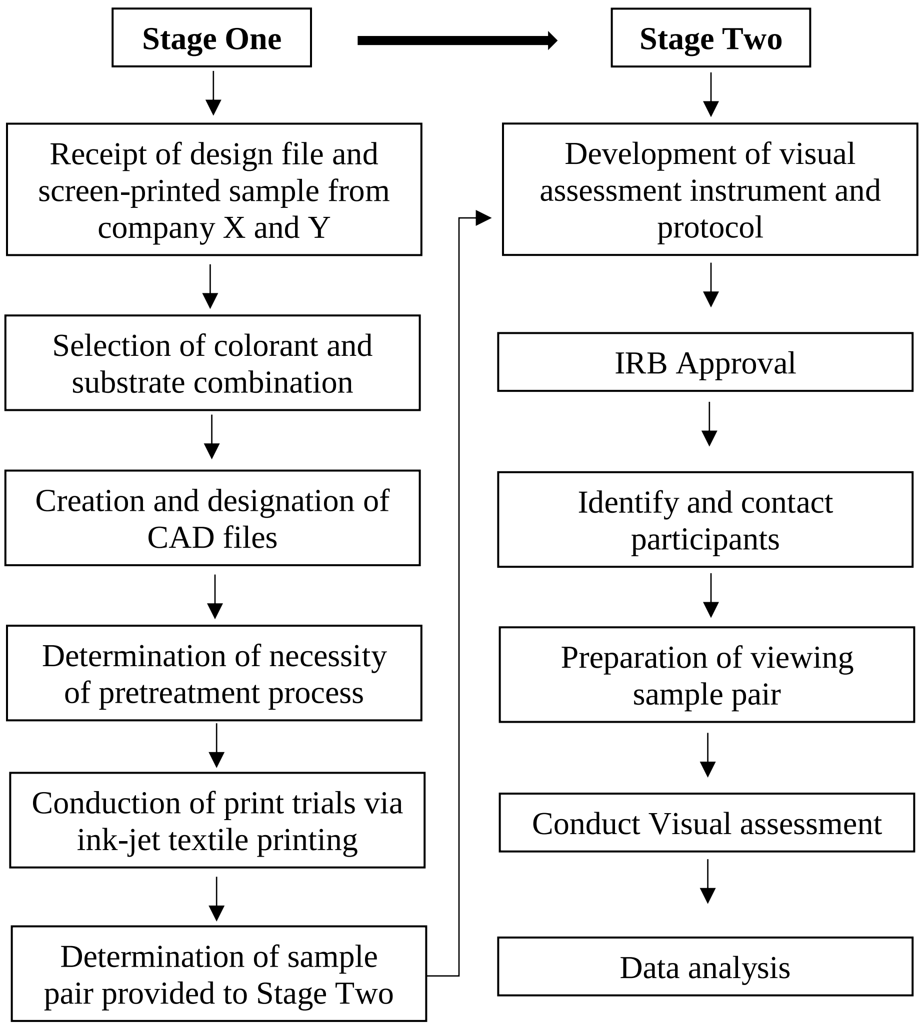



**Figure 18:** Research Diagram

## 3.2. Research Design

In Stage One, an optimal workflow for the ink-jet printing of fabrics that replicated screen-printed fabrics was established. The workflow was based on three approaches which including determination of the colorant and substrate combination, CAD file and the necessity of pre-treatment.

Color calibration, digital format selection, color reduction was conducted to gain suitable CAD files to improve the color matching accuracy. The effect of the pretreatment process was evaluated according to the comparison between the pre-treated fabric and non-pretreated PET fabric. After color gamut analysis and observation, pretreatment was chosen for the substrate preparation process.

Regarding to determination of the colorant and substrate combination, a screen-printed cotton sample provided by company X and two screen-printed polyester (PET) samples provided by company Y as well as design files were received by principle investigator (PI). Totally twelve trials for ink-jet digital were printed by using three different substrates and ink set combinations. The three combinations were cotton and pigment (combination A), PET and pigment (combination B) and PET and disperse dye (combination C). Those printed trials were then evaluated by PI and designers from both companies, according to printing effect, and only one pair of them was chosen for stage two to conduct visual assessment based on its suitable color gamut, relative easy pre-treatment process and good color effect.

In Stage Two, a visual assessment instrument and protocol were designed for evaluating the ink-jet printed fabrics printed in Stage One. Then, a pilot visual assessment experiment by 12 expert participants was conducted to determine if the ink-jet digital printed sample was a suitable substitute for screen printed sample. 12 participants were all experienced experts from textile ink-jet digital printing related area or doctoral students focus on color science research. The visual assessment and protocol was designed to evaluate the acceptance of the ink-jet printed sample fully replicating screen-printed sample via six measured aspect. These five aspects were perceived color difference, color appearance, scale, line quality, visual texture, and overall appearance. The created quantitative survey instrument used in this pilot test presented to participants by using online surveys called *freeonlinesurveys.com*. Data which measured perceived differences gathered from the visual assessment was then analyzed and compared by using SPSS statistics software.

### 3.3. Research Objectives

The aim of this research is to replicate a screen-printed sample provided by a textile corporation via ink-jet digital printing, and to explore the potential for of digital ink-jet printing to replace the traditional screen printing. To achieve this goal, there are three research objectives of this research as follow:

[1] To develop a workflow for the fabric replication of a screen-printed fabric using ink-jet textile digital printing.

[2] To develop a visual assessment instrument and protocol to evaluate the acceptance of the replicated ink-jet printed fabric;

[3] To determine if the ink-jet digital printed sample was a suitable substitute for screen printed sample via an expert visual assessment testing.

### 3.4. Stage One: Development of Fabric Replication Workflow

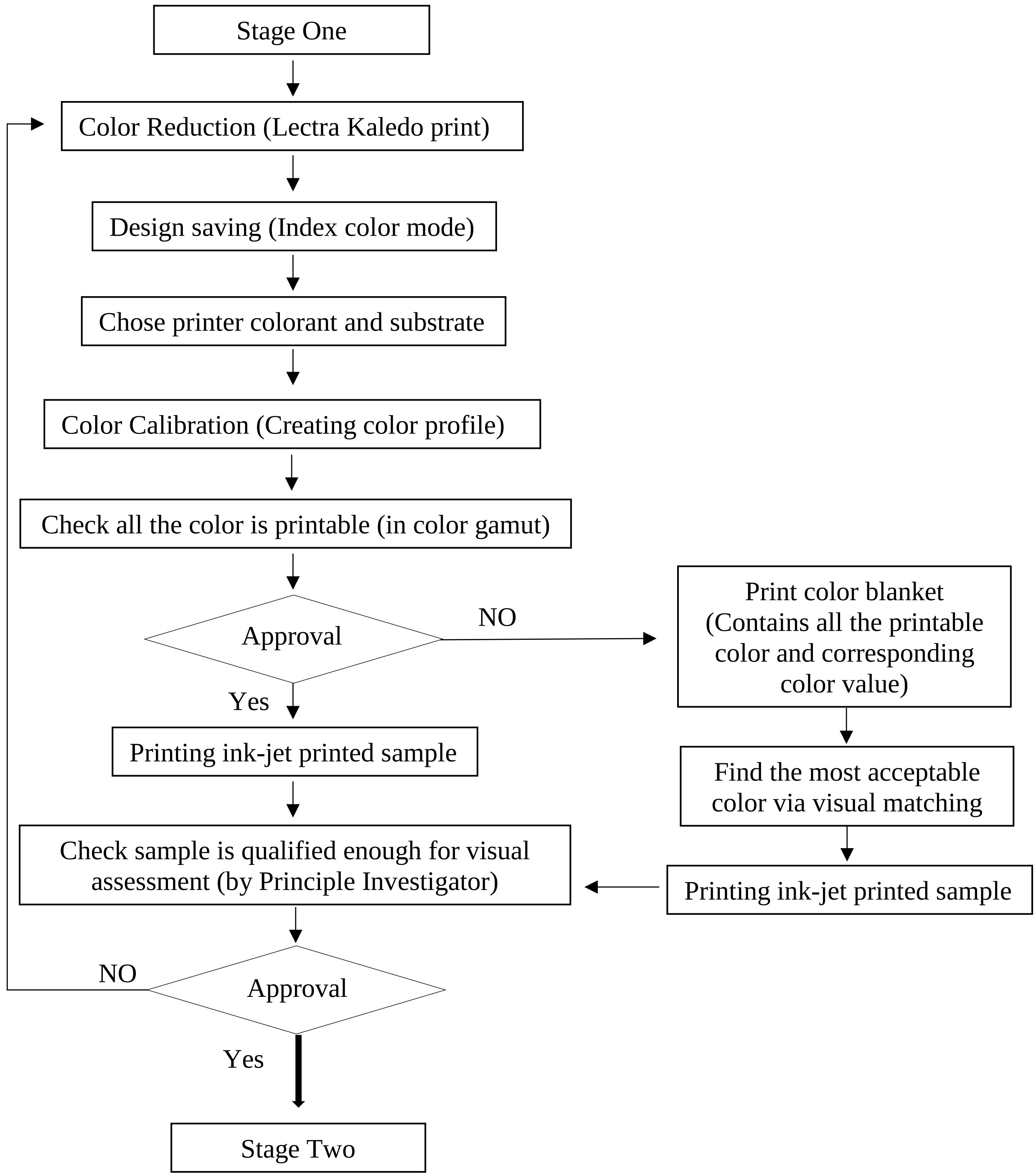



**Figure 19:** Workflow of Fabric Replication

The first objective of this research was to establish a workflow for replicating a screen-printed fabric via ink-jet textile printing. Three screen-printed samples used in this study were prepared by company X and company Y. A screen- printed cotton sample was provided by company X and two screen-printed polyester (PET) samples were provided by company Y. The corresponding design TIFF files provided by these company were also received by Principle Investigator (PI). All the ink-jet fabric used for printed trials in this stage were prepared by PI. The workflow was based on three approaches which including determination of the colorant and substrate combination, CAD file and the necessity of pre-treatment. Several ink-jet printed fabrics were printed and evaluated by PI, however only one pair of fabric was qualified enough to conduct the visual assessment in Stage two.

As shown in Figure 19, a fabric replication workflow was established during the research process. All the steps that listed in Figure 19 were discussed in the following sections.

### 3.4.1. Screen-printed Sample and Design File

Three screen-printed samples used in this study were provided to PI by company X and company Y. Company X provided a screen-printed sample A by using pre-treated 100% cotton fabric. Digital file for design A (TARANGO-Moonbeam) with eight channels and RGB color mode was also provided for digital printing.

Meanwhile, company Y provided a screen-printed sample B1 and sample B2 by using 100% polyester fabric.

PI also received pre-treated polyester and non-pretreated polyester fabric which was prepared for printing for research use from company Y (Table 6).

**Table 6 :** Fabric Provided and Their Digital Files

| Screen-Printed Fabric | | Corresponding Digital File (TIFF) | |
|---|---|---|---|
|  | Sample A<br><br>Cotton |  | Design A<br><br>8 channels & RGB color mode |
|  | Sample B1<br><br>Polyester |  | Design B1<br><br>8 channels & Index color mode |
|  | Sample B2<br><br>Polyester |  | Design B2<br><br>8 channels & Index color mode |

For research convenience, three screen-printed samples and their digital design file were labeled by PI (Table 6). One piece of screen-printed pre-treated cotton fabric named TARANGO-Moonbeam was provided by company X, which was labeled as Sample A. One digital file named TARANGO-Moonbeam with eight channels and RGB color mode was also provided for digital printing by company X, and was labeled as Design A.

Two pieces of screen-printed pre-treated polyester fabric were provided by company Y. One piece was named [1] 14197-22_PavillionBlack and the other was named [2] 14197-

22_PavillionBlack.These two pieces of fabric are labeled as Sample B1 and Sample B2, respectively.

In addition, two digital files named [1] 14197-22_PavillionBlack and [2] 14197-22_PavillionBlack were provided with eight channels and Index color mode. These two digital files are labeled as design B1 and design B2, respectively. As discussed in the last chapter, the main file format that is commonly used in digital ink-jet printing is shown in Table 3. The most popular one in industry is TIFF format. All the digital files that provided by company X and Y were in TIFF mode.

As in Table 6, one repeat for Design A, Design B1 and Design B2 is shown, and the screen-printed sample for Sample A and Sample B1and B2 are scanned and shown.

### 3.4.2. Color Reduction

Color reduction is necessary to keep the color accurate, clean up stray pixels, and ensure the color consistency. Lectra Kaledo Print software is a textile CAD software widely used in textile industry Ensuring color consistency. It aimed to create market right and cost effective prints from any digital art source. To ensure the best replication result, in this process, the Design A was saved in eight RGB color mode and then opened in Lectra Kaledo Print, color reduced, cleaned up stray pixels and recolored using an RGB color table, and kept in a RGB color mode, TIFF format (in Table 3). The Design B1 and Design B2 were saved in eight Index color mode and then opened in Lectra Kaledo Print, color reduced, cleaned up stray pixels and recolored using an Index color table, and kept in an Index color mode, TIFF format. The files were then reviewed by PI to pick up the color key.

### 3.4.3. Color key

Color key was a numbered list that created by PI to represent the main color on the screen-printed samples. Because there are many distinct colors appeared on the screen-printed sample, picking up the main color from the design can help PI or visual assessment participants see clearly the difference between screen-printed sample and ink-jet printed sample. In addition, three screen-printed samples were all multi-color samples, so colors would affect each other during the observation process. Variance could happen if an observer viewed color in a different order. Evaluating the color in the same order can eliminate the variance. For this reason, every color listed on color key were numbered Color 1, Color 2 and so on, observers (including the PI) view the sample though the numbered order.

Three sets of color keys were created for sample A, sample B1 and sample B2. Seven colors were picked up from the Sample A. These seven colors can typically represent the color of the design A and labeled from Color 1 to Color 7. In Appendix D, Color 1 is Black, Color 2 is Yellow, Color 3 is Dark Green, Color 4 is Gray, Color 5 is Blue, Color 6 is Red, and Color 7 is Cyan.

Seven colors were picked up from Sample B1. These seven colors can typically represent the color of the design B. These colors were labeled as background and Colors 1 to 6 (Appendix D). The color labeled background was Dark Black, Color 1 was Gray, Color 2 is Maize Yellow, Color 3 is Red, Color 4 is Yellow Green, Color 5 is Purplish Red, and Color 6 is Dark Red.

Six colors were picked up from Sample B2. These six colors can typically represent the color of the design B2 and labeled as background and from Color 1 to Color 5. In

Appendix D, Background is Dark Red, Color 1 is Gray, Color 2 is Olive Yellow, Color 3 is Brown, Color 4 is Black Red, Color 5 is Yellow.

### 3.4.4. Substrate and Ink Combination

The next step of this research was to select the most suitable substrate and ink combination for reproducing the screen-printed samples. Combination A used nano-pigment ink printed on cotton fabric. Combination B used to use nano-pigment ink printed on polyester fabric, and Combination C used disperse ink printed on polyester fabric.

**Table 7:** Three Substrate and Colorant Combination

| Ink / Substrate | Nano-pigment ink | Disperse |
|---|---|---|
| Cotton |  Combination A<br>Used for Design A | N/A |
| Polyester |  Combination B<br>Used for Design B1 |  Combination C<br>Used for Design B2 |

One ink-jet printed sample of design A was printed using combination A (Table 7). Twelve ink-jet printed samples of design B1 were printed with combinations A, B, and C. Six ink-jet printed samples of design B2 were printed with combinations A, B, and C. All digital printed samples were produced by using MS-JP5 Evo printer.

### 3.4.5. Creation and Designation of CAD files

#### 3.4.5.1. Textile CAD Software

Textile CAD software commonly used in textile industry was used in this research, specifically, Dr. Wirth RipMaster 10.0, Lectra Kaledo print and Adobe Photoshop CS6.1.

The Dr. Wirth RipMaster 10.0 can be used to control the printer from the computer, and transfers the digital design file into a raster-based image so it can be printed. It can also achieve color calibration and color reading process in combination with the X-rite i1iO spectrophotometer (Introduced in next section).

Lectra Kaledo print is used for color reduction to select the main color for the printing process.

Adobe Photoshop CS6.1 is widely used by textile designers, and for this research, it was used for color mode changing and file resaving.

#### 3.4.5.2. Spectrophotometer

Calibrated and profiled devices and systems are a critical and essential part of a successful, efficient, creative workflow. The color captured on camera, seen on the monitor, and projected by projector or mobile device needs to be well-matched in each device. The X-

Rite i1iO spectrophotometer enables hands-free test chart reading for automated color profiling on a variety of substrates with reduced risk of color measurement errors. In textile ink-jet printing, the X-Rite i1iO spectrophotometer connected with RipMaster 10.0 software is used for color management solutions for a high level of color accuracy in the industry.

(a) (b)

**Figure 20:** (a) X-rite i1iO Spectrophotometer (Color Calibration) (b) Target Color Reading

As in Figure 20 (a), the X-rite i1iO spectrophotometer processed color calibration, and in Figure 20 (b), the X-rite i1iO spectrophotometer is reading a target color. Together, the investigator can obtain the exact RGB value of the target color.

#### 3.4.5.3.Color Calibration

The aim of color calibration is to measure and adjust as needed the color response of a device (input or output) to a known state. Color calibration is a requirement for all devices taking an active part of a color-managed workflow. Color calibration is used by many industries, and in the textile industry, it is used to create a color profile that presents the range of printable color specifically for a specific substrate and ink combination. For digital textile printing, color calibration provides the color gamut and makes the printing process accurate. In this case, the PI performed color calibration every time either the substrate or ink was changed on the MS-JP5 Evo printer. Each substrate and ink combination (A, B, C) has its own color profile during printing. All the steps for creating an enhanced color profile followed the same workflow (Appendix G). Color calibration has been done by using RIP Master on the MS JP5 Evo printer for each group of inks set and substrate fabric combinations. A particular profile was used for the corresponding ink set and substrate fabric combination to keep the color right throughout the research period (Figure 21).

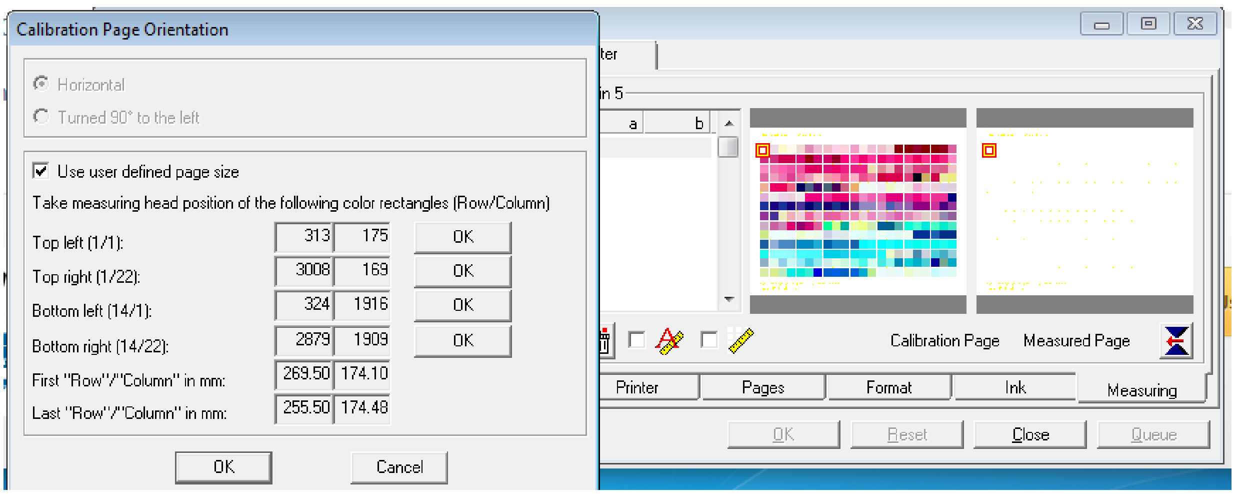



**Figure 21:** Creation of Enhanced MS-JP5 evo Color Profile

### 3.4.5.4.Color gamut

Color gamut in textiles refers to the range of colors a printer can reproduce. The larger or wider the gamut, the richer and more saturated are the colors available.

In this research, first the color profile was created by the Dr. Wirth RipMaster 10.0 (Figure 22). Then a color blanket, which represents the color gamut for the specific substrate, ink, and printer combination, was provided. The color blanket contains 36 pages. Every page was made up of color chips with the corresponding L*a* b values, so PI can easily see and input the target color value that is needed. The color blanket for each combination (Combination A, B, and C) was printed out. The PI used these color blanket to visually match the screen-printed samples to digitally printed fabrics.

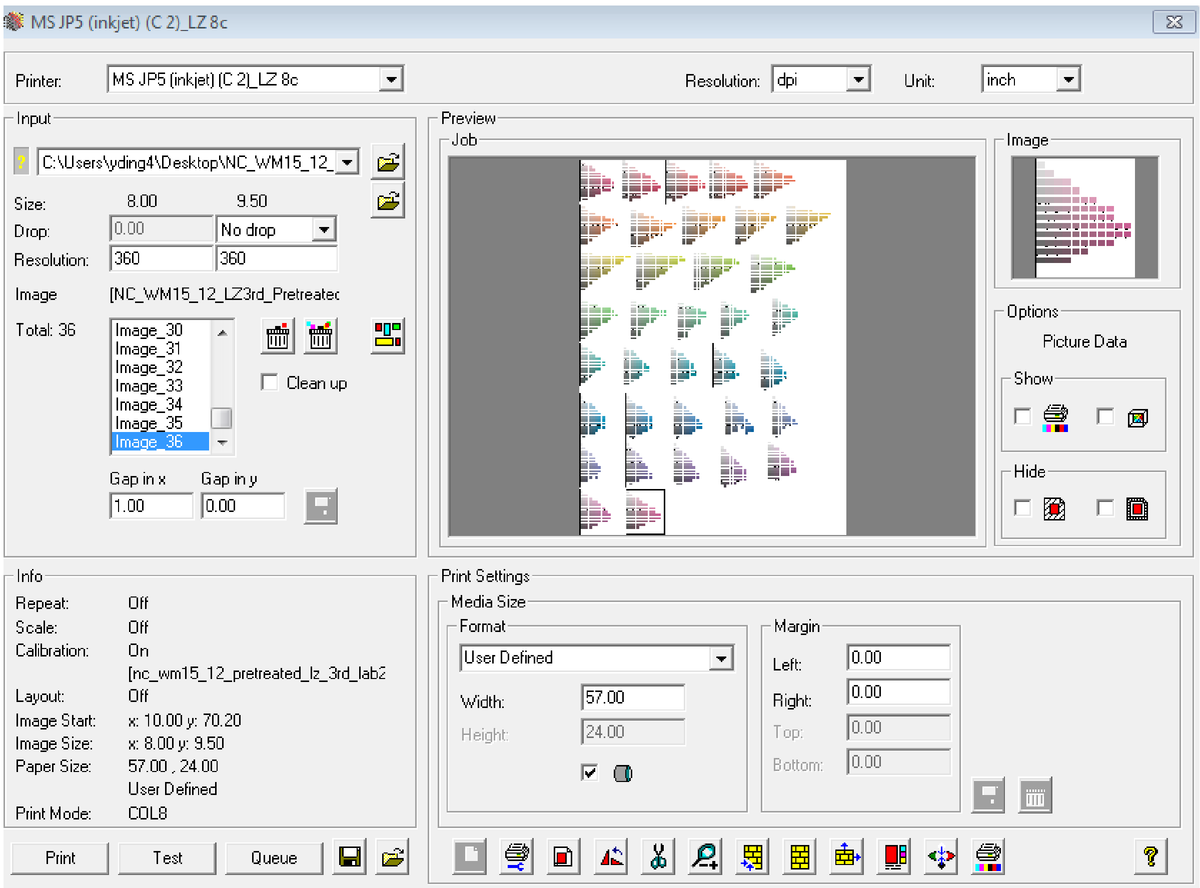



**Figure 22:** MS-JP5 Evo Printer Nano-Pigment Color Gamut

### 3.4.5.5.Color Matching

#### 3.4.5.5.1. Target color reading

After color profile and color gamut, color gamut can be seen in the RipMaster 10.0

software. The X-rite i1iO spectrophotometer can be used to read the screen-printed target sample and see whether the color is in the color gamut or not (Figure 23). If it is in the color range, then it can be printed out accurately on the fabric. If not, the color blanket should be used to find the color that is visually closest to the target color. Otherwise, the RipMaster 10.0 software will find the closest color by itself according to the L*a* b values.

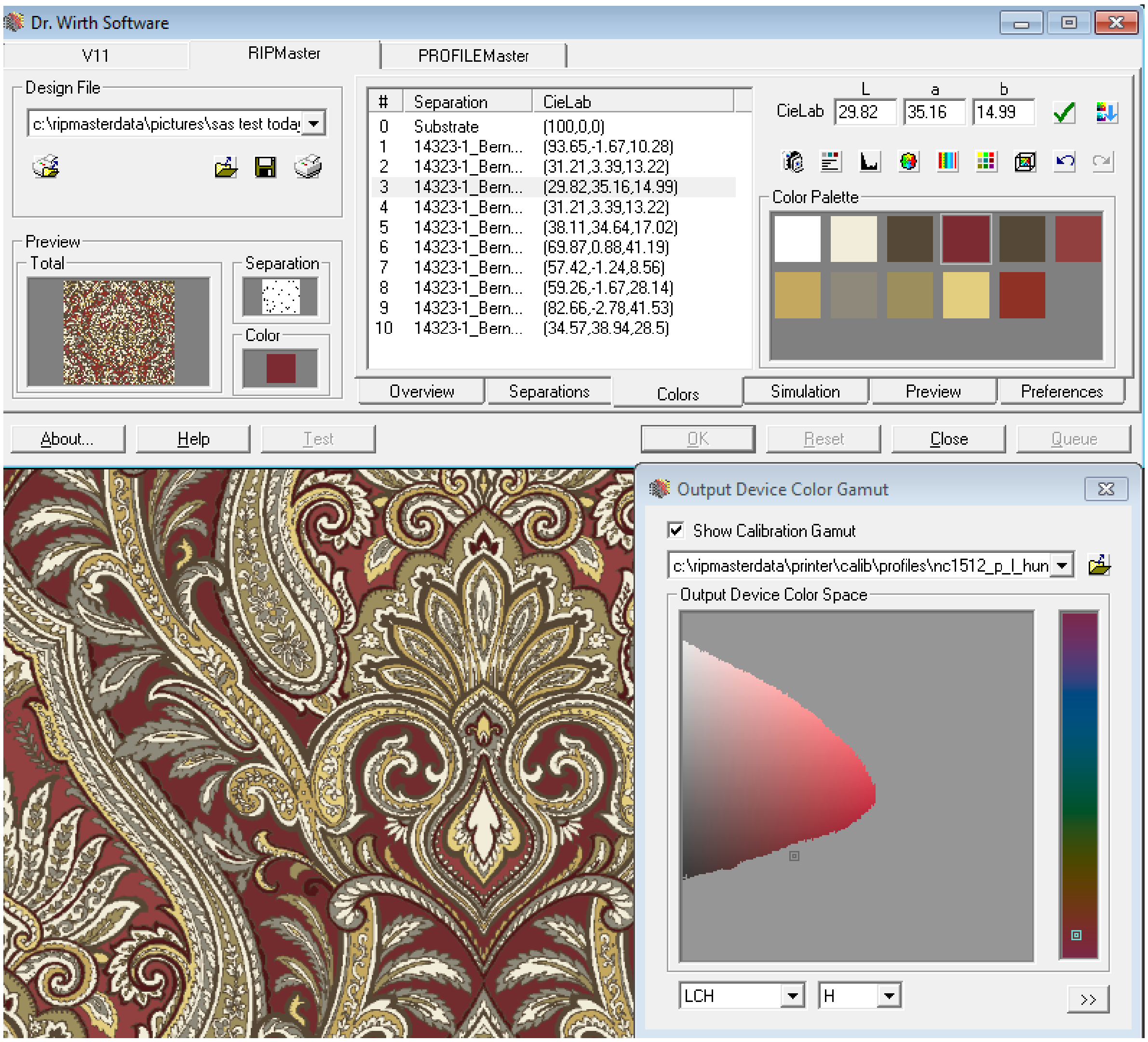



**Figure 23:** Target Color Reading (Slightly Out of Color gamut)

#### 3.4.5.5.2. Visual color matching

As mentioned before, if the target color is out of color gamut, visual color matching can be used to determine which color to use for the printing process, depending on how far out of the gamut the target color is. If the target color is badly out of the color gamut (Figure 24), it is better to change a substrate, ink and printer combination. If the target color is only slightly outside of the gamut (Figure 23), visual matching may be used for finding an acceptable alternative color. Visual matching may be used several times until the target color was found.

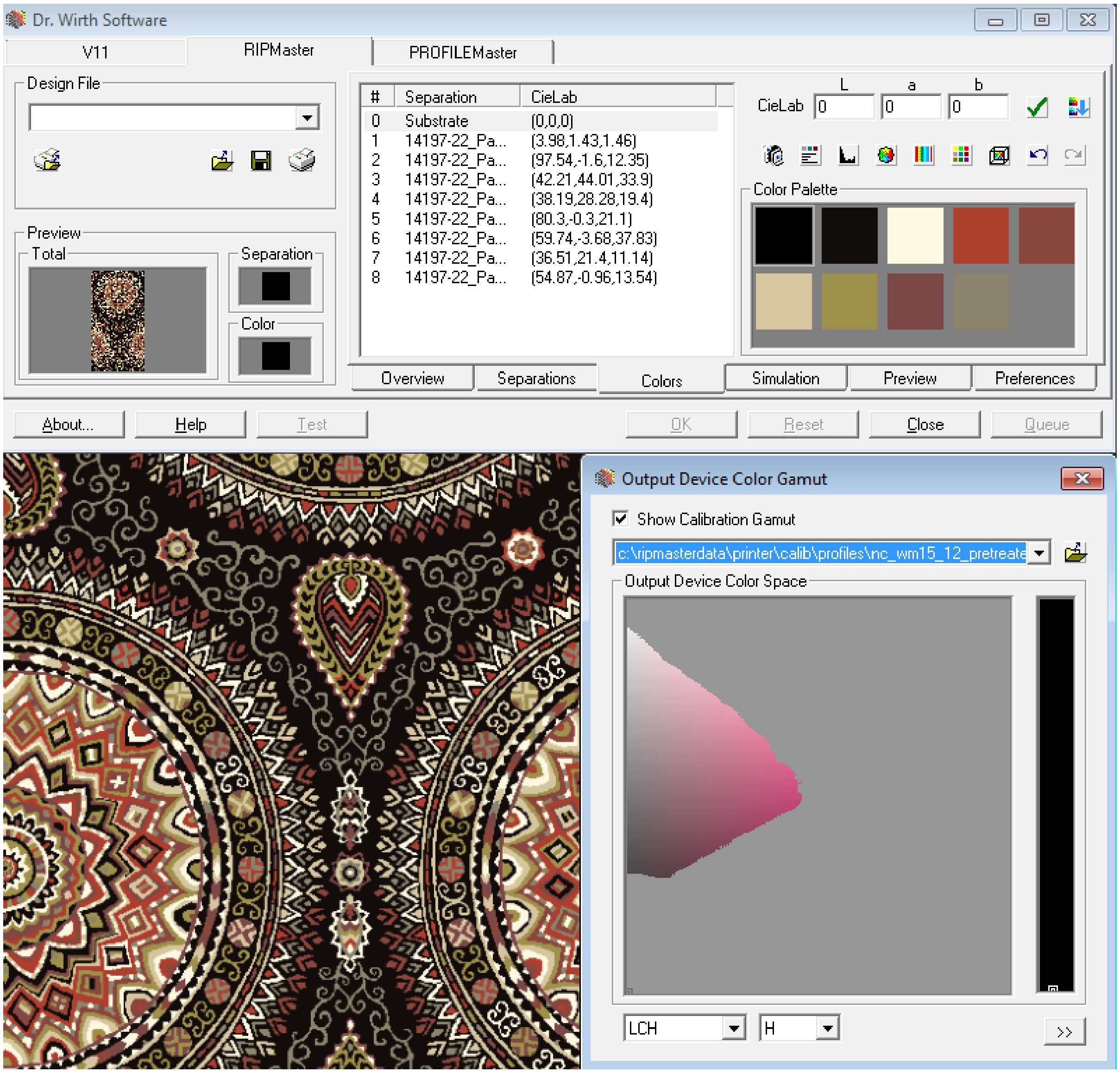



**Figure 24:** Target Color Reading for Red Color (Badly Out of Color Gamut)

### 3.4.6. Conduct Ink-jet Textile Print Trials

Total twenty ink-jet printing trials were conducted to find the best way to replicate the color from the screen printing sample. During this process, four main influence factors were examined: colorant and substrate combination, printing mode and ink limitation, pre-treatment and post-treatment.

### 3.4.6.1.Ink-jet Digital Printer

All the print trials were printed by using MS JP5 Evo Printer, which uses Drop-on-Demand (DOD) Piezoelectric ink-jet print heads (Figure 25).


**Figure 25:** MS JP5 Evo Printer

The production speed is up to 8 colors per 55 linear meters/ hour (linear meters/hour) and Production Speed CMYK is 100 linear meters per hour. It has four printing heads with each head containing up to two colors. The maximum Dpi resolution is 600*600 dpi, the printing width is up to 180 cm (70.8 inches). Gray levels are 16 and drop size is from 4 to 72 pl (Table 8).

**Table 8:** Technical specifications for MS JP5 Evo Printer

| TECHNICAL SPECIFICATIONS | |
|---|---|
| Production speed up to 8 colors | 55 lin.met./h |
| Production Speed CMYK | 100 lin.met./h |
| Printing heads | 4 |
| Dpi resolution | 600*600 dpi |
| Gray levels | 16 |
| Drop size | From 4 to 72pl |
| Features | - Open ink system<br>- Embedded remote diagnostic<br>- Embedded web server for cost report |
| Printing width | 180 cm |

First, the MsJP5 Evo Printer used nano-pigment ink set to finish printing on the cotton and polyester (Combination A, B). Next, the ink set was changed to disperse ink set and printed on polyester (Combination C). Both ink sets have eight colors, which were black, cyan, red, magenta, orange, yellow, violet and gray (Tables 9 and Table 10).

**Table 9:** MS JP5 Evo Printer Disperse Inks

| | | | |
|---|---|---|---|
| Black | Cyan | Red | Magenta |
| Orange | Yellow | Violet | Gray |

**Table 10:** MS JP5 Evo Printer Nano-Pigment Inks

| | | | |
|---|---|---|---|
| Black | Cyan | Red | Magenta |
| Orange | Yellow | Blue | Gray |

### 3.4.6.2.Printing Mode and Ink Limitation

The MS JP5 Evo Printer has different print modes that control the ink drop ranging from light color to dark color. And ink limitation can also be changed according to the research need. The most common setting for this printer is C2 100%, but if deeper color is wanted, either the print mode can be changed or the ink limitation can be raised. For example, if more ink drop is desired to produce a deeper color, the print mode can be changed from C to D or the ink limitation can be changed from 100% to 120%. For this research, settings were C-2 100%, C-2 120%, and D-2 100% during the color matching process.

(a) C-2 100% (b) C-2 120% (c) D-2 100%

**Figure 26:** Polyester Fabric (C-2 and D-2 printing mode)-Design B1

(d) C-2 100% (e) C-2 120% (f) D-2 100%

**Figure 27:** Polyester Fabric (C-2 and D-2 printing mode)- Design B2

As we can see from Figure 26 and Figure 27, for both Design B1 and Design B2 printed on polyester fabric, the color becomes deeper either by changing the color mode from C to D or by changing ink limitation from 100% to 120% for both background color (black) of Design B1 and Color 7 (Red) of Design B2, both of which allow more ink to be printed. By comparing the color change between (a) & (b) and (b) & (c), as well as (d) & (e) and (e) & (f), we can see that changing color mode will effectively produce deeper color.

**3.4.6.3.Conduct Ink-jet Printed Trials**

Total twenty ink-jet printing trials were conducted to find the best way to replicate the color from the screen printing sample, most of the ink-jet printed samples were discussed as follow, for all the screen-printed and ink-jet printed samples as well as their printing information (Appendix I).

For design A, only one print trial labeled Sample B was conducted using combination A (Nano-pigment and cotton). As shown in Table 11, this print trial use C-2 print mode with 100% ink limitation.

**Table 11:** Ink-jet printed Sample of Design A

| | Colorant and Substrate Combination | Print Mode | Ink Lamination | Visual Color Matching and Change |
|---|---|---|---|---|
| Sample B | Combination A | C-2 | 100% | No |

As shown in Figure 28, the ink-jet printed Sample B was well-matched in appearance, so the PI approved this sample pair and decided to use it for conducting expert visual assessment and developing protocol in Stage Two.

**Design A:**

Screen Printed Sample (Target) Combination A (Nano-pigment and Cotton)

**Figure 28:** Design A (Target & Printing Sample)

For Design B1, all three colorant and substrate combinations (A, B, and C) were used to produce the right color results for replicating. Specific color mode and ink limitation settings for each colorant and substrate combination was used. As shown in table 12, there are total 12 ink-jet printed samples of Design B1. Among these samples, four of them were printed on cotton fabric with nano- pigment ink (combination A), seven of them were printed on polyester fabric with nano-pigment ink (combination B), one sample was printed on polyester fabric with disperse dye (combination C).

**Table 12:** Ink-jet Printed Sample of Design B1

| | Colorant and Substrate Combination | Print Mode | Ink Lamination | Visual Color Matching and Change |
|---|---|---|---|---|
| Sample B1_A1 | Combination A | C-2 | 100% | No |
| Sample B1_A2 | Combination A | D-2 | 100% | No |
| Sample B1_A3 | Combination A | C-2 | 100% | Yes |
| Sample B1_A4 | Combination A | D-2 | 100% | Yes |
| Sample B1_B1 | Combination B | C-2 | 100% | No |
| Sample B1_B2 | Combination B | C-2 | 120% | No |
| Sample B1_B3 | Combination B | D-2 | 100% | No |
| Sample B1_B4 | Combination B | C-2 | 100% | Yes |
| Sample B1_B5 | Combination B | C-2 | 100% | Yes |
| Sample B1_B6 | Combination B | C-2 | 100% | Yes |
| Sample B1_B7 | Combination B | C-2 | 100% | Yes |
| Sample B1_C | Combination C | C-2 | 120% | No |

After reading the target color, the PI found the deep red (Color 7) of design B1 was badly out of color gamut. As shown in Figure 30, Sample B1_A1 and Sample B1_A2 were not well matched the Target Sample (Figure 29), visual color matching need to be conducted to find the closest alternative color.

**Figure 29**: Screen-printed Sample (Target) ,Design B1

(1) C-2 100%

(2) D-2 100%

**Figure 30:** Combination A, Design B1

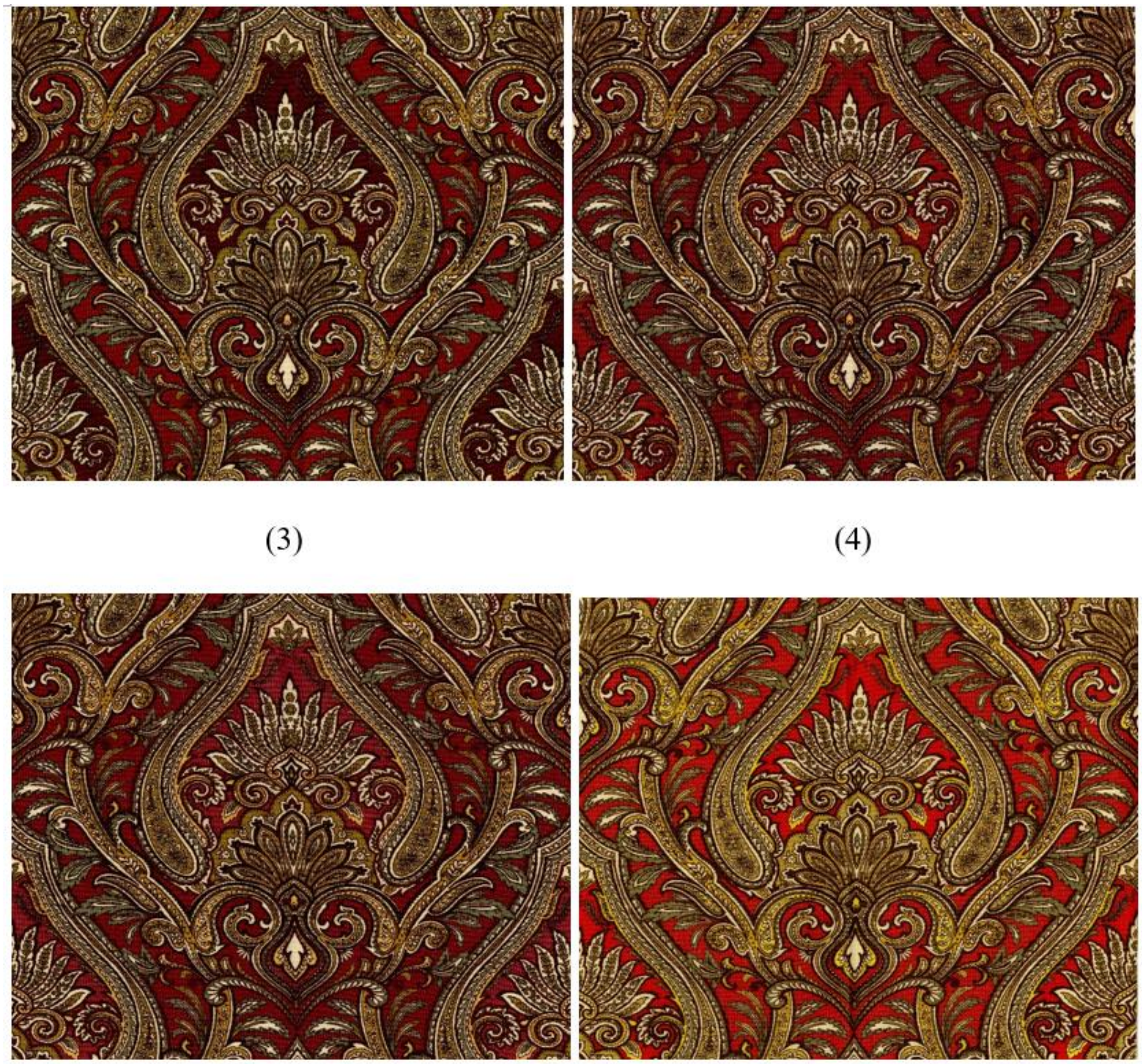
During the visual color matching process, the PI put the corresponding color blanket of combination and the target sample B1 side by side, then visually compare the color difference to find the most efficient alternative color. After finding the most efficient alternative color, the PI mark the color value and then put the value into Lectra Kaledo print software. All the dark red (color 7) in Design B1 were changed to the new color value, in another word, became a new color. It was conducted by the PI twice to find the closest color, but the results did not produce a match the color well enough (Figure 30). The PI decided not to use this combination of colorant and substrate to print Design B1.

(1) C-2 100%

(2) D-2 100%

**Figure 31:** Combination A, Design B2

After that, the same situation happened when printing Design B2 on polyester fabric with nano-pigment ink. The deep red (Color 6) of design B2 was still extremely out of color gamut (Figure 31, Appendix J), the visual color matching process was conducted by the PI four times to find the closest color, but the results did not produce a match the color well, either (Figure 32). Also, as can be seen from these four printing results in Figure 32 (3) - (6), (6) was very different from the other three, which means the PI's visual color matching can be influenced by aspects such as environment, light, and how the individual observer, perceives color, which means visual color matching is not as accurate as target color reading.



(3) (4)

(5) (6)

**Figure 32:** Combination B

Finally, the PI printed Design B2 on polyester fabric with disperse dye, but the appearance is extremely different from the Target Sample B1(Figure 33), thus the PI printed it once and decided not to use it. Moreover, compared to the previous sample, although the same printing environment except the colorant was applied on this trial, the color on the polyester printed by disperse dye was much deeper than the polyester printed by nona-pigment (Figure 33). As a result, the disperse dye showed a better ink penetration and color concentration than nano-pigment ink.

**Figure 33:** Combination C

For Design B2, also all three combinations (A, B, and C) were used to conduct the right color results for replicating, and different color mode and ink limitation settings were used.

**Table 13:** Ink-jet Printed Sample of Design B2

| | Colorant and Substrate Combination | Print Mode | Ink Lamination | Visual Color Matching and Change |
|---|---|---|---|---|
| Sample B2_A1 | Combination A | C-2 | 100% | No |
| Sample B2_A2 | Combination A | D-2 | 100% | No |
| Sample B2_B1 | Combination B | C-2 | 100% | No |
| Sample B2_B2 | Combination B | C-2 | 120% | No |
| Sample B2_B3 | Combination B | D-2 | 100% | No |
| Sample B2_C | Combination C | C-2 | 120% | No |

As shown in Table 13, there are totally 6 ink-jet printed samples of Design B2. Among these samples, two of them were printed on cotton fabric with nano- pigment ink (combination A), three of them were printed on polyester fabric with nano-pigment ink (combination B), one sample was printed on polyester fabric with disperse dye (combination

C).

**Figure 34:** Screen-printed Sample (Target), Design B2

(1) C-2 100%

(2) D-2 100%

**Figure 35:** Combination A

Deep black (Background) (in Appendix D) was the hardest color to match, which is also extremely out of color gamut (Appendix J). As shown in Figure 35 and Figure 36, the appearance color, especially the Deep black (Background) is not well matched (Appendix J) compared to the target screen-printed sample (Figure 34). Both C-2 print mode with 100% ink limitation and 120% ink limitation were used to print, but the results were not well enough.

**Figure 36:** Combination B (Nano-Pigment and Polyester)

The same situation happened when using disperse dye printing on polyester fabric, compared to the previous sample. Although the same printing environment except the colorant was applied on this trial, the color on the polyester printed by disperse dye (Figure 37) was much deeper than the polyester printed by nona-pigment (Figure 26 (2)). It proved that the disperse dye has a better ink penetration and color concentration than nano-pigment ink.

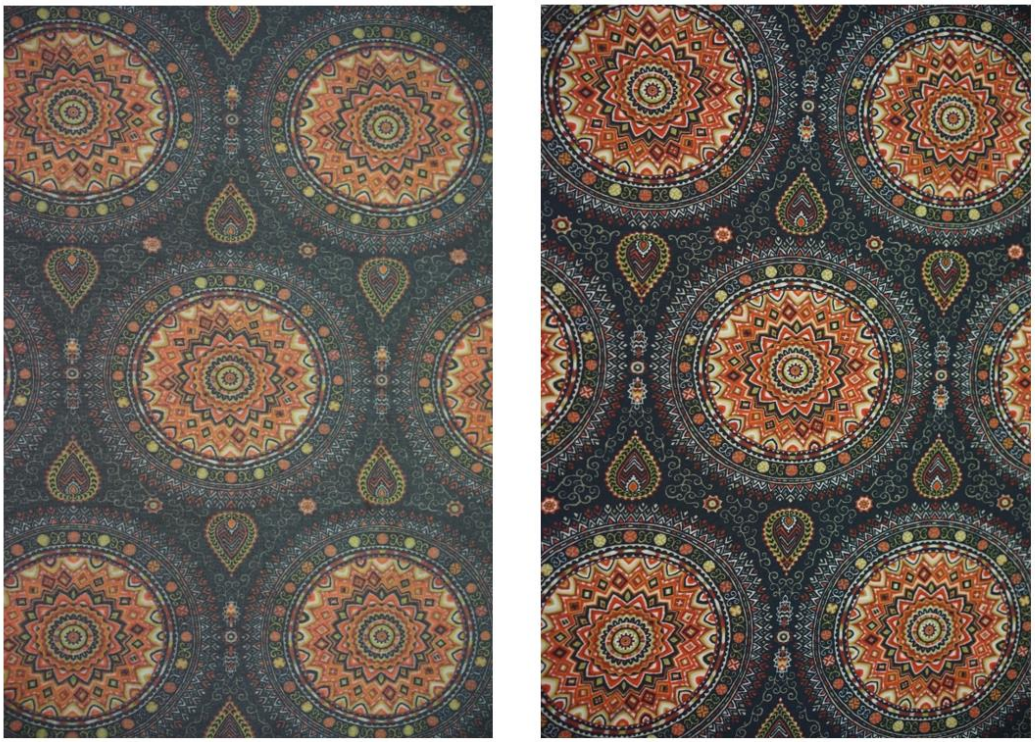
**Figure 37:** Combination C (Disperse and Polyester)

Regarding to all the print trials, twenty ink-jet printing trials were conducted to find the best way to replicate the color from the screen-printed sample. When disperse dye or pigment was used to print on pre-treated polyester. It is also found that digital textile ink-jet printing cannot achieve some specific colors which at least one Lab values close to 0 or 100 that screen printing can do. In other word, very high or low saturated color. In addition, in this situation, disperse dye have noticeable wider color gamut than pigment (Appendix K). However, after discussion with the designers from both company X and Y, the PI chose one print trial (Sample B) was conducted using combination A (Nano-pigment and cotton) which is well-matched with e screen printed sample to conduct the expert visual assessment.

#### 3.4.6.4.Necessity of Pre-treatment Process

Process pretreatment of textile is a mechanic and chemical process to textile materials made from both natural and synthetic fiber before the dyeing, printing and finishing process. The purpose of fabric pre-treatment is to remove all impurities to ensure the fabric is ready for the next step. Pre-treatment for disperse dye is usually required. However, fabric used for pigment printing is not required to be pretreated because no chemical reaction occurs. Pre-treatment is optional, as it can increase the color gamut. The pre-treatment process for polyester pretreated for disperse dye (combination C) was especially time-consuming, and the chemical that was used for pre-treatment also is expensive and harmful to the environment. If the non-pretreated fabric can produce an acceptable effect on printing quality for the screen printing replication process, then it will lower costs, save time and ink-jet printing will be more environmentally friendly. Therefore, both pretreated, and non-pretreated samples for design B1 and B2 (combination C) were printed to see whether the pretreatment process has a significant effect on the replacement process (Figure 38).

As shown in Figure 35, pre-treatment has a significant effect on the color gamut, it is obvious that the pre-treated PET fabric has a richer color gamut that can achieve deep color with high colorant concentration.



(1) Non-Pretreated PET Fabric (2) Pretreated PET Fabric

**Figure 38:** Comparison for Pretreated and Non-Pretreated PET Fabric (Color)

In addition, pretreated can significantly increase the printing line quality. If we magnify an arbitrarily area in Figure 38, it can be clearly found that there is some tiny white line on the non-pretreated fabric. Moreover, the pattern printed on the non-pretreated fabric is vague but it is clear on the pre-treated fabric. That is because the line quality can further influence the overall printing quality as well as the visual assessment process in stage two.

**Figure 39:** Comparison for Non-Pretreated and Pretreated PET Fabric (Line Quality)

So, it is an unavoidable process for the digital printing process to gain high quality products. According to the conclusion, PI used pre-treated fabric for all the print trials. Both cotton and polyester fabric are pretreated before printing.

**3.4.6.5.Post-treatment (Heat Setting and Wash & Dry)**

Both printed PET substrate fabric and the cotton substrate fabric were heat-set after printing by using a Practix Mfg heat calendar with different fixation temperatures and minute dwell times. Figure 40 shown the front picture of Practix Mfg heat calendar. For the printed

PET substrate, the fixation temperature was 340 degrees Fahrenheit with a one-minute dwell time. For the printed cotton substrate, the fixation temperature was 400 degrees Fahrenheit with 30 seconds of dwell time. For pigment inks, no steaming, fixation or washing process was required (Ervine et al., 2000; Sayed & Khobian, 2003). Therefore, only the PET was washed after printing. Washing and pretreatment of the PET fabric are described in Appendix I.

**Figure 40:** Practix Mfg heat calendar

In addition, it is found that the color printed by disperse dye shift a lot after fixation, however, the color printed by nano-pigment ink didn’t changed a lot. This effect confirmed the results in literature review that for disperse dye, color is brighter after fixation and color fastness and UV stability also increase (Clark, 2003; Fan et al., 2006).

## 3.5. Stage Two: Expert Visual Assessment and Protocol Development and Validation

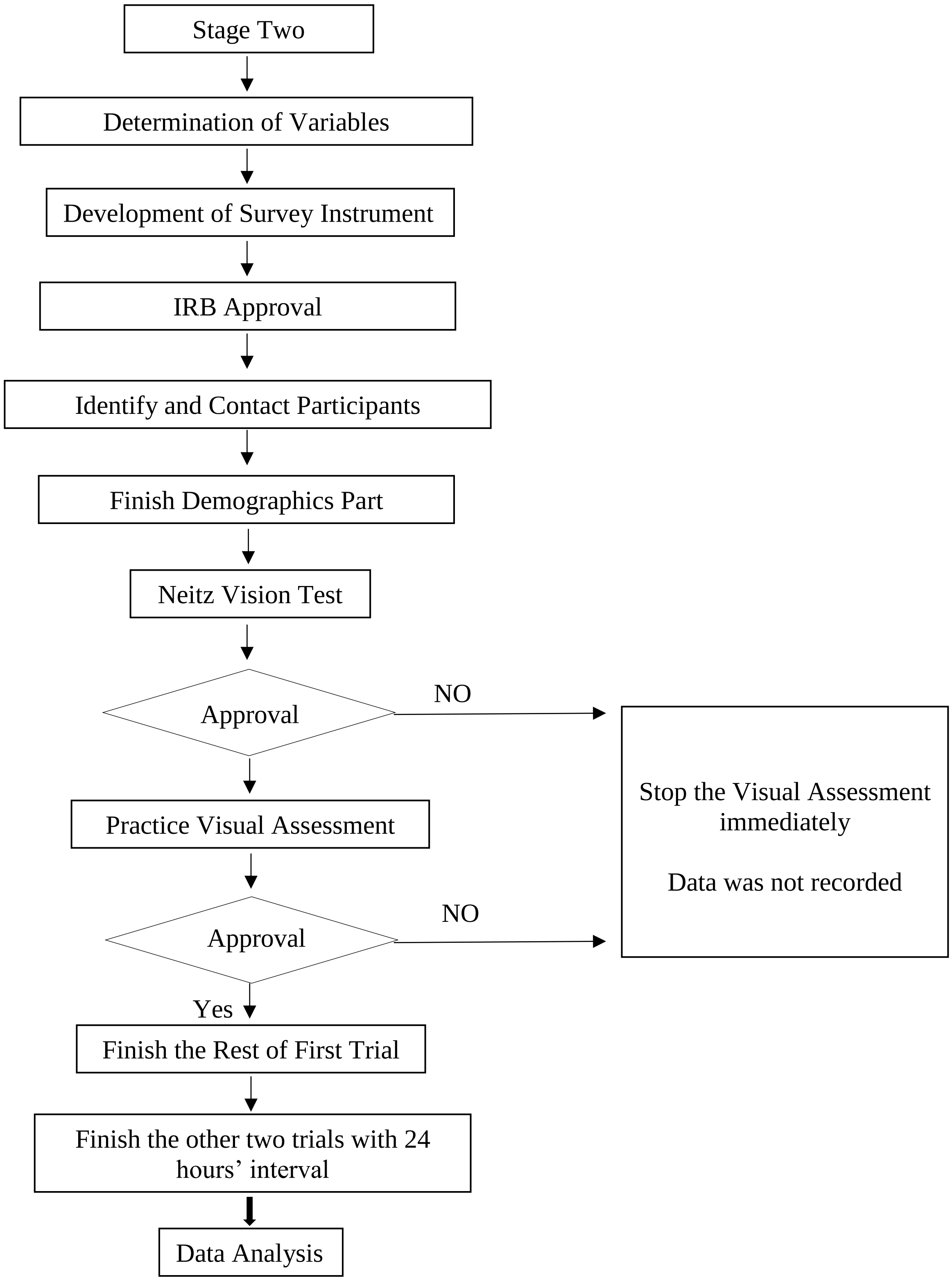



**Figure 41:** Expert Visual Assessment Protocol

After successfully conducting stage one, the second objective of this study is to develop a visual assessment instrument and protocol to evaluate the acceptance of the replicated ink-jet printed fabric. As shown in Figure 41, an expert visual assessment protocol was established during the research process. All the steps that listed in Figure 40 were discussed in the following sections.

Only one ink-jet printed sample was selected and approved by PI to conduct stage two, which is expert visual assessment and protocol development and validation. The sample was printed by pigment ink though MS JP5 ink-jet textile printer on pre-treated cotton fabric. The screen-printed sample (Target) was labeled as sample A in stage one, for research convenience, the digitally printed sample was labeled as sample B. As shown in Figure 42, there is a small color difference between samples A and sample B. That difference indicated that a visual assessment should be conducted to define the appearance difference between the digitally printed and screen-printed sample.

(a) Screen Printed Sample A (b) Digital Printed Sample B

**Figure 42:** Digital Printed and Screen-printed Sample Comparison

#### 3.5.1.1.Determination of Variables

After finishing Stage One, to conduct the visual assessment comparison between screen-printed sample (Sample A) and ink-jet printed sample (Sample B), variables need to be determined before designing the survey instrument.

Substrate and colorant combination as well as pre-treatment and post-treatment process were two important variables. These two variables were already eliminated during Stage One. Regarding to substrate and colorant combination, three combination (A, B, C) were examined, however, only one ink-jet printed sample was selected and approved by PI to conduct stage two. It is printed by pigment ink though MS JP5 ink-jet textile printer on pre-treated cotton fabric (Combination A). Regarding to pre-treatment and post-treatment process, all the fabric used for ink-jet textile printing were pre-treated. Pretreatment was determined necessary for the ink-jet textile printing process in Stage One. All the ink-jet printed fabric was fixed after printing.

Based on Knox (2014), and Dr. Shamey's (2011) previous work of visual assessment, six variables were chosen to evaluate the appearance difference: color difference, overall color, scale, line quality, visual texture, and overall appearance. Color difference was used to determine how close the color matched between ink-jet printed sample and screen-printed sample, which including comparison between color value matching and lightness of each single color listed on color key. Overall color would be used to evaluate how overall appearance of ink-jet printed sample match the screen-printed sample. Scale would be used to evaluate how correct the size proportion of ink-jet printed sample match the screen-printed sample. Line quality would be used to evaluate how well the weight, clarity, and uniformity of the stripes in the ink-jet printed sample compare to the screen-printed sample. Visual texture would be used to evaluate the ability of ink-jet printed sample replicate the woven structure appeared on screen-printed sample. Overall appearance would be used to evaluate the ability how well color, scale, line quality, and visual texture appear to interact in the ink-jet printed sample compared to the screen-printed sample.

Frequency to assess the samples is another variable need to be determined. According to the American Association of Textile Chemists and Colorists (AATCC) standard, the Principal Investigator decided that each participant would repeat the assessment three times with 24 hours between each trial. The time interval was needed as participants may memorize their answers or get tired if they complete three trials at once. To ensure the three separate trails are consisted, an analysis of the consistency between the three separated trials was also conducted in the result section.

In addition, to eliminate the variables and error that may occur due to unfamiliarity, as well as increase the results accuracy and consistency between three trials, a practice experiment was recommended. One blue sample pair from AATCC was used for practice before the official experiment. Moreover, to smooth and streamline the assessment process, all the participants in the assessment were experienced experts in fabric design, color matching, screen printing, ink-jet printing, apparel product development, home interior product development and other related areas.  All participants had some experience in approving color samples and familiar with the visual assessment process.

Finally, the participants must have the normal color vision. Neitz test (Appendix F) was used to determine whether one has normal or abnormal vision. Participants were required to take the test before they would start official experiment. If they pass the test, they would continue the assessment. Otherwise, they would stop the assessment immediately.

**3.5.1.2.Scale Description**

There were two kinds of comparison between Sample A (Screen-printed on the pre-treated cotton substrate) and sample B (digitally printed on the pre-treated cotton substrate), which were single color visual assessment and overall color visual assessment.

Regarding the single color visual assessment, seven colors picked up from the design A which labeled from Color 1 to Color 7 were evaluating. These seven colors can typically represent the color of the design and labeled from Color 1 to Color 7. As shown in Color key (Appendix D), Color 1 is Black, Color 2 is Yellow, Color 3 is Dark Green, Color 4 is Gray, Color 5 is Blue, Color 6 is Red, and Color 7 is Cyan. Participants evaluating the single-color change level using AATCC Gray Scale and their answers were recorded. Nine-step semantic differential scale with values ranging from 5 to 1 was used in the AATCC (American Association of Textile Chemists and Colorists) Gray Scale (Appendix E). AATCC Gray Scale was designed to identify color shade differences in lightness, hue, and chroma. The participant can move AATCC Gray Scale freely to compare the color difference without moving 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. The lightness, overall color appearance, scale, line quality, texture, overall color matching level were answered then by observation. For a copy of the AATCC Evaluation Procedure 1 in Appendix E and for a depiction of the gray scale, in Figure 43 below.


**Figure 43:** Gray Scale for Color Change (AATCC)

Regarding overall color visual assessment. Five various levels were given to participants to describe the overall color matching level between two samples (A and B). Five feasible options were given to participants which were Not at all (1), Slightly (2), Somewhat (3), Mostly (4), and Exactly (5), and each option was given a number for statistics analysis purpose. These options were for participants to describe their answers regarding overall color matching, line quality, visual texture and overall appearance for sample A and B. Regarding the question of scale matching, participants gave an answer of either yes or no.

**3.5.1.3.Development of Survey Instrument**

After determination of variables and review the previous work, a survey instrument was developed based on the previous work of Knox (2014) and Shamey (2011). PI refined the survey instrument for this research and developed the questions of survey instrument. The survey instrument was then input online by using *freeonlinesurveys.com* to make gathering data easier and to protect the anonymity of the participants. The survey was submitted to North Carolina State University's Institutional Review Board (IRB) for approval (Appendix A) before starting assessment.

The online survey is 9 pages and includes questions relating to three trials the participants were to complete. Each participant would repeat the assessment three times with 24 hours between each trial. During the first trial, participants were asked to finish pages 1 to 5, which including informed consent (page 1), demographics (2), Neitz vision test and practice visual assessment test (3), first assessment trial (4, 5). After gathering the basic information from the first three pages, participants didn't have to do it again. During the second and third trials, participants were asked to finish second assessment trial (6, 7) and third assessment trial (7, 8), respectively. However, in the pages of the second (6, 7) and third assessment trial (7, 8), the instrument repeated the same questions were asked in first assessment trial (4, 5). As a matter of fact, each participant repeated the assessment three times. PI would not inform the participants that the same questions were used as in the first assessment trial. Therefore, after 24 hours' interval between each trial, it reduced the possibility that participants recognized the question and give the same answer. Questions of this visual instrument were introduced as follows.

In the first page, the NC State informed consent form was given to participants, which allows them to choose either "I accept" or "I don't accept" to take part in the research. In the second page, questions 2-7 addressed participants' demographics. Question 2 records a participant's gender. As females and males may have different preferences on color (Bakker, Voordt, Vink, Boon and Bazley, C, 2015), the PI attempted to try to control for this factor by finding six female and male observers. Question 3 asks for participant's year of birth. The PI included this question to try to control for factors affected by participants' ages, and to include a wider age range than might be expected otherwise. Question 4 identifies the specific fields of expertise of the participant, and allows each participant to choose up to two area from the options of fabric design, color matching, screen printing, ink-jet printing, apparel product development and home interior product development. If a participant's focus area is not listed, then the participant could complete the blank for "other" at the bottom of the questionnaire. Question 5 asks the occupation of the participant, and because only experts were invited to conduct visual assessment, that question offers only three options: experienced educator/professor, industry professional or Ph.D. student from color science or digital printing. Each participant could select one occupation from those three occupational options. Questions 6 and 7 classifies the sample approval experience of participants by asking the length of time (Q6) they have been assessing color and the frequency (Q7) with which they have been making color assessments. For question 6, which asks the length of time, participants have six options, from no experience to “6 or more years.” For question 7, participants can choose one to three times a week, one to three times a month, one to three times a year or never.

In the third page, participants select “yes” or “no” according to whether they have passed the Neitz test. The answer determined whether they could continue the survey or discontinue it. As Knox (2014) stated, “The Nietz test for color vision was given to each participant to screen for a red-green and/or yellow-blue color deficiency.” The results will be checked by the Principal Investigator, if they fail the Neitz test (color blind), they must stop the survey; Otherwise, they can continue to question 9.

Before they answer question 9, prospective participants were tested with a pair of blue fabric samples, one light blue and one dark blue (Figure 44) from the AATCC. This sample testing, based on an approved, standard measurement, was to give participants a better understanding of how to use the AATCC Gray Scale to identify color differences. According to the AATCC Gray Scale principle (Appendix E), the value 5 means no perceived shade change and the value 1 means the highest level of perceived shade change. Question 9 uses a nine-step semantic differential scale with values ranging from 5 to 1, which represents the same meaning as the AATCC Gray Scale. Participants’ answers were compared to the previous data to determine each participant’s ability to observe color change. Previous data were already gathered by AATCC, the acceptable answer range given by AATCC technician is from 1.5 to 2.5. If the prospective participant’s answer was in that acceptable range of difference, then that participant continued to answer question 10, otherwise they have to stop and the information gathered from this participant will not be recorded.

Participants would continue to finish the first assessment trial, which contains page four and page five. Page four was titled as Single color visual assessment part 2. In page four, seven colors were selected from Design A and named Color 1 to Color 7 (Appendix D) by the PI, and were evaluated by observers one by one. The screen-printed on the pretreated cotton substrate sample (Sample A) and the ink-jet printed nano-pigment sample on the pretreated cotton substrate (Sample B) were compared using the AATCC Gray Scale. In question 10, sample A and sample B were compared by using AATCC Gray Scale for Color 1 to color 7. A nine-step semantic differential scale with values ranging from 5 to 1 (Appendix E) was used and the results recorded. In question 11, the values (lightness and darkness) of these two samples Color 1 through Color 7 were compared. For Color 1 to color 7, participants chose either “A is lighter than B,” “A is the same lightness as B” or “B is lighter than A.”

Page five was titled as Single Color Visual Assessment part 2, which consisted of questions 12 to 17. These questions were about differences in overall color appearance, scale, line quality, visual texture, overall appearance and overall color matching between sample A and sample B. All the answers had the same five-point scale except question 13, which offered a distinct set of options about whether the scales match: not at all, slightly, somewhat, mostly and exactly. Participants were to choose one answer from these five options. Question 12 asked about the overall color appearance matching. Question 13 asked about the scale matching. Question 14 asked for judgments about the line quality of sample A and sample B.

Question 15 asked about the visual texture matching; and question 16 asked about the overall appearance matching. Question 17 asked participants a question about cost: "If fabric design A and B were made as product A and B, as a customer, would you be willing to pay the same price for these two products? "From the responses to this question, participants' assessments of the overall matching level of samples A and sample B were obtained.

During the second trial, pages 6 and page 7, contained single color visual assessment part 2 and overall color visual assessment part 2. In page 6, which is single color visual assessment part 2, questions 18 and 19 is the same as question 10 and 11 in single color visual assessment part 1; In page 7, the question in overall color visual assessment part 2 from 20 to 25 is the same as questions 12 to 17.

During the third trial, pages 8 and page 9, contained single color visual assessment part 3 and the overall color visual assessment part 3. In page 8, single color visual assessment part 3, questions 26 and 27 are also the same as in questions 10 and 11. In page 9, overall color visual assessment part 3, questions 28 to 33 are also the same as overall color visual assessment part 1.

### 3.5.2. Validation of Expert Visual Assessment and Protocol

The third objective of this study is to determine if the ink-jet digital printed sample was a suitable substitute for screen printed sample via an expert visual assessment testing. In this part, a survey instrument was developed and total 12 participants, six males and six females, finished expert visual assessment. Regarding to previous literature review, experienced participants are recommended rather than inexperienced participants to increase the accuracy and shorten the total experiment time (Shamey et al., 2010). Therefore, all the participants are experienced industry professionals and Ph.D. or professors were doing research in color science field. All observers must pass the test visual assessment normal color vision tests. The observation environment which include consistent viewing conditions, a consistent size of test specimen, proximity of the observer to the sample, and level of illumination, were controlled and be the same throughout the whole experiment process (Fairchild, 2005, ASTM D 1729). Data gathered via visual assessment were recoded and would be analyzed in the next chapter.

#### 3.5.2.1.Identify and Contact Participants

Since the online survey was designed to be a visual assessment by experts, a list of possible participants either from experienced industry practitioners or Ph.D. professors from North Carolina State University was created. All the industry practitioners were working in the areas of fabric design, apparel product development, home interior product development, color matching, ink-jet printing, or screen printing. All the Ph.D. or professors were doing research in color science field. Research information and invitations were send out through email to 25 prospective participants (Appendix B). To help control for any possible effects caused by gender and occupation, six females and six male participants, and six from industry and six from academia, were selected.  All 12 participants passed the Neitz Test and finished all three trials. Data gathered from them were recorded and analyzed based on the results.

#### 3.5.2.2.Preparation of Samples

Design A was selected and textile ink-jet printed on the pretreated cotton substrate as digital printed sample B. The screen textile printed on the pretreated cotton substrate sample

A was provided by company X. Since the PI has to mail the original sample A back to company X without cutting or sewing after experiment, the screen printed sample A and the digital printed sample B were both folded into 17.5 x16 inch rectangles (Figure 45). The pattern shown was smaller than one motif to protect the copyright of company X. Every color used in Design A was shown. The PI selected seven colors, designated from 1 to 7, to conduct the visual assessment. Seven colors were picked up from the Sample A. These seven colors can typically represent the color of the design and are labeled from Color 1 to Color 7. In Appendix D, Color 1 is Black, Color 2 is Yellow, Color 3 is Dark Green, Color 4 is Gray, Color 5 is Blue, Color 6 is Red, and Color 7 is Cyan.

#### 3.5.2.3. Samples Viewing Condition

The visual assessments were carried out in the Color Science Lab in College of Textiles at North Carolina State University by using a set of AATCC test samples and sample pair A and B. To minimize variability, the 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 was the only illumination in the lab because the PI turned off all the lights except this one. Meanwhile, the screen of the electronic device that was used to display the survey instrument was set at the lowest light level to further minimize light effects from that source. The samples were placed on a 15 x 15 inch medium gray-colored PVC easel, which was set at a 45-degree angle at the center of the viewing booth. One 15 x 15 inch medium gray-colored PVC easel was used to do the test sample viewing. Two 15 x 15 inch medium gray-colored PVC easels were used, one for viewing the screen-printed sample and one for viewing the digital printed sample because those two samples were bigger. The lamp of the viewing booth has a color temperature of 6500 ± 200 K and constant illumination of approximately 1400 lx (Shamey, Cardenas, Hinks, & Woodard, 2010; Knox, 2014).

#### 3.5.2.4.Sample Viewing Protocol

The participants wore a pair of gray gloves to minimize color variability as well as to prevent damaging the samples and AATCC gray scales. The participants sat in front of the Macbeth Spectra Light III viewing booth the filtered tungsten daylight-simulating lamp (D65) was turned on by the Principal Investigator (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 were adapted to the viewing conditions in the lab, the first page of the survey instrument, which was the informed consent form, was shown to them. Once they gave their consent, the Nietz Color Vision Test (Appendix F) was given to the participants and their answers were judged by the PI immediately. While the PI scored their answers, the participants were asked to complete page 2 of the survey, which asked for demographic information. The PI assigned a pass or fail score to each participant based on that participant's answers to the Nietz Color Vision Test. Then page 3 was shown to the participants, where they would see question 8, "Did you successfully pass the Neitz Test of Color Vision?" If a participant failed the test, then that participant would enter "no" as the response for question 8 and the experiment would be immediately stopped. When the participant had passed the test, that participant would respond “yes” to question 8 and the experiment would continue on to the test sample viewing step.

For question 9, the test samples which were previously printed for the AATCC Color Change Evaluation Proficiency Testing Program were provided to participants so they could practice viewing samples.

A pair of blue 3 x 3 inch samples were placed in the viewing booth on the easel with a hairline gap between them (Figure 44). Participants sat in front of the viewing booth with gray gloves on so they could use the AATCC Gray Scale freely to identify the color shade change for this pair of samples. The PI stood near them and assisted them with using the AATCC Gray Scale as needed until they could use it correctly. Participants’ answers were compared to the previous data to determine each participant’s ability to observe color change. Previous data were already gathered by AATCC, the acceptable answer range given by AATCC technician is from 1.5 to 2.5. If the prospective participant’s answer was in that acceptable range of difference, then that participant continued to answer question 10, otherwise they had to stop. By observing participants’ performances and comparing their answers to the suggested answer, the PI decided whether an individual participant could continue in the experiment or not.

**Figure 44:** Viewing Booth Set Up for AATCC Test Samples

After practicing the AATCC Gray Scale by approving AATCC Blue sample (Figure 45), participants performed single color visual assessment part 1 (page 4 of the survey instrument), overall color visual assessment part 1 (page 5) was given to participants. The color key of Design A was also provided to the participants, which pointed out the specific color that need to be observed for any noticeable changes from color one to color seven (Appendix D). Sample A, the screen-printed sample on the pretreated cotton, and Sample B, the digital printed sample on the pretreated cotton using nano-pigment inks, were identified by labels on the back of the 15 x 15 inch medium gray-colored PVC easel (one for each sample) to maintain consistency during experiment.

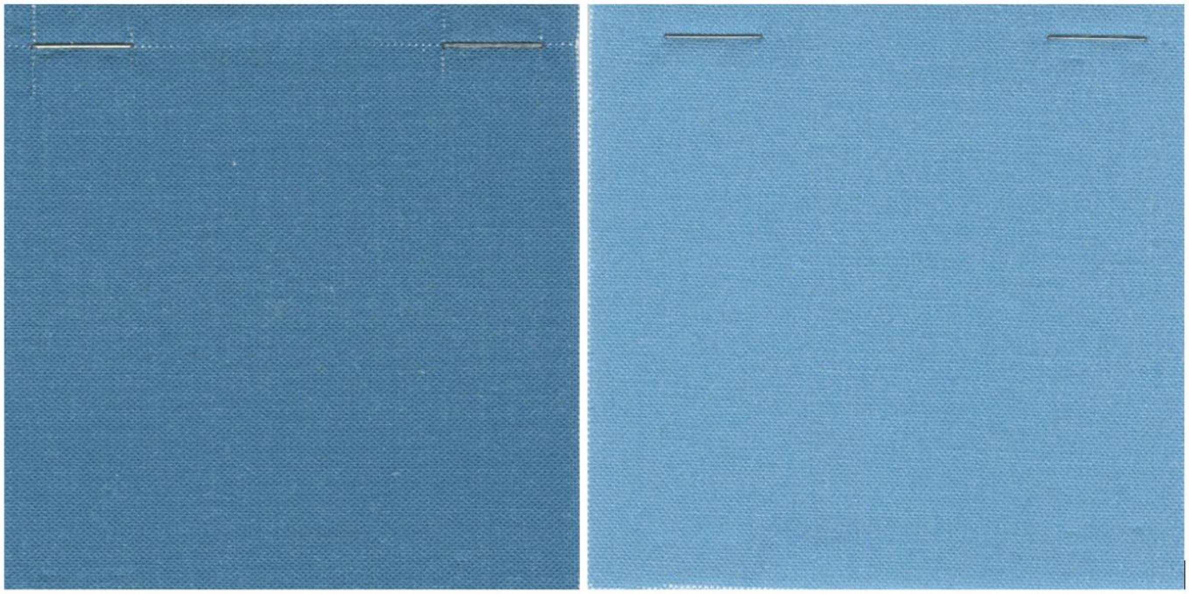


**Figure 45:** AATCC Blue Sample Printed on Cotton Sateen with Nano Pigments

The sample set-up in the viewing booth is shown in Figure 46. Sample A is on the left side, and Sample B is on the right side. The participants were free to move the color key and AATCC Gray Scale to identify the color change value for the seven corresponding colors between the pair of samples, but they were not allowed to move or change the display of samples. They were asked to finish all the questions for single color visual assessment part 1 (page 4) and overall color visual assessment part 1 (page 5), and their answers were recorded.


**Figure 46:** Viewing Booth Set Up for Samples A and B

Parts 2 and 3 of single color visual assessment and overall color visual assessment with the same question as part 1 were repeated, typically 24 hours between these three trials. Participants in these two parts assessed only Sample A and Sample B. The same sample sets, the same viewing booth, and the same viewing conditions were kept in each trial.

### 3.5.3. Challenge

The sample set of visual assessments conducted for comparing Sample A and Sample B did not exactly follow the AATCC visual assessment standard, which brought a big challenge for viewing accuracy. As shown in Figure 47, for test sample viewing which used AATCC standard, a pair of samples with only one blue color were placed adjacent with a hairline gap between them. For the multi-color sample A that provided by Company X, many colors were printed in the fabric and interacted with each other when viewing the samples. In addition, the seven-corresponding color couldn't be adjacent, since moving around the samples would increase the variability of the experiment. A distance existed between the corresponding color during the experiment, which increased viewing difficulty. At the beginning, the PI considered picking up the seven colors from Sample A and printing the seven-color spot one by one, then approving it separately. But this way, each color would lose connection with the other, which is different from the real color effect of products. After gathering suggestions from both industry practitioners and professors, the PI was informed that the visual assessment protocol used in this study was closer to the real industry standard rather than the AATCC visual assessment standard. In addition, using all experienced expert participants also increased the accuracy of the results. Thus, the PI believed the challenge existed but the results were still valid.

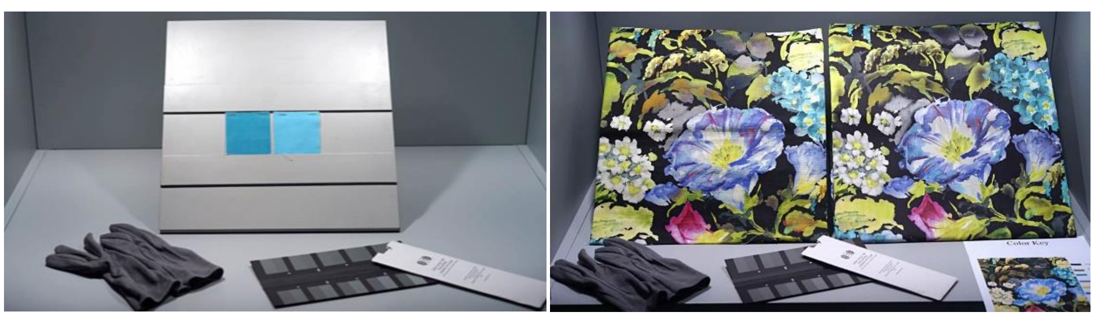


**Figure 47:** AATCC Visual Assessment Standard Sample (left) and Sample Pair

# 4. CHAPTER 4: RESULTS AND DISCUSSION

In this chapter, data gathered from Stage Two was analyzed to evaluate the acceptance of the replication of the screen-printed sample via ink-jet digital printing, and to explore the potential for of digital ink-jet printing to replace the traditional screen printing.

## 4.1. Print Trials Results

Ink-jet printed sample B was selected and approved by PI to conduct expert visual assessment. It was printed by MS JP5 printer with pigment ink onto pretreated cotton fabric. The combination A (nano-pigment and cotton) was approved as the optimal colorant and substrate combination to replicate the screen-printed sample due to its well-matched appearance. There was a small color difference between samples A and sample B. That difference indicated that a visual assessment should be conducted to define the appearance difference between the digitally printed and screen-printed sample.

For the other two colorant and substrate combination, the performance of black color concentration in disperse dyes and pigment inks on polyester fabric is lower for digital printing. For example, in the combination B, design B1 was printed with pigment ink on the polyester fabric. However, the deep black Background (Appendix D) was badly out of color gamut. Ink-jet printing could not achieve such high concentration of inks like screen printing did. The same situation happened in combination C, design B1 printed with disperse dye on the polyester fabric. The deep red Color 7 of design B1 was also out of color gamut (Appendix J) , which proved that, on this combination (disperse dye and polyester), the same high concentration of disperse dye as screen printing cannot be achieved via ink-jet textile printing.

Pre-treatment has a significant effect on the printing quality, so it is an unavoidable process for the digital printing process to gain good quality products. In addition, it is found that the color printed by disperse dye shifts a lot after fixation, while the color printed by nano-pigment ink did not change a lot. This effect proved the knowledge in literature review; for disperse dye, color is brighter after fixation and color fastness and UV stability also increase (Clark, 2003; Fan et al., 2006).

## 4.2. Subjects Characteristics

A total of 25 possible participants either working in U.S. textile industry or Ph.D. students were e-mailed in North Carolina State University. Twelve of them (48% of the possible participants) finished the visual assessment and their answers were recorded. To eliminate the gender influence on the results, six males and six females were involved in the assessment (Figure 48). Half of participants identified themselves as female (50.0%) and the other half identified themselves as male (50.0%).

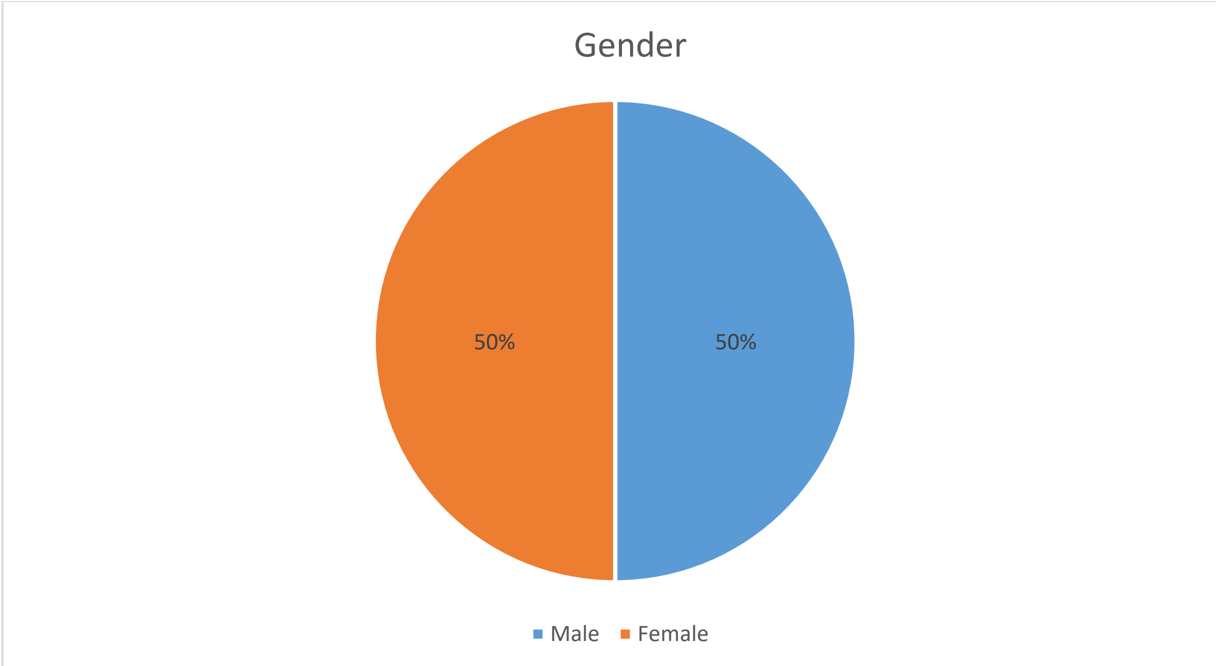



**Figure 48:** Gender in Percentage of Participants

The participants' ages were quite different. Young, middle aged and senior participants were all involved in the experiment. As shown in Figure 49, 32 percent of participants were born after 1990, 15 percent were born before 1979, and more than half (53 percent) of participants were born between 1980 and 1989.

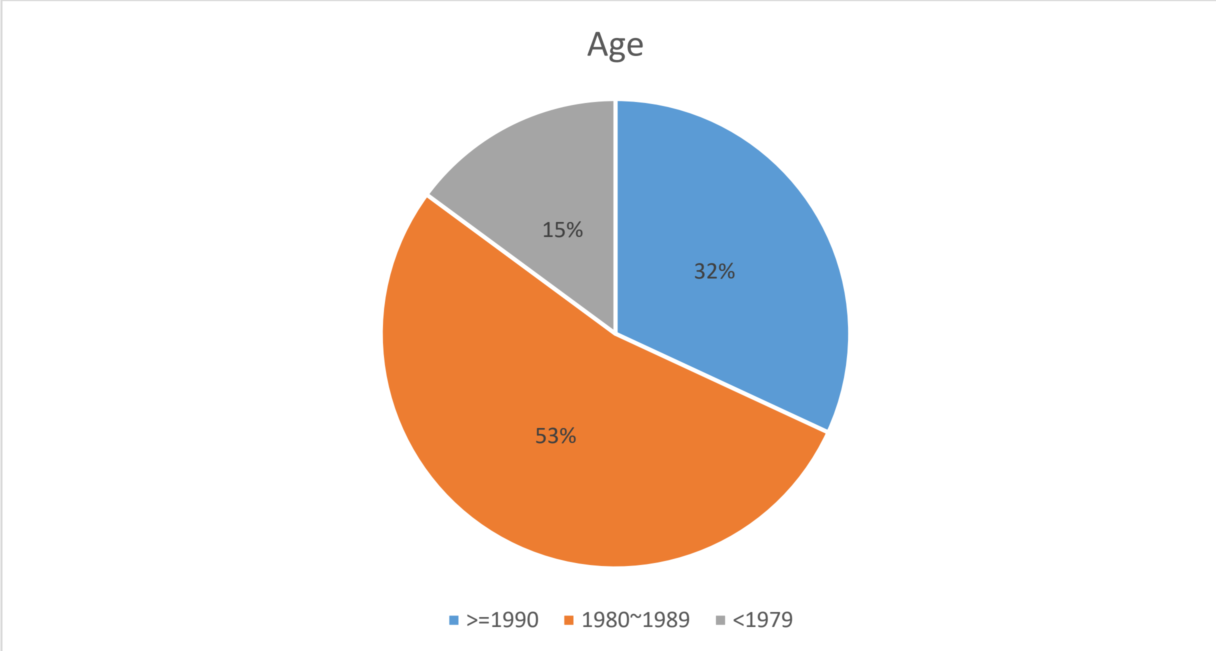



**Figure 49:** Year of Birth Response

As shown in Table 14, the minimum birth year was 1950 (66 years old), the maximum birth year was 1994 (about 22 years old), and 1978 (38 years old) was the mean birth year identified for all participants.

**Table 14:** Year of Birth Response (Mean & Range)

| | Mean |
|---|---|
| Birth Year | 1978.917 |
| Range | 1950~1994 |

Since six participants are Ph.D. students from North Carolina State University, six participants are from the U.S. textile industry. As in Figure 50, half the participants (6) identified their occupation as an/a Educator/Professor (50.0%), with the other half identifying their occupation as an Industry Professional (50.0%).

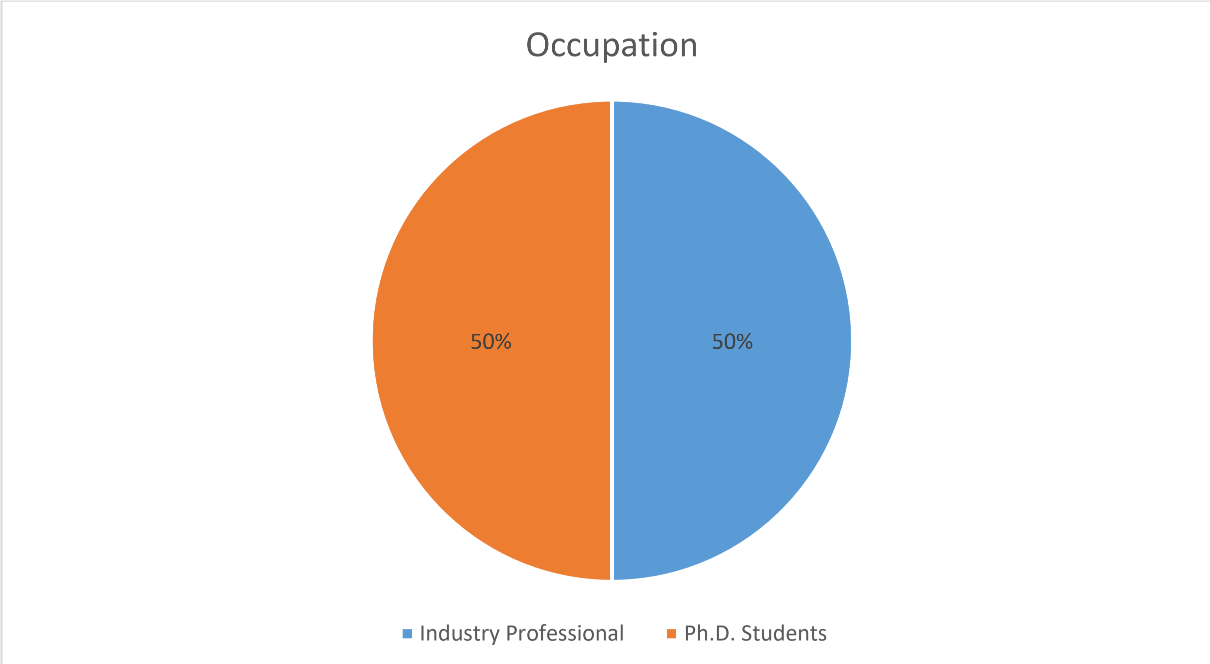



**Figure 50:** Occupation in Percentage of Participants

Table 15 shows that every participant selected at least one and up to three work areas. Participants also identified their specialization in the areas of fabric design (16.7%), color matching (41.7%), screen printing (0.0%), ink jet printing (41.7%), apparel product development (16.7%), home interior product development (0.0%), and other (25%).

**Table 15:** Area of Work Response

| Area of work | **Percent (%)** |
| --- | --- |
| Fabric Design | 16.7% |
| Color Matching | 41.7% |
| Screen Printing | 0.0% |
| Ink Jet Printing | 41.7% |
| Apparel Product Development | 16.7% |
| Home Interior Product | 0.0% |
| Other | 25% |

Note*: Each participant selected at least one and up to three of work (12 total responses).

A total of 17 responses were gathered, and the percentages reflect how many times this option was selected in the total 17 responses. Occupations provided by participants were association executive, dyeing, textile color matching method, and textile Chemistry (Table 16).

**Table 16:** Text Response (other)

| Area of work | Response number |
|---|---|
| Dyeing | 1 |
| Association Executive | 1 |
| Color Matching Testing Method | 1 |

Length of time and frequency of approving sample color difference reflected the participants' level of experience in visual assessment. For the length of time, as shown in Figure 51, the majority of participants identified their sample approval experience as 2-3 years (42%), 6 or more years (25%), 7 months to a year (17%), 1-6 months (8%), 4-5 years (6.7%). No one had never approved samples (0.0%). The standard deviation of the sample approving experience was 1.63.

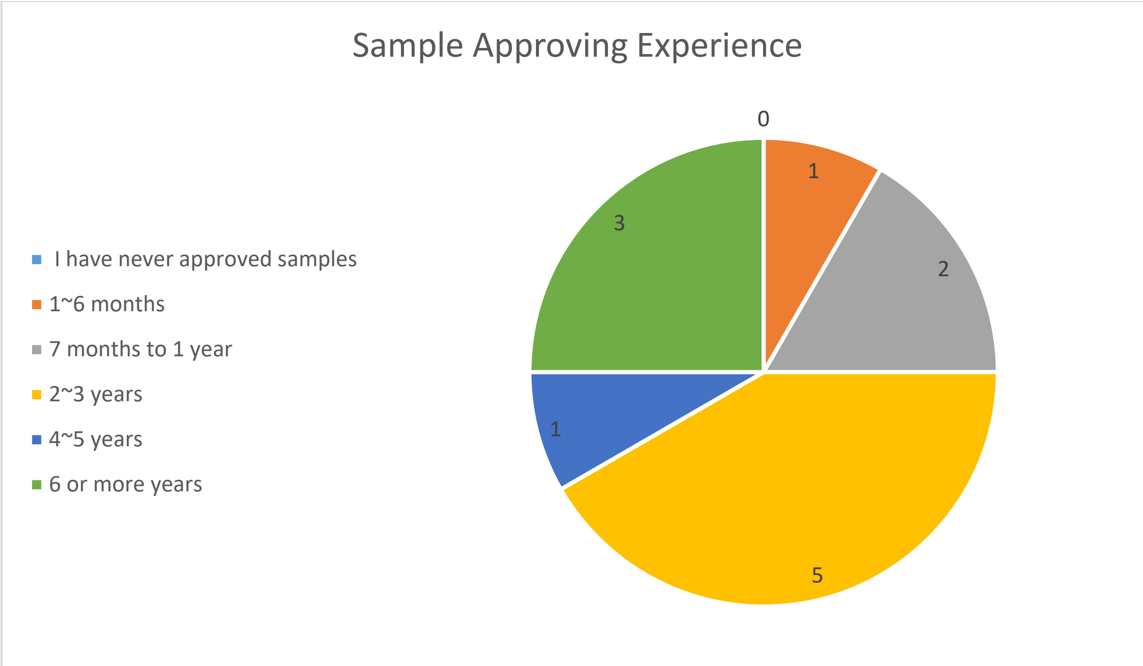



**Figure 51:** Sample Approving Experience

For the frequency, as shown Figure 52, most participants selected 1-3 times a week (42%) and 1-3 times a month (42%). Some selected 1-3 times a year (20%), and no one selected a frequency of never. The standard deviation of sample approval frequency is 2.12.

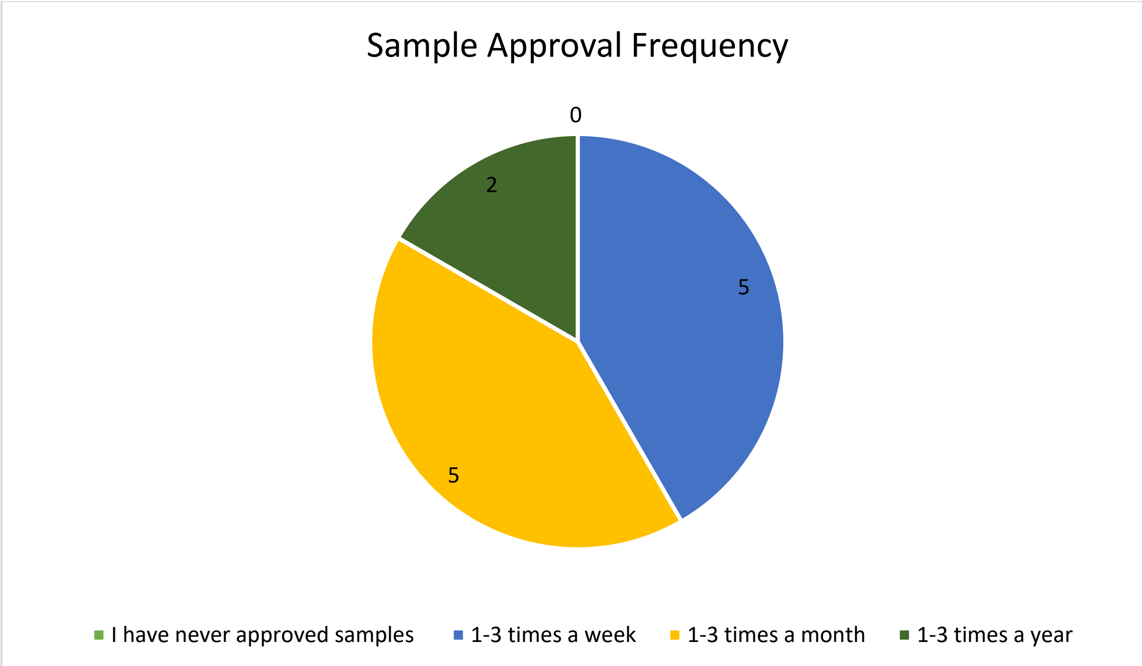



**Figure 52:** Sample Approval Frequency

After filling out the demographic part of the survey, participants took two tests. The first one was the Nietz test, which is used for a red-green and/or yellow-blue color deficiency. To validate the responses of the visual assessment, all the participants that attended the next step had to pass the test. The Principal Investigator evaluated the participants' Nietz test results and marked their results as "pass" or "fail." A "pass" score was defined as answering seven or more of the nine questions correctly. The version used for this experiment was the third version of the Nietz Test (Appendix F) and each version is the same for the color blindness test. All the participants (100%) passed the test, indicating there should be no negative mood influence on the next test step (Table 17).

There are three versions of the Nietz Test and all test equally for color blindness. The third version of the Nietz Test was used for this assessment and can is shown in Appendix G, along with the answer key.

**Table 17**: The Neitz Test Results

| | Percent (%) | Number |
|---|---|---|
| Yes | 100.0 | 12 |
| No | 0.0 | 0 |
| Total | 100.0 | 12 |

The second test was to practice the visual assessment by using AATCC Gray Scale. In the AATCC Gray Scale system, 1 means the most obvious color change, while 5 means no color change between two viewing samples. Participants assigned a number from a semantic differential scale with nine values to show their opinions of the color change value between the AATCC blue samples.

The PI identified the participants' understanding and ability to observe the sample color change using AATCC Gray Scale by referring to suggested color range. As shown in Table 18, a majority of participants identified their samples as 1.5 (58%); some participants identified their samples as 2 (33%), and fewer participants identified their samples as 2.5 (8.0%). Through discussing with AATCC technician, 1.5~2.5 is in the acceptable range, which indicated that participants understanding and ability to accurately perceive color shade change using the AATCC Gray Scale.

**Table 18:** Color change response for test sample

| Participants' Response | **Percent (%)** |
|---|---|
| 2.5 | 8% |
| 2 | 33% |
| 1.5 | 58% |
| Totally | 100% |
| Participants' Response Range | 1.5 ~ 2.5 |
| Acceptable Response Range | 1.5 ~ 2.5 |

## 4.3. Expert Visual Assessment Data Analysis

There were two kinds of comparisons between Sample A (screen-printed on the pre-treated cotton substrate) and sample B (digitally printed on the pre-treated cotton substrate), which were single color visual assessment and overall color visual assessment.

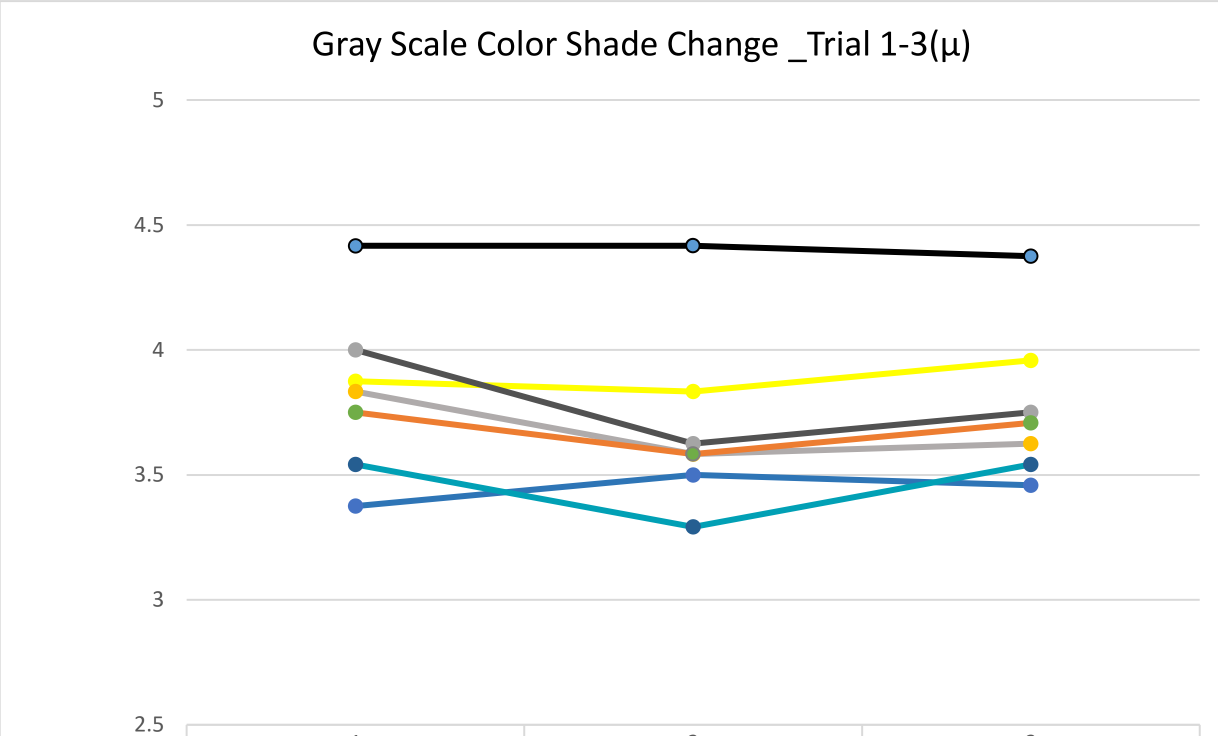
For the single color visual assessment, seven colors picked up from the design A, labeled Color 1 to Color 7, were evaluated. As shown in color key (Appendix D), Color 1 is Black, Color 2 is Yellow, Color 3 is Dark Green, Color 4 is Gray, Color 5 is Blue, Color 6 is Red, and Color 7 is Cyan. Participants evaluated the single-color change level using the AATCC Gray Scale and their answers were recorded. A nine-step semantic differential scale with values ranging from 5 to 1 was used in the AATCC (American Association of Textile Chemists and Colorists) Gray Scale. A number between 1 and 5 was given for each color by participants, with 5 representing no color difference between samples and 1 representing the highest color difference between samples.

Overall color difference was compared during this part of visual assessment. Five different options were used by participants to describe the overall color matching level between two samples (A and B). The five options were no match (1), slight match (2), somewhat (3), mostly (4), and exactly (5). Each option was given a number for statistical analysis. These options were used by participants to describe their answers regarding overall color matching, line quality, visual texture and overall appearance for sample A and B. Regarding the question of scale matching, participants answered either "yes" or "no."

Through talking with industry experts, there is a un-official industry standard, if the scale is above 3, it would be a good matched between two samples.

#### 4.3.1. Single Color Visual Assessment

For the single color visual assessment, seven colors were picked up from design A, labeled Color 1 to Color 7 for evaluation. Participants evaluated the color change level by using the AATCC Gray Scale and their answers were recorded. Sample A (screen-printed on the pre-treated cotton substrate) and sample B (digitally printed on the pre-treated cotton substrate) were compared. As we can see from Figure 53, Color 1 (Black) is obviously perceived to have the strongest shade change match for all three trials. Colors 2 (Yellow), Color 3 (Dark Green), Color 6 (Red) and Color 4 (Gray) are in the second strongest shade change match group. Color 3 (Dark Green) also has a big fluctuation between the three trials. Finally, the Color 5 (Blue) and Color 7 (Cyan) were perceived to have the weakest overall shade change match.




| | 1 | 2 | 3 |
|---|---|---|---|
| Color 1 | 4.4167 | 4.4167 | 4.375 |
| Color2 | 3.875 | 3.8333 | 3.9583 |
| Color3 | 4 | 3.625 | 3.75 |
| Color4 | 3.8333 | 3.5833 | 3.625 |
| Color5 | 3.375 | 3.5 | 3.4583 |
| Color6 | 3.75 | 3.5833 | 3.7083 |
| Color7 | 3.5417 | 3.2917 | 3.5417 |

**Figure 53:** Mean Responses for Gray Scale Color Change

Lightness is the most direct color visual effect and a very important quality index for a textile product. After identifying the single color change level, participants compared the lightness of each color and chose one option from three that best described the lightness relationship between two samples. The mean responses were consistent for all colors across all three trials of the assessment. As we can see from (Table 19), these three options presented as A is lighter than B1 (A>B), B1 is lighter than A (A<B), and A1 is the same

lightness as B (A=B). As shown in Table 19, most participants identified Color 1 (Black), Color 3 (Dark Green) and Color 4 (Gray) as appearing lighter in sample B1. The majority of participants identified Color 5 (Blue), Color 6 (Red) and Color 7 (Cyan) as appearing lighter in sample A, and besides that, almost 100 percent of participants identified Color 5 (Blue) and Color 7 (Cyan) as appearing lighter in sample A. For Color 2 (Yellow), it is hard to say what is the majority thought, but that result still indicated a color shade change in grayscale, the response was consistent.

**Table 19:** Perceived Light Selection

| | Lightness | Trial 1 (%) | Trial 2 (%) | Trial 3 (%) |
|---|---|---|---|---|
| Color 1 | A<B | 75.0 | 75.0 | 67.0 |
| | B<A | 17.0 | 25.0 | 33.0 |
| | A=B | 8.0 | 0.0 | 0.0 |
| Color 2 | A<B | 33.0 | 33.0 | 25.0 |
| | B<A | 42.0 | 50.0 | 75.0 |
| | A=B | 25.0 | 17.0 | 0.0 |
| Color 3 | A<B | 75.0 | 83.0 | 83.0 |
| | B<A | 8.0 | 8.0 | 8.0 |
| | A=B | 17.0 | 8.0 | 8.0 |
| Color 4 | A<B | 83.0 | 92.0 | 92.0 |
| | B<A | 17.0 | 8.0 | 8.0 |
| | A=B | 0.0 | 0.0 | 0.0 |
| Color 5 | A<B | 0.0 | 8.0 | 0.0 |
| | B<A | 100.0 | 92.0 | 100.0 |
| | A=B | 0.0 | 0.0 | 0.0 |
| Color 6 | A<B | 25.0 | 25.0 | 17.0 |
| | B<A | 67.0 | 75.0 | 83.0 |
| | A=B | 8.0 | 0.0 | 0.0 |
| Color 7 | A<B | 0.0 | 8.0 | 0.0 |
| | B<A | 100 | 92.0 | 100.0 |
| | A=B | 0.0 | 0.0 | 0.0 |

### 4.3.2. Overall Color Visual Assessment

The overall color effect change was analyzed in Table 20. A total of 12 answers were recorded, with standard deviations of 0.670, 0.450, and 0.450 for trials 1, 2 and 3, respectively. The means for these three trials are 3.500, 3.750, and 3.750, respectively, falling between Somewhat (3) and Mostly (4).

**Table 20:** Overall Color Appearance Response

| | Mean | Std. Deviation | N |
|---|---|---|---|
| Trial 1 | 3.5 | .67 | 12 |
| Trial 2 | 3.8 | .45 | 12 |
| Trial 3 | 3.8 | .45 | 12 |

Keeping the same scale is very important during the visual assessment process since different scales mean different color amounts participants can see in the samples. For the scale match response, all participants (100%) identified that the scales of sample A and B matched. In Table 21, the results identified the scale as being well matched during the whole experiment, keeping the color amount the same during all three trials.

**Table 21:** Scale Match Response

| | Trial 1 (%) | Trial 2 (%) | Trial 3 (%) |
|---|---|---|---|
| Yes | 100.0 | 100.0 | 100.0 |
| No | 0.0 | 0.0 | 0.0 |
| Total | 100.0 | 100.0 | 100.0 |

As we can see in Table 23. The mean response for line quality match between samples A and B are 3.500, 3.500 and 3.417 for trials 1, 2, and 3 respectively. The means fall between the selection options Somewhat (3) and Mostly (4).

**Table 22:** Line Quality Response

| | Mean | Std. Deviation | N |
|---|---|---|---|
| Trial 1 | 3.5 | .80 | 12 |
| Trial 2 | 3.5 | .52 | 12 |
| Trial 3 | 3.4 | .67 | 12 |

In Table 24, the mean responses for visual texture match between samples A and B are 3.250, 3.250, and 3.500 for trials 1, 2, and 3, respectively. The means fall between the selection options Slightly (2) and Somewhat (3).

**Table 23:** Visual Texture Response

| | Mean | Std. Deviation | N |
|---|---|---|---|
| Trial 1 | 3.3 | .62 | 12 |
| Trial 2 | 3.3 | .75 | 12 |
| Trial 3 | 3.5 | .52 | 12 |

As we can see in Table 25. The mean responses for overall appearance match between samples A and B are 3.667, 3.667, and 3.750 for trials 1, 2, and 3 respectively. The means fall between the selection options Somewhat (3) and Mostly (4).

**Table 24:** Overall Appearance Response

| | Mean | Std. Deviation | N |
|---|---|---|---|
| Trial 1 | 3.7 | .49 | 12 |
| Trial 2 | 3.7 | .49 | 12 |
| Trial 3 | 3.8 | .45 | 12 |

The last question asked if the fabrics A and B were made as products, would the participants as customers be willing to pay the same price for each product. This question was designed to determine whether the ink-jet printed sample quality was considered sufficient to replace the screen-printed sample. The average response for this question between samples A and B were 3.667, 3.667 and 3.750 for trials 1, 2, and 3, respectively. The means fall between the selection options Somewhat (3) and Mostly (4), which means the majority of participants would accept the ink-jet printed sample in place of the screen-printed sample (Table 25).

**Table 25:** Overall Matching

| | Mean | Std. Deviation | N |
|---|---|---|---|
| Trial 1 | 3.6 | .67 | 12 |
| Trial 2 | 3.5 | .90 | 12 |
| Trial 3 | 3.7 | .65 | 12 |

## 4.4. Correlation and Reliability Statistics

Although the viewing experiment was effectively controlled thorough the whole experiment process, the variables among observers may still exist, such as mood, fatigue or stress level, which may vary according to different trials (ASTM E 1499), influence by the researchers, or the experimental environment. For this reason, statistical analysis was conducted to examine the consistency and reliability of the results from all the three trials. Two methods, analysis of variance (ANOVA) and Pearson correlation reliabilities, were used to conduct the tests.

Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences among group means and their associated procedures (such as "variation" among and between groups), developed by statistician and evolutionary biologist Ronald

Fisher. In the ANOVA setting, the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are equal, and therefore generalizes the t-test to more than two groups. ANOVAs are useful for comparing (testing) three or more means (groups or variables) for statistical significance. It is conceptually similar to multiple two-sample t-tests, but is more conservative (results in less type I error) and is therefore suited to a wide range of practical problems.

ANOVA uses traditional standardized terminology. The definitional equation of sample variance is

$$s^2 = \frac{1}{n-1} \sum (y_i - \bar{y})^2,$$

Where the divisor is called the degrees of freedom (DF), the summation is called the sum of squares (SS), the result is called the mean square (MS) and the squared terms are deviations from the sample mean. ANOVA estimates 3 sample variances: a total variance based on all the observation deviations from the grand mean, an error variance based on all the observation deviations from their appropriate treatment means and a treatment variance. The treatment variance is based on the deviations of treatment means from the grand mean, the result being multiplied by the number of observations in each treatment to account for the difference between the variance of observations and the variance of means.

The fundamental technique is a partitioning of the total sum of squares SS into components related to the effects used in the model. For example, the model for a simplified ANOVA with one type of treatment at different levels.

$$SS_{\text{Total}} = SS_{\text{Error}} + SS_{\text{Treatments}}$$

The number of degrees of freedom DF can be partitioned in a similar way: one of these components (that for error) specifies a chi-squared distribution which describes the associated sum of squares, while the same is true for "treatments" if there is no treatment effect.

$$DF_{\text{Total}} = DF_{\text{Error}} + DF_{\text{Treatments}}$$

To determine whether any of the differences between the means are statistically significant, the investigator compares the p-value to the significance level to assess the null hypothesis. The null hypothesis states that the population means are all equal. Usually, a significance level (denoted as α or alpha) of 0.05 works well. A significance level of 0.05 indicates a 5% risk of concluding that a difference exists when there is no actual difference (Interpret the key results for One-Way, 2016, key-results /index.html). ANOVA was run to determine the relationship between the data collected for these three trials. The significance level of the seven individual color evaluation items was found to be more than 0.05, which means the results are positive. So, it is concluded that the results evaluation for these three trials are reliable without significant difference with each other. The three trials are continuous and reliable. For the ANOVA values for each of the six individual color evaluation items across the three trials, in Table 27 below. The color shade change difference response is also shown in Table 28 for comparison convenience.

**Table 26:** Color Difference - Analysis of Variance (ANOVA)

| | | SS | DF | MS | F | Sig |
|---|---|---|---|---|---|---|
| Color 1 | Between Groups | 0.14 | 2 | 0.007 | 0.079 | 0.924 |
| | Within Groups | 2.896. | 33 | 0.088 | | |
| | Total | 2.910 | 35 | | | |
| Color 2 | Between Groups | 0.097 | 2 | 0.049 | 0.405 | 0.670 |
| | Within Groups | 3.958 | 33 | 0.120 | | |
| | Total | 4.056 | 35 | | | |
| Color 3 | Between Groups | 0.875 | 2 | 0.437 | 2.287 | 0.117 |
| | Within Groups | 6.313 | 33 | 0.191 | | |
| | Total | 7.188 | 35 | | | |
| Color 4 | Between Groups | 0.431 | 2 | 0.215 | 1.714 | 0.196 |
| | Within Groups | 4.146 | 33 | 0.126 | | |
| | Total | 4.576 | 35 | | | |
| Color 5 | Between Groups | 0.097 | 2 | 0.049 | 0.255 | 0.776 |
| | Within Groups | 6.292 | 33 | 0.191 | | |
| | Total | 6.389 | 35 | | | |
| Color 6 | Between Groups | 0.181 | 2 | 0.090 | 0.317 | 0.730 |
| | Within Groups | 9.396 | 33 | 0.285 | | |
| | Total | 9.576 | 35 | | | |
| | Between Groups | 0.500 | 2 | 0.250 | 1.333 | 0.277 |
| Color 7 | Within Groups | 6.188 | 33 | 0.188 | | |
| | Total | 6.688 | 35 | | | |

As mentioned before, a significance level (denoted as α or alpha) of 0.05 works well. The significance level of the results regarding seven-individual color was found to be more than 0.05, it is concluded that the results evaluation for these three trials are reliable with no significant difference between the scores. The three trials are continuous and results are reliable.

**Table 27:** Color Shade Change Difference Response

| | | Mean | Std. Deviation | N |
|---|---|---|---|---|
| Color 1 | Trial 1 | 4.4 | 0.42 | 12 |
| | Trial 2 | 4.4 | 0.19 | 12 |
| | Trial 3 | 4.4 | 0.23 | 12 |
| Color 2 | Trial 1 | 3.9 | 0.38 | 12 |
| | Trial 2 | 3.8 | 0.39 | 12 |
| | Trial 3 | 4.0 | 0.26 | 12 |
| Color 3 | Trial 1 | 4.0 | 0.37 | 12 |
| | Trial 2 | 3.6 | 0.48 | 12 |
| | Trial 3 | 3.8 | 0.45 | 12 |
| Color 4 | Trial 1 | 3.8 | 0.39 | 12 |
| | Trial 2 | 3.6 | 0.36 | 12 |
| | Trial 3 | 3.6 | 0.31 | 12 |
| Color 5 | Trial 1 | 3.4 | 0.43 | 12 |
| | Trial 2 | 3.5 | 0.48 | 12 |
| | Trial 3 | 3.5 | 0.40 | 12 |
| Color 6 | Trial 1 | 3.8 | 0.50 | 12 |
| | Trial 2 | 3.6 | 0.56 | 12 |
| | Trial 3 | 3.7 | 0.54 | 12 |
| Color 7 | Trial 1 | 3.5 | 0.40 | 12 |
| | Trial 2 | 3.3 | 0.40 | 12 |
| | Trial 3 | 3.5 | 0.50 | 12 |

From Table 29, we can see that the significance level for Questions 11 to 17 is 0.429, 0.941, 0.549, 0.887 and 0.863, and all clearly above 0.05. From this analysis, we can see there is no significant difference between the three trials and the results are consistent (Table 29). These data indicate that the results are consistent and valid.

**Table 28:** Question 11 to 17 - Analysis of Variance (ANOVA)

| | | SS | DF | MS | F | Sig |
|---|---|---|---|---|---|---|
| 11.Overall appearance of color | Between Trials | 0.500 | 2 | 0.250 | 0.868 | 0.429 |
| | Within Trials | 9.500 | 33 | 0.288 | | |
| | Total | 10.000 | 35 | | | |
| 14.Line Quality | Between Trails | .056 | 2 | .028 | 0.061 | 0.941 |
| | Within Trails | 14.917 | 33 | .452 | | |
| | Total | 14.972 | 35 | | | |
| 15.Visual Texture | Between Trails | .500 | 2 | .250 | 0.611 | 0.549 |
| | Within Trails | 13.500 | 33 | .409 | | |
| | Total | 14.000 | 35 | | | |
| 16.Overall appearance | Between Trails | .056 | 2 | .028 | 0.121 | 0.887 |
| | Within Trails | 7.583 | 33 | .230 | | |
| | Total | 7.639 | 35 | | | |
| 17. Overall Matching | Between Trails | .167 | 2 | .083 | 0.148 | 0.863 |
| | Within Trails | 18.583 | 33 | .563 | | |
| | Total | 18.750 | 35 | | | |

To determine whether the responses were consistent during all three experimental trials for lightness comparison, a Pearson correlation coefficient was used for results from colors 1 to 7 (Table 28). The answers were coded for statistic purpose with “A1 is lighter than B1” represented by 1, “A1 is the same lightness as B1” represented by 2, “B1 is lighter than A1 represented by 3”. Data relationships between Trial 1 and 2, Trials 2 and 3, and Trials 1 and 3 were conducted by using the Pearson correlation coefficient. As Pearson (1895) pointed out, in statistics the Pearson product-moment correlation coefficient is a measure of the linear dependence between two variables X and Y. It has a value between +1 and −1 inclusive, where 1 is total positive linear correlation, 0 is no linear correlation, and −1 is total negative linear correlation (Pearson, 1895). Also, Knox (2014) stated that “The closer the value r is to -1 or 1 the stronger the correlation. The strength of the correlation can be described as: 0.00-0.19 very weak; 0.20-0.39 weak; 0.40-0.59 moderate; 0.60-0.79 strong; 0.80-1 very strong.” Since the results of Colors 5, only one participant chose B1 as being lighter than A1 in Trial 2, expect that, all the participants chose A1 is lighter than B1. The same thing happened to Color 7, all the participants chose A1 is lighter than B1 all cross the three trials. Therefore, reflected in the Pearson correlation, they were perfectly correlated. (Table 28, as noted by asterisks in columns for Colors 5 and 7). Colors 2, 4 and 6 have a strong/very strong correlation, while colors 1 and 3 have a slightly lower moderate/strong correlation. All values during the three trials were positive correlated.

**Table 29:** Color Lightness - Pearson Correlation Reliabilities

| | | T1&T2 | T1&T3 | T2&T3 |
|---|---|---|---|---|
| Color 1 | Pearson Correlation | 0.444 | 0.204 | 0.683 |
| | Sig. (2-tailed) | 0.149 | 0.525 | 0.014 |
| | N | 12 | 12 | 12 |
| Color 2 | Pearson Correlation | 0.736 | 0.502 | 0.750 |
| | Sig. (2-tailed) | 0.006 | 0.096 | 0.005 |
| | N | 12 | 12 | 12 |
| Color 3 | Pearson Correlation | 0.449 | 0.449 | 1.000 |
| | Sig. (2-tailed) | 0.143 | 0.143 | 0.000 |
| | N | 12 | 12 | 12 |
| Color 4 | Pearson Correlation | 0.674 | 0.674 | 1.000 |
| | Sig. (2-tailed) | 0.016 | 0.016 | 0.000 |
| | N | 12 | 12 | 12 |
| Color 5 | Pearson Correlation | * | * | * |
| | Sig. (2-tailed) | * | * | * |
| | N | 12 | 12 | 12 |
| Color 6 | Pearson Correlation | 0.949 | 0.735 | 0.775 |
| | Sig. (2-tailed) | 0.000 | 0.006 | 0.006 |
| | N | 12 | 12 | 12 |
| Color 7 | Pearson Correlation | * | * | * |
| | Sig. (2-tailed) | * | * | * |
| | N | 12 | 12 | 12 |

*Note: The data was perfect correlated.

# 5. CHAPTER 5: CONCLUSION

## 5.1. Conclusion

Ink-jet digital printing is fast, flexible, relatively inexpensive on sampling printing as well as relatively environmentally friendly and can be applied quickly in response to consumer demand. For these reasons, replicating the relatively slow and inflexible screen printing results by using ink-jet digital printing instead has significant meaning for the fashion, apparel, and textile industry. The aim of this research was to replicate a screen-printed sample provided by a textile corporation via ink-jet digital printing, and to explore the potential for of digital ink-jet printing to replace traditional screen printing. To achieve this goal, two stages of study were conducted.

In the first stage, this study succeeded in developing an optimal workflow for the replication of screen-printed fabrics via ink-jet textile printing. The process is streamlined and effective and can be used in the future by researchers and members of industry.

During this process, the pigment ink and pretreated cotton fabric was selected and approved as the optimal colorant and substrate combination to replicate the screen-printed sample based on its well-matched appearance. The polyester and disperse ink set combination (Combination C) and polyester and nano-pigment ink set (Combination B) were insufficient for use in the visual assessment since several of the colors. When disperse dye or pigment was used to print on pre-treated polyester, digital textile ink-jet printing cannot achieve some specific colors which at least one Lab values close to 0 or 100. In other word, very high (Ex. (3.98, 1.43, 1.46)) or low saturated (Ex. (97.54, -1.6, 12.35)) color. In addition, under the same print environment except for the colorant, the color on the polyester printed by disperse dye was found to be more saturated than the color on the polyester printed by nano-pigment, disperse dye have noticeable wider printable color gamut than pigment as well. It is indicated that the disperse dye have a better ink penetration and color concentration than nano-pigment ink. For the nano-pigment and pretreated cotton combination (Combination A), though, all the primary colors were in the color gamut. The appearance of nano-pigment ink set on cotton perfectly matched the screen-printed sample.

In addition, the nano-pigment printed cotton showed little or no color shift and shrinkage after heat set; however, the disperse printed polyester fabric showed noticeable color shift and shrinkage after fixation. This effect also supports the findings in the literature review, which indicated that for disperse dye, color is brighter after fixation, and color fastness and UV stability also increase (Clark, 2003; Fan et al., 2006). Therefore, the textile product developers do not have wait until the end of finishing process to adjust according to the print effect. From this point of view, the color performance can be predicted better before printing when use pigment rather than disperse dye based on accuracy within the color gamut, little or no color shift and shrinkage between printing and finishing.

Pretreatment can make a significant difference in the same fabric, based on comparison between pretreated and non-pretreated cotton and PET were conducted using both nano-pigment ink set and disperse dye ink set. And there is a significant improvement of the line quality, printing clarity, color accuracy after pre-treatment.

In stage two, the achievement of this research was the development of a visual assessment instrument and the ink-jet digital printed sample was examined by experts' visual assessment. The results of the survey instrument indicated that all the participants agreed that the digital printed Sample B matched very well the screen-printed Sample A, as judged by color difference, scale, line quality, visual texture, and overall appearance. From this perspective, the ink-jet digital printed sample was a suitable substitute for screen printed sample, and from this case, digital ink-jet printing demonstrates significant potential for replacing traditional screen printing.

For the color difference comparison, Color 1 (Black) was perceived to have the highest match and then followed by Colors 2 (Yellow) and Color 3 (Dark Green), Colors 4 (Gray) and Color 6 (Red), however Color 5 (Blue) and Color 7 (Cyan) which had the lowest perceived match. Overall, the primary colors picked up from the screen-printed sample were well matched by the ink-jet printed sample. Regarding consistency of the experimental trials, a positive correlation was found in the six individual color evaluation items across each of the three trials by using Pearson's Correlation. The conclusion is that all of the data indicate reliability of the responses across the data set. Also, the significance level of ANOVA calculated for Trials 1, 2, and 3 were always well above 0.05, indicating that the instrument will always elicit consistent and reliable responses. The three reliability coefficients calculated for Trials 1, 2, and 3 demonstrated consistency of the instrument.

The color difference, scale, line quality, visual texture, and overall appearance were well matched between two samples. Agreement was determined through reliability statistics with the data collected from identifying color change. However, the line texture and visual texture show insufficient compared with the other aspects, which indicates that compare to the express of color, digital printing technology at this stage cannot completely express the thick layering pattern effect that can be produced by traditional printing technology. In addition, compared to the other colors, digital printing technology cannot completely show some of the specific colors, such as blue and cyan. These two colors had the lowest mean among the seven colors throughout the whole assessment.

In a word, this research indicated that an ink-jet textile print could adequately simulate a screen-printed fabric as perceived by a textile product developer, we can see there is a significant potential for ink-jet printing replicating traditional screen-printing. However, obstacles such as price, capacity and technical shortcomings mean that innovative technology will be needed in the future to overcome these limitations.

## 5.2. Limitations and Recommendations for Future Research

The results from this research provide insight into the potential for ink-jet textile printing to replicate, and potentially replace, screen-printed fabrics. A few limitations of ink-jet textile printing were found, indicating that future research could focus on the use of alternative substrates, ink sets, printers, print heads, and RIP software once an evaluation method is standardized. It is suggested that questions regarding the participants' moods be asked at the beginning and the end of the survey to reduce the variables caused by personal issues.

Another limitation relates to the discovery that using multicolor samples can result in one color influencing the participants' evaluations of other colors. Meanwhile, since every key color is not near the corresponding one, participants can find it more difficult to approve the samples. That is one of the reasons the PI chose experts in printing and color matching as participants: to improve precision. One expert suggested that instead of putting samples in the viewing booth to do the assessment, put the samples directly on the ground under the D65 light. This way, gray scales will not be used for color shade changes, and experts can simply give comments and suggestions, according to the comparison of samples.

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Hunt, R. W. G., & Pointer, M. R. (2011). Measuring colour. John Wiley & Sons.

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# APPENDICES

Appendix A: IRB Approval

NC STATE UNIVERSITY

**Office of Research, Innovation and. Economic Development**
Sponsored Programs and Regulatory Compliance Services
research.ncsu.edu/sparcs/

Campus Box 7514
2701 Sullivan Dr. Suite 240
Raleigh, NC 27695-7514
P: 919.515-2444, F: 919-515-7721
E: sps@ncsu.edu

From: Deb Paxton, IRB Administrator
North Carolina State University
Institutional Review Board

Date: May 9, 2016

Title: Replication of Screen Printing Fabric via Inkjet Textile Printing

IRB#: 7930

Dear Ming Wang,

The project listed above has been reviewed by the NC State Institutional Review Board for the Use of Human Subjects in Research, and is approved for one year. **This protocol will expire on 4/25/17 and will need continuing review before that date.**

NOTE:

1. You must use the attached consent forms which have the approval and expiration dates of your study.

2. This board complies with requirements found in Title 45 part 46 of The Code of Federal Regulations. For NCSU the Assurance Number is: FWA00003429.

3. Any changes to the protocol and supporting documents must be submitted and approved by the IRB prior to implementation.

4. If any unanticipated problems occur, they must be reported to the IRB office within 5 business days by completing and submitting the unanticipated problem form on the IRB website.

5. Your approval for this study lasts for one year from the review date. If your study extends beyond that time, including data analysis, you must obtain continuing review from the IRB.

Sincerely,

Deb Paxton
NC State IRB

Appendix B: IRB E-mail to Participants

Attachment A
E-mail to Participants
Purpose: To gain permission to survey participants.

**North Carolina State University**
Study: Comparative Analysis of Ink-jet Printed and Screen-printed

Principal Investigator: Ming Wang Faculty Sponsor: Lisa Parrillo- Chapman

Dear (Name of Respondent),

My name is Ming Wang and I am in the process of conducting my thesis research at North Carolina State University. The purpose of my study is to measure product developers' perceptions of ink jet printing fabrics and screen-printed fabrics. The study will consist of participants that have knowledge in the areas of fabric design, apparel product development, home interior product development, screen printing, color matching, printing, and/or ink jet printing.

The assessment will be conducted in the Color Science Laboratory at the College of Textiles during which the participant will assess one set of samples under one lighting condition at three different times. The samples will be assessed based on color, scale, clarity of line, and texture.

All participants will fill out an informed consent form prior to completing the survey and the results of survey will remain anonymous. After analysis of the results I will gladly discuss the findings with all participants. Please let me know if you would be able to participate in my experiment. The survey should take no longer than fifteen to twenty minutes of your time. Thank you very much.

Sincerely,

Ming Wang

## Appendix C: Survey Instrument

1* The purpose of this study is to measure product developers' perceptions of the ability of ink-jet printed fabric to adequately represent screen printing fabric. The survey results will become part of the published thesis research conducted by Ming Wang.

The information in the study records will be kept strictly confidential. Data will be stored securely on a password protected server accessible only by the principal investigators. SSL encryption will be used for transmitting survey results. No reference will be made in the thesis which could link you to the study.

There is no monetary compensation awarded for participation in this study. However, one benefit of participating in this study is the knowledge that you will have contributed your expertise and experience to a greater body of work. There are no foreseeable risks associated with completing this survey.

If you have questions at any time about the study or the procedures, you may contact the researcher, Ming Wang (919-985-5757 ) or Lisa Parrillo-Chapman, (919-513-4020) at the College of Textiles, NCSU, and Raleigh NC 27695-8301. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Deb Paxton, Regulatory Compliance Administrator at dapaxton@ncsu.edu or by phone at 1-919-515-4514.

By checking the "I accept" box I acknowledge I have read and understand the above information and am over the age of 18. I may print a copy of this agreement for my records. I agree to participate in this study with the understanding that I may withdraw at any time.

- ☐ I accept
- ☐ I don't accept

## Demographics

2* What is your gender?

- [ ] Female
- [ ] Male

3* What year you were born?

4* What your specific focus of your work

- [ ] Fabric Design
- [ ] Screen Printing
- [ ] Apparel Product Development
- [ ] Color Matching
- [ ] Ink Jet Printing
- [ ] Home Interior Product Development

Other (Please Specify)

5* What is your occupation?

- [ ] Educator/Professor
- [ ] Industry Professional
- [ ] PhD Student

6* How long have you been approving samples?

- [ ] 1-6 months
- [ ] 7 months to 1 year
- [ ] 2-3 years
- [ ] 4-5 years
- [ ] 6 or more years
- [ ] I have never approved samples

7* How frequently do you approve samples?

- [ ] 1-3 times a week
- [ ] 1-3 times a month
- [ ] 1-3 times a year
- [ ] I have never approved samples

## Test

Neitz Test and test sample

8* Did you successfully pass the Neitz Test of Color Vision?

- [ ] Yes
- [ ] No

9* (Test Sample) What is the shade change value for the AATCC samples?

| | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 | 1.5 | 1 |
|---|---|---|---|---|---|---|---|---|---|
| Test Sample | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

## Single Color Visual Assessment Part 1

**For questions 10 and 11 you will use the AATCC Gray Scale for Color Change.**

[redacted] ***5 represents no shade change; 1 represents highest shade change.***

10* Compare the six colors in sample A to sample B.

What is the color difference between these two samples?

| | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 | 1.5 | 1 | Comments: |
|---|---|---|---|---|---|---|---|---|---|---|
| Color 1 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Color 2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Color 3 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Color 4 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Color 5 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Color 6 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Color 7 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |

11* How would you best describe the comparison of these two samples?

| | A is lighter than B | A is the same lightness as B | B is lighter than A | Comments: |
|---|---|---|---|---|
| Color 1 | ☐ | ☐ | ☐ | |
| Color 2 | ☐ | ☐ | ☐ | |
| Color 3 | ☐ | ☐ | ☐ | |
| Color 4 | ☐ | ☐ | ☐ | |
| Color 5 | ☐ | ☐ | ☐ | |
| Color 6 | ☐ | ☐ | ☐ | |
| Color 7 | ☐ | ☐ | ☐ | |

## Overall Color Visual Assessment Part 1

12* How does the overall appearance of sample A match that of sample B according to color?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Overall Appearance | ☐ | ☐ | ☐ | ☐ | ☐ | |

13* Scale is defined as the proportion or ratio that defines size relationship.

Does the scale of the pattern design in sample A1 match that of sample B1?

- ☐ Yes
- ☐ No

14* Line quality is defined as the appearance of the line.

How well does the line quality of sample A match that of sample B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Line Qualiry | ☐ | ☐ | ☐ | ☐ | ☐ | |

15* Visual texture is defined as the illusion of texture achieved through techniques (such as shading) that vary coloration and value.

How well does the visual texture of sample A match B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Visual Texture | ☐ | ☐ | ☐ | ☐ | ☐ | |

16* How well does the overall appearance of sample A match that of sample B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Overall Appearance | ☐ | ☐ | ☐ | ☐ | ☐ | |

17* If fabric design A and B were made as product A and B, as a customer, are you willing to pay the same price for these two products?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Matching | ☐ | ☐ | ☐ | ☐ | ☐ | |

## Single Color Visual Assessment Part 2

Repeat the question second time.

18* Compare the six colors in sample A to sample B.

What is the color difference between these two samples?

| | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 | 1.5 | 1 |
|---|---|---|---|---|---|---|---|---|---|
| Color 1 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 3 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 4 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 5 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 6 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 7 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

19* How would you best describe the comparison of these two samples?

| | A is lighter than B | A is the same lightness as B | B is lighter than A | Comments: |
|---|---|---|---|---|
| Color 1 | ☐ | ☐ | ☐ | |
| Color 2 | ☐ | ☐ | ☐ | |
| Color 3 | ☐ | ☐ | ☐ | |
| Color 4 | ☐ | ☐ | ☐ | |
| Color 5 | ☐ | ☐ | ☐ | |
| Color 6 | ☐ | ☐ | ☐ | |
| Color 7 | ☐ | ☐ | ☐ | |

## Overall Color Visual Assessment Part 2

Repeat the questions second time.

20* How does the overall appearance of sample A match that of sample B according to color?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Overall Appearance | ☐ | ☐ | ☐ | ☐ | ☐ | |

21* Scale is defined as the proportion or ratio that defines size relationship.

Does the scale of the pattern design in sample A match that of sample B?

- ☐ Yes
- ☐ No

22* Line quality is defined as the appearance of the line.

How well does the line quality of sample A match that of sample B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Line Qualiry | ☐ | ☐ | ☐ | ☐ | ☐ | |

23* Visual texture is defined as the illusion of texture achieved through techniques (such as shading) that vary coloration and value.

How well does the visual texture of sample A match B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Visual Texture | ☐ | ☐ | ☐ | ☐ | ☐ | |

24* How well does the overall appearance of sample A match that of sample B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Overall Appearance | ☐ | ☐ | ☐ | ☐ | ☐ | |

25* If fabric design A and B were made as product A and B, as a customer, are you willing to pay the same price for these two products?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Matching | ☐ | ☐ | ☐ | ☐ | ☐ | |

## Single Color Visual Assessment Part 3

Repeat the question third time.

26* Compare the six colors in sample A to sample B.

What is the color difference between these two samples?

| | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 | 1.5 | 1 |
|---|---|---|---|---|---|---|---|---|---|
| Color 1 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 3 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 4 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 5 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 6 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Color 7 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

27* How would you best describe the comparison of these two samples?

| | A is lighter than B | A is the same lightness as B | B is lighter than A | Comments: |
|---|---|---|---|---|
| Color 1 | ☐ | ☐ | ☐ | |
| Color 2 | ☐ | ☐ | ☐ | |
| Color 3 | ☐ | ☐ | ☐ | |
| Color 4 | ☐ | ☐ | ☐ | |
| Color 5 | ☐ | ☐ | ☐ | |
| Color 6 | ☐ | ☐ | ☐ | |
| Color 7 | ☐ | ☐ | ☐ | |

## Overall Color Visual Assessment Part 3

Repeat the question third time.

28* How does the overall appearance of sample A match that of sample B according to color?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Overall Appearance | ☐ | ☐ | ☐ | ☐ | ☐ | |

29* Scale is defined as the proportion or ratio that defines size relationship.

Does the scale of the pattern design in sample A match that of sample B?

☐ Yes
☐ No

30* Line quality is defined as the appearance of the line.

How well does the line quality of sample A match that of sample B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Line Qualiry | ☐ | ☐ | ☐ | ☐ | ☐ | |

31* Visual texture is defined as the illusion of texture achieved through techniques (such as shading) that vary coloration and value.

How well does the visual texture of sample A match B?

| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Visual Texture | ☐ | ☐ | ☐ | ☐ | ☐ | |

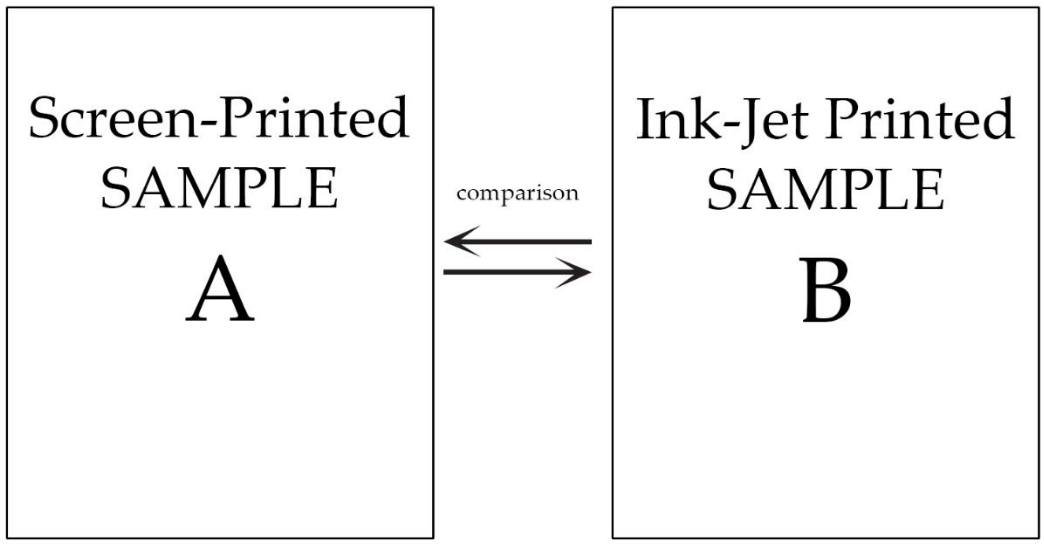
32* How well does the overall appearance of sample A match that of sample B?

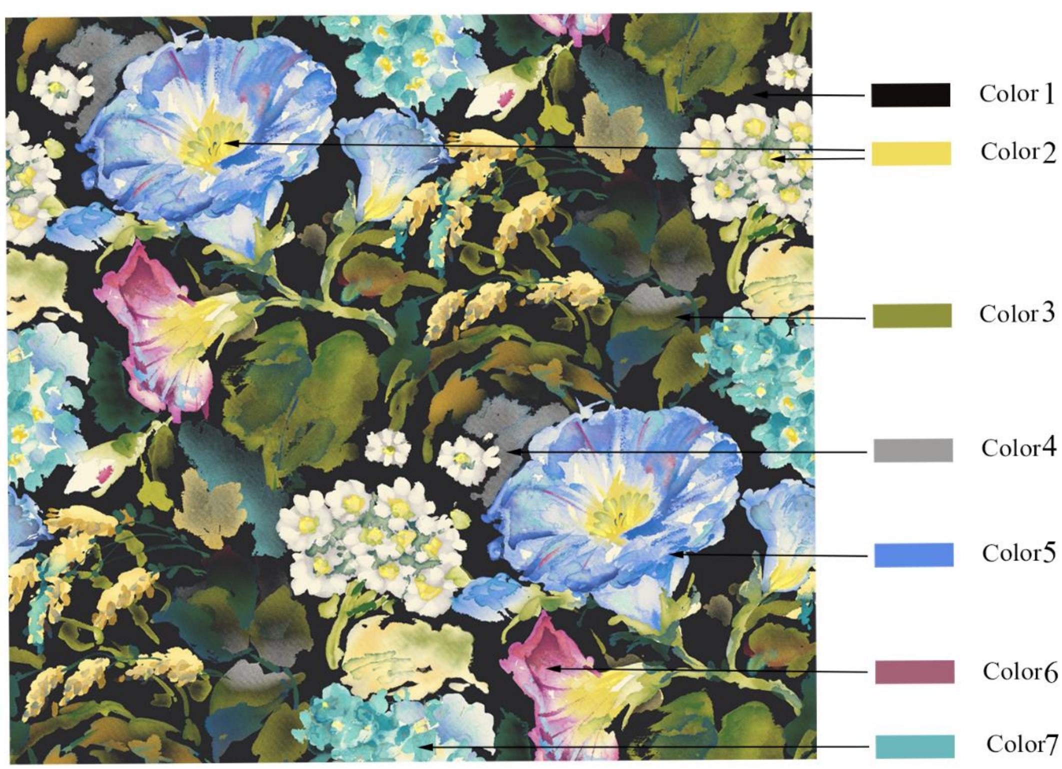
| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Overall Appearance | ☐ | ☐ | ☐ | ☐ | ☐ | |

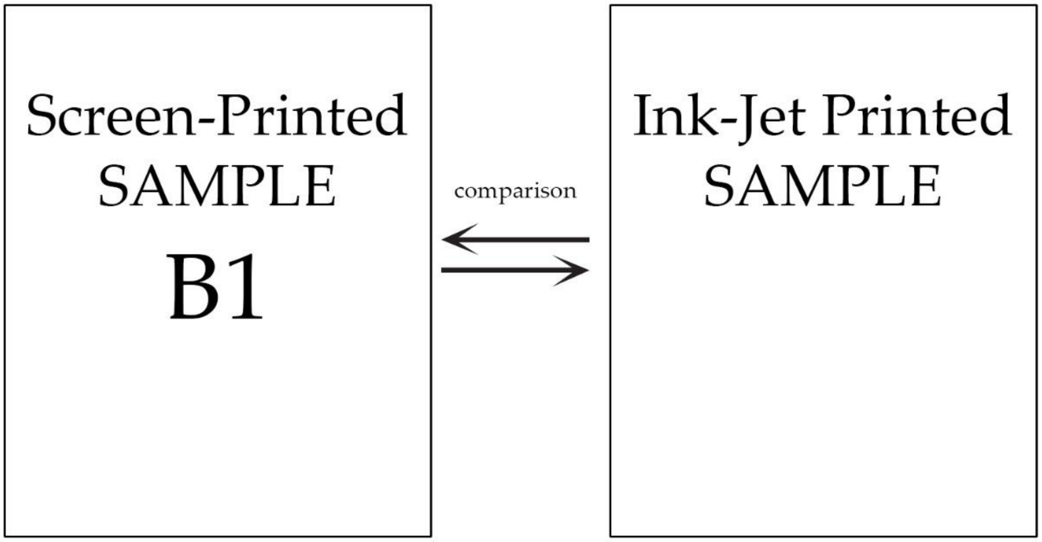
33* If fabric design A and B were made as product A and B, as a customer, are you willing to pay the same price for these two products?

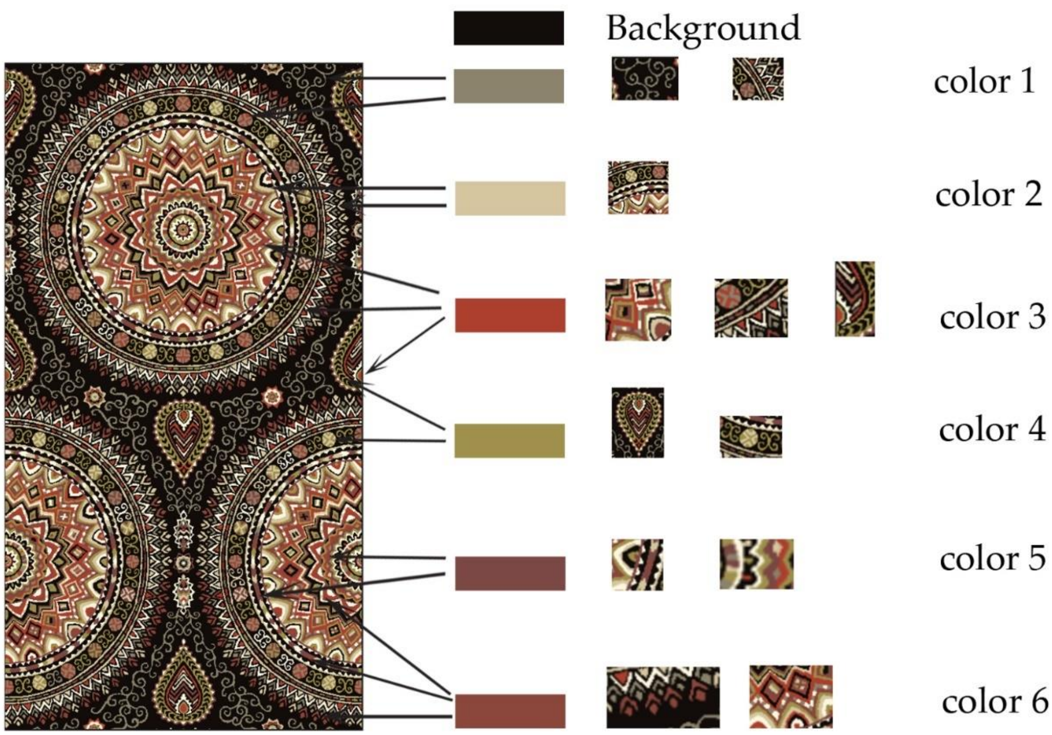
| | Not at all | Slightly | Somewhat | Mostly | Exactly | Comments: |
|---|---|---|---|---|---|---|
| Matching | ☐ | ☐ | ☐ | ☐ | ☐ | |

Appendix D: Color Key




Screen-Printed SAMPLE
B1
comparison
Ink-Jet Printed SAMPLE


Background
color 1
color 2
color 3
color 4
color 5
color 6

Screen-Printed SAMPLE

B2

comparison

Ink-Jet Printed SAMPLE

# Appendix E: AATCC Gray Scale Evaluation Procedure 1

**AATCC Evaluation Procedure 1-2012**

## Gray Scale for Color Change

**Adopted in 1954 by AATCC; under jurisdiction of AATCC Committee RA36; revised 1979, 1987, 2002, 2012; editorially revised 1991, 2009, 2011; editorially revised and reaffirmed 1992; reaffirmed 2007. Technically equivalent to ISO 105-A02.**

### 1. Scope

1.1 This evaluation procedure describes the use of a Gray Scale for visually evaluating changes in color of textiles resulting from colorfastness tests. For instrumental assessment of change of color of a test specimen refer to AATCC Evaluation Procedure 7. A precise colorimetric specification of the differences between the reference and the 9-step Scale is given as a permanent record against which newly prepared Gray Scales, and old scales that might have changed, can be compared.

### 2. Principle

2.1 The result of a colorfastness test is rated by visually comparing the difference in color or the contrast between the untreated and treated specimens with the differences represented by the Scale (see 8.1). The colorfastness grade is equal to the gray scale step which is judged to have the same color or contrast difference.

### 3. Terminology

3.1 **color change,** n.—a change in color of any kind whether in lightness, hue or chroma, or any combination of these, discernible by comparing the test specimen with a corresponding untested specimen.

3.2 **colorfastness,** n.—the resistance of a material to change in any of its color characteristics, to transfer of its colorant(s) to adjacent materials or both, as a result of the exposure of the material to any environment that might be encountered during the processing, testing, storage or use of the material.

3.3 **Gray Scale,** n.—a scale consisting of pairs of standard gray chips, the pairs representing progressive differences in color or contrast corresponding to numerical colorfastness grades.

### 4. Description of the Scale

4.1 Colorfastness grade 5 is represented on the scale by two reference chips mounted side by side, neutral gray in color and having a *Y* tristimulus value of 12 ± 1. The color difference of the pair is 0.0-0.2.

4.2 Colorfastness grades 4.5 to 1, inclusive, are represented by reference chips like those used in Step 5 paired with lighter neutral gray chips of similar dimensions and gloss. The visual differences in the whole step pairs — colorfastness grades 4, 3, 2 and 1— are in geometric steps of color difference, or contrast. The differences in the half-step colorfastness grade pairs — 4-5, 3-4, 2-3 and 1-2 — are intermediate between the whole step pairs (see 8.2, 8.3 and Fig. 1).

### 5. Use of the Scale

5.1 Place a piece of the original textile and its corresponding exposed test specimen side by side in the same plane and oriented in the same direction. Take special care to create a sharp junction between the two pieces of material. Place the Gray Scale along the edges of the test specimen and original textile sample with the junctions of the textile and the Gray Scale pair aligned. Place the gray mask (*Y* tristimulus of 53 ± 1) provided with the scale over the samples and the scale to eliminate any influence of the surrounding areas. Back the specimens, both the original and tested, with a white material having a *Y* tristimulus value of at least 85. If the specimens are permanently mounted on a card, it must be with a *Y* tristimulus value of at least 85. Any means of attachment (staples, etc.) must not be in the area viewed (see Fig. 2).

Illuminate the surfaces with a daylight simulator with illumination level at the specimen plane in the range of 1080-1340 lx (100-125 fc) (see 8.4). The light should be incident upon the surfaces at 45 ± 5° and the direction of viewing 90 ± 5° to the plane of the surfaces (see Fig. 3).

Compare the perceived visual difference between original and tested textile with the perceived differences represented by the Gray Scale. The colorfastness grade is that number of the Gray Scale pair whose contrast corresponds to the contrast between the original and tested specimens. A grade of 5 is given only when there is no perceived difference in color or contrast between the original material and tested specimen. The cleanliness and physical condition of the Gray Scale is extremely important in obtaining consistent results (see 8.5).

5.2 When a number of assessments have been made, it is very useful to compare all the pairs of original and tested specimens which have been given the same numerical grade. This gives a good indication of the consistency of the grades, since any errors become prominent. Pairs which do not appear to have the same degree of contrast as others with the same grades should be re-checked against the Gray Scale and, if necessary, the grades should be changed.

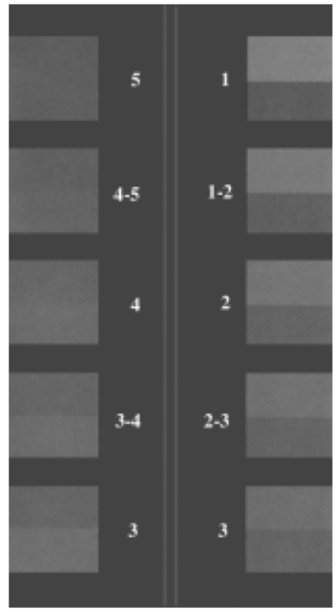



**Fig. 1—Gray Scale for Color Change.**

### 6. Describing Color Changes in Colorfastness Tests

6.1 In using the Gray Scale, the overall, total color difference or contrast between the original and tested specimens is evaluated. This evaluation procedure is not used to rate the changes in the individual components of lightness, chroma and hue. If a description of these component changes is required, the observer may add appropriate qualitative terms to the numerical grade, as illustrated in Table I.

### 7. Colorimetric Specification of Color Differences of the Gray Scale

7.1 The color differences and tolerances between the reference gray and the

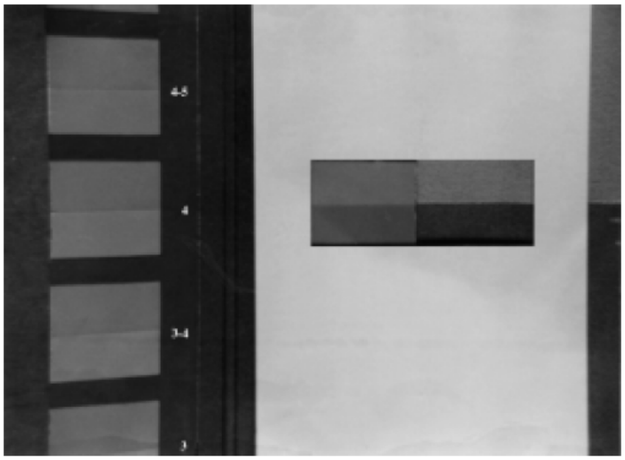



**Fig. 2—Illustration of how to use scale.**

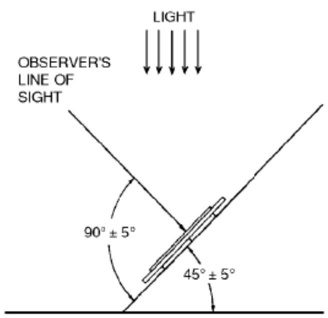



**Fig. 3—Illumination and viewing angles for rating samples.**

nine steps of the scale are expressed as total color difference $\Delta E^*_{ab}$ using the CIE 1976 L*a*b* color difference formula:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

where:

$$L^* = 116\,(Y/Y_n)^{1/3} - 16$$
$$a^* = 500\,[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$
$$b^* = 200\,[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$
$$(X/X_n,\ Y/Y_n,\ Z/Z_n > 0.01)$$

The tristimulus values $X_n$, $Y_n$, $Z_n$ define the color of the nominally white object-color stimulus.

7.2 Permissible tolerances for the Gray Scales used as working standards are given in the last column of Table II, Appendix A.

## 8. Notes

8.1 Available from AATCC, P.O. Box 12215, Research Triangle Park NC 27709; tel: 919/549-8141; fax: 919/549-8933; e-mail: orders@aatcc.org; web site: www.aatcc.org.

8.2 The colorfastness grades of the scale steps and the corresponding total color differences and tolerances, determined by the CIE 1976 L*a*b* (CIELAB) formula, are given in Table II, Appendix A. Sphere geometry spectrophotometric measurements of the chips shall be taken with the specular component included. A 0°/45° (45°/0°) geometry is an acceptable alternate. The colorimetric data shall be calculated using the CIE 1964 10° observer data for Illuminant $D_{65}$.

8.3 Any test specimen which has a change in color or contrast decidedly greater than a grade of 1 may be rated a 0.

8.4 See AATCC Evaluation Procedure 9, Visual Assessment of Color Difference of Textiles, for notes on choice of daylight simulator and illumination level.

**Table I—Color Difference Direction Descriptors**

| | |
|---|---|
| Lightness | Lighter, Darker |
| Chroma | More (or higher) chroma and Less (or lower) chroma |
| Hue | Redder, Greener, Yellower, Bluer |

8.5 The Scale should be inspected frequently for fingerprints and any other marks. If the marks are considered to interfere with the rating process, then the Scale should be replaced. The Scale can also be physically damaged through handling. Again, if the physical damage to the Scale interferes with the rating process, it should be replaced. Periodically, the Scale can be measured on a spectrophotometer or colorimeter to ensure that the total color differences are within specification as shown in Table II, Appendix A. Keep the Scale in its case when it is not in use.

## Appendix A

A.1 Table II provides the color difference values in CIE 1976 L*a*b* (CIELAB) units for the grade pairs in each step of the Gray Scale for Color Change. This table is for instrumental measurement and confirmation that a Gray Scale is within tolerance, only. Table II is NOT to be used for assigning a Gray Scale grade based on instrumental measurement of two specimens (see AATCC Evaluation Procedure 7, Instrumental Assessment of the Change in Color of a Test Specimen).

**Table II**

| Colorfastness Grade | Total Color Difference CIELAB Units | Tolerance for Working Standards CIELAB Units |
|---|---|---|
| 5 | 0.0 | + 0.2 |
| 4-5 | 0.8 | ± 0.2 |
| 4 | 1.7 | ± 0.3 |
| 3-4 | 2.5 | ± 0.3 |
| 3 | 3.4 | ± 0.4 |
| 2-3 | 4.8 | ± 0.5 |
| 2 | 6.8 | ± 0.6 |
| 1-2 | 9.6 | ± 0.7 |
| 1 | 13.6 | ± 1.0 |

Appendix F: Neitz Test of Color Vision

# Neitz Test of Color Vision

Test Sheet

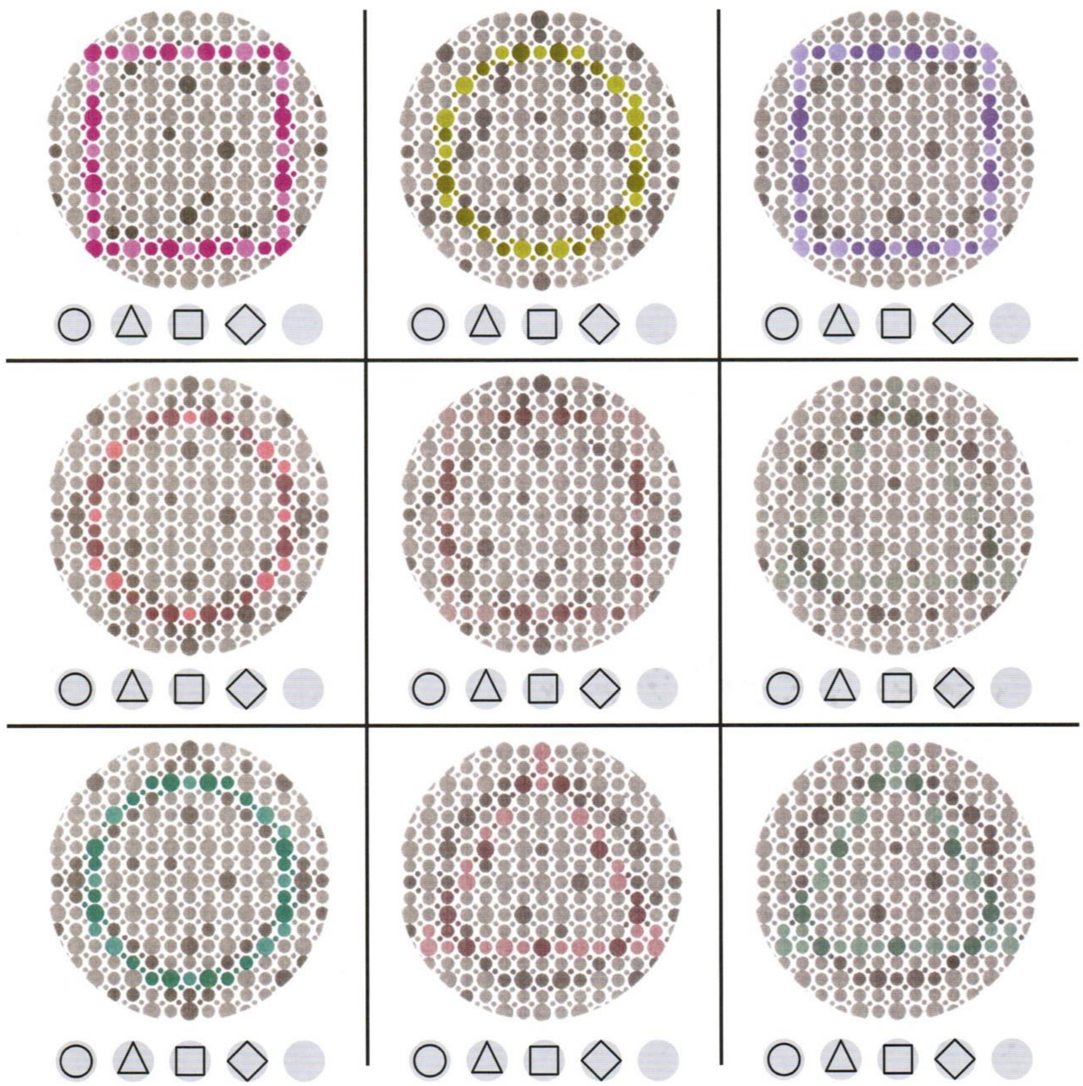
by Jay Neitz, Ph.D., Phyllis Summerfelt, and Maureen Neitz, Ph.D.

Published by
WPS WESTERN PSYCHOLOGICAL SERVICES
12031 Wilshire Blvd., Los Angeles, CA 90025-1251
Publishers and Distributors

**Name:** ______ **ID:** ______ **Date:** ______ **Age:** ______

**Gender:** ☐ Male ☐ Female **Ethnicity:** ☐ Asian ☐ Black ☐ Hispanic ☐ Native American ☐ White ☐ Other ______

**Classification:** ______



This is a precisely calibrated testing instrument. Reproductions cannot be used to accurately test color vision.

W-377A(3)


1 2 3 4 5 6 7 8 9
Printed in U.S.A.

# Neitz Test of Color Vision

## Scoring Key

by Jay Neitz, Ph.D., Phyllis Summerfelt, and Maureen Neitz, Ph.D.

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WESTERN PSYCHOLOGICAL SERVICES
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Los Angeles, CA 90025-1251
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### DIRECTIONS FOR SCORING

There are three versions of the test: 1(■), 2(■■), and 3 (■■■). The version number is indicated on the Test Sheet by the number in parentheses following the WPS Product Number in the bottom left-hand corner and by the number of squares in both upper corners.

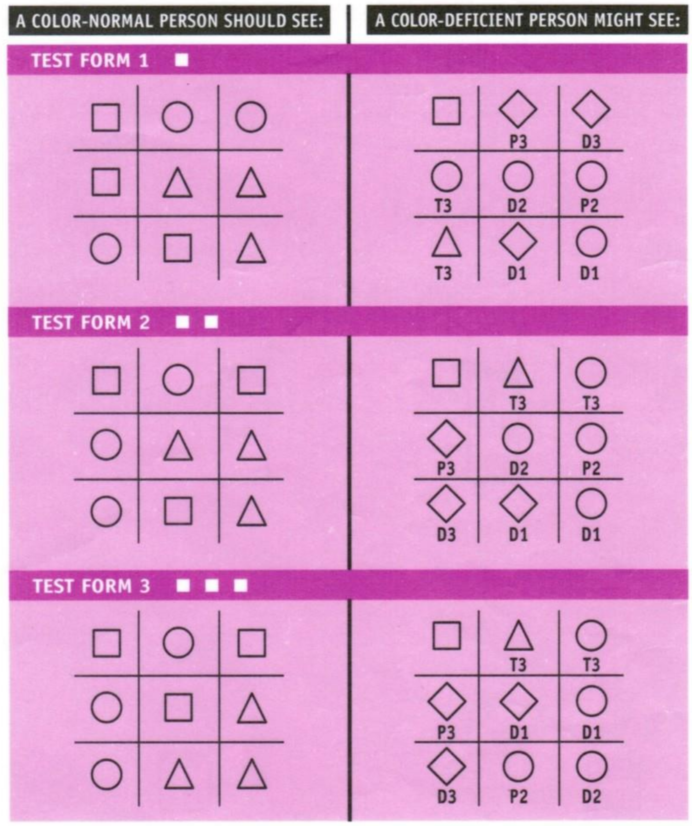
Place the Scoring Key over the completed Test Sheet, carefully aligning the pattern of squares at the upper corners of the Test Sheet with the same pattern on the Scoring Key so that the square outlines on the Scoring Key frame the correct responses on the form. Record incorrect responses directly on the Test Sheet.

Verify incorrect responses using the diagrams in the columns to the right. Each diagram in the first column shows what "a color-normal person should see" on each version of the test. Each diagram in the second column, showing what "a color-deficient person might see," is an *error matrix* that assigns a letter-number combination to each of the likely errors.

If there are errors, consult the table below. Using the error matrix for the relevant version of the test, find the incorrect responses that include the highest numbers (e.g., P3 and D2). On the table, locate the intersection of the row and column headed by those two numbers; if there is only one error, use its designation on the error matrix (e.g., D1) to select both the row and the column. Any error labeled "T3" indicates a tritan deficiency. The resulting classification of color-vision deficiency may be entered on the Test Sheet and used when referring the individual for further testing and diagnosis.

### IMPORTANT:

This test works best when administered under bright fluorescent lighting; dim lighting will not produce responses that are consistent with an individual's ability to discriminate color. DO NOT administer this test under incandescent lighting (regular light bulbs). See the test Manual for full lighting specifications.




### CLASSIFYING RED-GREEN COLOR-VISION DEFICIENCIES

| | | D1 | D2 | P2 | D3 | P3 |
|---|---|---|---|---|---|---|
| | | *Mild* | *Moderate* | | *Severe* | |
| D1 | *Mild* | Mild deutan | Moderate deutan | Moderate protan | Severe deutan | Severe protan |
| D2 | *Moderate* | Moderate deutan | Moderate deutan | Moderate unspecified | Severe deutan | Severe protan |
| P2 | *Moderate* | Moderate protan | Moderate unspecified | Moderate protan | Severe deutan | Severe protan |
| D3 | *Severe* | Severe deutan | Severe deutan | Severe deutan | Severe deutan | Severe protan |
| P3 | *Severe* | Severe protan | Severe protan | Severe protan | Severe protan | Severe protan |


Printed in U.S.A. 1 2 3 4 5 6 7 8 9

W-377C

Appendix G: Creation of Color Profiles

1. Open Dr. Wirth Software and select the Color Management Tab

2. Select the Create New Calibration button, when the window opens name the color profile (MS JP5 cotton and pigment /MS JP5 polyester and disperse/MS JP5 polyester and pigment), select Enhanced for calibration type and select OK

3. Select the Printer tab and under printer description select the printer (MS JP5 Printer ) that the color profile is being created for, type Textile under Paper/Textile Specifications, under Inks change the names of Ink 1 through Ink 8 to the corresponding ink colors used by the printer (Ink 1 is the first color that appears when a nozzle check is done and Ink 8 is the last (Black, Cyan, Magenta, Yellow, Orange, Red, Violet, Grey), the box labeled black is checked only for the black ink, select OK

4. Select the Pages tab and select the Print all Pages of selected page group button

5. Once print window opens select the Calibration button to make sure the Activate/Deactivate Calibration box is unchecked, select Print to print the two pages (after the pages are printed they are heat set)

6. Select the Format tab and select the Greytag-xy-table from the pull-down menu

7. Select the Measuring tab and then the Measure (xy) button

8. The Calibration Page Orientation window will open and the Use user defined page size box is then checked. The first of the two printed pages is placed on the X-Rite spectrophotometer where the arm of the spectrophotometer is placed over the Top left (1/1) corner color chip and OK is selected. This is also done for the Top right (1/22), Bottom left (14/1), and Bottom right (14/22) color chips. After all four are entered select OK at the bottom of the window. Repeat this step for the second printed page.

9. After completion 42 new pages are created highlight the Main 1 page under the Pages tab and select the Print all pages of selected page group button

10. Once print window opens the select the Calibration button to make sure the Activate/Deactivate Calibration box is unchecked, select Print to print 38 pages (after the pages are printed they are heat set)

11. Repeat steps 7 and 8 for all 38 pages

12. Select the CTB tab after all 38 pages have been measured, select From LAB to printer COL8 from the pull down menu, check the box labeled Include Gamut Data, and select the Gamut mapping details button.

13. Once Details of printer calibration window opens select Absolute colorimetric from the pull down menu and make sure the box labeled White is checked, select OK to complete the creation of the color profile.

Appendix H: Washing and Pretreatment Instruction of PET Fabric.

1. Scour the fabric twice; the first scour should be at neutral and the 2nd scour should be at a PH of 9 or 10 (using soda ash).

2. Do not add any surfactants

3. The Thermal (also could be named Propjet) and the UV fast can be mixed and padded together. Both pre-treatments should be mixed at a 5% solution and padded with 80% wet-pickup.

Appendix I: Screen-printed and Ink-jet printed Samples

**Design A**

| | Colorant and Substrate Combination | Print Mode | Ink Limitation |
|---|---|---|---|
| Sample B | Combination A | C-2 | 100% |

Screen Printed Sample (Target)

Combination A (Nano-pigment and Cotton)

Design B

| | Colorant and Substrate Combination | Print Mode | Ink Lamination | Visual Color Matching and Change |
|---|---|---|---|---|
| Sample B1_A1 | Combination A | C-2 | 100% | No |
| Sample B1_A2 | Combination A | D-2 | 100% | No |
| Sample B1_A3 | Combination A | C-2 | 100% | Yes |
| Sample B1_A4 | Combination A | D-2 | 100% | Yes |
| Sample B1_B1 | Combination B | C-2 | 100% | No |
| Sample B1_B2 | Combination B | C-2 | 120% | No |
| Sample B1_B3 | Combination B | D-2 | 100% | No |
| Sample B1_B4 | Combination B | C-2 | 100% | Yes |
| Sample B1_B5 | Combination B | C-2 | 100% | Yes |
| Sample B1_B6 | Combination B | C-2 | 100% | Yes |
| Sample B1_B7 | Combination B | C-2 | 100% | Yes |
| Sample B1_C | Combination C | C-2 | 120% | No |

Screen-printed Sample B1 (Target)

(1) C-2 100%
Sample B1_A1

(2) D-2 100%
Sample B1_A2

(1) C-2 100%
Sample B1_A3

(2) D-2 100%
Sample B1_A4

(d) C-2 100%

Sample B1_B1

(e) C-2 120%

Sample B1_B2

(f) D-2 100%

Sample B1_B3

(3)

Sample B1_B4

(4)

Sample B1_B5

(5)

Sample B1_B6

(6)

Sample B1_B7

Sample B1_C

Design B2

| | Colorant and Substrate Combination | Print Mode | Ink Lamination | Visual Color Matching and Change |
|---|---|---|---|---|
| Sample B2_A1 | Combination A | C-2 | 100% | No |
| Sample B2_A2 | Combination A | D-2 | 100% | No |
| Sample B2_B1 | Combination B | C-2 | 100% | No |
| Sample B2_B2 | Combination B | C-2 | 120% | No |
| Sample B2_B3 | Combination B | D-2 | 100% | No |
| Sample B2_C | Combination C | C-2 | 120% | No |

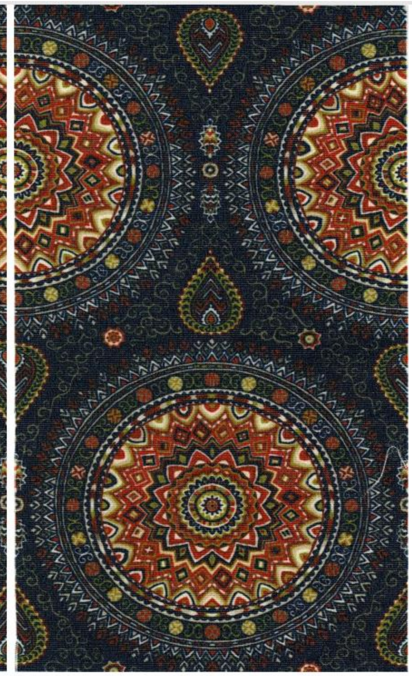
Screen-printed Sample B2 (Target)

(1) C-2 100%

Sample B2_A1

(2) D-2 100%

Sample B2_A2



(a) C-2 100%

(b) C-2 120%

(c) D-2 100%

Sample B2_B1

Sample B2_B2

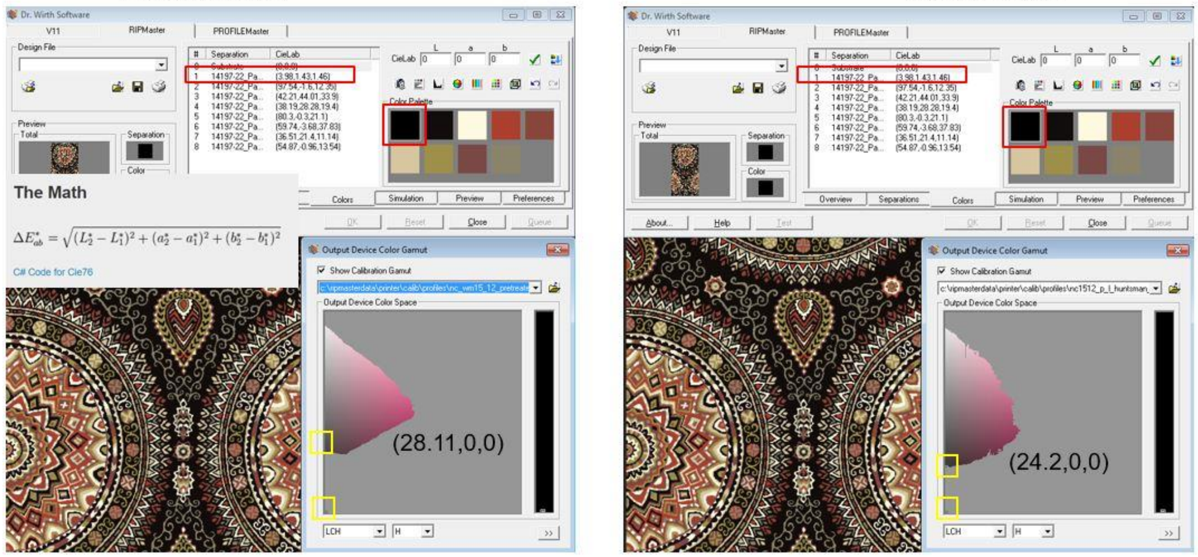
Sample B2_B3

Sample B2_C

Appendix J: Unprintable Colors for Design B1 and B2

When disperse dye or pigment was used to print on pre-treated polyester. It is also found that digital textile ink-jet printing cannot achieve some specific colors which at least one Lab values close to 0 or 100 that screen printing can do. In other word, very high or low saturated color.

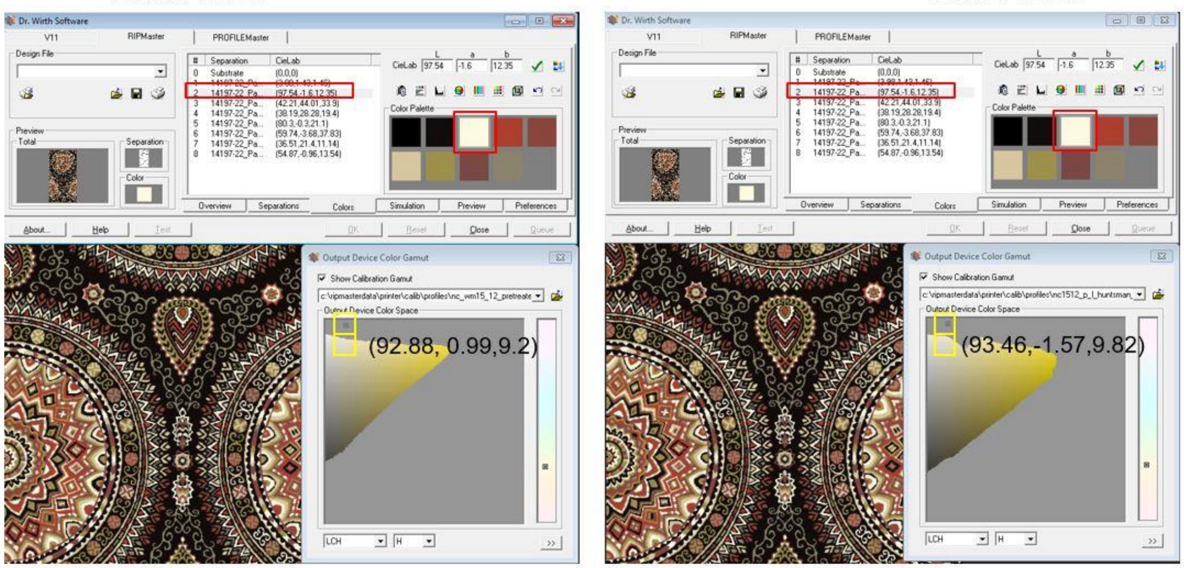
Delta E: **24.2164** Background (Black) Lab value: (3.98, 1.43, 1.46) Delta E: **20.323**




**Pigment** on pre-treated polyester **Disperse** on pre-treated polyester

Background (Black) of Design B1

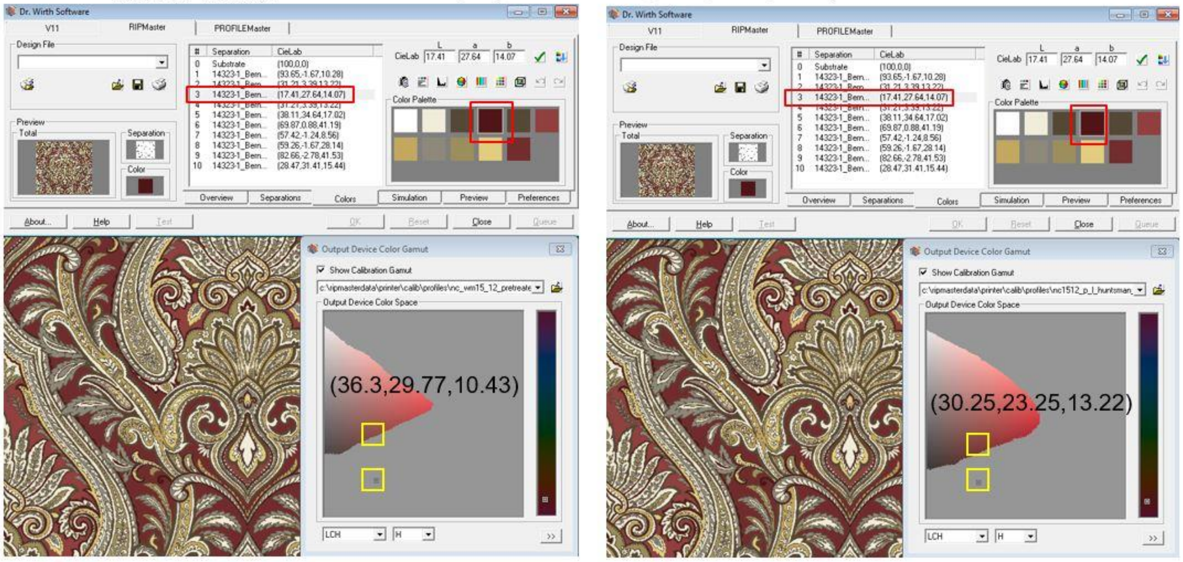
Delta E: **6.1924** Color 2 Lab Value: (97.54, -1.6, 12.35) Delta E: **4.8009**




**Pigment** on pre-treated polyester **Disperse** on pre-treated polyester

Color 2 of Design B1

Delta E: **19.3551** Color 4 (Red) Lab value: (17.41, 27.64, 14.07) Delta E: **13.5963**




**Pigment** on pre-treated polyester **Disperse** on pre-treated polyester

Color 4 (Red) of Design B2

## Appendix K: Comparison of Color Gamut Between Pigment and Disperse

When disperse dye or pigment was used to print on pre-treated polyester, disperse dye have noticeable wider color gamut than pigment