ON TEXTILE PRINTING WITH THERMOCROMIC INKS

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ABSTRACT

This thesis describes an exploration of the principles of applying leuco dye-based inks to textile design practice. The main motivation has been to explore the design properties and potentials of leuco dye-based thermochromic inks when printed on textiles in order to obtain an understanding and facilitate the design of dynamic surface patterns. The significance of this is related to the development of a methodology to assist designers in seeing possibilities, making informed decisions, and predicting colour transitions at different temperatures when designing a dynamic surface pattern.

The research was conducted by undertaking a series of design experiments using leuco dye-based thermochromic inks, which resulted in various working methods and two pedagogical tools. This process offered the insight and depth of understanding required to design dynamic surface patterns, in that it highlighted the different colour-changing properties of leuco dye-based thermochromic inks, which have the potential to create a more complex and dynamic range of patterns on textiles than those that exist today. There is much to explore beyond the current design possibilities offered by thermochromic inks, and it is hoped that designers and researchers can apply the knowledge that has been obtained during the work of this thesis to their practical explorations so as to move towards new ways of thinking and designing, and further innovation in textile design.
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1. PUBLICATIONS

1.1 List of appended papers


F) Kooroshnia, M., Thermochromic colour sample spectra: a pedagogical tool for studying and teaching leuco dye-based thermochromic inks in textile design, submitted to *journal of Textile Design Research and Practice*. 
1.2 Exhibitions


Smart textiles sample collections: Exhibited 5-9 February, 2013 at Stockholm Furniture Fair, Sweden.


Crafting with thermochromic conductive yarn: Exhibited 13-17 October, 2014 at Shaping (un)common grounds exhibition, ArcInTex, Eindhoven, Netherlands; 24-31 November, 2014 at Shaping (un)common grounds exhibition, ArcInTex, Ronse, Belgium.


1.3 Workshops


Thermochromic workshop, 25-27 February, 2013 at Department of Design, Aalto University, Helsinki, Finland.

Thermochromic workshop, 10-11 April, 2014 at School of Art and Design, Auckland University of Technology, New Zealand.

Bi-annual, three-day thermochromic workshop, 2010-present at Swedish School of Textiles, University of Borås, Sweden.
2. INTRODUCTION

What are the key aspects that textile designers must be aware of when designing using leuco dye-based thermochromic inks? What new possibilities and alternatives are offered by these inks when they are printed on textiles? What are the challenges for textile designers who wish to create dynamic surface patterns? What do textile designers need to know about leuco dye-based thermochromic inks in order for the field of dynamic surface patterns to be further developed?

For over a decade, materials scientists have increasingly paid attention to functional, rather than structural, materials (McQuaid, 2005; Addington & Schodek, 2005; Wang & Kang, 2013). These developments have attracted the interest of experimental textile designers, and have caused an inevitable movement in the textile design field towards the use of so-called ‘smart’ materials, a term which refers to advanced functionality and the ability to sense and respond to one or more external factors (cf. Tao, 2001).

Smart materials introduce new possibilities for design practice, but their properties and capabilities also entail a need to expand the range of design methods and techniques beyond those traditionally used in textile design; to develop ones that not only capture the inherent potential of smart textile materials, but facilitate practical and theoretical development in design practice.

Leuco dye-based thermochromic inks are colouring agents that have been used for more than a decade in the creation of interactive textile displays, but their full potential has not yet been fully realised or explored. There is a need for textile researchers to develop methods with which to support ways of conceptualising and describing their potentials in textile design practice. For this purpose, the research presented in this thesis focuses on explorations of the design properties and potentials of leuco dye-based thermochromic inks (referred to hereafter as ‘thermochromic inks’) when printed on textiles to create a wider range of colour-changing effects.

It should be noted that the knowledge that designers possess about colour has been drawn from various different disciplines, including physics, chemistry, physiology, and psychology (Sivik, 1974; Hård et al., 1996; Hård & Sivik, 1981; Billger, 1999; Fridell Anter, 2000; Berns, 2000; Itten, 2003; Green-Armytage, 2006, 2010; Collis & Wilson, 2012; Klaren et al., 2013). The intention of the work that is described in this thesis was never to define whether thermochromic inks is the one that physicists
2.1 INTRODUCTION

measure or psychologists study. Knowledge derived from these disciplines is valuable in relation to using colour in design practice, of course, but this thesis focuses on thermochromic inks as textile materials/colours and their behaviour when printed on textiles, which have the potential to precipitate a change in textile practice by opening a path to new possibilities that were previously unthinkable (cf. Manzini, 1989).

2.1 The structure of this thesis

Chapter 1 lists the six appended papers and other publications, including exhibitions and workshops, that form the basis of this thesis.

This chapter introduces the content of this thesis.

Chapter 3 provides an introduction to thermochromic inks, and then presents an overview of current design practice relating to the use of thermochromic inks within the textile design area. It also touches upon some of the issues within textile design practice, highlights areas in which there is more work to be done, and reviews existing colour systems while simultaneously stressing the need for one that facilitates discussion of the design properties and possibilities of thermochromic inks when printed on textiles.

Chapter 4 describes the research programme as a framework for the exploration of the design properties and possibilities of thermochromic inks, and introduces the objectives of the research.

Chapter 5 presents the practice-based design research methodology and methods used in this thesis so as to provide a basis for understanding its structure in relation to design practice. It describes the research process with reference to the design of surface patterns, the methods used to create and analyse fabric samples, and the formulation of the results.

Chapter 6 presents seven series of experiments and the methods used for creating each colour-changing effect. It describes some of the effects that thermochromic inks can offer during design development. Experiment I involved exploring the basic design properties and potentials of thermochromic inks with activation temperatures of 15 and 31°C. Experiment II introduced a method of forming temperature-sensitive mixtures consisting of multiple colours, and a method for revealing latent colours and designs. Experiment III utilised a textile printing method that combined the offset method of printing with the temperature-sensitive colour mixture process of Experiment II. Experiment IV proposed a pedagogical tool for teaching the behaviour of thermochromic inks to students of textile design. Experiment V explored a method of creating a wide spectrum of colours that would appear at different temperatures. Experiment VI consisted of the creation of thermochromic colour transition sample spectra, which can be used as guidelines for studying and teaching thermochromic inks and designing dynamic patterns on textiles.

Chapter 7, the concluding discussion, stresses the need for a new colour system, explores what a thermochromic colour system may look like, and offers recommendations for future work. It also discusses the colour-changing potential of thermochromic inks with regard to creating dynamic optical illusions on textiles. In addition, it presents pieces of technical advice, and discusses the types of fabric that are important to know when working with thermochromic inks. Finally, the chapter describes how the use of different heat sources creates different colour-changing effects on textiles.
3. BACKGROUND

3.1 leuco dyes based thermochromic inks

In 1909, Prague-based chemist Hans Meyer observed thermochromic behaviour in certain organic compounds; in 1954 and 1963, E. Harnik and G.M.J. Schmidt, along with J.F.D. Mills and S.C. Nyburg, published several articles about thermochromism [Harnik & Schmidt, 1954; Mills & Nyburg, 1963]. In 1983, heat-sensitive encapsulated thermochromic inks were created by the Pilot Corporation of Japan, to be used primarily with plastics or textiles in commercial applications such as thermochromic paints or wrapping materials (Kito et al., 1983). In the latter decades of the twentieth century, a number of products with thermochromic characteristics reached the market; these included a ‘mood ring’, thermochromic dyed clothing (in high demand at the beginning of the 1970s), a battery life indicator on Duracell batteries [Philips, 2000], a toothbrush, and a drinking vessel (Ritter, 2007, p. 87). At present, thermochromic inks are commercially available from several manufacturers, including Zenit and LCR Hallcrest. The inks’ qualities, along with the availability of colours, vary slightly between different manufacturers.

There are two major types of thermochromic ink: liquid crystal and leuco dyes. The former provide a continuously changing spectrum of colour when exposed to temperature changes. Below their activation temperature they are colourless but, as the temperature rises, they change colour; for example, from colourless to red at one specific temperature and, as the temperature increases, through the other colours of the visible spectrum in sequence (orange, yellow, green, blue, violet). Eventually, they become again colourless at a yet-higher temperature. The colour changes are reversible, and as they cool the colour-change sequence occurs in reverse order. To observe the full range of colours offered by liquid crystals, a dark – ideally black – background is required. Liquid crystals can be highly temperature sensitive, and can display many colours, but are more expensive than leuco dyes (Homola, 2003), which are available in a wider variety of colours and temperatures. To observe the colour-changing effects of leuco dyes, a light – ideally white – background is required. As they are less temperature sensitive than liquid crystals, they are suitable for use as general indicators that display approximate temperatures (i.e. ‘cool’, ‘warm’, ‘hot’). The scope of this thesis is limited to reversible, water-based, leuco dye-based thermochromic inks.
3.1 BACKGROUND

The interactive properties of thermochromic inks, which suggest new forms of communication and expression, have been explored by several researchers in the field of textile design (Hallnäs et al., 2002; Redström et al., 2005; Worbin, 2010). 'The Skin Stories' (Berzina, 2004) is a practice-based multidisciplinary research project wherein the interactive and decorative potential of thermochromic inks was investigated and interactive textile surfaces for use in home interiors were created. The thermochromic inks, along with scents and the heat generated by electronic equipment or the human body, were used to design various multisensory interactive surfaces that behave in a manner similar to human skin. For example, the prototype Touch Me is a colourfully striped wallpaper printed with thermochromic inks: By touching it, a temporary handprint appears, an aroma-therapeutic fragrance is released, and the incorporated phase-change materials release heat to prolong the visual effect produced by the thermochromic ink (Fig. 1).

![Fig. 1. Touch me (2004) by Zane Berzina.](image)

The interactive surfaces that resulted from the 'Electronic Textiles' project (Orth, 2004) used woven electronic circuitry in combination with thermochromic printed textiles to demonstrate the beautiful visual effects that can be achieved using thermochromic inks. Prototypes were created to challenge user perceptions about the static and dynamic relationships that exist between the compositional elements. The prototype known as 'Dynamic double weave I' consists of thermochromic printed patterns printed on an electrode-woven fabric that react to the heat produced by the conductive yarns. When the 64-pixel display is connected to a power supply each pixel receives an electrical current, the resistive yarns are heated, and the colours of the print change from dark to light (Fig. 2).

![Fig. 2. Dynamic Double Weave I (2004) by Maggie Orth.](image)

Other examples of interactive textiles include a piece created as a result of the 'Shimmering Flower' project, consisting of a soft woven circuit board (produced on a Jacquard loom) which activates and controls thermochromic prints with individually programmable pixels in parts of the design. Electronics send current to the pixels, heating the resistive yarns and changing the colour of the print (Berzowska, 2005), as well as two pieces of furniture that respond to the presence of a person by...
changing colour in response to body temperature, and retain this colouring for several minutes after the person has left (BAN, 2007; also see Ritter, 2007). Furthermore, the ‘AmbiKraf’ project used Peltier semiconductor modules to rapidly heat and cool a textile printed with thermochromic ink, actively animating it (Peiris et al., 2009).

In the ‘Designing Dynamic Textile Patterns’ research project (Worbin, 2010), a series of examples were created that display the potential of thermochromic inks for textile applications with particular regard to ways of activating and controlling the printed patterns on these textiles. One of the particularly interesting outcomes is a prototype entitled ‘Being Square’, which consists of an electrode-woven apron printed with thermochromic ink. When the apron is connected to a power supply, electronics send current to different parts of the apron, causing the resistive yarns to heat up. This causes the striped pattern, printed in black thermochromic ink on the apron, to change to a checked pattern similar to that of a tablecloth. Through practice-based multidisciplinary research, Worbin’s work combines traditional textile design processes and colour-changing and computational technologies to create and control dynamic textile patterns (Fig. 3).

‘An investigation of the design potential of thermochromic textiles used with electronic heat-profiling circuitry’ (Robertson, 2011) discusses the design potential of thermochromic colours (leuco dyes and liquid crystals) in relation to textiles activated by integrated electronic systems. Screen-printing and laser technology were combined with heat-profiling mechanisms as part of the experimental process in order to explore the aesthetic qualities of thermochromic colours when used in combination with heat-profiling circuitry. The research resulted in a series of prototypes with complex and highly unusual colour-change effects. For one of these, a design was produced on black cotton using laser engraving technology, then screen printed with a layer of red thermochromic ink with an activation temperature of 47°C. This was overprinted with two liquid crystal layers with activation temperatures of 27 and 31°C, and finished with a layer of Revacryl 275 in order to protect the surface of the fabric. Finally, the sample was used in combination with heat-profiling circuitry and linked to the digital mix system (DMX). As the temperature increases to or exceeds these, the liquid crystals are activated and begin to travel through their range of colours. When the temperature reaches or exceeds 47°C, the red thermochromic ink begins to change from red to colourless, and the laser-engraved pattern is revealed. A full range of colour changes is seen in this prototype, which is due to the way the colours were mixed (Fig. 4).
3.1 BACKGROUND

In another, more recent, research project, entitled ‘Thermochromic textiles and sunlight activating systems: an alternative means to induce colour change’ (Ledendal, 2015), a series of examples of different ways of using sunlight as a direct or indirect activator of thermochromic ink printed on textiles was created. For one of these prototypes, a print was produced using magenta thermochromic ink, then etched with a butterfly pattern. The print changes colour when it is bathed in more sunlight, and the etched pattern slowly becomes less visible. Subsequently, both the colour and the pattern return to their non-activated states if, for example, the sky clouds over (Fig. 5).

![Fig. 5. Thermochromic printed fabric by Marie Ledendal.](image)

As can be seen in Fig. 4, which is borrowed from Robertson (2011), aesthetically complex and highly unusual colour-change effects were created through the combination of liquid crystals and leuco dyes, but the use of leuco dye-based thermochromic inks in this research project was limited to ones which changed from one colour to another. Similarly, in the research projects discussed above, colour-changing effects were explored through experimentation with either thermochromic inks alone or a mixture of thermochromic inks and static pigments, allowing prints to change from one colour to another in different contexts. This, however, led to the question of whether thermochromic inks offer other design possibilities.

These research projects have provided successful examples of interactive textiles, and broadened the area by proposing ways of activating and controlling dynamic surface patterns and integrating electronic technologies and thermochromic inks. However, research into creating dynamic surface patterns for textiles has progressed relatively slowly. This may be due to a lack of exploration of the wide range of design possibilities afforded by thermochromic inks, and a lack of available information to guide textile designers regarding how these colours may be applied to textiles. These deficiencies may have led to more emphasis being placed on how to activate or control printed patterns produced by thermochromic inks than on more profound explorations of their design properties. These deficiencies may have also caused textile designers to frequently adopt a trial and error approach, as not knowing where to start with and how to use thermochromic inks, and lacking knowledge regarding their design properties and possibilities, is likely challenging and frustrating. Designers may thus see complexity in the use of thermochromic inks, rather than extensive and practical possibilities.

The review of research projects has inspired the design direction of the research carried out for and described in this thesis, which was directed towards exploring a wide range of design properties and potentials, as well as defining working methods for creating ideas and inspiration for continuing investigations through design.

In addition, an analysis of prior research projects indicated that existing colour systems and their terminologies are not sufficient for describing the expressions achieved during a design process involving thermochromic inks. To discuss the design properties and potential of thermochromic inks when printed on textiles, and to construct detailed descriptions of working methods and approaches, a detailed theoretical and practical investigation into other existing colour systems was carried out.

3.2 Colour systems

As most professional textile designers are aware, a colour can be described based on three properties: hue, value, and saturation (Wong, 1997; Itten, 2003, p. 34-55; Hornung, 2012, p. 22-30). ‘Hue’ refers to a specific colour from the colour circle by its name, for example ‘red’. ‘Value’ (also known as ‘lightness’ or ‘luminosity’) refers to the relative lightness or darkness of a colour; colours that are high in value approach white, while colours that are low in value approach black. ‘Saturation’ (also known as ‘chroma’ or ‘intensity’) describes the purity of a hue.
In practice, when any type of pigment such as textile pigment paste is used, the primary colours are pure yellow, pure red, and pure blue. These cannot be made by combining other colours. Equally, all other colours can be made by mixing two or more primary colours. When two pure primary colours are mixed, the secondary colours are created; these include orange, violet, and green (Osborne, 2008, p. 4). When a pure primary colour is mixed with a nearby secondary colour, the tertiary colours are created, for example yellow-orange, red-orange, red-violet (Feisner, 2006, p. 9).

Over the centuries, colours have been mixed according to three basic colour mixing systems; subtractive, additive, and partitive. Subtractive colour mixing is the process of mixing pigments together, as seen in painting and printing processes, and begins with white; colours are added until the result is dark grey leaning towards black (Albers, 2006, p. 27). Additive colour mixing is the process of mixing coloured light, as in computer and television displays (Gordon & Gordon, 2002, p. 72; Burger & Burge, 2012, p. 239). Partitive colour mixing is based on the viewer’s reaction to colours when these are seen in relation to other colours, such as an afterimage and optical illusion (Albers, 2006, p. 22).

These models have formed the foundations of colour systems for centuries. Although many systems exist, some have had a greater impact than others on the development of colour theory and practice in both academia and industry.

Colour wheels and systems are “colour arrangements or structures” (Feisner, 2006, p. 8) that enable designers to organise and predict colours, colour mixtures, and their interactions. The first colour wheel was designed by Sir Isaac Newton in 1666, and contains red, orange, yellow, green, blue, blue-violet, and violet, which were obtained by the passage of a ray of white light through a prism. This was translated into a two-dimensional circle, where the size of each segment corresponded to his calculations of the colour’s wavelength.

In 1810, two major works on the subject of colour were published. Goethe’s Theory of Colours proposed a colour wheel in which the three primary colours are yellow, red, and blue and the three secondary colours are orange, green, and violet. Runge’s colour spheres, however, offered the first three-dimensional colour model, and were based on the interaction of three chromatic (yellow, red, and blue) and two achromatic (white and black) colours. Runge’s primary colours are yellow, red, and blue, and his secondary colours are orange, green, and violet. Six additional colours are placed between these, each of which is mixed in two stages; with white (at the top of the sphere) and black (at the bottom of the sphere) (Feisner, 2006, p. 13-15).

In the early twentieth century, Albert Munsell created a three-dimensional model that was based on human perception and published as Colour Notation. In contrast to Runge’s sphere, Munsell’s system suggested, for the first time, that a colour could be described by the numerical values of three independent properties – hue, value, and saturation. Munsell’s system was thus the first to systematically illustrate colours in three-dimensional space, in a manner known as a ‘colour tree’. Cutting horizontally through the centre of the model is a circle consisting of twenty colours, each made using the five main hues of red, yellow, green, blue, and purple with a middle colour between each.

Munsell’s vertical axis is a scale of neutral grey values from No.10 (white) at the top to No.0 (black) at the bottom. Extending horizontally from the y axis at each grey value is a gradation of colour, progressing from neutral grey to a full saturated hue in seven stages. 5B6/8, for example, denotes a blue colour (5B) of medium value (located five stages above the black base), and of a fairly saturated colour (located eight stages from the central grey axis (About Munsell color, n.d).

In the early twentieth century, the International Commission on Illumination (CIE) created a system for colour matching that was based on both the additive mixing of light and XYZ tri-stimulus values, the latter of which are associated with a colour space that can be conceptualised as amounts of red, green, and blue light. These values are calculated using a standardised light source and an observer, and the sample’s spectral curve. The CIE presented the reflected light wavelengths as numerical values, which were recorded as points across the visible spectrum and termed ‘spectral data’. The CIE normally represented in the form of a flat, tongue-shaped structure, on which are plotted the chromatic colours as they occur under standard lighting conditions. The CIE system became a building block on which many other colour measurement systems were based, and there have been several revisions, including ‘CIE Lab’ and ‘CIE L*a*b*’ (Feisner, 2006, p. 13-22).
3.2 BACKGROUND

In 1961, Johannes Itten, inspired by the work of Newton, Goethe, and Runge, developed a contrast-based system to study and use color. He identified seven “color contrasts” and organized them into as many harmonious color strategies: of hue, of light and dark (value), of warm and cool, of complements, simultaneous contrast, of saturation, and of extension. He also created a twelve-part color circle, in the middle of which are a triangle and a hexagon. The circle featured primary, secondary, and tertiary colors, with the primary colors (yellow, red, and blue) in the equilateral triangle, with yellow at the top, red in the lower right, and blue at the lower left. The secondary colors (orange, green, and violet) are positioned in the isosceles triangles between the adjacent sides of the hexagon. Both the primary and secondary colors are repeated at their appropriate locations on the color circle. The tertiary colors are located between each primary and secondary color. Colors that are diametrically opposite each other within the circle are complementary, and mixing them should yield a natural grey. Itten described color harmonies as any two complementary colors of the color circle, any three colors that form an equilateral triangle, and all four color combinations that form squares or rectangles [Itten, 2003].

Josef Albers’ Interaction of Color (2006), first published in 1963, suggested an approach to studying and teaching color that was based on learning through direct perception, rather than theories and color systems. Albers’ color theory was based on concepts of color harmony and “simultaneous contrast”, which Itten describes as resulting “from the fact that for any given color the eye simultaneously requires the complementary color, and generates it spontaneously if it is not already present” [Itten, 2003, p. 52]. Albers’ primary color system is an equilateral triangle, developed by one of his students, that is divided into three equal parts, which are further subdivided to create a total of nine small triangles. In the corners, he placed the primary colors yellow, red, and blue. The secondary colors orange, green, and violet were located midway between the corners, and the tertiary colors were placed in each remaining triangle. The combination of two or more colors of a corner of the triangle produces a natural grey [Albers, 2006, p. 66].

The same year, Lawrence Herbert’s Pantone Matching System (PMS) was introduced. Still in use today, it utilizes a numbering system, with a variety of color samples and chips, as well as a digital color-matching system, that assists designers in comparing different types of coated, uncoated, and matte colors. Herbert adopted a similar approach to Munsell, with a color circle consisting of 64 saturated colors made from the five main hues of red, yellow, green, blue, and purple. The vertical axis is a scale of neutral grey values, with white at the top and numbered 11, and black at the bottom and numbered 19. Extending horizontally from the y axis at each grey value is a gradation of color, progressing from neutral grey to full saturation in 64 stages. 16-2430 TCX Pantone, for example, denotes a purple-reddish sample (hue No. 30), consisting of 16% lightness and 24% saturation [Osborne, 2008, p. 33; Gordon & Gordon, 2002, p. 193].

In 1979, Anders Hård and Lars Sivik [Hård & Sivik, 1981] introduced the Swedish Natural Colour System (NCS), which defines colors more precisely than previous systems as it is based on the visual appearance of colors, has a broad color range, and facilitates the matching of colors. A circle of fully saturated colors based on four main ones (yellow, red, blue, and green) divides the colors horizontally, with each quarter of the circle being further divided into 100 equal parts. Cutting through the circle vertically gives a set of color triangles. Each triangle has black at the bottom, white at the top, and a color of maximum saturation at the far right. Inside the triangle, any color can be located in terms of its degree of similarity to any of the following colors: yellow, red, blue, green, white, and black [Fig. 6].

![Fig. 6. The NCS Natural Color System (The Natural Colour System is the copyright and trademark property of NCS Colour AB) (1979) by Anders Hård and Lars Sivik.](image-url)
3.2 BACKGROUND

Until 1998, colour systems always took the form of a circle, sphere, or triangle, but this changed with the advent of a three-dimensional colour cube. As has been discussed above, computer and television displays and digital scanners are based on the additive mixing colour system (RGB), whereby red, green, and blue lights are projected together to produce white light. Offset and digital printing on any surfaces such as fabric, paper, plastic, etc. are based on the subtractive mixing colour system (CMYK), in which cyan, magenta, yellow, and black are mixed to form other colours. The three-dimensional RGB colour cube system integrates the two, defining subtractive colours (cyan, yellow, and magenta) as primary and additive colours (red, blue, and green) as secondary. This system describes colours within a colour space based on the input quantities for primary colours that are used to make a colour; this is in contrast to other colour systems, which are based on measured output values, i.e. what a colour looks like.

With the RGB colour cube, each colour has a numeric identifier, which indicates the input values that were used to produce it, and a position within the cube, ensuring that one can easily map both positional and mixing information. Moreover, if the mixing information is given the positional information can be derived, and the reverse is also true. The greatest advantage of the colour cube is that it greatly facilitates the mapping of complementary colours, harmonious colours, warm and cool colours, tints, and shades (Petronio Bendito, 2000; Norman, 1933).

Detailed theoretical and practical investigation into existing colour systems raises a number of important issues. These systems allow textile designers, particularly those who are interested in textile printing techniques, to determine a colour, as well as to determine the reaction or interaction that a particular colour would cause in a specific scenario. They do not, however, support textile designers during design processes that involve thermochromic inks, as they cannot display the behaviour of thermochromic inks in relation to other static textile pigment pastes and varying temperatures.

Based on the above-discussed research projects, a programme to explore the design properties and potentials of thermochromic inks when used on textiles was formulated. This was intended to produce knowledge regarding the colour-changing properties of thermochromic inks and printing principles, in order to assist textile designers in design processes and develop the colour-changing design field.
As a result of the technological progression of materials science, the palette of colours with which to print on textiles has expanded beyond those with well-known properties and expressions and to a new generation, which feature more advanced functionalities and expressional properties. This new range of colours is characterised by its ability to change colour in response to external factors. Often referred to as ‘smart colours’, these include thermochromic inks, photochromic inks, photoluminescent pigments, and etc., introduce new possibilities for textile design, and challenge current theory and practice by allowing designers to suggest certain perceptions, reactions, and activities through design.

To design a dynamic pattern on a textile, a textile designer requires basic knowledge regarding how to use thermochromic inks to achieve different colour-changing effects, as well as an understanding of how different methods, approaches, and procedures can affect design decisions. Experimental textile researchers play a key role in exploring the design properties and possibilities of these colours, and work to enlarge the body of knowledge related to understanding, describing, and working with these smart colours in connection with textiles.

The research programme of this thesis, carried out by conducting experiments, was: to explore the design properties and potentials of thermochromic inks when used on textiles, and to facilitate improved understanding and design of dynamic surface patterns in the context of textile design. The programme, as an area of the research, provided a foundation and framework for experimentation, and interpretation of it directed actions towards a goal. It outlined a specific perspective for interpreting the design experiments, and formed a basis for constructing a theoretical foundation.

The objectives were to:

1. Explore the design properties and potential of thermochromic inks and investigate how to apply them in practice, in order to expand the range of colour-changing effects offered by thermochromic inks on textiles. See Experiment I and Paper A; Experiments II and III and Paper C; Experiment V and Paper E.

2. Explore ways of communicating the design properties and potentials of thermochromic inks, in order to facilitate communication regarding, understanding of, and design with thermochromic inks. See Experiment IV and Paper B; Experiment VI and Paper F.
Investigating thermochromic ink's broader applications was not the aim of this research; rather, it was to allow thoughts, flexible imagination, and discovery to be cultivated and supported in order to explore the expressive qualities of thermochromic inks and, consequently, suggest new working methods that could further change design practice.

Fig. 7. A thermochromic print shown at a non-heated state (top left) and at the end-colour loss point (bottom right).
This research has been carried out following the principle of experimental exploration in basic design research (Jones, 1992, p. ix-6; Frayling et al., 1997; Durling et al., 2002; cf. Albers, 2006; Sevalson, 2010). It focuses on experimental research as a means of exploring and investigating the expressive qualities of a design material (Hallnäs & Redström, 2006, p. 133-140), in order to expand the boundaries of design space and develop the design field (Noever, 2010, p. 33; Dagmar, 2013). The research was undertaken in the context of textile design and using textile printing techniques, with particular reference to hand-screen printing.

In short, the process began with an initial idea and formulation of the design programme, which was realised through experimentation and analysed and evaluated by reflecting upon and formulating the results (cf. Redström, 2011). In all of the experiments, surface patterns were designed in order to assist the exploration and examine the artistic and expressive possibilities of such patterns. The primary sources of inspiration were Persian designs; this was due to a personal interest and cultural background, and focused particularly on the fresco and plasterworks of palaces, flower and bird paintings, and arabesque patterns. However, while colour was at the core of the research, colour selection was not always based on the design, but often dictated by market availability.

The experimentation direction has been based on the objectives of the stated research programme, the author’s previous experiences with using thermochromic inks on textiles, and themes, ideas, and findings generated by literature studies and sketching processes. Within the programme, each experiment began by asking a series of ‘what if...?’ questions and testing them in practice. As a result of each series of experimentation, expressions, in the form of fabric samples, were developed to suggest alternative ways of achieving colour-changing effects on textiles. At each stage, fabric samples were gathered. The author, as a reflective practitioner and critical investigator (Schön, 1995; Niedderer & Reilly, 2010), analysed and evaluated each series of fabric samples in order to form a foundation for the next stage, each of which developed and expanded the findings by creating a wider range of colour-changing effects. They also opened up for new possibilities and insight by suggesting alternative ways of creating these effects.
5. METHODOLOGY

The collection of fabric samples contains both explicit and implicit content (Stappers, 2007); the explicit was the collection of fabric samples itself (Biggs, 2006), which displays diverse colour-changing effects, while the implicit required that each series of samples be interpreted as a ‘text’ in order to be made comprehensible and to aid in the generation of explicit knowledge and the construction of the theoretical foundation. The ‘text’ is a suggestion in the form of working methods that relate to further changes in design practice (Hallnäs, 2010), and thus constitutes a methodological development for designing dynamic surface patterns. This relates more broadly to the issue of generating, developing, and discussing concepts so as to construct a foundation for further innovation in the design field (Jones, 1992, p. xi; Biggs, 2004; Hallnäs, 2010).

The working methods were not intended to be entirely replicable or to produce identical results, but a means of bringing forth ideas and inspiration. A designer may, in order to understand the principles involved, recreate the expressions shown by exactly following the working methods given, but they would be better served by using the methods as inspiration for continued investigation through design. It is, in a sense, comparable to the methods of successful chefs: They travel the world, learning how various foods are made, then use these methods and ingredients as creative inspiration for their own food, and so create new dishes.

Fig. 8. (opposite) Fabric samples from Experiment VI printed with the mixture of thermochromic inks and static textile pigment paste.
This thesis uses the terminology given in the data sheets provided by LCR Hallcrest [Thermochromic technology, n.d.], a thermochromic ink supplier, to describe the heating and cooling cycles of thermochromic inks:

- 'Activation temperature' is the point at which a thermochromic ink has lost 90-95% of its colour.

- 'Start colour-loss point' is the point at which the colour change begins. It is usually a few degrees Celsius below the activation temperature of the ink.

- 'End colour-loss point' is the point at which a thermochromic ink has entirely lost its colour. It is usually a few degrees Celsius above the activation temperature of the ink.

- 'Start colour-return point' is the point at which a thermochromic ink begins to return to its original phase. It is usually a few degrees Celsius below the end colour-loss point.

- 'Full colour-return point' is the point at which the thermochromic ink has returned to its original colour due to no longer being heated. It is usually several degrees Celsius below the activation temperature of the ink.

6.1 Experiment I: Basic design properties and potentials of thermochromic inks

One way of using a material is to follow technical guidelines provided by either the thermochromic ink supplier or other researchers/practitioners. The first test had a ratio of thermochromic slurry to extender of 3:97 (for a more in-depth discussion of mixing colouring agents, see Worbin, 2010, p. 83). This recipe created a lighter colour than that of the thermochromic slurry used for making thermochromic ink, which raised a number of questions: What if thermochromic slurries are mixed with extender in other proportions? What if thermochromic inks are mixed with static textile pigment pastes in other proportions? What is the behaviour of prints produced using the above mixtures when they are heated or cooled? This experiment thus explored the design properties of thermochromic inks with activation temperatures of 31 and 15°C.
6.1 EXPERIMENT I

Two thermochromic inks of the same colour (blue) but different activation temperatures (31 and 15°C) were used to explore the properties of a single colour of thermochromic ink when being applied to textiles. Both blue slurries were mixed with an acrylic-based extender in different proportions and printed on textiles, resulting in differing shades of blue in a non-heated state. The acrylic-based extender is a pigment binder, which has the ability to hold the pigment particles on the surface of a textile substrate (Wells, 2000, p. 59). Although numerous shades of blue were possible, this experiment sought to investigate six shades for each thermochromic ink, and so tones which clearly differed from one another were chosen.

The blue shades produced by both inks were tested at above 31°C and below 15°C in order to explore the design properties of thermochromic ink at different temperatures. A clothes iron was used to warm the fabric samples, and an ice bag was used to cool them. The colour-changing effects achieved at above 31°C and below 15°C were photographed in order to create printed colour diagrams. These facilitated comparison between the effects of heating and cooling (Figs. 9 and 13).

Yellow static textile pigment paste was then mixed with the blue shades of the previous experimental stage to explore further colour-changing effects. The same methods of cooling and heating were used to explore the design potential of the mixtures at different temperatures.

Two more printed colour diagrams, depicting the colours at three different temperatures (non-heated state; end colour-loss point, i.e. above 31°C; full colour-return point, i.e. below 15°C), were then created. These demonstrated the effects of heating and cooling on the printed green shades produced by mixing yellow static textile pigment paste and blue thermochromic inks with activation temperatures of 31 and 15°C (Figs. 10, 11, 14, and 15).

Tests were conducted with different plain woven fabrics, including 100% cotton, 50:50 cotton/polyester, and 100% polyester fabrics. Using 100% cotton allowed the structure of the fabric to be seen through the print, while 100% polyester resembled a coated, rather than printed, surface. The effect produced on the 50:50 cotton/polyester fell between these two extremes.

It should be noted that in the process of heating and cooling the print in Fig.17, it was observed that one of the thermochromic inks used in the experiment has an activation temperature 31°C. However, it was noted in paper A as a thermochromic ink with an activation temperature 27°C. The activation temperature of 31°C has been further confirmed with the ink supplier. Paper A focuses on thermochromic colour mixtures and how the prints produced using the mixtures behave when they are heated or cooled. Whether the inks have an activation temperature 27°C or 31°C do not effect the overall result of the experiment.

Result

This experiment resulted in printing paste recipes (Figs. 9-15) that could be used to investigate how thermochromic inks can be used on textiles (see Paper A). A ratio of ink to extender of 1:99 resulted in transparency above 15°C, and light blue at the full colour-return point (below 15°C). Such a property could be used to hide or reveal surface patterns.
6.1 EXPERIMENT I

Fig. 9. Thermochromic inks produced by mixing thermochromic slurry with an activation temperature of 31°C and extender. A ratio of 25:75 (thermochromic slurry to extender) produced a colour with maximal colour intensity in a non-heated state and maximal residual colour at the end colour-loss point. A ratio of 1:99 produced a light colour in a non-heated state, but less or even non-residual colour at the end colour-loss point (inks supplied by Zenit).

Fig. 10. One of the two ways of mixing differing amounts of thermochromic ink (activation temperature of 31°C) with a static textile pigment paste. The colour mixtures were different in a non-heated state, but became the same colour (that of the mixed pigment, though lighter) at the end colour-loss point. It should be noted, if the green colours in Fig. 11 appear to be different to those shown in this figure, that the qualities of inks vary slightly between manufacturers (inks supplied by Zenit).
Fig. 11. (opposite) The other way of mixing differing amounts of thermochromic ink (activation temperature of 31°C) with a static textile pigment paste. The colour mixtures were different both in a non-heated state and at the end colour-loss point (inks supplied by LCR Halcrest).
Fig. 12. Examples of how two design possibilities created by mixing thermochromic inks with different static pigment pastes can change.

<table>
<thead>
<tr>
<th>Heating</th>
<th>Colours at end colour-loss point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture of blue thermochromic ink and yellow static pigment paste</td>
<td>Variable colours in a non-heated state, changes to two different colours at the end colour-loss point.</td>
</tr>
</tbody>
</table>

Table 1: Experimental Results

<table>
<thead>
<tr>
<th>Heating</th>
<th>Colours at end colour-loss point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture of blue thermochromic ink and yellow static pigment paste</td>
<td>Variable colours in a non-heated state, changes to two different colours at the end colour-loss point.</td>
</tr>
<tr>
<td>Mixture of yellow thermochromic ink and blue static pigment paste</td>
<td>Variable colours in a non-heated state, changes to one colour at the end colour-loss point.</td>
</tr>
</tbody>
</table>
6.1 EXPERIMENT I

Fig. 13. Thermochromic inks produced by mixing thermochromic slurry with an activation temperature of 15°C and extender. A ratio of 25:75 (thermochromic slurry to extender) produced a colour with maximal colour intensity at the full colour-return point and maximal residual colour at the end colour-loss point. A ratio of 1:99 produced a white or very light colour (activated inks), and a light colour at the full colour-return point (inks supplied by Zenit).

Fig. 14. One of the two ways of mixing differing amounts of thermochromic ink (activation temperature of 15°C) with a static textile pigment paste. The colour mixtures produce different activated colours, but became the same colour (that of the mixed pigment, though lighter) at the end colour-loss point. The colour mixtures produce different colours at the full colour-return point (inks supplied by Zenit).
Fig. 15. (opposite) Flow of the two ways of mixing thermochromic ink (activation temperature at 15°C) with a static textile pigment paste, using different proportions of thermochromic ink with different proportions of static textile pigment paste. The colour mixtures produce different colour activated inks, at the end colour-loss point, and at the full colour-return point (inks supplied by LCR Hallcrest).
Fig. 16. (opposite) Two design possibilities; one that used thermochromic ink with an activation temperature of 15°C, and one that involved mixing thermochromic ink with an activation temperature of 15°C and a static textile pigment paste:

1 (top) – A white (activated ink) changes to a light colour at the full colour-return point.

2 (bottom) – An activated colour becomes another colour at the end colour-loss point, and yet another colour at the full colour-return point.

6.1 EXPERIMENT I

Activated thermochromic ink

Colour at full colour-return point

Cooling

Colour at end colour-loss point

Mixure of blue thermochromic ink and yellow static pigment paste

Heating

Colour at full colour-return point

Cooling
A dynamic pattern created by thermochromic inks with activation temperatures of 31°C (thermochromic slurry mixed with extender in a ratio of 5:95) and 15°C (thermochromic slurry mixed with extender in a ratio of 1:99), shown from a non-heated state (25°C) to the full colour-return point (22°C) (for the inks with an activation temperature of 31°C), and shown from the end colour-loss (16°C) to full colour-return (11°C) points (for the ink with an activation temperature of 15°C) (inks supplied by Zenit).
6.2 Experiment II: A method for forming temperature-sensitive colour mixtures

The results of the initial experiments raised the question: what if multiple colours could be concealed or revealed at once? The results of the initial experiment formed a basis for the development of more complex colour-changing effects, which were intended to conceal or reveal more than one colour at once. Experiment II sought to explore methods of creating a temperature-sensitive multi-colour mixture.

The first test involved attempting to conceal one colour of a two-colour surface pattern. One colour of static textile pigment paste and one colour of thermochromic ink that were similar to each other were mixed with more extender or other colours of thermochromic ink until they looked entirely alike. They were then printed onto the textile and left to dry (for a more in-depth discussion of mixing colouring agents, see Worbin, 2010, p. 83). In a non-heated state the surface pattern had only one colour, but at the end colour-loss point the parts printed with thermochromic ink became colourless (fully activated colour), revealing the pattern that had been printed using static textile pigment paste.

In order to conceal and reveal two latent colours – blue (Colour A) and magenta (Colour B), for example – two temperature-sensitive colour mixtures were made in the following order: The first was made by mixing blue thermochromic ink (Colour A) with an activation temperature of 31°C and magenta static textile pigment paste (Colour B). The resulting mixture was violet (Colour C) in a non-heated state and magenta (Colour B) at the end colour-loss point (fully activated colour). The second temperature-sensitive colour mixture was made by mixing magenta thermochromic ink (Colour B) with blue static textile pigment paste (Colour A), and was violet-greyish (Colour D) in a non-heated state and blue (Colour A) at the end colour-loss point (fully activated colour). The same principle was then used to prepare six temperature-sensitive colour mixtures (Figs. 18 and 19).

A screen-printed pattern was produced by printing each temperature-sensitive colour mixture next to the others. As the temperature was raised, the temperature-sensitive colour mixtures activated and began to change, from violet-greyish to the four different colours (Fig. 21).

These transformative visual qualities were one of the most interesting results of this stage of the research, and provided the idea of creating patterns that were altered through colour-changing.

This experiment did not result in precise printing paste recipes in the same manner as the first due to a lack of a thermochromic database with which to measure the dynamic prints using a spectrophotometer.
6.2 EXPERIMENT II

Result

This approach resulted in a method of mixing colours for creating a temperature-sensitive colour mixture consisting of multiple colours (Figs. 18 and 19). It expanded the range of possibilities for designing dynamic surface patterns in terms of revealing latent colours and designs (see Paper C).

The experiment illustrated the possibilities offered by utilising a common background colour in a non-heated state which, when heated, generated a multi-coloured background at the end colour-loss point. With reference to Experiment I, the temperature-sensitive colour mixtures can be made using thermochromic inks with low activation temperatures, for example 15°C. They thus become visible when exposed to a change in temperature; i.e. the temperature-sensitive colour mixtures are slightly coloured (pastel colours) in a heated state, and more strongly coloured when cooled to the full colour-return point.

For Experiment II, the temperature-sensitive colour mixtures were mixed with thermochromic inks with a single activation temperature (31°C). An alternative approach would be to use inks with differing activation temperatures (for a more in-depth discussion of mixing colouring agents, see Berzin, 2004), as well as (Paper E).
6.2 EXPERIMENT II

Fig. 19. (opposite) Six temperature-sensitive colour mixtures; all were of the same colour in a non-heated state, but different at the end colour-loss point (inks supplied by LCR Hallcrest).
6.2 EXPERIMENT II

Fig. 20. A design possibility produced by mixing thermochromic inks with an activation temperature of 31°C and static textile pigment pastes. It consists of six temperature-sensitive colour mixtures of the same colour in a non-heated state, which became different at the end colour-loss point.
Fig. 21. (pp. 89-106) A printed fabric was produced using four temperature-sensitive colour mixtures consisting of thermochromic inks with an activation temperature of 31°C and a static textile pigment paste, shown from a non-heated state (25°C) to the full colour-return point (22°C) (inks supplied by LCR Hallcrest).

- Mixture of yellow, red, green thermochromic inks with activation temperatures of 31°C and blue static textile pigment paste
- Mixture of yellow, blue, green thermochromic inks with activation temperatures of 31°C and red static textile pigment paste
- Mixture of red, blue, yellow thermochromic inks with activation temperatures of 31°C and green static textile pigment paste
- Mixture of red, blue, green thermochromic inks with activation temperatures of 31°C and yellow static textile pigment paste
- Mixture of red, yellow, green thermochromic inks with activation temperatures of 31°C and blue static textile pigment paste
6.3 Experiment III: A method for printing a complex dynamic pattern on textiles

The results of Experiment II raised the question: what if temperature-sensitive colour mixtures are printed in layers on top of each other? This experiment, thus, explored a method for printing a complex dynamic pattern on textiles.

In the paper printing industry, offset lithography is one of the most common techniques for printing entirely flat, full-colour images or photographs, and involves a series of steps, or transformations, to generate a quality colour reproduction. Two graphic techniques are required to prepare an image for four-colour printing: the separation of the full-colour image into four different colours (colour separation), and the translation of each colour layer to halftone. The process of colour separation is begun by separating the original image into cyan, magenta, yellow, and black layers, abbreviated as ‘CMYK’. Each single-colour layer is then converted to halftone, as the printing press cannot vary the amount of ink applied to particular areas of the image; lighter shades are thus represented as tiny dots. During the colour-printing process, the halftone layers are printed in succession, with inks printed on top of one another so as to produce different colours. Green is thus produced by printing yellow and cyan inks on top of one another. The halftone grids (dots) run at different angles to give the impression of infinite colours, in a kind of optical illusion.

This experiment was based on the offset method of printing, as well as the method of forming a temperature-sensitive colour mixture consisting of multiple colours, as described for Experiment II. A full-colour pattern, inspired by Persian patterns featuring flowers and birds, was designed. This was changed to CMYK mode using Photoshop, and each channel was then converted to halftone (Image > Mode > Bitmap > Halftone method). Angles of 60 degrees for cyan, 110 for magenta, 120 for yellow, and 30 for black halftone were used. Each halftone colour channel or layer was then exposed on a silk-screen frame and hand-screen printed.

Colour preparation was performed as for Experiment II. The first of four temperature-sensitive colour mixtures was made by mixing magenta, yellow, and black thermochromic inks with a cyan static textile pigment paste, resulting in a dark brown in a non-heated state and magenta at the end colour-loss point (fully activated colour). The second temperature-sensitive colour mixture was made by mixing cyan, yellow, and black thermochromic inks with magenta static textile pigment paste, giving dark brown in a non-heated state and magenta at the end colour-loss point (fully activated colour). The third and fourth mixtures were made following the same principle, but with yellow and black static textile pigment pastes, respectively. All four temperature-sensitive colour compositions looked similar in a non-heated state (Fig. 22).

It should be noted that temperature-sensitive colour mixtures often tend towards either dark brown or violet-greyish, although this depends strongly on the mixing batch that is selected as a basis for comparison and adjustment (see paper F). For this reason, the experiment used the same method of creating temperature-sensitive colour mixtures as is described for Experiment II, although all four temperature-sensitive mixtures were dark brown in a non-heated state, instead of violet-greyish.

Screen-printed patterns were produced, with the first layer consisting of cyan textile pigment paste, and additional layers, consisting of magenta and yellow textile pigments were printed; this was then overprinted with a layer of black. When the temperature was increased, the temperature-sensitive colour mixtures were activated, and started to change from dark brown to vibrant colours (Fig. 23).

To determine the correct fabric for the design, tests were conducted with different fabrics and thicknesses, including different types of woven cotton and polyester. The results were all fairly similar, meaning that, for this particular method, it seems possible to achieve sharp, defined forms using most woven fabrics.

Result

This approach resulted in a textile printing method which combined the offset method of printing and the above-discussed method of creating a temperature-sensitive colour mixture consisting of multiple colours.

This method demonstrated that it is possible to create a wide range of colour-changing effects by layering different temperature-sensitive colour mixtures and combining this with an offset printing technique. Thus, it allowed for more complex
6.3 EXPERIMENT III

dynamic patterns on textiles, in which the colour of the pattern changed from one colour, possibly, with different nuances to multiple vibrant colours [see Paper C].

Digital printing methods can produce similar effects, as was demonstrated in this experiment, without any restriction of colour profiles, but it is not yet possible for them to be used with thermochromic inks. The approach used in this experiment constitutes a method for obtaining a similar effect to those that can be achieved with digital printing through the use of thermochromic inks.

Fig. 22: A design possibility produced by mixing thermochromic inks with an activation temperature of 31°C and static textile pigment pastes. It consists of four temperature-sensitive colour mixtures printed on top of one another, and has one colour in a non-heated state and multiple vibrant colours at the end colour-loss point (inks supplied by Zenit).
Fig. 23. (pp. 112-129) A printed fabric, produced using four temperature-sensitive colour mixtures consisting of thermochromic inks with an activation temperature of 31°C and static textile pigment pastes, shown from a non-heated state (25°C) to the full colour-return point (22°C) (inks supplied by Zenit).
6.4 EXPERIMENT IV

6.4 Experiment IV: A pedagogical tool for teaching the behaviour of thermochromic inks

Working with thermochromic inks, be that in the form of studying and teaching or designing dynamic surface patterns using them, relates to a large degree to thermochromic colour transitions. Teaching the behaviour of thermochromic inks in relation to other static colours and varying temperatures, and based on existing colour theories and practical exercises, is almost impossible. This raises the question; what if the first and last stages of thermochromic colour transitions could be illustrated to provide students with a better understanding of the phenomenon? As a result, this experiment proposed a pedagogical tool for teaching the behaviour of thermochromic inks to students of textile design.

As a Master’s student at the Swedish School of Textiles at the University of Borås, the author participated in workshops on liquid crystals and photochromic and thermochromic inks. All of the workshops began with the lecturer giving an oral presentation on the topic, followed by some experimental work without any specific direction. Consequently, following and interpreting the content, which was mainly related to colour transition, through verbal communication alone was difficult, and thus so too was predicting colour transitions prior to experiments. These workshops could be improved by having a systematic teaching approach to learning new skills and stronger planning with regard to meeting the needs, desires, and requirements of learners (see Shreeve et al., 2010; Drew, 2004; Sork, 1997). Thus, when the author was asked to hold a thermochromic workshop, students were offered a hands-on experience that was followed by a set of structured tasks (Ginsberg & Wlodkowski, 2009) that demonstrated the colour-changing effects of thermochromic inks at various temperatures, in order to help them achieve a better understanding of this phenomenon.

For this purpose, the experiment began with two collections of fabric samples [prints]; one with blue, magenta, orange, turquoise, and black thermochromic inks with activation temperatures of either 27°C or 15°C, and the other with the same thermochromic inks mixed with yellow textile pigment paste. The prints were then measured with a spectrophotometer at three different temperatures – in a non-heated state, after heating (at the end colour-loss point), and after cooling (at the full colour-return point) – and the measurements were translated into colour swatches, which were printed using the textile pigment pastes. The swatches made it possible to effectively demonstrate the colour transitions of thermochromic inks at different temperatures.

A printed thermometer was placed on the table of the printing lab in order to illustrate the three different temperatures. The right side of the thermometer was used to display the effects produced by inks with an activation temperature of 27°C, while the left side displayed the effects produced by inks with an activation temperature of 15°C. The colour swatches were placed on the table so as to provide a point of comparison to the effects produced by the thermochromic inks or the mixtures of ink and yellow textile pigment paste in a non-heated state, after heating, and after cooling (Fig. 24).

As it was important for the students to arrive at a detailed understanding, the author’s strategy was to give them tasks that would allow them to experience the phenomenon for themselves. Some were structured, while others were more free, assisting in students’ development of their ability to design dynamic surface patterns.

Result

The result of this experiment was a pedagogical tool for teaching the behaviour of thermochromic inks to students of textile design. The printed colour swatches demonstrated the colour transitions of thermochromic inks at different temperatures. The structured tasks created opportunities for students to learn the principles of colour transition by actually experiencing them, and the more free tasks showed the students that the possibilities are endless.

The workshop was evaluated by considering the student’s design outcomes. These indicated that the tool allowed the students to integrate their new knowledge of the behaviour of thermochromic inks with what they already knew about static pigments in relation to the design of a surface pattern. Moreover, it allowed them to work on their ideas using their design skills, and assisted in developing their ability to predict the consequence of their design decisions in terms of where and how to apply thermochromic colours in relation to other design elements when designing dynamic surface patterns [see Paper B].
Fig. 24. Colour swatches made using static textile pigment paste, which were created to demonstrate the varying colours of thermochromic inks at different temperatures.
6.5 Experiment V: Thermochromic inks with different activation temperatures

Thermochromic inks were used in the previous experiments to make temperature-sensitive colour mixtures with similar activation temperatures. This raised the question; what if the thermochromic inks have different activation temperatures? This experiment therefore explored thermochromic inks with different activation temperatures in order to create a wide spectrum of colours that would appear at different temperatures.

Although the original intention of the research was to work primarily with textiles, this experiment used a light grey Nm 10/3 conductive yarn (80% Polyester ecru; 20% Stainless steel, 12 micron). A yarn, rather than a woven textile, was chosen; this was because the aim of the experiment was to create a colour-changing textile, rather than to simply print a colour changing-pattern onto a textile. However, although this experiment primarily used yarn it began with printing, since observing the colour transition of thermochromic inks at different temperatures is more easily accomplished with textiles than with yarn.

The first test was conducted using four different thermochromic inks with four different activation temperatures (15, 20, 31, and 37°C). Each temperature-sensitive colour mixture was made by mixing a static textile pigment paste with a thermochromic ink of either blue or red with an activation temperature of 15°C, one of the thermochromic inks with an activation temperature of 31°C (magenta, turquoise, or orange), and a black thermochromic ink with an activation temperature of 37°C. The mixture was then applied to both a plain white poplin cotton fabric and the yarn.

The fabric samples were cooled, then heated using an electrical heating and cooling device (the specifics of which are given in Paper E) to 40°C. This did not, however, achieve the anticipated colour, which can likely be ascribed to the fact that the activation temperature of one of the inks (31°C) was very close to that of another (37°C) and that, had they been further apart, this would not have occurred.

The heating process indicated that the minimum difference between the activation temperatures of the inks used in order for the colour-change process to work correctly is 10°C. In addition, this test indicated that the darkest colour should have the lowest activation temperature, and the lightest colour the highest (see also Berzina, 2004, p. 156).

Next, thermochromic slurries were used; blue with an activation temperature of 27°C, magenta with an activation temperature of 37°C, and yellow with an activation temperature of 47°C. The colour strength of each was determined in advance, and was found to be achievable with 25% slurry and 75% extender. The thermochromic inks were printed on the textile in different orders (in ascending order of activation temperatures, or the reverse, for example). The same method of heating was used, producing gradual colour transitions (Fig. 25).

Green static textile pigment paste was then mixed with each of the mixtures of the previous experimental stage in order to add a further colour-changing effect. The same method of heating was used, producing gradual colour transitions (Fig. 25).

A screen-printed pattern was produced using blue, magenta and yellow thermochromic slurry with activation temperatures of 27, 37, and 47°C mixed with extender in a ratio of 2:98. Pattern was also produced by mixing all three inks with or without static textile pigment paste (green) in one mixing batch in a ratio of 25:75. The pattern displayed different colours at the first, second, and end colour-loss points, i.e. when the temperature was increased to above 27, 37, and 47°C (Fig. 26).

Once it had been ascertained that the desired colour-changing effects could be achieved by mixing all three inks – with or without static textile pigment paste in one mixing batch, the mixture was applied to the yarn, as well as to the ready made lace that this experiment ultimately resulted in (discussed below). The lace used was produced by Museum de Kantfabriek, using machines from the 1930s. The technique used to make it, along with its structure, allowed the conductive yarn to run in parallel and each to be individually manipulated. The conductive yarn in the lace structure acted simultaneously as a sensor and an actuator. When a touch is registered it slowly heats up to above 47°C, causing the lace to change from one colour to a different one at each of the three colour-loss points, i.e. when the temperature was increased to above 27, 37, and 47°C (Fig. 27).
6.5 EXPERIMENT V

Result

The use of the painted conductive yarn offered an opportunity to create a colour-changing lace, which in turn facilitated the creation of a dynamic surface pattern that was based on the structure of the lace and provided the ability to control the colour-changing effects on each strand of painted yarn.

This approach resulted in an improved understanding of the principles relating to the use of thermochromic inks with different activation temperatures [Fig. 25]. Moreover, it led to the range of colour-changing effects offered by thermochromic inks becoming more diverse, as each appears in sequence due to increasing temperature, and provided a different type of colour-changing effect on textiles that varies depending on which colour is activated and at what temperature. For example, in the case of a dynamic surface pattern printed using thermochromic inks with activation temperatures of 27°C (blue), 37°C (magenta), and 47°C (yellow), one colour-changing effect can be achieved by increasing the temperature slowly from 18°C to above 47°C, which would cause the pattern to change from its initial dark red-brownish to orange above 27°C, then to yellow above 37°C, and to a white with a grey-yellowish tint above 47°C. Another possibility would be to start at 32°C and increase the temperature to above 47°C, which would cause the pattern to change from red-brownish to yellow above 37°C, and to white with a grey-yellowish tint above 47°C (see Paper E and F).

Fig. 25. The process of creating thermochromic inks with activation temperatures of 27, 37, and 47°C respectively from top to bottom.
Fig. 26. (pp. 138-198) A printed fabric produced using: Inks with activation temperatures of 27, 37, and 47°C (in a ratio of 2:98, slurry:extender); a mixture of inks with activation temperatures of 27, 37, and 47°C (in a ratio of 25:75, slurry:extender); a mixture of inks with activation temperatures of 27, 37, and 47°C and a static textile pigment paste (in a ratio of 25:75, slurry:extender). It is shown from a non-heated state (19°C) to the full colour-return point (18°C) (inks supplied by LCR Hallcrest).
Fig. 27. The lace made using conductive yarns painted with the mixture of inks with different activation temperatures (27, 37, and 47°C) and a static textile pigment paste (inks supplied by LCR Halcrest).
6.6 EXPERIMENT VI

6.6 Experiment VI: Thermochromic colour transition sample spectra

The previous experiments explored colour-changing effects in a non-heated state, at the end colour-loss point, or at the full colour-return point. This raised the question; what if the states of thermochromic colour transitions between non-heated, heated, and cooled are properly visualised? This experiment thus involved the creation of thermochromic colour transition sample spectra.

Primary colours (red, yellow, and blue) of both thermochromic inks with an activation temperature of 31°C and static textile pigment pastes with similar degrees of colour strength were used. Based on the results of the previous experiments, four series of prints were produced. The first of these consisted of three fabric samples, produced using thermochromic inks in primary colours; the second consisted of six fabric samples made using one colour of thermochromic ink and one colour of static textile pigment paste; the third consisted of six fabric samples produced using more than one colour of thermochromic ink and one colour of static textile pigment paste; the fourth consisted of two fabric samples, one produced using three thermochromic inks with different activation temperatures and the other with three thermochromic inks with different activation temperatures and a static textile pigment paste. The fabric samples were slowly heated and cooled using an electrical heating and cooling device [the specifics of which are given in Paper F], and the entire process of heating and cooling was photographed.

In addition, several screen-printed patterns were produced, which involved printing using the temperature-sensitive colour mixtures described above. These contributed to further exploring thermochromic colour transitions using surface patterns [Figs. 17, 21, 26, 32].

Result

The result of this experiment was a series of thermochromic colour transition sample spectra that can be used as guidelines for studying and teaching thermochromic inks. The experiment demonstrated that thermochromic colour transitions entail a movement from Colour A to Colour B and back again to Colour A, occurring when the temperature changes.

This transition can be subdivided into three categories:

1 – Fading: A graduated scale, ranging from Colour A to a lighter version of Colour A, and back again to Colour A (Fig. 28).

2 – Bridge: A graduated scale, ranging from Colour A to Colour B, and back again to Colour A.

• Single bridge: Colour A is a colour mixture wherein two different colours – one of thermochromic ink and one of static textile pigment paste – are mixed. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B, and back again to Colour A.

• Double bridge: Two similar Colour A, each of which is a mixture of a thermochromic ink and a static textile pigment paste. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B or C, and back again to Colour A (Fig. 29).

• Triple bridge: Three similar Colour A, each of which is a mixture of two thermochromic inks and a static textile pigment paste. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B, C, or D, and back again to Colour A.

This may continue ad infinitum, with quadruple, quintuple, sextuple and so on bridges.

3 – Continuum bridge: Graduated scales, consisting of at least three Bridges that are connected together and range from Colour A to Colour B [the end of the first Bridge], from Colour B to Colour C [the end of the second Bridge]; from Colour C to Colour D [the end of the third Bridge]; and back again from Colour D to C, B, and A [Fig. 31].

The thermochromic colour transition sample spectra can be used as practical communication tools to assist textile designers in making informed decisions and predicting colour transitions at different temperatures when designing a
6.6 EXPERIMENT VI

dynamic surface pattern. They show that different thermochromic inks with the same activation temperature may have different start colour-loss, end colour-loss, start colour-return, and full colour-return points. From a textile design perspective this is not necessarily a problem, however, as it expands the range of design possibilities offered by thermochromic inks on textiles.

The thermochromic colour transition sample spectra can be seen as a first step towards constructing a thermochromic colour system that could visually and verbally represent the principles guiding the use of thermochromic inks in textile design.

Fig. 28. The thermochromic colour transition ‘Fading’, produced using yellow, red, and blue thermochromic inks with an activation temperature of 31°C (inks supplied by LCR Hallcrest).
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Fig. 29. (opposite and above) The thermochromic colour transition ‘Double bridge’, which occurs according to graduated scales ranging from Colour A to Colour B or C, and back again to Colour A (inks supplied by LCR Hallcrest).
Fig. 30. The thermochromic colour transition 'Sextuple bridge', which occurs according to graduated scales ranging from Colour A to Colour B, C, D, E, F, or G, and back again to Colour A (inks supplied by LCR Hallcrest).

6.6 EXPERIMENT VI

Fig. 31. The thermochromic colour transition 'Continuum bridge', consisting of three Bridges, connected together. It was produced using different colours of thermochromic ink with activation temperatures of 27, 37, and 47°C, which were mixed without (top) and with (bottom) green static textile pigment paste (inks supplied by LCR Hallcrest).
Fig. 32. (pp. 210-226) The thermochromic colour transition of a fabric printed with six temperature-sensitive colour mixtures with an activation temperature of 31°C, shown from a non-heated state (24°C) to the full colour-return point (22°C) (inks supplied by LCR Hallcrest).
This concluding discussion chapter opens by stressing the need for a new colour system; one that can describe the behaviour of thermochromic inks in relation to static pigments in varying temperatures. Then, from a design perspective, it discusses the colour-changing potential of thermochromic inks with regard to creating dynamic optical illusions on textiles. This is followed by presenting pieces of technical advice, and highlights the range of fabrics that are important to know when working with thermochromic inks. Finally, there is a brief description of how different heat sources create different colour-changing effects on textiles.

7.1 A thermochromic colour system

During the research process that led to this thesis, it became apparent that providing detailed descriptions of the methods and approaches for working with the design properties and possibilities of thermochromic inks when printed on textiles is not entirely straightforward. This is due to the lack of a thermochromic colour system, which is problematic because, in the words of Richard Norman in Electronic Color: “To speak the language of color, one must have both a color vocabulary and an understanding of how colors interact. This requires a familiarity with some system of order - a color model” (Norman, 1933, p. 69). At present, the absence of a thermochromic colour system complicates matters in terms of not only the author explaining and transforming her knowledge regarding thermochromic inks, but also in relation to the decision-making and colour-transition-predicting processes of textile designers, and so constitutes a serious impediment to the development of dynamic prints. During the latter stages of the research process, attempts have thus been made to develop a thermochromic colour system, the latest version of which is based on the thermochromic colour transition sample spectra presented in Paper F and discussed in brief here.

The results of the theoretical and practical investigations of other existing colour systems suggest that a two-colour combination can be represented linearly, while three colours can be represented using a two-dimensional form such as a triangle. With four or more colours, a colour combination could perhaps be represented using a three-dimensional shape such as a pyramid.

Accordingly, inspiration for a three-dimensional colour system was taken from Munsell’s and Lambert’s (Kuehni, 2011) models, and led to a pyramid with a triangle base of fully saturated colour, based on the three primary colours of yellow, red, and
blue. The three lateral faces of the pyramid have colourless acrylic-based extender (é) at the top vertex [Fig. 33], which was chosen because, in textile printing, pigments and thermochromic slurries are mixed with extender, rather than with white, to create intermediate grades. The pyramid’s isosceles lateral faces are thus blue-red-colourless, red-yellow-colourless, and yellow-blue-colourless, and its base is blue-yellow-red. The three primary colours are represented by both thermochromic slurries and static textile pigment slurries, both of which were mixed with extender. Colour strengths for the mixtures were determined in advance: 25:75 slurry:extender for the thermochromic inks, and 4:96 for the static textile pigment pastes.

Each lateral face has two main colours – one of thermochromic ink and one of static textile pigment paste – so that designers can select which is thermochromic and which is static. Mixing these two colours creates the requisite number of intermediate grades. In total, each triangle is subdivided into 45 compartments [selected as this number provides a good balance between facilitating differentiation and ensuring smooth gradation], each with a colour that is determined by its position. In this system, colours are given numbers, and the example below is for one of the lateral faces of the pyramid:

é8

é7r1, é7Y1
é6r2, é6r1Y1, é6Y2
é5r3, é5r2Y1, é5r1Y2, é5Y3
é4r4, é4r3Y1, é4r2Y2, é4r1Y3, é4Y4
é3r5, é3r4Y1, é3r3Y2, é3r2Y3, é3r1Y4, é3Y5
é2r6, é2r5Y1, é2r4Y2, é2r3Y3, é2r2Y4, é2r1Y5, é2Y6
é1r7, é1r6Y1, é1r5Y2, é1r4Y3, é1r3Y4, é1r2Y5, é1r1Y6, é1Y7
r8, r7Y1, r6Y2, r5Y3, r4Y4, r3Y5, r2Y6, r1Y7, Y8

The numbers indicate how many parts are used of each colour; an upper-case letter denotes a thermochromic ink, a lower-case letter a textile pigment paste, and ‘é’ extender. ‘é2r2Y4’ thus indicates that there are two parts extender (é2), two parts red textile pigment paste (r2), and four part yellow thermochromic ink (Y4). The same colour-mixing principle is used for the base of the pyramid [Fig. 34].
7.1 A thermochromic colour system

Subsequently, an attempt was made to map the first two thermochromic colour transition spectra – ‘Fading’ and ‘Single bridge’ [see Paper F] – on the lateral faces of the pyramid. ‘Fading’ was deemed to be possible to demonstrate in this way (Fig. 35), but in order to map ‘Single bridge’ a larger triangle with an increased number of stages between each colour was found to be necessary. The reason for this is that, as the model functions at present, the stages between each colour of the thermochromic colour transition ‘Single bridge’ differ from those predicted by the model. In other words, the actual transition of ‘Single bridge’ is not a smooth one that can be translated into a straight line in the model; rather, it may be a curving, zigzagging, or wavy line (Fig. 36) that may be illustrated with an increased number of colour stages.
7.1 A thermochromic colour system

In order to demonstrate the thermochromic colour transition spectra of Triple, Quadruple, etc., as well as Continuum bridges, colours of the pyramid's base must be connected to those of the lateral faces. This requires a digital, three-dimensional representation of the model so as to simulate the interior of the pyramid, and thus the colour transitions within.

In other words, the suggested model in its present state is not able to describe all possible transitions, which would be optimal in terms of improving the ability of designers to make informed decisions and predict the colour-changing effects of dynamic surface patterns. The thermochromic colour system needs to be further developed so as to enable designers to categorise thermochromic inks and their transitions more precisely, which would in turn allow more effective communication regarding them. It is recommended that future work continues the development of a thermochromic colour system that assists experimental design practitioners and researchers in expanding the boundaries of traditional design methods as relates to designing and opening up new ways of thinking about dynamic surface patterns.

Fig. 36. The stages between each colour of the thermochromic colour transition 'Single bridge' differ from those predicted by the model. There are three transition points or gaps between colours on the colour transition of 'Single bridge' which may not create a straight colour transition line between colours.
7.2 Dynamic optical illusions

7.2 Dynamic optical illusions

Through Alber’s (2006) concept of colour interaction, a textile designer gains knowledge regarding how to create optical illusions and predict which illusions that may occur. Using thermochromic inks to create dynamic patterns on textiles offers the possibility of dynamic colour interaction, providing illusions at three different phases: in a non-heated state, at the end colour-loss point, and between the two. Optical illusions can occur in a non-heated state and become another illusion at the end colour-loss point, or not be apparent in a non-heated state and be revealed at the end colour-loss point. This is exemplified in the examples below.

The ‘Bezold effect’ is an optical illusion wherein adding or changing one colour of the composition can, under certain circumstances, alter the colour of the entire design (Albers, 2006, p. 33). Two identical coloured shapes are each surrounded by a thin border, one white and one black, with the latter appearing to be darker than the former.

Thermochromic inks offer a variation on this: One coloured shape of static textile pigment paste is surrounded by a thin border of black thermochromic ink, which is then heated. For example, a red shape made by static textile pigment paste is surrounded by a thin black thermochromic ink border. Its expression in a non-heated state is dark red but, when heated to its activation temperature, the colour of the thermochromic ink border becomes colourless, creating a lighter colour expression (Fig. 37).

Fig. 37. (opposite) The ‘Bezold effect’ created by using thermochromic ink with activation temperature 31°C and static textile pigment paste shown at a non-heated state (left) and at the end colour-loss point (right) (inks supplied by LCR Hallcrest).
Optical colour mixing occurs when small amounts of two different colours are placed side-by-side, such that they appear to create a third colour. This usually involves small, coloured dots placed very close together and against a white background. Yellow, red, and blue dots on a white background, for example – preferably from a distance – combine to create colours such as orange, violet, and green.

Thermochromic inks offer at least two variations on this, both of which involve the method used in Experiment III (see Paper C), which combined offset printing with the creation of a temperature-sensitive colour mixture consisting of multiple colours. Four temperature-sensitive colour mixtures are formed, and applied to textiles through offset printing. Due to the illusion of optical colour mixing, the viewer sees a colourful pattern at the end colour-loss point (Fig 23). The second variation involves the illusion being hidden in a non-heated state, and revealed at the end colour-loss point as a result of the use of a temperature-sensitive mixture of multiple colours. This involves, for example, forming three temperature-sensitive colour mixtures that all look alike in a non-heated state but become yellow, red, and blue at the end colour-loss point, and using these to make a pattern consisting of small, coloured dots, placed very close to one another. This would be violet-grey in a non-heated state and a colourful mixture of yellow, red, and blue at the end colour-loss point.

A colour movement illusion is created by choosing, for example, a colour, making its saturation or value continuous, and placing them next to one another. By using thermochromic inks, however, colour movement can be achieved in another way. A print produced using, for example, a mixture of one thermochromic ink and one static textile pigment paste is divided into six individual parts. When each part is heated, the colour changing-effects created lead the eye in a certain direction.

An illusion of size, perspective, or distance can be created by using intense and darker colours in the foreground; similarly, lighter colours can create a sense of distance. The colour-changing effects created by thermochromic inks can change the size of a form, and thus create perspective or distance. For instance; consider a pattern consisting of several large, violet-greyish circles against a white background, such that each circle consists of a central circle and an outer ring. The centre is printed with a static pigment, and the outer ring with a mixture of three different colours of thermochromic ink with three different activation temperatures (27°C, 37°C, and 47°C). In a non-heated state the entire circle is violet in colour, but when the pattern is heated to above 27°C the centre remains violet-greyish but the outer ring becomes orange-red. When the temperature increases to above 37°C, the core stays violet-greyish but the perimeter becomes a light yellow. Due to the interaction of the colours, the centre and outer ring look more visually distinct from one another than they are in reality: The centre is perceived as darker and closer, while the perimeter is perceived as lighter and farther. When the temperature increases to above 47°C, the core stays violet-greyish but the perimeter becomes colourless. The colour-changing effects at each colour-loss point finally reduces the circle to only the centre (Fig. 38).

In addition, in textile design – and more particularly in textile printing – repeating patterns are used extensively to fill a surface and create a sense of movement (cf. Gombrich, 2012, p.10-16; Trilling, 2001). This movement can be created using contrasting forms and colours throughout the composition as a whole. By skilfully using the colour-changing effects afforded by thermochromic inks on textiles, the range of novel visual expressions that can hold and direct a viewer’s attention in another way can be expanded; moreover, these could communicate other types of information, such as temperature, air pollution, sound, and so on.
The ability to blend thermochromic inks with static textile pigment pastes offers a wide range of colour-changing effects on textiles. Mixing one colour of thermochromic ink with another of static textile pigment paste requires that a balance be established between the relative percentages of the two, in order to create the desired colour in both a non-heated state and at the end colour-loss point. An efficient approach is to ensure that the colour of the temperature-sensitive colour mixture is not similar to that of the mixed static textile pigment paste; if red thermochromic ink is mixed with yellow pigment, for example, the colour of the mixture should be orange-red rather than yellow-orange or toward yellow.

If the intention is to achieve two different colours in a non-heated state that become the same at the end colour-loss point (Fig. 12), it is important to be aware of the strength of colour of static textile pigment paste. This should be lower when a print is produced using only static textile pigment paste than when mixing static textile pigment paste with thermochromic ink. This is because the extender, which is mixed with the thermochromic slurry to produce the thermochromic ink, affects the strength of colour of the static textile pigment paste, making it lighter.

Prints should then be cured at 150°C for approximately four minutes.

Thermochromic inks have a limited lifespan as compared to static textile pigment pastes, and can be damaged by environmental conditions such as long exposure to UV light or high temperatures. These factors may be considered to be impediments to a design process, but could also be considered to constitute design potentials.

Based on the observations made in connection with the work presented in this thesis, thermochromic inks of the same colour but from different suppliers differ slightly in terms of their properties. This is particularly noticeable in instances where inks have been produced at different times, for example if one was made recently and the other has been stored for a couple of years. Older inks take longer to reach their full colour-return point than newer ones. In order to ensure that the desired expression is achieved, it is important that designers are aware of this.
7.4 Range of fabrics & 7.5 Heat sources

7.4 Range of fabrics

Thermochromic inks can be used on a broad variety of textile materials and thicknesses. The nature of a textile material and structure of the fabric greatly affect the expression of the printed colour. Those of plain silk organza, for example, meant that colour was applied unevenly and the printed colour was thus insufficiently saturated in a non-heated state. The use of plain poplin cotton, however, led to an even, saturated printed colour in a non-heated state, and also allowed the structure of the fabric to be seen through the print.

Furthermore, the choice of textile has a significant impact on colour-changing effects, in that it can influence how fast heat is conducted by the textile. To return to the previous example; the silk organza printed fabric was very thin. As the temperature increased, it changed, from a coloured fabric to a colourless one, in the blink of an eye. The heat that was transferred to the plain poplin cotton fabric, however, spread more slowly, giving a viewer more time to observe the thermochromic colour transition (Papers D).

The selection of the fabric should be done in the early stages of a design process, as it has a great impact on the overall aesthetic expression.

7.5 Heat sources

Developing any techniques for generating or controlling heat output was not in the scope of this research. In order to observe the variety of effects that thermochromic inks can offer during design development, warm air, body heat, conductive yarn, and electrical heating were used. Most of the experiments initially used warm air from a hair drier or a clothes iron, and the prints were then heated using an electrical heating and cooling device. In some cases, body temperature or breath was used to activate the inks.

Visual comparisons showed that different heat sources create different colour-changing effects due to differences in thermal energy output, the amount of time required for sufficient heating to take place, and the distribution of heat, which also influenced how the forms/motifs of dynamic surface patterns changed.

The heat generated by the iron, for instance, was high, meaning that the change in colour occurred so quickly that only two states were discernible; one expression (colour) before, and another after. This was fairly similar to the hair drier, although the heat absorbed by the ink and thus the speed of the colour change was dependent on orientation and distance of the air stream. Both the iron and the hairdryer could activate all of the prints at the same time, meaning that the time interval for the colour transition was short, but that of the start colour-return to full colour-return points was comparatively longer.

In contrast, the heat of breath or the body was cooler, creating a gradual change in colour (Fig. 39). In one research project it was found that colour changes were strongly influenced by an individual’s specific body shape and temperature; one result, for example, was achieved very quickly, as the prints were in direct contact with the body. Human body shape and temperature created temporal patterns, which were unique but wild, messy, uncontrolled, difficult to reproduce, and temporary. The patterns that were observed resulted from body temperature and movement in terms of arm bending, walking, and turning of the body. The duration of the colour-changing process (from non-activated to fully-activated and vice versa) as compared to those of the iron and the hair drier was much longer (see paper D).
7.6 Heat sources
Fig. 39: Two series of photographs showing how the heat of breath or the body creates a gradual change in colour.
In contrast, the heating and cooling device (the specifics of which are given in Paper F) allowed heat output to be more precisely controlled, for example to heat and cool the printed textile very slowly by changing the output by increments of 1°C. This provided an opportunity to observe the complete range of thermochromic colour transitions on textiles over a longer period of time and in greater detail [see Paper F].

The use of conductive threads created another type of colour-changing effect, in which the conductive threads themselves created a dynamic surface pattern based on the structure of the knit or lace. For instance, a single jersey cotton fabric that was knitted with a conductive thread was printed with three temperature-sensitive colour mixtures that looked alike in a non-heated state and changed to three different colours at the end colour-loss point. By passing a current through the conductive thread and thus producing heat, a textural expression based on the structure of the knit appeared on the textile in three colours (Fig. 40). Moreover, as it was possible to control the amount of heat, colour transitions were discernible and added a further dimension to the visual expression [see Papers C and E].

The results produced using the above heat sources demonstrated that, through continued interaction between heat sources and thermochromic inks, pattern shadows were left on the surface of the textile – imprints of the previous interaction [Fig. 39]. From a textile design perspective, a gradual change of colour provides textile designers with a new palette [Nilsson et al., 2011] and this, along with the pattern shadows, could be further developed so as to create more complex effects featuring multiple colour changes.

It should also be noted that using different heat sources leads to different colour-change results, but also different after-effects on the printed fabric as a result of the distribution of heat. For example, the iron left the temporary imprint of its bottom plate on the print, and a hand left behind a hand print [Fig. 41].

Fig. 40. The conductive threads themselves created a dynamic surface pattern based on the structure of the knit.
Fig. 41. The after-images of heat sources on printed fabrics.
8. REFERENCES


8. REFERENCES


9. APPENDED PAPERS

List of appended papers


PAPER A

Abstract

Although there has been some research on the use of leuco dye-based thermochromic inks in textile and fashion design, there is still a lack of research on how these inks can be used on textiles to create complex surface patterns. This paper aims to provide information on the properties of leuco dye-based thermochromic inks to facilitate the understanding and designing of dynamic surface patterns, and demonstrates the color transitions of thermochromic inks at different temperatures. A practice-based design method was chosen to investigate two different reversible and water-based blue inks with activation temperatures of 27°C and 15°C. The result showed scales comprising the recipes that were used as a guide for designing textile surfaces. This paper contributes by making the color-changing process understandable and demonstrating the actual effects of leuco dye-based thermochromic inks at different temperatures for textile and fashion design. This facilitates designers to achieve more advanced textile surface patterns.

Keywords: leuco dye-based thermochromic inks, textile pigment paste, fashion design, printing technique, color-change, smart materials

Introduction

In recent years, there has been growing interest in the use of leuco dye-based thermochromic inks as smart materials in textile and fashion design. Fabric displays have been created for new forms of communication and expression such as the Reach [1], and the Ambikraft [2] projects. In those, leuco dye-based thermochromic printed fabrics were combined with technology to create interactive textile displays allowing us to reconsider relationships between human behaviors and the surrounding environments. Furthermore, in the research theses Skins [3], and Designing Dynamic Textile Patterns [4] thermochromic printed fabrics have been combined with technology to explore ways to control and develop dynamic textile expressions. However, most of this research has focused on combining thermochromic printed fabric with computational technology and exploring ways of heating or cooling the thermochromic printed fabric. There is a lack of documented information on how thermochromic inks can be used on textiles. This paper aims to provide information on the properties of leuco dye-based thermochromic inks to facilitate the understanding and designing of dynamic patterns. Textile dynamic patterns are described by Worton (2010) as “a textile pattern that reacts to environmental stimuli and always returns to a given initial expression” [4].

Leuco dye-based thermochromic inks

Leuco dye-based thermochromic inks are specialized dynamic inks that change color when exposed to different temperatures, i.e., below their activation temperature they are colored and above their activation temperature they are clear or slightly colored. They are usually blended with some other pigments (non-heat sensitive pigment) change from one color to another [5]. The activation temperature is defined as the temperature above which the ink has almost achieved its final clear or light color end point. The color starts to fade at approximately 4°C below the activation temperature and will be in between colors within the activation temperature range. Leuco dye-based thermochromic inks [6] can be made to change color at temperatures ranging from -15°C to 60°C. The ink’s temperature can be chosen when it is ordered.

There are some important factors, which should be considered before starting to work with leuco dye-based thermochromic inks: the ambient temperature (20°C) (non-heated state of e.g. the printing lab); temperature sensitivity of the inks; and the properties of the inks. The ambient temperature at the printing lab at the Swedish School of Textiles at the University of Borås, where this study was conducted, was 20°C. Temperature sensitivity of the chosen inks were 27°C and 15°C. The inks were reversible and water-based. Therefore, the most desirable printing effect was achieved by printing them on cellulose fabric. White plain cotton-weaved fabric was used as a background. The method used was silk-screen printing and the size of the silk-screen mesh was 43 threads per centimeter.

A single color of leuco dye-based thermochromic ink with activation temperatures 27°C and 15°C

The thermochromic ink was mixed with binder to attach the ink onto fabric. Binder is defined as “the chemicals, which have the ability of forming a three-dimensional film used to hold the pigment particles in place on the surface of a textile substrate” [7]. In this experiment, binder was acrylic-based extender. Both inks were mixed with extender in different proportions that produced different shades of blue at ambient temperature (20°C).

Although numerous shades of blue were possible, this paper was limited to investigate six shades for each thermochromic ink with activation temperatures 27°C and 15°C (See figures 1 & 2).

As shown in figure 2, the recipe consisting of 25% ink and 75% extender provided a good textile-printing effect with maximum color intensity at ambient temperature (See figure 3).

Figure 1: From left to right shows the blue shade produced by the thermochromic ink with activation temperatures 27°C, and 15°C at ambient temperature (20°C).

Figure 2: shows the result of mixing and printing the ink with activation temperatures 27°C, 15°C, with the extender in different proportions produced different blue shades at ambient temperature (20°C).

Since thermochromic inks are specialized dynamic inks that change color with exposure to different temperatures, the produced blue shades (with activation temperatures 27°C and 15°C) were tested at 15°C or less, and also at 27°C or more in order to explore the design potentials of leuco dye-based thermochromic ink at different temperatures. An ice bag was used to cool the thermochromic printed fabrics down to 15°C and below. An iron was used to warm the thermochromic printed fabrics up to 27°C and above. The effect of cooling the printed blue shade produced by the ink with activation temperature 27°C was identical to the blue shade at ambient temperature (20°C). Whereas, the effect of the printed blue shade produced by the ink at an activation temperature 15°C was a dark blue shade compared with the one at ambient temperature (20°C) (See figures 4, 5, 6 & 7).

From the textile design perspective this experiment highlighted one particular aspect. Reversible leuco dye-based thermochromic ink is not available in white. However, as shown in the last row of figure 5, the mixture of 11% of 15°C thermochromic ink with 99% extender resulted in white at ambient temperature (20°C) and light blue at equal or less than 15°C. This possibility can be used to reveal hidden designed surface patterns (See figure 7).

The effect of heating the printed blue shade produced by the ink with activation temperature 27°C was a light gray-yellowish shade compared with the blue shade at ambient temperature (20°C). Whereas, the effect of the printed blue shade produced by the ink at an activation temperature 15°C was a light gray shade. This is because the leuco dye-based thermochromic inks are always clear or slightly colored above their activation temperature (See figures 9, 10, 11 & 12).
A particular amount of yellow textile pigment paste was mixed with the used blue shades in previous experiment with the same activation temperatures. The color combinations created different green shades at ambient temperature (20°C). The green shade produced by the mixture of ink with activation temperature 27°C was darker than the green shade produced by the mixture of ink with activation temperature 15°C (See figures 12, 13 & 14).

The same methods of cooling and heating were used to explore more design potentials of mixture of leuco dye-based thermochromic ink and textile pigment paste at different temperatures. Thus the mixtures were examined at 15°C or less and also at 27°C or more.

The effect of heating both green shades produced by the blue ink with activation temperatures 27°C, 15°C and the yellow pigment paste resulted in a slightly lighter yellow that of the yellow pigment paste. Based on thermochromic ink’s characteristic the mixture of leuco dye-based thermochromic ink and textile pigment paste always changes to the color of the mixed pigment paste, only slightly lighter (See figures 19, 20, 21 & 22).
The effect of cooling the printed fabric was 25% ink+ 75% extender+ 4% pigment. The chosen temperature 27°C and yellow pigment. The chosen produced by the mixing of blue ink with activation Figure 21: The effect of heating the printed fabric and the effect of cooling.

Figure 15: From left to right, and top to bottom shows the printed green shade produced by the mixture of inks with activation temperatures 27°C, 15°C and the yellow at ambient temperature (20°C), cooling with ice-bag and the effect of cooling.

Figure 16: shows and compares the effect of cooling the printed green shades produced by the blue thermochromic ink at activation temperatures 27°C, 15°C and yellow textile pigment paste.

Figure 17: The effect of cooling the printed fabric produced by the mixing of blue ink with activation temperature 27°C and yellow pigment. The chosen recipe was 25% ink+ 75% extender+ 4% pigment.

Figure 18: At ambient cooling result of cooling

Figure 19: From left to right, and top to bottom shows the printed green shade produced by the inks with activation temperatures 27°C, 15°C and the yellow at ambient temperature (20°C), heating with iron and the effect of heating.

Figure 20: shows and compares the effect of heating the printed green shades produced by the blue thermochromic ink at activation temperatures 27°C, 15°C and yellow pigment.

Figure 21: The effect of heating the printed fabric produced by the mixing of blue ink with activation temperature 27°C and yellow pigment. The chosen recipe was 25% ink+ 75% extender+ 4% pigment.

Figure 22: The effect of heating the printed fabric produced by the mixture of red ink with activation temperature 15°C and yellow pigment. The chosen recipe was 10% ink+ 90% extender+ 4% pigment.

Figure 16: shows and compares the effect of heating the printed green shades produced by the blue thermochromic ink at activation temperatures 27°C, 15°C and yellow textile pigment paste.

Figure 23: From left to right: The printed fabric produced by the inks with activation temperatures 27°C and 15°C, the effect of cooling the printed fabric and the effect of heating the printed fabric.

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Discussion and conclusion

This paper has aimed to provide printing paste recipes in order to provide fundamental knowledge of how leuco dye-based thermochromic inks can be used on textiles. The figures presented, consisting of scales at three different temperatures (ambient temperature, at equal or more than 27°C and at equal or less than 15°C). Each scale has shown a recipe as a guide for designing dynamic textile surface patterns. These recipes are reliable references for any types of leuco dye-based thermochromic inks such as water-based or UV cured. This paper has also demonstrated the actual effects of leuco dye-based thermochromic with the aim to help designers achieve more advanced textile surface patterns (figure 23).

Finding the exact color of printed fabric using thermochromic ink in Photoshop, and matching the color theory vocabulary to describe color of printed fabric were the main limitation of this experiment. One suggestion for further studies would be a technical investigation in Photoshop to make a color index of leuco dye-based thermochromic inks transition.

References:

DEMONSTRATING COLOR TRANSITIONS OF LEUCO DYE-BASED THERMOCHROMIC INKS AS A TEACHING APPROACH IN TEXTILE AND FASHION DESIGN

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ABSTRACT

Although there are a lot of interest concerning the use of leuco dye-based thermochromic inks in Textile and Fashion Design, there is still a lack of teaching approach to help students arrive at a better understanding of the color transitions of leuco dye thermochromic inks. This paper aims to share a systematic approach for teaching the behavior of leuco dye-based thermochromic inks to students in Textile and Fashion Design. Printed color-swatches and exercises were used as the central part of the approach. Through the approach it was described what printed color-swatches were and how to use them effectively to make color transitions understandable. The approach has been applied in several workshops at both Bachelor and Master level. The samples made by the students in the exercises clearly revealed that the approach created opportunities for students to craft an understanding of using leuco dye thermochromic inks through experimentation and individual exploration. Ultimately, this approach plays a fundamental role in the design process, the creation and the development of dynamic patterns.

INTRODUCTION

Nowadays by entering leuco dye-based thermochromic inks into the textile and fashion design area, new type of challenges appear in order to use thermochromic inks effectively in design process. Albers (1975) proposes an approach to studying color and of teaching color based on learning by direct perception, and not by theories or color systems. Collins and Wilson (2012) discuss an investigation in how to deal with color accuracy in digital-printed textiles while there is dearth information about how textile digital printing is being used in textile. However, the approaches provides profound insight about how to use colors in different contexts, and how to match color and media but they are not adequate to apply to studying and of teaching Leuco dye-based thermochromic inks that are dynamic colors, and not static. Studying leuco dye-based thermochromic inks is mainly about color transition, so when I was asked to hold the thermochromic workshop I decided to plan my workshop based on notion of learning by doing (Drew, 2004), motivational framework (Wlodkowski, 1999), and adopt it to my own way of thinking about planning (Ginsberg & Wlodkowski, 2009) to help students achieve a better understanding of the behavior of leuco dye-based thermochromic inks at various temperatures. This paper aims to share a systematic approach for teaching the behavior of leuco dye-based thermochromic inks to students in Textile and Fashion Design. It has focus on demonstrating the color changing process to facilitate the understanding and designing of dynamic surface-patterns at different temperatures. The approach introduces printed color swatches, explains what printed color-swatches are, and discusses how they can be used in a workshop on Leuco dye-based thermochromic inks. It also describes how to use printed color-swatches to effectively demonstrate the color transition of the ink.

THERMOCHROMIC INK

Thermochromic inks constitute one of the major groups of color-changing inks. Developed in the 1970’s, these inks are temperature sensitive compounds that temporarily change color with exposure to heat. Bamfield and Hutchings (2010) describe thermochromic ink as consisting of two major types of thermochromic inks: liquid crystals and leuco dyes. Because liquid crystals are more sensitive to temperature changes than leuco dyes and require highly specialized printing techniques, they are considered difficult to work with. Leuco dyes are more easily handled and are used more frequently in screen-printing. They can be found in a variety of products, such as textile applications, color changing T-shirts (which were in high demand at the beginning of the 1990’s), interactive plastic baby-safety feeding-spoons, coffee mugs, and toys. They are suitable for use in general indicators that display approximate temperatures such as cool, warm and hot.

LEUCO DYE-BASED THERMOCHROMIC INKS

Bamfield and Hutchings (2010) define leuco dye-based thermochromic inks as colored in a non-heated state (below their activation temperature) and become clear or slightly colored in a heated state (above their activation temperature). Also, they are usually blended with other pigments (non-heat sensitive pigments), allowing them to change from one color to another.

COLOR OF THE INK

Leuco dye-based thermochromic inks are produced to be reversible or irreversible. Reversible inks change from a colored state to a clear or slightly colored state as a result of increasing the temperature to above the activation temperature of the ink. The color returns upon cooling. This procedure may be repeated over a long period of time. Irreversible inks are invisible until they are exposed to high temperatures, at which time they change from a clear state to a colored state. This change in color is permanent, which means that once the change from clear to colored state has occurred, it will not revert. Kulcar states that irreversible inks normally begin color transition at 65°C and complete the transition at 90°C.

In addition, a wide range of leuco dye-based thermochromic inks are available, such as solvent-based, water-based, UV cured, epoxy, etc., and are used for printing on textiles, plastic, paper and metal (Kulcar et all 2012).

COLOR BACKGROUND

Leuco dye-based thermochromic inks must be printed over a light background. If they are printed on a background color other than white, the background color will influence the color of the ink in both the non-heated and heated state: e.g. a blue ink printed over a yellow background will change from green to yellow when heated.

COLOR OF THE INK

Leuco dye-based thermochromic inks can be produced in most colors, except for white. The most common colors are magenta, blue, black, turquoise and orange with good intensity.

Available Temperature of Leuco Dye

Leuco dye-based thermochromic inks are formulated to change color at temperatures ranging from -15°C to 60°C. The temperature at which the ink changes color can be chosen when it is ordered (Chromazone, accessed April 2013).

PROPERTIES OF LEUCO DYES

Leuco dye-based thermochromic inks are produced to be reversible or irreversible. Reversible inks change from a colored state to a clear or slightly colored state as a result of increasing the temperature to above the activation temperature of the ink. The color returns upon cooling. This procedure may be repeated over a long period of time. Irreversible inks are invisible until they are exposed to high temperatures, at which time they change from a clear state to a colored state. This change in color is permanent, which means that once the change from clear to colored state has occurred, it will not revert. Kulcar states that irreversible inks normally begin color transition at 65°C and complete the transition at 90°C.

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COLOR OF THE INK

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STRUCTURE OF THE METHOD

Before starting work with leuco dye-based thermochromic inks, it is essential to be aware about the following factors: the ambient temperature (non-heated state of e.g. the printing lab), temperature sensitivity of the inks, and the properties of the inks. The ambient temperature at the printing lab at the Swedish School of Textiles at the University of Borås, where this study was carried out, was 20°C. The temperature sensitivity of the
chosen inks was 27°C and 15°C. The inks were reversible and water-based. The most desirable printing effect would be achieved on cellulose fabric. White plain cotton-weaved fabric was used as a background. The size of the silk-screen mesh was 43 threads per centimeter. In addition, the thermochromic inks had to be mixed with binder in order to attach the ink to the fabric. In addition, binder is defined as “the chemicals, which have the ability of forming a three-dimensional film used to hold the pigment particles in place on the surface of a textile substrate” (China Tianyu Nickel Screen CO., accessed April. 2013). In this paper, binder name is acrylic-based extender.

Leuco dye-based thermochromic inks, like other pigment printing pastes, require certain equipment, such as a textile lab with high-tech temperature testing capacity. I did not have a proper chamber, so I made color-samples with the chosen leuco dye-based thermochromic inks. The samples were then measured with a spectrophotometer at three different temperatures: at the ambient temperature (20°C), after heating (up to 30°C or above), and after cooling (down to 5°C or below). These measurements were then followed by creating printed color-swatches with the produced databases, using the textile pigment printing pastes. As a result, the color-swatches I made produced it possible for me to demonstrate the color changing of leuco dye-based thermochromic inks at different temperatures (see Figure 1). In addition, scanned images of printed color-swatches were used to support the figures.

Figure 1. shows color-swatches made with textile pigment pastes to demonstrate the varying colors of leuco dye-based thermochromic inks at different temperatures.

**HOW TO TEACH ACCORDING TO THE APPROACH**

A printed thermometer was placed on the table of the printing lab in order to illustrate the ambient temperature. The ambient temperature was showing 20°C. Three grams of blue ink with activation temperature 27°C was mixed with 97 grams of acrylic-based extender, hand screen-printed on the chosen fabric, and then placed on the right side of thermometer. The same recipe was used for the black, magenta, turquoise and orange inks. The prints displayed the following colors at ambient temperature (20°C): light blue (14-4214 TCX), light black (17-0613 TCX), magenta (17-2520 TCX), blue green (14-4811 TCX) and light orange (15-1435 TCX). Colors’ name and color-coding were used to convey information quickly for reader, as well as to facilities understanding of visual display (cf. Green, 2010).

The blue and red inks with activation temperature 15°C were screen-printed on the chosen fabric with the same recipe and method, and then placed on the left side of thermometer. The prints displayed the following colors at ambient temperature (20°C): white with a blue tint (11-4604 TCX) for the blue ink and white with a pink tint (11-1005 TCX) for the red ink (see in Figure2).

![Color Swatches](image)

Figure 2. shows how the effect of printed fabrics produced by the mixture of 3g of ink with activation temperature 15°C and 21°C with 97g of extender look like at ambient temperature (20°C). From bottom to top the effect of mixing 3 grams of blue and the red inks with activation temperature 15°C and 97 grams of extender and the effect of mixing 3 grams of the blue, black, magenta, turquoise and orange inks with activation temperature 27°C and 97 grams of extender at ambient temperature (20°C).

The effect of heating the fabrics printed with blue, black, magenta, turquoise and orange inks with activation temperature 27°C was, for both blue and black ink, white with a yellow tint (11-4301 TCX), white with a pink tint (11-2409 TCX) for the magenta ink, for the turquoise ink it was white with a yellow tint (12-1009 TCX), and for the orange ink it was white with a yellow tint (11-0603 TCX).

The effect of heating the fabrics printed with blue and red inks with activation temperature 15°C were white with a yellow tint (11-4604 TCX) for the blue ink and for the red ink it was white with a pink tint (11-2309 TCX) (see Figure 3).

![Color Swatches](image)

Figure 3. shows how the effect of printed fabrics produced by the mixture of 3g of ink with activation temperature 15°C and 21°C with 97g of extender look like at ambient temperature (20°C). From bottom to top the effect of mixing 3 grams of blue and the red inks with activation temperature 15°C and 97 grams of extender and the effect of mixing 3 grams of the blue, black, magenta, turquoise and orange inks with activation temperature 27°C and 97 grams of extender at ambient temperature (20°C).

The temperature was then increased to 30°C or above. The effect of heating the fabrics printed with blue, black, magenta, turquoise and orange inks with activation temperature 27°C was, for both blue and black ink, white with a yellow tint (11-4301 TCX), white with a pink tint (11-2409 TCX) for the magenta ink, for the turquoise ink it was white with a yellow tint (12-1009 TCX), and for the orange ink it was white with a yellow tint (11-0603 TCX).

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![Color Swatches](image)

Figure 4. shows how the effect of printed fabrics produced by the mixture of 3g of ink with activation temperature 15°C and 21°C with 97g of extender look like at ambient temperature (20°C). From bottom to top the effect of mixing 3 grams of blue and the red inks with activation temperature 15°C and 97 grams of extender and the effect of mixing 3 grams of the blue, black, magenta, turquoise and orange inks with activation temperature 27°C and 97 grams of extender at ambient temperature (20°C).

The first result is that by increasing the temperature to a level equal or to above the activation temperature of the ink, the reversible leuco dye-based thermochromic ink always changes from a colored state to a clear or slightly colored state.

Four grams of yellow textile pigment printing paste (14-0756 TCX) was mixed with each of the leuco dye-based inks (blue, black, magenta, turquoise and orange) with activation temperature 27°C, screen-printed on the chosen fabric, and then placed on the right side of thermometer. At the ambient temperature (20°C), the prints made with the mixture of inks and yellow pigment paste displayed the following colors: green-ochre (16-0540 TCX), gray-ochre (16-0540 TCX), reddish-brown (16-1350 TCX), greenish-yellow (15-0343 TCX) and orange (15-1157 TCX).

The same recipe and method was used to mix the blue and red inks with activation temperature of 15°C with the yellow textile pigment paste, and then placed on the left side of thermometer. The colors displayed by the prints at the ambient temperature (20°C) were a light greenish-yellow (11-0620 TCX) for the blue ink and for the red ink it was a light pinkish-yellow (12-0721 TCX) (see Figure 4).

![Color Swatches](image)

Figure 4. shows how the effect of printed fabrics produced by the mixture of 3g of ink with activation temperature 15°C and 21°C with 97g of extender look like at ambient temperature (20°C). From bottom to top the effect of mixing 3 grams of blue and the red inks with activation temperature 15°C and 97 grams of extender and the effect of mixing 3 grams of the blue, black, magenta, turquoise and orange inks with activation temperature 27°C and 97 grams of extender at ambient temperature (20°C).

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![Color Swatches](image)

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The same recipe and method was used to mix the blue and red inks with activation temperature of 15°C with the yellow textile pigment paste, and then placed on the left side of thermometer. The colors displayed by the prints at the ambient temperature (20°C) were a light greenish-yellow (11-0620 TCX) for the blue ink and for the red ink it was a light pinkish-yellow (12-0721 TCX) (see Figure 4).
The temperature was then increased to 30°C or above. The result of heating the fabric printed with the inks with activation temperatures 27°C and 15°C were colors identical to the mixed yellow pigment paste, only slightly lighter (12-0752 TCX) (see Figure 5).

The second result is that by increasing the temperature to 30°C or above, the fabrics printed with the inks with activation temperature 15°C produced the dark blue and dark red (18-4045 TCX) and dark red (15-1920 TCX) (see Figure 6).

The third result is that by decreasing the temperature to 15°C produced the dark blue and dark red. Fabrics printed with the blue and red inks with activation temperature 15°C became dark bluish-green (17-5111 TCX) and light reddish-yellow (16-1632 TCX) (see Figure 7).

The forth result is that by decreasing the temperature to 5°C, the fabrics printed with the inks with activation temperature 27°C and the yellow textile pigment paste look like at ambient temperature (20°C). Therefore, a good strategy for creating and managing a high quality workshop environment was essential (Ginsberg, M.B. & Wlodkowski, 2009). My strategy was to give students exercises in order to experience the content. The exercises engaged the students in their design process. I started them off with easy exercises and followed up with increasingly challenging ones.

At the Swedish School of Textiles, University of Borås, thermochromatic workshops are one part of the dyeing and printing course. The students were asked to bring two silk-screen frames (frame No.1 and frame No.2) on which the patterns were already exposed. The first exercise was to work with leuco dye-based thermochromic inks and textile pigment paste at ambient temperature (20°C). The white plain cotton-weaved fabric was given to the students. The students were then instructed to choose one warm color and one cold color from among the inks of an activation temperature of 27°C and then mix 3 grams of the chosen inks with 97 grams of the extender. They overprinted one of the patterns (frame No.1) with the chosen cold color and the other one (frame No.2) with the chosen warm color. In addition, in all exercises, they were required to wait until the printed fabrics were dry. Afterward, they heated up their printed fabrics to 30°C using a hair dryer or a heating pad in order to examine and observe the first result at the previous section (see Figure 8).
The second exercise was to work with the inks with activation temperature 15°C. The students were instructed to choose only one color of ink, either warm or cold. Two different recipes were given to them. One recipe was to mix 3 grams of the chosen ink with 97 grams of the extender (the first recipe) and the other one was to mix 1 gram of the chosen ink with 99 grams of the extender (the second recipe). After mixing the two recipes, they overprinted one of the patterns (frame No.1) with the first recipe and the other one (frame No.2) with the second recipe. At first, they heated up the printed fabrics to 30°C using a hair dryer or a heating pad to test the first result at the previous section. Then, they cooled the printed fabrics down to 8°C using a freezer, testing the third result at the previous section (see Figure 9).

The third exercise was to mix the inks with activation temperature 27°C with the textile pigment paste. The students were instructed to use a textile pigment color of their own choosing and mix it with both recipes from the second exercise. They overprinted one of the patterns (frame No.1) with a mixture of the first recipe and the chosen pigment paste and the other one (frame No.2) with a mixture of the second recipe and the chosen pigment paste. They heated up the printed fabrics to observe the second result at the previous section. Afterward, they cooled the printed fabrics to examine and analyze the fourth result at the previous section (see Figure 11).

The fourth exercise was to mix the inks with activation temperature 15°C with the textile pigment paste. The students were instructed to use a textile pigment color of their own choosing and mix it with both recipes from the second exercise. They overprinted one of the patterns (frame No.1) with the mixture of the ink and the pigment paste of a cold color and the other one (frame No.2) with the mixture of the ink with a warm color and the pigment paste. After doing this, they heated up the printed fabrics to explore the result of the second exercise at the previous section (see Figure 10).

At this point, the students had had enough experience working with the inks with activation temperatures 27°C and 15°C. They were in a situation that challenged their previous conceptions about color. The situation created a forum for open discussion of the exercises and so they were instructed to bring all samples of printed fabrics for discussion. Afterward, I showed them some examples of dynamic patterns used in textile applications.

The last exercise was an assessment exercise based on the process (what they had learned so far). The exercise was to design a dynamic surface pattern that would give the audience different information or produce different expressions at different temperatures. Textile dynamic pattern is described by Worbin (2010) as “a textile pattern that reacts to environmental stimuli and always returns to a given initial expression”. The point of this exercise was to give the students a chance to construct their own meaning (Biggs, 2003) & (Wlodkowski, 2008), when learning the properties of thermochromic inks (see Figure 12 & 13).
DISCUSSION/ CONCLUSION

The aim of this paper has been to share a systematic approach of teaching the behavior of leuco dye-based thermochromic inks in Textile and Fashion Design. It has focused on demonstrating the color transition of the thermochromic inks to facilitate the understanding and designing of dynamic surface-patterns at three different temperatures: the ambient temperature (non-heated state of e.g. the printing lab); a heated state, i.e. a temperature above the activation temperature of the ink; and a cold state, i.e. a temperature below the activation temperature of the ink.

Printed color-swatch samples made with the textile pigment printing pastes and exercises created opportunities for students to craft an understanding of the design potential of using leuco dye thermochromic inks through experimentation and individual exploration. 

This approach has been applied as a three days workshop at both Bachelor and Master level, as well as textile designers. The length of workshop and plan designed created active learning environments where students had hands on practice with high degree of learning (Sork, 1997).

The samples made by the students in the final exercise has indicated that the approach creates a new way for me as a lecturer to convey thermochromatic knowledge to the students and also creates a unique set of fundamental skills for students to learn color transition principles in a more quick and easy way for designing dynamic patterns through the experimental workshop. The approach seems to be an efficient approach allowing students to develop their ideas through pushing the properties of thermochromic inks supported by design skill and predicting color transition while they are designing dynamic surface-patterns (Drew, 2004) & (Ginsberg & Włodkowski, 2009).

Previous approaches Albers (1975) and Collis and Wilson (2012) reveal that essential knowledge regarding color within a particular context can be achieved through experiential learning, materiality and experimental processes. By entering smart colors such as leuco dye-based thermochromic ink into textile and fashion area, the design process has been directed towards a new face of design, which needs new approaches. One suggestion for further studies would be more investigation on how to use the leuco dye-based thermochromic ink in textile digital printing, and how to describe color transition of leuco dye-based thermochromic ink in a proper color systems.
EXPLORING THE RELATION BETWEEN TIME-BASED TEXTILE PATTERNS AND DIGITAL ENVIRONMENTS

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Abstract

Presently, digital sketching environments have come to be used as a complement to the traditional manufacturing techniques for textiles; the research presented here looks into the area of time-based patterns and their relation to digital tools and textile structural techniques. Thus, the aim of this work is to expand on the existing methods used by designers, and to explore ways for capturing and expressing the complexity and temporality of pattern changes in textiles. Furthermore, our result sketches a method for using dynamic colors to design complex surface patterns for textiles by utilizing methods that facilitate the hiding and/or revealing of multiple colors and shapes on the printed surface of the textile; this method is discussed in connection to the different expressions that can be achieved by using knitting as media for print.

Keywords: leuco-dye based thermochromic inks, dynamic surface design, time-based textile patterns

1 Introduction

In textile design, the relationship between the material and the graphical drawing is quintessential to the definition of the surface pattern. The design of surface patterns for textiles has traditionally been supported by a range of manufacturing techniques, e.g. screen-printing or structural techniques such as Jacquard knitting or weaving; thus, the material itself has come to play an important role in the definition of the expression together with colors and forms. Accordingly, these established methods have allowed the designer to explore the synergy between the surface pattern and the character of the material texture in the design process.

As computer software has come to be used as a complement to the traditional manufacturing techniques in the design process for knits and weaves, a wide range of digital environments that support the design process of surface patterns has emerged. These environments are capable of creating either static (e.g. Adobe Photoshop and Corel Draw) or dynamic forms (e.g. Processing and Java). It is possible that digital tools may not just introduce new aesthetics but a different way of sketching complex patterns by introducing digital elements such as pixels and vectors as design fundamentals [1]. In structural techniques for the design of surface patterns, i.e. Jacquard weaving and knitting, bitmap images have become mediators between the digital environment and the physical world, facilitating the translation of digital images into textile constructions; thus, the manner in which digital elements, such as the pixel, are defined become fundamental to the translation of the depth of the pattern expression. Compared to the solid, monochromatic fields produced by screen printing, the ability to define the properties of individual pixels in digital printing allows for the creation of a different kind of surface expressions, which are based on gradation and an unlimited range of colors. Examples of artistic works explore the design potential of digital pattern design and which proposes ways to manipulate a surface expression in order to create illusions in the perception of the surface pattern in space are, or enhance the sensuality of the material by creating an illusion of depth and volume[2, 3].

Moreover, the research presented here looks into the area of time-based patterns and their relation to digital tools and textile manufacturing techniques, aiming to explore methods for capturing and expressing the complexity and temporality of pattern changes in textiles. In so doing, a new area for textile design explorations is framed.

2 Designing dynamic surface patterns for textiles

In addition to existing digital methods for surface design, new techniques for coloring textiles, such as printing with thermochromic inks, contribute with rich variables to the design of dynamic patterns in physical space. Compared to conventional textile materials, which have static expressions, thermochromic inks are able to change between multiple states; thus providing a range of different expressions in textiles. Leuco dye-based thermochromic inks have the ability to change color in response to temperature variations; these changes are reversible, which allows for repeated changes from state A to state B and then back to state A again [4]. In the search of a conductive textile medium on which to print thermochromic inks, some research projects have taken to exploring different ways of combining structural textile techniques, such as weaving, with the aim of finding a method for controlling and composing with the temporal and spatial activation of the dynamic printed patterns. Dynamic Double Weave[5] and Shimmering Flower[6] are two experimental projects which investigate the interactive potential of printing with leuco dye-based thermochromic inks on textiles, the inks were used in combination with woven elements and the design of color-changing textiles which posed a challenge to the user’s perception of surface patterns. In a related experimental design research project, Recurring Patterns, the leuco-dye based thermochromic inks were printed on a double woven surface, and as the textile was heated by the running of an electrical current through the conductive yarns on the backside of its surface, the patterns changed color. This project discusses the complexity of designing dynamic surface patterns and proposes a method for relating the gradual changes in temperature to the changes in color and shades when designing time-based expressions for textiles [cf. 7].

The research projects mentioned above all consider weaving only in the role as a structural fabrication technique for conductive textile materials to print the patterns on, and as no other printing methods besides conventional screen-printing were used, however, these methods are limiting the depth that can be achieved in the surface expressions by using dynamic colors. Although the contributions made by these research projects improve on the understanding of the aesthetic qualities achievable through the use of leuco dye-based thermochromic inks in combination with heat-profiling circuitry, a great deal of work remains to be done on the aesthetical possibilities inherent in textile structural techniques and how to relating them to the printing process, i.e. proposing methods in which the conductive textile structure is considered as part of the design process and in which the depth of the printed pattern is included in the sketching. The research project presented here takes as its point of departure the vast complexity of the surface patterns possible to design using digital printing techniques, and focuses on exploring mixed methods as synergies between physical and digital media i.e. to create new ways to design dynamic textiles. Thus, the aim of this work is to expand on the existing methods used by designers to translate complex time-based patterns into textile surface expressions by utilizing methods that facilitate the hiding and/or revealing of multiple colors and shapes on the printed surface of the textile. Furthermore, our result sketches a method for using dynamic colors to design complex surface patterns for textiles, which will be discussed in connection to the different expressions that can be achieved by using knitting as media for print.

3 Methods

Since the project explores the relation between programmable textiles (supporting and activating media) and thermochromic prints (reactive media), the design experiments presented here involved three layers of experiment: 1. methods of knitting patterns which allow the conductive circuits to be hidden from the surface of the textile, based on inlay techniques and knitted on a single or double bed machine; 2. a method of forming temperature sensitive color mixtures using leuco dye-based thermochromic inks; 3. a method of printing a dynamic surface-pattern on textiles using Offset method of printing with temperature sensitive color mixtures;

In this research project, reversible and water-based leuco dye-based thermochromic inks, with an activation temperature of 31°C, were used. A recipe consisting of 25% ink and 75% binder was selected [8] in order to provide a good textile-printing effect with maximum color intensity at the ambient temperature. The printing method used was traditional hand silk screen printing, and the size of the silk-screen mesh was 43 threads per centimeter. For the first series of experiments, black thermochromic ink was mixed with orange textile pigment paste.

Methods of knitting patterns which allow the conductive circuits to be hidden from the surface of the textile, based on inlay techniques and knitted on a single or double bed machine;

Printing was explored in relation to three different types of knitted structures:

1. 1. Single bed knit: The first structure was a single jersey cotton fabric with conductive yarns inserted into every sixth wale using loops and floats as shown in the picture below. As the textile was heated, the first visible change appeared after 5 seconds as the loops created a clear shape on the printed layer. After 20 seconds of heating, the floats on the
back of the textile structure became visible, changing the color of the whole print, as the shape of the wale was mirrored by the pattern created by the heat. After 30 seconds maximum diffusion of the pattern was achieved in the shape of the conductive wale (see Figure 1).

![Figure 1 Single Jersey structure showing (from left to right) the colour change after 5, 20 and 30 seconds](image)

1.2 Double bed rib: The second structure was a full rib knitted in cotton with the conductive yarn knitted in every sixth loop on the front bed and as a tuck stitch in every third loop on the back bed. When the textile was heated, the first visible change took place after five seconds as the loops became visible as diffuse dots on the printed face. After 20 seconds of heating, the floats between the beds became visible, changing the color of the whole print, as the shape of the conductive wale was mirrored by the pattern created by the heat. After 30 seconds the conductive wale was fully heated mirroring the tuck stitches from the back bed to the printed front of the surface, at which point the pattern took on the diffuse form of a straight line (see Figure 2).

![Figure 2 Double bed rib structure showing (from left to right) the colour change after 5, 20 and 30 seconds](image)

1.3 Jacquard net structure (1X2): This type of structure allowed the conductive threads to be embedded only in the front side of the knitted fabric, thus enabling the textile material to be heated so as to form specific patterns, and by adjusting the density of the conductive loops in specific places in these patterns it was also possible to vary the textures of the material. After 5 seconds of heating, the shapes of the pattern became visible, and after 20 seconds, the floats between these shapes became visible as the heat changes the color of the whole print; in this way, the textile surface is divided into areas with different visual textures. After 30 seconds of heating maximum diffusion of the pattern was achieved, at which point the printed layer displayed the diffuse form of a straight line (see Figure 3).

![Figure 3 Double bed rib structure showing (from left to right) the colour change after 5, 20 and 30 seconds](image)

During the conducting of these experiments, it was observed that the area around the interface between the knitted material and the printed layer reacted to the heat emitted by the conductive yarn. The shape of this area was circular due to the shape of the stitches, and its radius depended on the length of the stitches; the color change introduced an offset radius of up to 4 millimeters around each stitch. The precision with which the surface pattern embedded in surface of the knitted fabric was translated by the heat depended on the distance between the loops of conductive yarn which came in direct contact with the printed layer, and also on the amount of heat applied. In order to achieve a pixelated expression, the heat has to be planned so as to turn on/off at five second intervals, and for an organized expression, the distance between the loops has to exceed the size of the offset circle around each stitch. For the exact shape of a whole wale of knit to be transferred to the printed surface by the heat, the conductive threads have to stay activated for 20 seconds; if the activation time exceeds 30 seconds, the knitted line becomes completely diffused. The times stated here are primarily included to facilitate comparisons between the examples, as the exact times vary with the amount of current used.


The results of the experiments presented above highlight the need to expand on designers’ possibilities to create more innovative dynamic surface patterns than offered by existing methods, and to do so by utilizing a technique where multiple colors and patterns are hidden and/or revealed. Thus, further experiments were conducted to accomplish this.

In order to hide and reveal more than one latent color of the surface pattern, there was a need of forming temperature sensitive color mixtures. For hiding and revealing each color, temperature sensitive color mixtures had to be prepared. The first of five temperature sensitive color mixture was made by mixing magenta, yellow, orange and black leuco dye-based thermochromic inks with a cyan textile pigment paste, resulting in a dark grey below 33°C and cyan at or above this temperature. The second mixture was formed by mixing cyan, yellow, orange and black leuco dye-based thermochromic inks with magenta textile pigment paste, giving dark grey below 33°C and magenta at or above and so on. All five temperature-sensitive color mixtures looked similar at or below 33°C, and produce five different color transitions above 31°C.

The work illustrates the possibilities of having one common background color below the activation temperature of inks, which, if heated, generates a multi-colored background at equal or above the activation temperature of the inks. In contrast to the existing methods available to designers, in which thermochromic inks are used to provide multi-colored patterns which become transparent when heated, the examples in this paper illustrate how to design dynamic patterns which display a single color at temperatures below the activation temperature, and a multi-colored at higher temperatures (see Figure 4).

![Figure 4 Pictures showing one common background color below the activation temperature of inks, which, if heated, generates a multi-colored background](image)

3. A method of printing a complex dynamic surface pattern on textiles using the Offset method of printing with temperature sensitive color mixtures.

In the paper printing industry, the offset litho printing method is one of the most commonly flat printing techniques used for printing full-color images or photos; it is performed in a series of steps starting with process of color separation, during which the image is decomposed into the four process colors (CMYK color separation, four temperature-sensitive color mixtures were prepared. The four temperature-sensitive color mixture resulted in a gray-brownish color below 31°C and cyan, magenta, yellow, and black above 31°C. The layers were printed in succession from light to dark colors, which means the temperature sensitive color mixture made by black pigment was printed last, i.e. over all the others (see Figure 5).

![Figure 5 Pictures showing (from left to right) the printed pattern on white plain cotton-weave at ambient temperature (20°C) and the effect of heating](image)
As a complex pattern, and the knitted structure forms the background; as the knitted material is heated, the surface exposure to heat. Thus, the structure of the knitted material adds to the expression of the printed layer, and the diffusion of heat over time creates the possibility to design new time-based expressions, e.g., revealing the knitted structure in order to create the illusion of a three-dimensional texture or the emergence of an unexpected textural pattern of colors (see Figure 7).

4 Expressions

The complexity of a design process of a printed pattern increases when time is added as a design variable. Colors are no longer static or limited to binary changes between A to B to A; rather, in our design experiments, they change from A to 2 and then back to A again with any number of steps in between, and the speed of these changes vary as it is determined by whether the conductive yarn is heating up or cooling down. The complexity increases even further when these parameters are taken together with those representing material properties, to the point where it becomes exceedingly difficult to predict the exact outcome of a design process [7]. Thus, the conducted experiments take into consideration all variables relevant to the understanding of the final pattern expression, even those representing material properties such as the character of the yarns, stitch length, and the structural properties of the textile material. Three overlapping layers of information, i.e., knit, ink, and print, have been identified, and the method is discussed in relation to the basic expressions that can be achieved by using knitted materials as printing media. Consequently, two types of surface pattern expressions are presented. In the first type, the expression of the knitted material defines the foreground of the dynamic surface pattern, with the printed area as the background; the surface reveals a visual textural expression based on knitted forms as the one of the printed layer transforms as the result of exposure to heat. Thus, the structure of the knitted material adds to the expression of the printed layer, and the diffusion of heat over time creates the possibility to design new time-based expressions, e.g., revealing the knitted structure in order to create the illusion of a three-dimensional texture or the emergence of an unexpected textural pattern of colors (see Figure 7).

For the second type of surface pattern expressions, the expression of the print defines the foreground, creating a complex pattern, and the knitted structure forms the background; as the knitted structure is heated, the surface reveals multiple colors and shapes within the initial pattern (see Figure 8).

5 Discussion

The increased involvement of computation in the design process brings two questions to mind: How does it influence the textile expressions designers create? Is it even fruitful to consider the idea that it may give rise to certain aesthetics? Digitally printed textiles or three-dimensionally printed garments do in fact materialize intricate design expressions, based on complex design variables and the relationships between them; these expressions carry a distinct depth, sharpness, and accuracy regarding details which result from the digital parts of the design process. As figures 7 and 8 illustrate, textiles add to the digital a strong material expression based on the structural techniques used. Consequently, the introduction of computational properties may also be regarded from different angles; for example, the same raster principle used to enhance the expression of depth in digital printing can be applied to hand silk screen printing with thermochromic inks (a type of ink which is still incompatible with digital printers). In the same manner, a knitted structure can be regarded as a set of pixels, although the type of stitch used is not a binary parameter as there is also a third possibility: the tuck. Moreover, a textile material knitted on a flat bed or double bed machine and printed with thermochromic inks is able to alter between multiple colors and visual textures; thus, such a “pixel” would not only need to contain information about the surface structure of the material but color values as well. When combining two layers, e.g., a printed layer (with variables such as color changes and printing method) and a knitted material (type of structure) they will together define the qualities of the digital unit (see Figure 9). The digital environment may be a meeting point between different design methods where the pixel becomes the fundamental unit for the communication of the pattern design, and from which the pixel takes the step into the physical space in the form of a stitch. In this perspective, the smallest element used to design a pattern intended for printing does not only contain information about color, but also about the conductive structure of the textile material; thus, it becomes the bearer of the very idea that determines the visual appearance and the dynamics of the final product.

Figure 9 A drawing unit combining printing and knitting in the design of the time-based pattern

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Future works may consider the fact that the dynamic digital sketching environments, e.g., Processing and Java, introduce another intriguing aspect into the field of textile design as they allow the elaboration of time-based form processes. In addition to exploring the expressive potential in the use of these environments to design textiles, it may also be fruitful to explore methods for capturing the complexity of digital generative form processes and the accurate translation of them into a material environment as dynamic patterns. Subsequently, in a digital environment a surface containing information not only about color but also about the dynamic possibilities could be mapped to any object: flat ones as well as three dimensional ones; through the use of tools, e.g., Processing and Java, the temporal aspects could be included, substantially increasing the designers possibilities of sketching time-based textile patterns in three dimensional objects.

References

Performative interactions between body and dress: thermochromic print in fashion

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Performativity has been used to describe performance art, a term that is closely tied to the idea that the work of art is the performance itself, but not necessarily its exhibition. While performance art has been used to describe a range of art practices, including installation art and happenings, it is also often used to describe the relationship between body and space; here, dancers wore interactive dresses equipped to send out a radio signal that changed with their body movements. The receiver was placed in a thermochromic printed tapestry hanging from a wall, and the changing signal caused changes of colour in the tapestry; thus, the choreographed body movements of the dancers affected the visual expression of the wall in real time.

Another project, entitled Repetition (Dumitrescu, Lundstedt, Persson, & Satomi, 2012), was also designed to explore relationships between body and space as a method of remediating, in an interactive way, the wearer’s body movements. The interactive wall hanging incorporated electronics that react to the tactile interaction provided by a dancer who wore a garment printed with thermochromic ink. After coming into contact with the heat-conducting threads, which were knitted into the textile wall, the interactive garment changed colour according to the movement of the body.

Subsequently, the design project Unlace (Lubbers, 2013) was an interactive lace lingerie garment, which combined an old bobbin lace technique and printed thermochromic thread. The interactive garment promoted contact, interaction, and awareness between individuals through changing colour, as electrically conductive threads in the garment produced heat as a result of one person touching the wearer.

While the aforementioned researchers and their projects have presented a range of combinations of dynamic prints and digital technology and created interactive garments...
which prompt reconsideration of the externt relationships between human behaviour and the surrounding environment, these researchers did not consider the role of the body and those properties that may be utilised in an inter-active manner with a dynamic printed garment or the world as a whole. Thus, this project addresses the gap between the Hypercolour T-shirts of the early nineties and the digital applications described here. It explores possibilities of expressing one’s personality in more ways, that is, to integrate dynamic prints into the construction of the garment in order to improve its interactive qualities. Specifically, the paper reports on the use of dynamic prints in garments as well as ways of adapting cutting patterns to the dynamic printing methods. Moreover, in exploring the interactive quality of a garment, focus is placed on the performative aspects of the garment, which is the func- tion that establishes the interaction between the wearer and the garment; here, performative as is derived from Austin’s (1975) speech act theory, that is, as the function of an object to induce a bodily reaction based on its form and matter. Thus, in this particular case, the performative func- tion of the garment implies the garment’s ability to perform an action upon the wearer through the behaviour of the dynamic prints in combination with the construction of the garment. Thus, ‘performative’ and ‘performativity’ are here used in their broad sense and not limited to or focused on the interactive quality of a garment, for fashion designers to consider.

The normal body temperature of a healthy adult is 37°C; this may, however, fluctuate to a large degree, due to such factors as metabolic rate, time of day, physical exertion, and the surrounding environment. In addition, it is important to note that the central areas of the body contain more blood than the peripheral areas and are thus higher in temperature. To account for these differences in body temperature, reversible, and water-based leuco dye-based thermochromic inks are used with an activation temperature of 31°C were used due as their activation temperature is close to that of the normal human body temperature (Kooroshnia, 2013) in order to provide a good effect with maximum colour intensity at body temperature, reversible, and water-based leuco dye-based thermochromic inks with an activation temperature of 31°C were used due as their activation temperature is close to that of the normal human body temperature.

Dynamic prints
Print (surface pattern) in fashion has always been con-sidered to be a means of communicating values and serves various purposes, from pure aesthetics to support- ing the concepts of structure and shape (Fogg, 2006). Contemporary textiles are now used to apply colour to fabric in order to create desired images. With the development of new functional materials, the range of colour possibilities in clothing has expanded from a limited range of static colours, which can be used for either decoration or highlighted/diffused cutting lines, to dynamic colours which are able to suggest or elicit certain perceptions, reactions, and activities in terms of usage. The dynamic colours are able to change due to external factors and internal programmes such as leuco dye-based thermochromic inks, which generally change colour in response to temperature fluctuations (i.e. below their activation temperature they are coloured, and above their activation temperature they are clear or of a light hue). Thermochromic inks are usually blended with other pigments that are not heat-sensitive, enabling them to change from their colourless form to their coloured form. In a heated state, the solvent melts and the interaction between the solvent and the colour-former disrupts the composite, thus causing the colour-former to adopt its colourless form (Hamfield & Hutchings 2010, pp. 38–47). Thermochromic inks are composed of a binder selected (Kooroshnia, 2013) in order to provide a good effect with maximum colour intensity at body temperature, reversible, and water-based leuco dye-based thermochromic inks with an activation temperature of 31°C were used due as their activation temperature is close to that of the normal human body temperature.

The concept of nudity was chosen because, as Lamp (2010, para. 86) argued, ‘no society exists that would con-sider a person clothed if the genitals are exposed, regard-less of how thoroughly the rest of the body is enclosed in parkas and snow pants and gloves.’ Moreover, ‘most soci-eties in the twenty-first century find complete nudity in public inappropriate.’ The critical aspect of Lamp’s argu-ment in relation to the research is that ‘all concepts of nudity include fundamentally the exposure of the genitals and then, for some, other parts of the body as well’ (2010, para. 86). Thus, clothing is a means of exploring the notion of being dressed or undressed, depending on the garment’s relation to the body (cf. Barnard, 2002). Privacy or shy-ness, on the other hand, relates to the gestures and acts of the wearer as they react to and counteract the experience of sensations related to nudity.

In respect to the above notion, dynamic prints were placed near to specified body parts in order to enhance, control, and integrate the changing effects which occurred during the performative photography session. In order to observe the colour-changing effect on the garments and the performative qualities of the dresses, two models were asked to wear them in a semi-public space. Observations of the models wearing the two garments in a semi-public place were conducted by a male observer. The models were given no other instructions than that they were to wear the dresses during a photographing that would last for around 15 min per dress. During the photographing, the models only occasionally received instructions regard-ing their facial expressions, but were continually given directions regarding movement and posture.

In the first series of tests, very basic versions of a dress and trousers, with a minimum amount of seams and curves, simple sleeves, and straight cutouts, were chosen for making the garments. The cutting patterns were applied to the knitted cotton-silk organza fabric, and covered by a multi-layered union textile created for the upper part of the dress towards her body with her hands and pulling it away, thus stopping or letting the dress slip downwards in order to enhance the colour-changing effect in the upper part of the dress. However, observation of the model’s behaviour suggested that this interaction was more of a form of playing around with possibilities rather than, for example, conscious reactions related to nudity or any other obvious motive (see Figure 2).

An analysis of the photographs from the perspective of the wearer revealed that all concepts of nudity include exposure of the geni-ta1s or other parts related to nudity such as, for example, the ‘obvious motive’ (see Figure 2). The interaction between the garments and the wearers’ bodies created patterns, which were unique but wild, messy, uncontrolled, impossible to reproduce, and temporary, although the garments did not in any way expose the wearer’s genitals or any other parts of the body associated with nudity according to the above definition.

The patterns that were observed resulted from body temperature and movement in terms of arm bending, walk-ing, and turning; that is, they visualised the contact surfaces between the body and the garment, depending on the specific and clearly defined parts of the body or more espe-cially, parts associated with nudity. The garments reacted to the body temperature very quickly, especially those parts of the garment that were in direct contact with the body (e.g. torso, shoulders). The result was varied dependent on the individual’s body shape, temperature, and movement. The models did not report any discomfort or a feeling of unease, nor did they shy away from reflecting the effects and changes in the dynamic prints (see Figure 1).

In order to gain control over the creation of the patterns, two other dresses were designed. These dresses were con-structed based on the principles detailed in the design of the first garments, but with more width, volume between the garment and the body. The altered construction also put more weight on the shoulders in order to increase the fabric drape over the upper part of the body. In addition four strips were attached so to as allow adjustments to be made to the garments at certain points by tying them togeth-er (e.g. the looser the straps, the less colour changing, which made the body shape become less apparent due to a decrease in contact between the body and the dynamic prints).

While wearing this dress, the model showed a slight increase in conscious awareness of the dress in relation to her body, indicated by her apparent awareness of the bare shoulder. During the roughly 15-minute-long photographing, in spite of the fact that the photographer only gave the model instructions regarding facial expression, she var-ied the position of the neckline several times, upwards and downwards, for both shoulders during the 15-minute-long photographing. Furthermore, she altered between pressing the upper part of the dress towards her body with her hands and pulling it away, thus stopping or letting the dress slip downwards in order to enhance the colour-changing effect in the upper part of the dress. However, observation of the model’s behaviour suggested that this interaction was more of a form of playing around with possibilities rather than, for example, conscious reactions related to nudity or any other obvious motive (see Figure 2).
The interaction between the garments and the wearer’s body, displaying the patterns which were unique but wild, messy, uncontrolled, impossible to reproduce, and temporary.

chest and bottom of the dress through a close but not skinny fit of the dress. The first of these dresses was a long cotton dress made with a straight-edged black shape on the left side and a long black dynamic print on the right. The reason for choosing this cutting pattern was to extend the colour-changing effect over a large area, as well as to create a greater contrast between colour and form based on a clearer shift in print alongside the whole of the body, including the seat and chest, and thereby partially outlining the surface of the body underneath, and adding further contrast and emphasis by making the other half of the dress in a non-dynamic black fabric (see Figure 3).

Throughout the 15-minute-long photographing of this dress (Figure 3), the model orchestrated her movements so that, rather than trying to avoid exposing body parts, she appeared to embrace such occurrences and increased the dress’s articulation of the outline of her body, drawing further attention to the bottom of the dress and to the chest through her postures. Whether the performance was a reaction to an unspoken expectation or a natural act was, however, difficult to ascertain (Figure 3).

The second of these dresses was a silk organza dress, printed with black leuco dye-based thermochromic ink, except for the areas around the chest and crotch, which were printed with black block shapes, which did not disappear entirely when activated by heat thus framed the areas of the dress covering the seat, crotch, and chest. By wearing the garment, the body temperature caused the dynamic prints to disappear in the blink of an eye, leaving only the three black blocks. Thus, although the body was fully covered, it appeared to be naked, offering an interesting interplay between what was on display and what was hidden (see Figure 4).

For the duration of the photographing of this dress the model attempted to adjust her posture, mainly by turning her back against the photographer and male observer for most of the time during the session and keeping her pose very straight and upright so as not to increase the changes in the 15-minute-long photographing of this dress (Figure 3), the model orchestrated her movements so that, rather than trying to avoid exposing body parts, she appeared to embrace such occurrences and increased the dress’s articulation of the outline of her body, drawing further attention to the bottom of the dress and to the chest through her postures. Whether the performance was a reaction to an unspoken expectation or a natural act was, however, difficult to ascertain (Figure 3).

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in the dynamic print. On several occasions, when she was asked to face the photographer, the model either covered or kept one or both her hands close to her crotch (see Figure 4).

Discussion and conclusions

This research project explored several possibilities for developing items of clothing that may also function as interactive tools through using dynamic print in the design and construction of garments. It focused on the shape of the body and its temperature zones. Body temperature was a dynamic, rather than stable, design variable that provided challenges for us, while simultaneously offering a foundation for a new area of wearable communication. In this research project, design decisions were made after analysing the photos taken of the garments developed for the research.

The initial tests indicated that the interactive garments reacted to body temperature very quickly, particularly in parts of the garments that had direct contact with parts of the body. The results revealed a unique expressiveness in each garment due to the individual’s distinct body shape and temperature that in turn highlighted the role of body shape in the construction of these interactive garments.

The series of garments developed, especially those garments featured in Figures 3 and 4, also revealed that the dress may not be so much a matter of imitation and distinction, in the sense of social expression of human conditions or other demographic variables, as the garments were seen to direct the wearer’s attention towards her own body, making her increasingly aware of it in relation to the dress, rather than to displace her focus onto relationships between her dress and the context. In other words, this means that the concept of fashion may be understood as a rather dynamic concept as the thermochromic printed dresses have demonstrated not only expressive qualities but also performative qualities. The garments, here based on a process of self-limitative representation, have shown themselves to be agents capable of giving rise to conscious bodily movements.

Instead of a garment representing something [fashion], the agency and the performative quality of a garment means that the pragmatics of the garment, in terms of what it does to its wearer, that is, the expressive (communicative) act it produces in its wearer (cf. Austin, 1975), is a vital force causing an inward communication and internal system of interactive communication between garment and the wearer. Hence, performativity in clothing needs to continue to be explored. We must consider to what extent clothing as an object may open up, control, constrain, or make possible particular actions through the self-awareness they induce in the wearer. The interaction between garment and the body has not only created chaotic and impermanent patterns, but has led to what may be regarded as a new engagement with clothing.

As with any research project, this project has a limitation. The mixtures of thermochromic inks with conventional textile pigment paste always changed from a dark colour to a bright one, a limitation to design capabilities.

Acknowledgements

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References


Figure 4. A silk organza dress, printed with thermochromic ink, except for the areas around the chest and crotch, which were printed with black block shapes to create an ambiguous but defined focus on the area of the chest and bottom of the dress.
Crafting Butterfly Lace – Conductive Multi-Color Sensor-Actuator Structure

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Abstract
The work describes background and methods involved in the development of Butterfly Lace, a conductive multi-color sensor-actuator structure that lies in the intersection of traditional craft and smart materials. Traditional craft is introduced as inspiration for developing smart textiles in lace structure. Both, the process of dyeing conductive threads with multi-color thermochromic pigment mixes and the technical set up for the sensor-actuator system are described. The possibilities and challenges for the multi-color sensor-actuator combination in a lace structure are discussed based on the experience gained from working with the material. Potential applications are glanced for inspiration and future directions.

Author Keywords
Smart textiles; craft qualities; thermochromic inks.

Introduction
By introducing smart materials to design area, experimental design researchers spend long hours in their workshops exploring expressiveness qualities of smart materials through applying and testing different techniques and methods. By doing that, they try to gain knowledge and understanding of the particular materials and its design possibilities. Therefore, craft may serve as a platform for inspiration and carrier for smart textiles development (Kuusk et al., 2012, Baggerman et al., 2013).

The potential of defining interaction behavior of smart textiles by a traditional textile technique is explored in Butterfly Lace (Figure 2). It combines a sensor and an actuator in the same structure. In Butterfly Lace the conductive yarn detects the human touch and attached electronic module heats the same yarn up to a certain temperature to reveal the defined color pallet. The Leuco dye-based thermochromic inks are used to create color-changing effect on the yarn. The lace structure is used for the property of controlling each yarn independently. Each separate thread of the structure can sense the user input and display a different color accordingly. In that way the traditional textile technique defines the interaction behavior of the smart textile. Conceptually, Butterfly Lace reflects the property of any traditional textile that is changing color in time while being exposed to the UV-light.

First try outs of lace making with dyed conductive threads are shown in Figure 1. In ambient temperature the black conductive thread in grey surface stands out and the black dyed conductive thread in black surface is blended in. When heated to 40°C (below), the black conductive thread looses its thermochromic black layer and appears as its original color – grey, therefore blending into grey and standing out in black lace.

The performative properties of thermochromic inks that suggest new forms of communication and expression (Halikas et al., 2002) have been explored previously by Kososhnia (2015), Robertson (2011) from the printing perspective, and more from integrating technology perspectives by Jacobs & Worbim (2005) and Dumitrescu et al. (2012). Several design examples (for example Bondesson et al., 2015; Lubbers, 2013) have been proposed to explore the relationship between the body and the space in thermochromic color change context.

Perins and Nakatsu (2013) explored the combination of using touch for temperature element activation and thermochromic ink for color change in the surface. They described a system, which detects subtle temperature differences caused by a fingertip, and used those differences as the detection trigger.

By constructing Butterfly Lace yarn by yarn, with conductive and color changing properties in mind the programming ability of textile as well as the pattern creating ability of technology are implemented. The physical construction of lace threads in the pattern determines the flow of current through the threads. When placing the threads in a pattern that is desired form the technical circuit perspective, new kind of patterns are created. Patterns in textiles being an important carrier for culture and information literally carry the interaction properties of the lace in this project.

Developing the Butterfly Lace
The development of Butterfly Lace started and carried on as an extension of ArcinTex network workshop (ArcinTex, 2015). Multi disciplinary team of researchers collaborated while situated in three countries, to realize conductive multi-color sensor-actuator structure. Over several prototyping sessions, Skype conversations and e-mail exchange, the lace is made in a traditional lace...
To control the color change on the yarn by a human touch, the yarn is set up as part of an electric circuit, which uses the yarn itself as a sensor. The duration of the touch is measured by using a capacitive sensor, and the heating power is set according to the duration measured. Brief touch is needed for a small trigger, and maximum power is achieved after a few seconds of touch. This can be adjusted to different yarns and required feedback as necessary. The designed circuit varies between detection-mode and actuation mode. In the detection mode the signal acts as a capacitive detector, and in the actuation, it is used as high-current PWM output. If there is no touch signal detected for a while, the heating is eventually switched off.

The heating process indicated that the best differentiate between activation temperatures should be at least 10°C. In addition, it indicated that the darkest color should have the lowest activation temperature and lightest color should have the highest activation temperature.

Consequently, for the second series of experiment, blue leuco dye-based thermochromic ink with activation temperature of 27°C, magenta with activation temperature of 37°C, and yellow with activation temperature of 47°C were used. Through the first test, all three inks were mixed together at a 2:6 ratio of ink to binder. Then the mixture was applied on the yarn. In the other test, the inks were applied on the yarn with different order e.g. second test was conducted through painting yarn first with yellow 47°C, then magenta 37°C and last blue 27°C. The third test was first magenta 37°C, yellow 47°C and blue 27°C, etc. The reason for doing that was to understand whether the order from low activation temperature to higher one or from higher to lower was crucial or not. After heating them, it was observed that the lightest color should have the highest activation temperature and should be the one applied to the yarn first, followed the darkest color should have the lowest activation temperature and applied the last. With this systematic order the garish yarn at ambient temperature, orange at 37°C and yellow at 47°C was achieved.

The circuit used for detecting touch is shown in Figure 3. It is a combination of push-pull output and capacitive single-slope detector. Q1 and Q2 transistors, which form the push-pull circuit are used for controlling power to the yarn, while the resistor R is used as a pull-up resistor for the capacitive detector. When the yarn Y is touched with a finger, the rise-time of the measurement pin changes, which is directly affected by the human body capacitance. Without a finger, only the input capacitance of the measurement pin and the pull-up resistor R dictate the value. The finger directly increases the input capacitance, altering the rising time of the slope.

P-type FET Q1 and n-type FET Q2 form push-pull output, which is used to supply power for the conductive thermochromic yarn (Y). The power can be controlled with normal PWM using the power control pin, when the +V control pin is used to supply power to the yarn.

In the Figure 4, the process of heating is shown. There are six pairs of temperatures, starting with 24°C - 27°C (table temperature), and in 29°C, 33°C, 40°C, 45°C and 52°C. The visual change is shown next to the actual yarn. The warm blotch on the left side of the heated yarn is where the lace has been touched.
Conclusion

Going into more detail within the textile construction process allows each yarn to be controlled separately. Every yarn that is part of the lace can act as a separate sensor, therefore allowing the trace of the input e.g. touch to be read in a very detailed level understanding the direction, pressure, temperature and so forth. Similarly, each thread is able to act as an actuator to display different (or same) color in its lengths.

The complex input and output possibilities in one lace allow rich interaction canvas for different touches to be recognized and various color patterns to be displayed. The Craft Qualities (Kuusk et al., 2014) have been used to identify in the Butterfly Lace guide the possible future applications towards personal and intimate use of the technology, close to the body. For example, if the body itself would act as a trigger to be sensed by the lace structure, the body could be warming up would be part of the wearables and movement. In daily clothing, considering that rehabilitation area to provide instant feedback on touch and movement could open up possible uses in health and surfaces changing effects on textiles.

Conclusions

The complex input and output possibilities in one lace allow rich interaction canvas for different touches to be recognized and various color patterns to be displayed. The Craft Qualities (Kuusk et al., 2014) have been used to identify in the Butterfly Lace guide the possible future applications towards personal and intimate use of the technology, close to the body. For example, if the body itself would act as a trigger to be sensed by the lace structure, the body could be warmed up would be part of the wearables functionality, the pressure in specific areas could indicate tightness and find its use in tailoring or fitting purposes. The possibility to follow subtle color change on one’s body brings different mindfulness practices into consideration for the future uses of the technology. Giving the wearer the freedom to define the visual patterns, with their shapes, sizes and colors on the body by their movement and touch opens up alternative directions for personalisable garment and fashion design.

References


PAPER F
**Thermochromic colour transition sample spectra: a pedagogical tool for studying and teaching leuco dye-based thermochromic inks**

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**ABSTRACT**

This research project presents thermochromic colour transition sample spectra as guidelines for assisting with thermochromic colour studies. The research involved creating a series of design experiments using leuco dye-based thermochromic inks that demonstrated the thermochromic colour wheel, possible colour mixtures, and the basic and complex colour transitions of thermochromic inks at different temperatures. The sample spectra are an effective practical communication tool to assist textile designers in making informed decisions and predicting colour transitions at different temperatures while designing a dynamic surface pattern.

**Keywords**

Colour transition sample chart, leuco dye-based thermochromic inks, textile, design, surface pattern.

**INTRODUCTION**

This research project presents thermochromic colour transition sample spectra that assist in visually and verbally describing the behaviour of thermochromic inks in relation to other static pigments at different temperatures.

The significance of this for textile design is related to the ability of a textile designer to deal with the complexity of a design process in which dynamic surface patterns are created using thermochromic inks on textiles. It also relates to the ability of a textile designer to make informed decisions and predict colour transitions at different temperatures when designing dynamic surface patterns.

In the latter decades of the twentieth century, chromic colours, which reversibly change colour according to external environmental conditions, were introduced and included in the colour palettes of designers, and particularly textile designers. They are classified depending on the stimulus that triggers them; this can be e.g. light for photochromic inks, and heat for thermochromic ones.

Leuco dye-based thermochromic inks (referred to hereafter as simply ‘thermochromic inks’) are colouring agents, and are characterised by their ability to change in response to temperature fluctuations. They are coloured in a non-heated state and become colourless or have a very light colour in a heated state (cf. Bamfield & Hutchings, 2010). They are usually blended with other (static) pigments, allowing the mixture to change from one colour to another.

Although many experimental textile practitioners and researchers have experimented with and investigated the design possibilities offered by thermochromic inks (cf. Hallnäs et al., 2002; Berzina, 2004; Orth, 2004; Berzowska, 2005; BAN, 2007; Worbin, 2010; Peiris et al., 2010; Robertson, 2011; Calder et al., 2013; Ledendal, 2015), only a few have taken the time to provide an explanation of the principles relating to working with thermochromic ink, and how to apply them in practice. Berzina (2004) formulated the ‘Multicolour Chromic Design System’, a way of designing and printing a multicolour dynamic pattern on textiles that incorporates thermochromic inks with different activation temperatures. The system is presented in the form of a table containing the optimal sequence for printing different colours of thermochromic inks, as well as the order in which inks should be chosen based on their activation temperatures (Berzina, 2004, pp. 156-158). Worbin (2010) defined the principles of thermochromic studies linguistically, by denoting the colour transitions of thermochromic inks with sequences such as “A → B → A”. The prototype “Bing Square”, for instance, is an apron which features an electronic circuit woven into its surface; the circuit sends a current to different parts of the apron, causing the resistive yarns to heat up and a striped pattern, printed with black thermochromic ink, changes to a checkered pattern similar to that of a tablecloth printed with conventional/static textile pigment paste, which is located nearby. Worbin describes the colour-changing principle of this prototype as follows: “Pattern expression A: stripes on textile surface; changes to Pattern expression B: checks on a textile surface; changes back to Pattern expression A: stripes on a textile surface A → B → A” (Worbin, 2010, p. 99). A year later, Nilsson et al. (2011) presented their graphically illustrated “colour scale of nuances”, a tool with which to describe a colour transition when a thermochromic print changes colour, either from one colour to a almost lighter colour of the same colour or from one colour to another. Building on the thinking of Worbin, Nilsson et al. used arrows – “A →B →A” – to describe the colour transitions of thermochromic inks. Later, a pedagogical tool for teaching the behaviour of thermochromic inks to students of textile design was designed by the author (Kooroshnia, 2013a). This uses colour swatches printed with static textile pigment pastes, to visually imitate and demonstrate the behaviour of thermochromic inks at different temperatures. Subsequently, Ledendal suggested graphical illustration as a communicative tool for demonstrating the principles of thermochromic ink studies (2015, p. 106).

However, while all of these tools attempt to facilitate the understanding and design of dynamic surface patterns, they are limited to either explaining or demonstrating only the first (non-activated) and last (fully-activated) colours. Thus, there is still a need for a tool which shows the colour transitions of thermochromic inks step by step – from a non-heated state to above the activation temperature, with all of the stages in between. At present, in the absence of a tool that describes the complete range of colour transition, and because of a lack of terminology with which to describe in detail the behaviour of thermochromic inks in relation to other static textile pigment pastes and different temperatures, textile designers see complexity and limited design options in the use of thermochromic inks, rather than extensive and practical possibilities that may lead to new and innovative avenues of textile design, particularly in the area of textile printing. This research project presents thermochromic colour transition sample spectra to provide a fundamental, detailed explanation of the principles related to working with thermochromic ink, and facilitates communication and understanding regarding, and design with, thermochromic inks.
Figure 1: A thermochromic colour wheel, created using thermochromic inks with an activation temperature of 31°C. The wheel also includes the effects (colours) at the end colour-loss point.

In order to explore possible colour mixtures when two different primary colours – one of thermochromic ink and one of textile pigment paste – were mixed in pairs, six colour scales were created. Mixing two colours (one of thermochromic ink and one of textile pigment paste) in different proportions until the desired number of intermediate colours was obtained produced a gradation of colour, progressing from one colour to another.

A key element of the thinking behind the research was to have the mixing process grounded in mathematical accuracy, rather than observation and estimation. This is to say that colours were identified by the ratio that indicates the percentage used of each colour. For instance, one test involved mixing red (R) thermochromic ink and yellow (Y) static textile pigment paste as follows:
A ratio of R25:y75 indicates that the mixture consisted of 25% red thermochromic ink and 75% yellow textile pigment paste. In total, each scale had nine steps, or colours. This number was chosen so as to enable the author to visually distinguish between them (Fig. 2).

With reference to the design methods that were developed during the author’s previous thermochromic studies (Kooroshnia, 2015), which offer ways of creating a wide range of colour-changing effects on textiles, it was obvious that, in order to fully describe these effects, there was a need to visually represent the colour transitions of thermochromic ink in stages, ranging from non-activated to fully activated states.

Accordingly, it was decided to explore and document three types of colour transition in particular:

1. **Fading**: A graduated scale, ranging from Colour A to a lighter version of Colour A and back again to Colour A; occurs when the temperature increases to above the activation temperature of the ink and then decreases to the non-heated state.

2. **Bridge**: A graduated scale, ranging from Colour A at one end to Colour B, and back again to Colour A; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.
   - **Single bridge**: Colour A is a colour mixture wherein two different colours – one of thermochromic ink and one of static textile pigment paste – are mixed. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B, and back again to Colour A; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.
   - **Double bridge**: Two similar Colour A, each of which is a mixture of a thermochromic ink and a static textile pigment paste. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B or C, and back again to Colour A; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.
   - **Triple bridge**: Three similar Colour A, each of which is a mixture of two thermochromic inks and a static textile pigment paste. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B, C, or D, and back again to Colour A; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.
   - **Quadruple bridge**: Four similar shades of Colour A, each of which is a mixture of three thermochromic inks and a static textile pigment paste. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B, C, D, or E, and back again to Colour A; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.
   - **Quintuple bridge**: Five similar shades of Colour A, each of which is a mixture of four thermochromic inks and a static textile pigment paste. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B, C, D, E, or F, and back again to Colour A; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.

Figure 2: Six thermochromic colour scales when two different primary colours – one of thermochromic ink (represented by a capital letter) and one of textile pigment paste (lower-case letter) – were mixed at different ratios.
• **Sextuple bridge**: Six similar shades of Colour A, each of which is a mixture of five thermochromic inks and a static textile pigment paste. The colour transition occurs according to a graduated scale, ranging from Colour A to Colour B, C, D, E, or F, and back again to Colour A; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.

This may continue ad infinitum.

3- **Continuum-Bridges**: Graduated scales, consisting of at least three Bridges that are connected together and range from Colour A at one end to Colour B at the end of the first Bridge, from Colour B to Colour C at the end of the second Bridge, and from Colour C to Colour D at the end of the third Bridge; occurs when the temperature increases to above the activation temperature of the inks and then decreases to the non-heated state.

**Fading**

Red (R100%), yellow (Y100%), and blue (B100%) thermochromic prints with activation temperatures of 31°C were selected from the thermochromic wheel, heated slowly, and allowed to cool, with the entire process of heating and cooling being recorded.

In order to heat and cool them slowly, all of the samples discussed in this research project were heated and cooled with a device that was made specifically for this experiment, consisting of two separate systems: One used a Peltier device to cool the space by transferring heat from one side to the other, creating a temperature drop on one side and an increase on the other, and the other used a line of resistors, which heated up when they ‘held back’ high currents. In order to transmit the heat in the right direction, the resistors were mounted on the rear of a thin aluminium plate using a thermal adhesive. Styrofoam was used to insulate the back of this setup so as to direct the heat through the aluminium.

To record the heating and cooling process, a Flir E40 Compact IR Thermal Imaging Camera was used, in natural daylight conditions.

Observations of colour-changing effects, from a non-heated state to above 31°C, indicated that, for yellow and red selected prints, changes in colour began to occur at 25°C, and for blue at 27°C – termed ‘start colour-loss point’ – and end colour-loss happened for yellow and red at 33°C, and blue at 34°C. The cooling cycle began at 28°C for yellow and red, 30°C for blue, with full colour-return occurring at 22°C for yellow and red, and blue at 24°C (Fig. 3).

It was interesting to observe that, in spite of the fact that all three prints were produced using thermochromic ink with the same activation temperature (31°C), they did not have the same start colour-loss point, end colour-loss, colour-return and full colour-return points.

Residual colour at the end colour-loss point was due to a high ratio of pigment to solvent in the molecular structure of the thermochromic ink. The structure of thermochromic ink is described by Bamfield and Hutchings (2010) as consisting of a colourant (pigment) and a colour developer dissolved in a solvent, together making up the thermochromic composite. This composite is microencapsulated in a protective coating to protect the content from undesirable effects caused by the environment. In a non-heated state, the composite remains in solid form, and the colourant adopts its coloured form. In a heated state, the solvent melts and the interaction between the solvent and the colourant destroys the composite, thus causing the colourant to adopt its colourless form.

Our vocabulary for naming colours in both the non-heated state and end colour-loss point is quite limited. Two vital terms for the purpose of describing the colour-changing effects of thermochromic inks at different temperatures were suggested; “non-activated colour”, and “fully-activated colour”. The former refers to any colour/print produced using thermochromic ink in a non-heated state, and the latter to any colour/print produced using thermochromic ink that has reached the end colour-loss point.

**Figure 3**: The first thermochromic colour transition, Fading, produced using yellow, red, and blue thermochromic inks with an activation temperature of 31°C.

**Single bridge**

To demonstrate this thermochromic colour transition, a graduated scale, ranging from Colour A at one end to Colour B, and back again to Colour A, was made. An orange print that was made using red thermochromic ink and yellow textile pigment paste in a ratio of R25:y75, a green print that was made using blue thermochromic ink and yellow textile pigment paste in a ratio of B25:y75, and a violet print which was made using...
blue thermochromic ink and red textile pigment paste in a ratio of B37.5:r62.5 were selected from the scales. It should be noted that the ratio for the violet print was not the same as the others, as this ratio provided a brighter violet as compared to another colour produced using blue thermochromic ink and red textile pigment paste in a ratio of B25:r75.

The same procedures of heating and cooling were used to demonstrate gradual transitions, from non- to fully-activated colour. It was observed that the start colour-loss point was for orange at 25°C, and for green and violet at 27°C, and the end colour-loss point was for orange at 33°C, and green and violet at 34°C. The cooling cycle began at 28°C for orange, and 30°C for green and violet, with full colour-return occurring at 22°C for orange, and green and violet at 24°C.

Reviewing these three colour transitions suggested that it would be useful to switch the colours of thermochromic ink and static textile pigment paste, e.g. making orange using yellow thermochromic ink and red textile pigment paste, green using yellow thermochromic and blue textile pigment paste, and violet using red thermochromic and blue textile pigment paste.

As a result of mixing the newly defined orange, green, and violet colours, it was observed that, although prints produced using primary colours of both colour sources looked alike in a non-heated state with regard to the colour strength, this was not the case when the colours were used in a mixture. For instance, both yellow prints – one produced using yellow thermochromic ink and one using yellow static textile pigment paste – looked alike in a non-heated state, but when used in a mixture they were not equally strong. Yellow and red thermochromic inks were less strong as compared to their static textile pigment paste counterparts. Thus, in order to make the orange and green colours, a significant portion of yellow thermochromic ink was required; the same was true for the violet colour with regard to red thermochromic ink. Orange, with a ratio of Y84.4:r15.6 (non-activated colour) changed to red (fully activated colour); green, with a ratio of Y84.4:b15.6 (non-activated colour) changed to blue (fully activated colour); violet, with a ratio of R84.4:b15.6 (non-activated colour) changed to blue (fully activated colour), all as a result of increasing the temperature to the end colour-loss point (Fig. 4).
Figure 4: Top: The second thermochromic colour transition. Single bridge, a graduated scale, ranging from Colour A at one end to Colour B, and back again to Colour A. At bottom: An example of how six different Single-Bridges can be used in production of a dynamic surface pattern.

**Sixtuple bridge**

To demonstrate this colour-changing effect, graduated scales ranging from Colour A at one end to Colours B, C, D, E, F or G, and back again to Colour A, six printed colour mixtures were made using five different colours of thermochromic ink and one colour of textile pigment paste in each batch. All six prints looked alike, or near-alike in a non-heated state, but changed to six different colours at the end colour-loss point (Kooroshnia, 2015). For this experiment, yellow (100%), red (100%), blue (100%), orange-yellow, green-yellow, and violet-red, all of which used both colour sources were required.

Each of the six colour mixtures to be printed on textiles was made by mixing a colour of static textile pigment paste with the five thermochromic inks in differing quantities until the desired colour was obtained. For example, the first mixture was made by combining green static textile pigment paste and yellow, red, blue, orange, and violet thermochromic inks, resulting in violet-greyish in a non-heated state and green when fully activated, at the end colour-loss point. The second mixture was formed by mixing orange static textile pigment paste and yellow, red, blue, green, and violet thermochromic inks, producing violet-greyish in a non-heated state and orange when fully activated, at the end colour-loss point. The third mixture consisted of red static textile pigment paste and yellow, blue, orange, green, and violet thermochromic inks, giving violet-greyish in a non-heated state and red when fully activated colour, at the end colour-loss point. The process continued in a similar manner for the other mixtures (Fig. 5).

The six mixtures produced in the first trial were too uneven in terms of colour differences, and so considered to be unsatisfactory. To deal with this, one of the batches was selected as a basis for comparison, and different colours of thermochromic ink were added, in very small increments, to the other colour mixtures until all six looked alike in a non-heated state.

In addition, determining a recipe or ratio to be used for each mixture so as to ensure that all colour mixtures looked alike was difficult as quantities – i.e. measured weights. The lack of a thermochromic database with which to measure the colour samples with a spectrophotometer exacerbated this difficulty.

The same procedures for heating and cooling as in previous experiments were used. The start colour-loss point was 26°C, end colour-loss point at 34°C. The cooling cycle began at 29°C, with full colour-return occurring at 22°C.
Figure 5: Top: The thermochromic colour transition, Sextuple-Bridges, consisting of graduated scales ranging from Colour A at one end to Colours B, C, D, E, F or G, and back again to Colour A. Bottom: An example of how a dynamic surface pattern consisting of quadruple Bridge can be produced in practice.
To demonstrate this thermochromic multicolour transition, which consisted of at least three Bridges, connected together, yellow, magenta, and blue thermochromic inks with activation temperatures of 47, 37, and 27°C, respectively, were used. Berzina (2004) argues that the process of utilizing thermochromic inks with differing activation temperatures has to be systematic:

\[ \text{The lightest colour has to be the one that is applied to fabric first, followed by other darker colour shades and finishing with the darkest. Additionally, ink with the highest activation point temperature should be of the lightest colour shade and ink with the lowest activation point temperature should be the darkest one.} \quad (\text{Berzina, 2004, p. 157}). \]

The first test was conducted in order to ascertain whether the order of activation temperatures (from low to high or vice versa) was crucial, and so a first layer of blue thermochromic ink with an activation temperature of 27°C was printed, followed by a layer of magenta thermochromic ink 37°C, then a layer of yellow thermochromic ink 47°C. Another test was conducted which involved printing on fabric; the first layer was yellow 47°C, the next was magenta 37°C, and the last was blue 27°C. A final test mixed blue 27°C, magenta 37°C, and yellow 47°C, and the mixture was then printed on fabric.

All of the prints were dark red-brownish in a non-heated state. When the temperature was raised to 27°C, the blue thermochromic ink was activated and orange appeared at the end colour-loss point of the first Bridge. The temperature was then raised above 37°C, and so the magenta thermochromic ink was activated and a yellow-orange was achieved at the end colour-loss point of the second Bridge. Finally, when the temperature was raised above 47°C, the yellow thermochromic ink was activated, and white with a yellow tint was obtained at the end colour-loss point of the third Bridge. This meant that the order of printing – inks with low activation temperatures first – was not as important as ensuring that the ink with the highest activation temperature was of the lightest colour, and that each ink with a successively lower activation temperature was darker than the last.

Subsequently, green static textile pigment paste was used to add an additional colour at the last end colour-loss point of the third Bridge. For this, the green static textile pigment paste was mixed with all three thermochromic inks, and the mixture was printed on fabric. For the second test, the green static textile pigment paste was first printed on the fabric, then overprinted with layers of blue, magenta, and yellow thermochromic ink with activation temperatures of 27, 37, and 47°C, respectively. Another test involved printing a first layer of green static textile pigment paste, additional layers of yellow then magenta thermochromic ink with activation temperatures of 47 and 37°C, respectively, and overprinting with a layer of blue 27°C. It was observed that all prints were dark brown in a non-heated state. As the temperature was raised to above 27°C, the blue thermochromic ink was activated and a brown-yellow appeared at the end colour-loss point of the first Bridge. The temperature was then raised to above 37°C and the magenta thermochromic ink was activated, resulting in a green-yellow at the end colour-loss point of the second Bridge. Lastly, when the temperature was raised to above 47°C, the yellow thermochromic ink was activated and green was obtained at the end colour-loss point of the third Bridge.

The results of both parts of these experiments indicate that the most desirable printing approach was to mix all three inks – with or without static textile pigment paste – in one batch, as this method created a solid print.
Discussion

This research project resulted in the production of thermochromic colour transition sample spectra that can be used as guidelines for studying and teaching thermochromic inks.

Artists and designers are often visual learners, and thus learn through observing. This tool makes it possible to demonstrate the colour mixtures offered by thermochromic inks, and visually represents the basic and complex colour transitions of thermochromic inks at different temperatures. It is an effective practical communication tool to assist textile designers in making informed decisions and predicting colour transitions at different temperatures when designing a dynamic surface pattern. The approach taken by this project has been not simply theoretical, as it has produced a practical toolkit for understanding colour – one that unlocks the doors of creation (Albers, 2006).

Observation of textile students during thermochromic workshops has shown that, when designing dynamic surface patterns, they often focus on the aesthetic expressions in a non-heated, heated, or cooled state; that they do not consider the design possibilities offered by thermochromic inks with regard to the states between non-heated, heated, and cooled – those which may add an extra dimension of aesthetic expression to a dynamic surface pattern. If designers consider the design possibilities offered by thermochromic inks and combine them with heating technologies that provide a specific temperature range in order to reach the necessary
activation temperatures, they will have control over colour-changing effects, and so create new expressions on textiles.

When two different primary colours – one of thermochromic ink and one of textile pigment paste – are mixed in equal proportion, two different colours are created (see Fig. 2). For instance, a print produced using 50% red static textile pigment paste and 50% yellow thermochromic ink is different to a print made using 50% yellow static textile pigment paste and 50% red thermochromic ink. This difference can be ascribed to the fact that the molecular structure of thermochromic particles is different to that of static textile pigment particles, in that they reflect and absorb certain wavelengths of visible light in different ways, causing a variation in how they are seen. This is also related to the degree of weakness of colour of thermochromic inks as compared to static textile pigment pastes.

In addition, as shown in Figure 1, primary thermochromic colours worked optimally when unadulterated, but resulted mostly in impure, dull, and unsaturated colours when mixed, and so secondary thermochromic colours are less vibrant than primary ones. Primary static textile pigment colours, on the other hand, worked well both unmixed and in mixtures.

As shown in Figure 3, a ratio of 25% thermochromic slurry to 75% extender produced residual colour at the end colour-loss point. This can be improved by reducing the ratio of thermochromic slurry to extender to e.g. 1:99 (Kooroshnia, 2013b). This may result in thermochromic colour with a very low degree of strength (a very light colour in a non-heated state), but less or even non-residual colour at the end colour-loss point (see figure 7).

In addition, as shown in Figure 7, print on the left was produced using yellow, magenta, and blue thermochromic inks with activation temperatures of 47, 37, and 27°C, respectively, at a ratio of 25:75. Print on the right was produced using yellow, magenta, and blue thermochromic inks with activation temperatures of 47, 37, and 27°C, respectively, at a ratio of 2:98.

Residual colour is an important concern as it affects the transition from one colour (non-activated) to another (fully-activated). For example, a violet print produced using blue thermochromic ink and red textile pigment paste changed colour in response to heat in a different manner than was expected; to red with a touch of blue, instead of to a slightly lighter red. This is not necessarily a limitation, however, but can be seen as an opportunity to design dynamic surface patterns.

In addition, Figures 3 and 4 show how different colours of thermochromic ink with the same activation temperature have different start colour-loss point, end colour-loss, start colour-return, and full colour-return points. From a textile design perspective this is a valuable design possibility, as e.g. a three-colour dynamic pattern can be produced, with three different colours of thermochromic ink with activation temperatures of e.g. 31°C. When a heat source equally heats the entirety of the print, the parts that have been printed with e.g. red thermochromic ink, or a mixture of red thermochromic ink and a static textile pigment paste, change colour faster than other parts printed with blue thermochromic ink and return to their original colour more slowly than other parts printed with blue thermochromic ink.

It is noted that the time measurements described in here are approximations, as the properties of the thermochromic inks usually differ slightly between suppliers and the use of different heat sources led to differing quantities of thermal energy, time, and colour-change periods.

As shown in Figure 4, although the six prints were made using five different, maximum-saturated colours of thermochromic ink and one maximum-saturated colour of textile pigment paste, the colour-changing effects at the end colour-loss point did not exhibit the maximum saturated colour. Instead, their colours were unsaturated and lacking in vibrancy. This behaviour can be explained by the fact that the colours from both colour sources were slurries that were mixed with extender, and the more a colour required a well-defined mixture, the more extender was used; consequently, many of the colour mixtures were unsaturated.

In addition, as shown in Figure 5, the degree of strength of blue static textile pigment paste was higher than other colours of static textile pigment pastes. It caused the blue to be seen at the very early stage of heating cycle, as well as at the very last stage of cooling cycle. This can be seen as a design option while designing dynamic patterns on textiles.

The results of detailed theoretical and practical investigations of existing colour systems (Wong, 1997; Hård & Sivik, 1981; Gordon & Gordon, 2002; Itten, 2003; Feisner, 2006; Albers, 2006; Osborne, 2008; Burger & Burger, 2012) indicate that, although existing colour systems allow textile designers, who are interested in textile printing techniques, to learn how to expand the palette of colours available to them for use with textiles, these systems were not designed to deal with thermochromic colours or their properties: They are insufficient for verbally and visually describing the colour-changing effects offered by thermochromic inks when used with textiles, and dealing with temperature as a design variable when colour transitions are described in relation to textiles.

The next step is to create a thermochromic colour system that can visually and verbally represent thermochromic ink principles, and describe the connections between all of the colour transitions in one system. Insight and deep understanding of thermochromic design possibilities, and how to apply them in practice, will assist experimental textile design practitioners and researchers in pushing the boundaries of traditional design methods. This is especially true in relation to designing surface patterns, and consequently to opening up new ways of thinking about designing dynamic patterns on textiles.

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