How to visually represent the colour theory of thermochromic inks

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Abstract:
Colour theories have been established in order to allow artists and designers to understand the relationship between colours, and to determine how a chosen colour will react or interact with another. Smart colours - such as leuco dye-based thermochromic inks - have entered into the textile and fashion design world, bringing with them new challenges. This paper stresses the fact that, in order to demonstrate and describe the behaviour of these inks at different temperatures when printed on textiles, a new colour system is required. Four design experiments using thermochromic inks are described and these, along with the discussion presented, highlight the need to develop a thermochromic colour system which can not only visualise and describe the behaviour of these inks in relation to other static pigments and temperatures, but also assist textile designers in making informed decisions during the design process.

Keywords
leuco dye-based thermochromic inks, colour system, textile, design, surface pattern

This paper is a part of an experimental design research programme which explores the design properties and potential of using leuco dye-based thermochromic inks on textiles in order to facilitate the understanding and design of dynamic surface patterns. The research was undertaken in the context of textile design, and carried out using textile-printing techniques, in particular hand screen-printing.

In short, each series of experimentation began with the testing of ideas generated by literature studies and sketches of ideas and continued through the development of expressions in fabric samples, which suggested alternative ways of achieving colour-changing effects on textiles. At each stage, fabric samples were gathered and analysed so as to create a foundation for future exploration. The outcome of this process was a series of working methods which offered the insight and depth of understanding required in order to design dynamic surface patterns through the use of thermochromic inks (Kooroshnia, 2015).

As a result of the analysis of the experiments, it became increasingly evident that existing colour systems and their terminologies were unable to describe the expressions achieved during the process. Therefore, this paper stresses that, due to the absence of a thermochromic colour theory that can visually and verbally describe the colour-changing effects offered by thermochromic inks, it would be difficult for textile designers to fully grasp the logical foundations of the proposed design methods and, as a consequence, these designers are unable to internalise the methods thoroughly enough to use them for further investigation through design.
BACKGROUND

*Leuco dye-based thermochromic inks*

With the technological progress of materials science, the palette of colours with which to print on textiles has expanded beyond those with known properties and expressions to a new generation, with more advanced functionality and expressive properties.

This new range of colours is characterised by their ability to change colour in response to external factors. Often referred to as ‘smart colours’, these include thermochromic inks, photochromic inks, photoluminescent pigments, etc. Leuco dye-based thermochromic inks are colouring agents characterised by their ability to, when printed on textiles, change colour in response to temperature fluctuations (referred to hereafter as ‘thermochromic inks’). Below their activation temperature they are coloured, and above their activation temperature they are clear or have a light hue (cf. Bamfield & Hutchings, 2010). They are usually blended with static pigments, allowing them to change from one colour to another. The activation temperature is defined as the temperature at which the ink has almost achieved its final state - transparent or lightly coloured.

These reversible thermochromic inks have attracted the interest of experimental textile practitioners and researchers because they can offer new forms of communication and expression (Orth, 2004; Berzowska, 2005; Worbim, 2010; Calder, Robertson, Louchart, 2013). In all of these examples, the colour-changing effects have been explored mostly through experimentation with blends of thermochromic inks and static pigments, which allow prints to change from one colour to another in different contexts. The colour-changing effects thus illustrate transitions from Colour A to Colour B, and back again to Colour A. For example, the prototype entitled *Touch Me*, created by Berzina (2004), is a colourful, striped pattern wallpaper, printed with thermochromic inks with activation temperatures of either 26 or 31°C. By touching a violet stripe on the wallpaper, for example, a temporary white-ish handprint appears, and the phase change materials incorporated in the wallpaper release heat so as to extend the effect produced by the thermochromic ink. Another example is a set of furniture, printed with magenta thermochromic ink, which is able to respond to the presence of a person by changing to a white-ish colour in response to the heat of a human body, and to retain this colouring for several minutes after the person has left (BAN, 2007; also cf. Ritter, 2007).

Despite the fact that these and other research projects are successful examples of how these inks can be used on textiles, research into creating dynamic patterns for textiles has progressed relatively slowly. This may be due to a lack of exploration into the complete range of design possibilities afforded by thermochromic inks, as well as a lack of documented information to guide textile designers with regard to how these colours may be applied in textile practice. This lack has thus led to more emphasis being placed on how to activate or control printed patterns produced by thermochromic inks than on exploring what the complete range of design possibilities could be. Consequently, the practical experiments on which this paper is based were directed towards exploration of the complete range of design properties and potentials of leuco dye-based thermochromic inks when printed on textiles, with the aim of creating a wider range of colour-changing effects.

An analysis of all the experiments, however, indicated that, although they offered insights into and an understanding of the behaviour of thermochromic inks, they also emphasised the fact that exploring the design properties of thermochromic inks is not concerned solely with the discovery of new design possibilities; rather, the experiments demonstrated the need for the creation of a new terminology with which to discuss these design possibilities (cf. Manzini, 1998). Based on this, it was
decided that a detailed theoretical and practical investigation into other existing colour systems was to be carried out. As a result, a number of important issues arose:

- Whether the existing colour systems were capable of describing the colour-changing effects offered by thermochromic inks on textiles.
- How a certain colour combination or colour transition created through the use of thermochromic inks could be defined using existing colour systems.
- How existing colour systems deal with temperature when describing colour transitions on textiles.

**Colour systems**

In practice, when any type of pigment, such as textile pigment paste, is used, the primary colours are considered to be yellow, red, and blue, as these hues cannot be produced through any combination of other colours. Equally, all other colours can be produced through the combination of two or more primary colours: orange, violet, and green can all be made by mixing two primary colours in roughly equal amounts (Osborne, 2008, p 4). Tertiary colours are a mixture of a primary colour and a nearby secondary, e.g. yellow-orange, red-orange, red-violet, etc. (Feisner, 2006, p. 9). In addition, colours that oppose each other directly on the colour wheel are called ‘complementary colours’; e.g. red is the complementary colour of green, orange of blue, yellow of violet, etc.

Colour wheels/circles represent the relationships between colours. Wheels include a number of saturated hues, and sometimes show a variety of tints, tones, and shades. They constitute the most common and convenient method for visually representing colour theory, and help us to understand and compare the relationships between different hues.

In the early 1900s, Albert Munsell created a three-dimensional model based on human perception, which he presented in his book *A Color Notation*. Munsell’s system suggested, for the first time, that colour could be described using numerical values of three independent properties - hue, value, and saturation - and was the first to systematically illustrate colour in three-dimensional space (Feisner, 2006, p. 13-22; see Fig. 1). In 1961, Johannes Itten developed a contrast-based system with which to study and use colour. He organised colours according to contrasts, identifying them through harmonious colour strategies (Itten, 2003; see Fig. 2). Josef Albers’ (2006) *Interaction of Colour*, which was published in 1963, proposed an approach for studying and teaching colour based on learning by direct perception, rather than through theories or colour systems (see Fig. 3). The same year saw the invention of the Pantone Matching System (PMS) by Lawrence Herbert, in which a numbering system is utilised to identify colours. Still in use today, the PMS employs a variety of colour sample books and chips which help designers to compare colours on different types of textiles and papers, as well as provide a computer colour-matching system (Gordon & Gordon, 2002, p. 193; see Fig. 4). In 1979, Anders Hård introduced the Natural Colour System (NCS), which adopted a similar model and theory as Munsell’s and the PMS (Hård & Sivik, 1981); it defines the actual colour more precisely than previous systems as it is based on the visual appearance of colours, has a broad colour range, and provides an easy way of matching hues (see Fig.5).
The existing colour systems mentioned above allow textile designers, who are interested in textile printing techniques, to learn how to mix primary colours in various proportions, expand the palette of colours for use with textiles, and ascertain how colours change in varying circumstances - they can be made to appear lighter, darker, or transparent, and to be more or less prominent relative to other colours. These systems are unable, however, to support a textile designer in a design process which involves the use of thermochromic inks. These colour systems were created for and intended to accommodate only static textile pigments and, thus, were not designed to deal with smart and dynamic colours or their properties. For this reason, textile designers are unable to define a temperature-sensitive colour mixture and its various stages of colour transition using any of the colour systems discussed above.

This paper attempts to highlight the need for a new colour system; one which can describe the behaviour of thermochromic inks in relation to other static pigments and varying temperatures (cf. Manzini 1989, p. 34). The significance of this for textile design is related to the development of a methodology for designing dynamic surface patterns. To design such a pattern, a textile designer requires basic knowledge regarding how to use thermochromic inks on textiles, as well as an understanding of how to apply thermochromic ink principles to textile design practice through the use of different methods, and approaches. At present, in the absence of a thermochromic colour system, it is difficult to construct detailed descriptions of the methods and approaches, and how they could assist a textile designer in creating a wider range of colour-changing effects on textiles. As a consequence, the ability of a textile designer to make informed decisions and to predict colour-changing effects when designing dynamic surface patterns currently suffers from severe limitations. This is exemplified...
by the four design experiments described below, in which thermochromic inks were used; Experiment IV provides a further basis for discussion regarding the problems related to the lack of a thermochromic colour system in textile design practice.

Experiments

Experiment I

When a material is new to us, one way of learning how to use it is to follow another person’s advice regarding technical procedures, as a certain amount of basic knowledge is needed in order to begin the exploration. The aim of the first series of experiments was to determine the ratio of thermochromic ink to textile pigment paste for the recipe. The first attempt was a 3:97 ratio of blue thermochromic ink (with an activation temperature of 27°C) to acrylic-based extender (for more information on mixing colouring agents see Worbin, 2010). The mixture was silkscreen-printed by hand on a plain white cotton weave fabric. The effect produced was a lighter blue than that of the pure blue thermochromic ink, which gave rise to the idea of mixing the thermochromic ink and extender in other proportions. Thus, in the next step, two thermochromic inks of the same colour (blue) but with different activation temperatures (27°C and 15°C) were mixed with extender in different proportions, producing different shades of blue at ambient temperature (20°C). It was observed that ratios of 99:1, 75:25, and 50:50 of thermochromic ink to extender were problematic as, after removing the silkscreen, most of the ink remained stuck to the screen; this was most likely due to the thermochromic ink and extender having been mixed in a faulty proportion, resulting in it not properly adhering to the fabric. Further experimentation showed that a 25:75 ratio of thermochromic ink to extender provided a desirable textile printing effect, with maximum colour intensity at ambient temperature (20°C). The effects produced by both inks at ambient temperature led to the idea to explore colour-changing effects at different temperatures. The blue shades were then tested at equal to or below 15°C and at or above 27°C. An ice bag was used to cool the printed fabrics, and an iron was used to warm them. It was observed that a 1:99 ratio of ink (with an activation temperature of 15°C) to extender resulted in a colourless (or transparent) at ambient temperature (20°C) and light blue at equal to or less than 15°C, which suggested that this effect may be used to hide or reveal surface patterns. After an understanding of how thermochromic ink printed on textiles behave at different temperatures had been reached, a yellow textile pigment paste was mixed with the inks used to produce the blue shades of the previous experimental stage in order to explore additional effects. The same methods of cooling and heating were used to explore the design potential of the mixture at different temperatures (see Fig. 6).

The outcome of this experiment was the formulation of printing paste recipes, presented as printed colour scales. The scales showed and facilitated comparisons of the effect of cooling and heating the blue or green shades, providing valuable information on how thermochromic inks can be used and how they behave when printed on textiles.

In all of the experiments, surface patterns were designed in order to assist the exploration of the design properties and potentials of thermochromic inks through their artistic expression. The primary inspirations when designing with the thermochromic inks were Persian designs; this was due to the personal interest and cultural background of the author.
Experiment II

The results of the initial experiments formed a basis for the development of more complex colour-changing effects, where the colour transition was not from Colour A to Colour B and back again to Colour A, but rather from Colour A to Colours B, C, D, E, F, etc., and then back again to Colour A.

Due to the molecular structure of leuco dye-based thermochromic inks (Kooroshnia, 2013), it is not possible to make a single ink that is able to change from one colour to many different colours. This fact directed the second experiment towards the creation of colour mixtures which would have a similar hue at temperatures below the activation temperature but which, at temperatures above it, would show multiple colours. The experiment used two different colours, blue and magenta, in an attempt to achieve this.

Just as both one plus two and two plus one equal three, mixing blue (1) and magenta (2) in a particular proportion result in the same violet (3) hue as mixing magenta (2) and blue (1). Thus, with both the above theorem and the previous experiment, in which it was found that each colour mixture should consist of at least one pigment colour and one thermochromic ink, in mind, blue thermochromic ink with an activation temperature of 27°C and magenta textile pigment paste were mixed, which resulted in violet below 27°C and magenta at or above 27°C. Next, magenta thermochromic ink with an activation temperature of 27°C and blue textile pigment paste were mixed, which resulted in violet below 27°C and blue at or above 27°C. A screen-printed pattern was produced, which involved printing each violet shade next to the other. As the temperature was raised, the violet colour mixtures activated and started to change, from violet to blue and magenta.
The above result directed the exploration towards working with multiple colour-changing effects rather that just one or two, at once. To propose another theorem, $1+2+3+4$ equals 10, and the same is true for $2+1+3+4$, $3+1+2+4$, and $4+1+2+3$. In this experiment, colours were given a number - blue (1), magenta (2), yellow (3), and green (4) - and combined so that, in each mixture, the first colour was a normal pigment and the rest were thermochromic inks. For example, the mixture of blue (1), magenta (2), and yellow (3) thermochromic inks with an activation temperature of 27°C and a green (4) textile pigment paste resulted in violet-greyish (5) below 27°C and green (4) at or above 27°C. The mixture of blue (1), yellow (3), and green (4) thermochromic inks with magenta (2) textile pigment paste resulted violet-greyish below 27°C and magenta at or above 27°C. The same principle was then used to prepare four colour mixtures. Another screen-printed pattern was produced, which involved printing each colour mixture next to the other ones. As the temperature was raised, the colour mixtures activated and started to change, from brown-greyish to four different colours (see Fig. 7).

This approach resulted in a method of mixing colours for formulating a temperature-sensitive colour mixture consisting of multiple colours. It expanded the available range of possibilities for designing dynamic surface patterns in terms of revealing latent colours and designs.

The method suggested greater colour-changing possibilities than seen in earlier interactive textiles, in which thermochromic inks were used to create multi-coloured patterns that simply became transparent when heated. The approach discussed above offers the opposite transition, i.e. from a single-coloured (plain) background to one with several colours (see Fig. 8).
Fig. 8. A printed fabric produced using four temperature-sensitive colour mixtures with activation temperatures of 27°C (at a ratio of 25:75), shown at ambient temperature (left) and heated to above 27°C (right).

With reference to Experiment I, temperature-sensitive colour mixtures can be made using thermochromic inks with activation temperatures lower than ambient temperature, e.g. 15°C. They thus become visible when exposed to a change in temperature; i.e. the temperature-sensitive colour mixtures are slightly coloured in a heated state, and more coloured when cooled.

**Experiment III**

The results of Experiment II suggested the potential of layering colour mixtures. In the paper printing industry, the offset lithography printing method is one of the most common techniques used to print full-colour images or photographs. It is performed in a series of steps beginning with colour separation, during which the image is decomposed into the four process colours (CMYK), followed by translation into halftones. This technique inspired the printing of a pattern with the colour mixtures developed in Experiment II, and involved the digital design of a full-colour surface pattern and its preparation for four-colour printing in Photoshop, using the Channels function. This included creating four halftones by selecting each channel in turn and exporting the result as a bitmap image. Based on the principles of CMYK separation, four ink mixtures were prepared, all of which were a greyish-brown colour below 31°C, but which changed to cyan, magenta, yellow, and black, respectively, at or above 31°C. The layers were printed in succession, with halftone screen angles (cyan 60°, magenta 110°, yellow 120°, and black 30°). The colour mixture made with black pigment was thus printed last, i.e. over all of the others. When the temperature was increased, the temperature-sensitive colour mixtures were activated, and started to change, from dark greyish-violet to vibrant colours (see Fig. 9).
Fig. 9. A printed fabric produced with four temperature-sensitive colour mixtures with activation temperatures of 27°C (at a ratio of 25:75). The original pattern comes from one of Lotfali Shirazi’s paintings, Iran 1846.

This approach resulted in a textile printing method which combined the offset method of printing and the method of forming a temperature-sensitive colour mixture comprising multiple colours.

This method demonstrated that it was possible to create a wider range of colour-changing effects through layering different temperature-sensitive colour mixtures, which allows for more complex dynamic surface patterns on textiles, in which the pattern changes from one colour, possibly in different shades, to continuous tones. Although leuco dye-based thermochromic inks cannot currently be used in the digital printing process, this technique offers a new method for obtaining an effect similar to that of digital printing.

**Experiment IV**

Studying and teaching how to use thermochromic inks involves an understanding of colour transition. We often teach in the way that we ourselves were taught; it is, however, almost impossible to teach the behaviour of thermochromic inks by employing existing theories and practical exercises intended for static colours. In the absence of a proper colour theory and system for thermochromic inks, one way of teaching this subject is to demonstrate the colour transitions of thermochromic inks at various temperatures. When the author of this article was asked to hold an experimental workshop, it was decided that this should take place in the form of a hands-on experience where, first of all, the basic colour transitions of thermochromic inks were demonstrated at various temperatures via colour swatches, in order to help students better understand this phenomenon. Additionally, in order to further encourage the learning process, some exercises were designed so as to more fully engage students in practice-based processes.

For this purpose, the experiment began with two collections of colour-samples; one with only the thermochromic inks in different colours, with activation temperatures of
either 27°C or 15°C, and the other a mixture of thermochromic inks and yellow textile pigment paste. The colour samples were then measured with a spectrophotometer at three different temperatures: at ambient temperature (20°C), after heating (above 27°C), and after cooling (below 15°C). The measurements were then translated to colour swatches, made using the textile pigment printing pastes; these swatches made it possible to effectively demonstrate the colour transitions of the thermochromic inks at different temperatures.

A printed thermometer was placed on the table of the printing lab in order to illustrate three different temperatures. The colour swatches were placed on the table so as to display and compare the effects produced by either the inks with activation temperatures of 27°C or 15°C, or the mixture of the inks and yellow textile pigment paste at ambient temperature, after heating, or after cooling (see Fig. 10). As it was important to provide the students with a thorough understanding, the strategy followed was to give them exercises which allowed them to experience the phenomenon for themselves.

Fig. 10. Colour-swatches made with textile pigment, demonstrating the varying colours of thermochromic inks at different temperatures.

A pedagogical tool for teaching the behaviour of leuco dye-based thermochromic inks to students in textile design was the result of this experiment.

The exercises involving colour swatches helped the students to learn the principles of colour transition in an easy way and step-by-step. While this teaching approach increased their ability to design dynamic patterns for textiles and created inspiration for continued investigation through design, it was, however, limited to basic colour transitions - from Colour A to Colour B and back again to Colour A. Thus, the more complex transitions of Experiments II and III, i.e. from Colour A to Colours B, C, D, E, F, etc., and back again to Colour A, were not demonstrated.

Discussion and conclusion

In order to obtain knowledge and improve our understanding of materials, verbal instruction is not sufficient; rather, what is required is a more engaged form of study so as to truly experience and demonstrate material properties (Albers, 2006). Experimental research through design is one way of gaining new knowledge which develops new knowledge which assists in developing the field of [textile] design with suggestions for a change of practice by introducing design programmes, methods,
and techniques (Hallnäs, 2010; Durling, Friedman, & Gutherson, 2002; Frayling, 1993).

Although the experiments have created insight and understanding, they have also emphasised the fact that exploring thermochromic inks is not just about finding new design possibilities; rather, the need for a new terminology, so as to be able to discuss these possibilities, has been demonstrated (cf. Manzini, 1998). This paper has shown that a new language is required in order to discuss colour-changing effects at varying temperatures. For example, in Experiment I it was observed that a pattern printed on a white textile using a 1:99 ratio of thermochromic ink (with an activation temperature of 15°C) to extender became transparent at ambient temperature (20°C) and light blue at equal to or less than 15°C. With reference to existing colour systems, light blue is made by adding a large quantity of white to blue; in Experiment I, however, there was no white added to the blue thermochromic ink, which indicates that, at present, the lack of linguistic terminology makes it very difficult to describe a colour-changing effect without giving the audience the wrong impression when, for example, attempting to describe the behaviours of thermochromic inks at varying temperatures.

Experiments II and III resulted in examples of how to combine a static pigment and thermochromic inks into temperature-sensitive colour mixtures which are able to change from single to multiple colours. Almost all existing colour systems explain the alternating relationships between primary, secondary, and tertiary colours, as well as the relationship of each of them to black and white. The fact that they are unable to describe how temperature-sensitive mixtures can change from one colour to various others at different temperatures and then back again, however, indicates the need to incorporate the dimensions of temperature and time into existing colour systems.

Lastly, Experiment IV clearly indicated the need for a colour theory which visualises the behaviour of thermochromic inks at different temperatures and proposes terminology for discussing the behaviours of thermochromic inks. The pedagogical tool presented in this article increases the ability of students to integrate their new knowledge of the behaviour of thermochromic inks with what they already know about static pigments in relation to the design of a dynamic surface pattern. However, the workshops were limited to basic colour transitions – i.e. from Colour A to Colour B and back again to Colour A - and the colour swatches alone were not able to demonstrate the more complex colour transitions that were demonstrated in Experiments II and III - i.e. from Colour A to Colours B, C, D, E, F, etc., and back again to Colour A. Therefore, the difficulties in effectively communicating during the study, application, and instruction of the thermochromic inks showed that there is a need for a more complete pedagogical tool.

Designing with thermochromic inks is largely concerned with colour transition. A thermochromic colour system would be able to demonstrate and describe a variety of colour transitions, e.g. from Colour A to colourless and back again to Colour A; from Colour A to Colour B and back again to Colour A; from Colour A to Colours B, C, D, E, F, etc., and back again to Colour A. Thus, such a system would provide a greater insight into and understanding of the behaviour of thermochromic inks when printed on textiles. As a consequence, the ability of textile designers to articulate ideas, make better-informed design decisions, and push the boundaries of their understanding of the role of thermochromic inks in a textile design context would increase, leading to previously unimaginable outcomes (cf. Manzini, 1989).

In addition, the thermochromic colour system would promote knowledge transformation and collaborative work between disciplines such as textile design, interaction design, computer science, and many more fields.
References


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Biography

Marjan Kooroshnia is a lecturer and PhD candidate at The Swedish School of Textiles, University of Borås. Much of Marjan’s time as a Master’s student in Textile Design was spent at the printing lab, learning about colour-changing technology and designing dynamic surface patterns. In her PhD research she explores the design properties and potentials of leuco dye-based thermochromic inks and photo-luminescent pigment on textiles in order to develop design methodologies related to dynamic patterns on textiles.