Challenging current colour theory and practice using thermochromic and photochromic inks in textile design

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ABSTRACT
This paper attempts to use two series of design experiments, which used reversible, water-based thermochromic and photochromic inks, to highlight the challenges that come with using them when studying, teaching, and designing with them. It stresses the fact that we, as textile teachers, researchers, and designers, need to rethink the ways in which we teach, study, and design with colours. The complexity of the challenge that we face today perhaps lies in the foundations of our colour knowledge and design processes, which are not appropriate when smart colours are involved. It may be that an entirely new colour system or model that can be applied to both static and dynamic colours should be established.

Keywords Thermochromic inks, photochromic inks, textile design, dynamic surface patterns, colour theory and practice.

INTRODUCTION
In the latter decades of the twentieth century, chromic colours that reversibly change colour according to external environmental conditions were introduced, and so became available to designers, including textile designers. Often referred to as ‘smart colours’, these included thermochromic inks (activated by heat), photochromic inks (ultraviolet [UV] light), electrochromic inks (electricity), hydrochromic inks (water), and piezochromic inks (mechanical pressure). These introduced new design possibilities for textile and fashion design, and challenged and questioned colour theory and practice.

Leuco-dye based thermochromic inks (referred to hereafter as simply ‘thermochromic inks’) are coloured when below their activation temperature and clear or have a very light hue above the activation temperature (Bamfield & Hutchings, 2010). They are usually blended with static pigments in order to change from one colour to another.

Photochromic inks are clear when not activated, and become coloured after exposure to sunlight or other UV radiation for 5 to 10 seconds (Ibid.).

A colour can be described with regard to three properties: hue, value, and saturation (Wong, 1993; Itten, 2003: 34-55). In practice, the primary colours of most types of pigment are pure yellow, pure red, and pure blue, and every other colour can be made by mixing two or more of these. When two pure primary colours are mixed, a secondary colour is created; these include orange, violet, and
Challenging current colour theory and practice using smart colours in textile design

When a pure primary colour is mixed with a nearby secondary colour, a tertiary colour is created, for example yellow-orange and red-orange (Anderson, 2006: 9).

Over the centuries, colours have been mixed according to three basic colour-mixing systems; subtractive, additive, and partitive (Gordon & Gordon, 2002: 72; Albers, 2006: 22-27). These models have formed the foundations of colour systems for centuries. Although many such systems exist, some have had a greater impact on the development of colour theory and practice in both academia and industry than others. Colour wheels and systems are “colour arrangements or structures” (Anderson, 2006: 8) that enable designers to organise and predict colours, colour mixtures, and their interactions, as well as to communicate colour choices to manufacturers, customers, and other designers (Itten, 2003; Albers, 2006; Hård & Sivik, 1981).

Detailed theoretical and practical investigation of existing colour principles and 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 and photochromic inks, as they cannot predict the behaviour of thermochromic and photochromic inks in relation to external stimuli such as heat and UV light.

Although many textile practitioners and researchers have experimented with and investigated the design possibilities offered by thermochromic and photochromic inks (Melin, 2001; Orth, 2004; Berzina, 2004; Berzowska, 2005; Ledendal, 2009; Worbin, 2010; Robertson, 2011; Hashida et al., 2011; Rajapakse et al., 2015), research into creating dynamic surface patterns for textiles has progressed relatively slowly. This may be due to a lack of understanding of the challenges that textile designers face when designing dynamic surface patterns using thermochromic and photochromic inks, the unchallenged status of existing colour principles and systems with regard to the properties of thermochromic and photochromic inks, and a lack of proposed solutions to these issues. This deficiency may have caused textile designers to see only complexity in the use of thermochromic and photochromic inks, rather than extensive and practical possibilities. This paper presents two series of design experiments that used reversible, water-based thermochromic and photochromic inks in order to highlight the challenges that are involved in studying, teaching, and designing using smart colours.

RESEARCH PROCESS
Thermochromic inks: Experiment series 1

This experimental research project began by using the printing paste recipes suggested in the author's PhD thesis (Kooroshnia, 2017: 43-57), consisting of thermochromic inks with activation temperatures of 31 and 15°C. The inks change colours, presenting different hues in non-heated, heated (or the end colour lose point), and cooled states (or colour returned point). This was achieved by mixing thermochromic slurry with activation temperatures of 31 and 15°C with extender in different proportions (Fig. 1).

A method of mixing colours to create a temperature-sensitive mixture of multiple inks (Ibid.: 82-88) was then used to expand the range of ways of designing dynamic surface patterns in terms of revealing latent colours and designs. Four temperature-sensitive colour mixtures were produced; as the temperature was raised, the mixtures activated and began to change from dark brown to four different colours (Fig. 2).
Challenging current colour theory and practice using smart colours in textile design

Figure 1: Printing paste recipes consist of thermochromic inks with activation temperatures of 31°C (on the right) and 15°C (on the left). The inks change colours, presenting different hues in non-heated, heated, and cooled states.
Challenging current colour theory and practice using smart colours in textile design

Two or three different dynamic patterns were designed for each series of experiment. All of the patterns were inspired by Persian designs due to personal interest and cultural background, and featured flowers, birds, Islamic geometrical patterns, and arabesque designs.

The first pattern had three different visual expressions; one at non-heated state (ambient temperature), one in a heated state, and one in a cooled state. A dynamic pattern was created using thermochromic inks with activation temperatures of 31°C (green) and 15°C (blue), and yellow static textile pigment paste (Fig. 3).

For the second pattern, a printed fabric was produced using four temperature-sensitive colour mixtures (Fig 2); these consisted of thermochromic inks with an activation temperature of 31°C and extender, mixed in a ratio of 25:75. Magenta static textile pigment paste was used in the first mixture, yellow in the second, blue in the third, and green in the fourth (Fig. 4).

For the third pattern, a textile printing method (Ibid.: 108-111) that combined the offset method of printing with a temperature-sensitive mixture of multiple inks was used. A screen-printed pattern on 100% polyester fabric was produced using the temperature-sensitive colour mixture; the first layer consisted of cyan textile pigment paste, and layers of magenta, yellow, and then black textile pigment pastes were printed on top. When the temperature was increased, the temperature-sensitive ink mixtures were activated and changed from dark brown to vibrant colours (Fig. 5).

It should be noted that the figures used in this paper consist of photographs of the prints.
Challenging current colour theory and practice using smart colours in textile design

Photochromic inks: Experiment series 2

This series of experiments began by using photochromic inks in primary colours (magenta, yellow, and blue), which were printed on a plain white woven poplin cotton fabric. Photochromic slurry was mixed with extender in a ratio of 50:50.

In order to explore colour mixtures when two different photochromic inks in primary colours are mixed, three colour scales were created. Mixing two photochromic inks in different proportions until the desired number of intermediate colours was obtained produced a graded scale, progressing from one colour to another. In total, each scale had eleven steps/shades. The colour-changing effects were possible to observe through exposure to sunlight or UV light (Fig. 6).

Observation of the colour-changing effects suggested the idea of mixing photochromic inks with static textile pigment paste to expand the range of colour-changing effects. When this was put into practice, the results indicated that the static textile pigment paste prevented UV light from reaching the ink, inhibiting the colour-changing process of the photochromic inks. The best way to combine photochromic inks with static textile pigment paste seems to be to use the halftone technique, which allows UV light to reach and activate the photochromic inks (Fig. 8).
A dynamic geometrical pattern was created using photochromic inks. The aim was to design a pattern which had only one visual expression after exposing to daylight and UV light (Fig. 7).

Figure 7: from left to right: the printed fabric produced using photochromic inks, the effect at non-exposed state, the effect of exposing the printed fabric to sunlight.

For the second pattern, which was similar to the third pattern of Experiment 1, the offset method of printing was used to design a dynamic pattern. For the reasons stated above the halftone technique was later chosen in order to expand the range of colour-changing effects offered by photochromic inks. A screen-printed pattern on 100% polyester fabric was produced using photochromic inks; the first layer consisted of cyan, which was followed by magenta and yellow layers. This was then overprinted with a layer of black static textile pigment paste, as photochromic inks are not available in black. Exposure to sunlight activated the photochromic inks, which changed to vibrant colours (Fig. 8).

Figure 8: from left to right: the printed fabric produced using photochromic inks overprinted with a layer of black static textile pigment paste, the effect at non-exposed state, the effect of exposing the printed fabric to sunlight.

**CHALLENGES**
Designing dynamic patterns

The fundamental skills required to successfully design a surface pattern include drawing expertise, knowledge of printing techniques, and the ability to understand the context of a design (Terashima, 2009; Cole, 2007). Traditionally, the surface pattern design process begins with a theme or brief as a guideline that directs the textile designer towards the desired visual elements (Wong, 1993). During the process of visual development, colour plays an important role due to its ability to enhance, redefine, disguise, diffuse, or emphasise other design elements. Colour should be selected in such a way that the effect of the chosen colour is impossible to attain using another colour. Finally, textile designers must know how to turn their designs into a seamless, repeating pattern (Day, 1999; Russell, 2011).

The introduction of thermochromic and photochromic inks to textile printing, however, has challenged textile designers, offering a range of colours that can change the visual expression of textiles. As a result, textile designers also need to understand how thermochromic and photochromic inks behave under different conditions, and how this may impact the design process.

Moreover, textile designers need to know all possible printing paste recipes, as well as how each recipe behaves when temperature or light conditions change. A thermochromic slurry to extender ratio of 25:75, for example, produced a mixture with maximal colour intensity in a non-heated state and maximal residual colour in a heated state. A ratio of 1:99 produced a light colour in a cooled state, but less or even non-residual colour at ambient temperature (Fig. 1). Based on this knowledge, a thermochromic, geometrical pattern was designed. Green thermochromic ink with an activation temperature of 31°C (thermochromic slurry mixed with extender in a ratio of 10:90) was used to produce less residual colour in a heated state. Blue thermochromic ink with an activation temperature of 15°C (thermochromic slurry mixed with extender in a ratio of 1:99) was used, and was invisible in a heated state and produced a light blue colour in a cooled state (Fig. 3). A conversational photochromic pattern was printed based on the knowledge gained as a result of the creation of the recipes (Fig. 8). Cyan (slurry to extender ratio of 50:50), magenta (slurry to extender ratio of 10:90), and yellow (slurry to extender ratio of 50:50) photochromic inks were layered. The reason for the ratio of magenta differing from the other two inks was that the scales representing the mixtures of yellow and magenta and blue and magenta showed that true orange or violet can be achieved if the percentage of magenta in the mixture is 10% (Fig. 6).

In designing a dynamic surface pattern, inks and their behaviours, the quality of the chosen fabric, heat and UV sources (the sun or a UV bulb), and time should be considered as design variables from the beginning of a process, potentially simultaneously due to the fact that all have a strong impact on the overall aesthetic expression.

Textile designers must be able to predict the visual expressions that result from different conditions, and clearly visualise which colours are visible in a non-activated state and which are invisible or visible in an activated state, as well as which balance which others. Figure 3 shows a process in which colours and forms for the three different phases were decided simultaneously. Sometimes, the method of printing decides the order of colours. Combining the offset method of printing with a temperature-sensitive colour mixture, for example, is a complex process with regard to creating the temperature-sensitive colour mixtures, but it is fairly easy to decide the order of the
layers and predict the colour-changing effects because the offset technique itself defines these (Fig. 2).

These inks can be used on a broad variety of textile materials and thicknesses. The choice of textile has a significant impact on colour-changing effects, in that it can influence how quickly heat, for example, is conducted by the textile. A silk organza thermochromic printed fabric is very thin, and so as the temperature increases it changes from a coloured fabric to a colourless one in the blink of an eye. The heat that was transferred to the plain cotton fabric and polyester used in the sample prints, however, spread more slowly, giving a viewer more time to observe the thermochromic colour transition. In addition, the density of the chosen plain cotton and polyester fabrics provided a greater contrast with regard to observing the photochromic colour transition after exposure to sunlight.

Different heat and light sources create different colour-changing effects due to variation in thermal energy output, the time required for sufficient heating to take place, and the distribution of heat, which also influence how the forms and motifs of dynamic surface patterns change. The heat generated by the iron that was used in this research project, for example, was high, meaning that the change in colour occurred so quickly that only two states were visible; one expression (colour) before, and another after. The heat generated by the body, on the other hand, is less intense, creating a gradual change in colour. The use of conductive threads in woven or knitted textiles creates another type of colour-change effect, in which the conductive threads themselves create a dynamic surface pattern that is influenced by the structure of the weave or knit (Worbin, 2010: Dumitrescu et al., 2014). Similarly, light intensity and time of exposure affect the colour-changing effects produced by photochromic inks, in that the amount of UV light on cloudy and sunny days are different, for example, leading to different photochromic colour transformations.

With regard to digitally designing a dynamic surface pattern, finding the exact colour of thermochromic and photochromic inks in software packages such as Adobe Photoshop or Illustrator, as well as predicting the resulting colour transition, is difficult. Further research of a technical nature regarding graphical applications is required in order to create a colour index of thermochromic and photochromic ink transitions.

In addition to these factors, and how each affects colour-changing effects, the concept of dynamic colour interaction should be considered when planning a design process. Through Alber’s (2006) concept of colour interaction, a textile designer gains an understanding of how to create optical illusions and predict which illusions will occur. Using thermochromic inks to create dynamic patterns on textiles offers the possibility of dynamic colour interaction and illusions at three different points in time; when the textile is in a non-heated state, when it is in a heated state, and when it is at a point in time between the two. An optical illusion can occur in a non-heated state and become another illusion in a heated state, or not be apparent in a non-heated state and be revealed in a heated state. Similarly, photochromic inks can create dynamic colour interactions, as is exemplified in the following examples.

The ‘Bezold effect’ is an optical illusion wherein adding or changing one colour of a composition can, under certain circumstances, alter the colour of the entire design (Ibid., p. 33). Here, two identically coloured shapes are surrounded by a thin border; one is white and one is black, and so the colour of the latter appears to be darker than that of the former.

Thermochromic inks offer a variation on this concept: One of static textile pigment paste is surrounded by a thin border of black thermochromic ink. Red static textile pigment paste, for example, is surrounded by a thin black thermochromic ink border. The expression in a non-heated
state is dark red, but when the textile is heated to the activation temperature of the ink, the thermochromic ink border becomes colourless, creating a lighter red colour.

Optical colour mixing occurs when two or more colours are placed in close proximity to one another against a white background. Using this technique, yellow, red, and blue dots on a white background combine to create orange, violet, and green. Using photochromic inks and the offset method of printing described above, a variation on this was achieved: Blue, magenta, and yellow photochromic inks and black static textile pigment paste were applied to textiles through offset printing, and exposing the print to sunlight caused viewers to perceive a colourful pattern due to the phenomenon of optical colour mixing (Fig. 8).

A colour-movement illusion is created for example by choosing two coloured sections and altering their saturation or values that a continuous colour spectrum is created. By using thermochromic inks, however, colour movement can be achieved in another way. The thermochromic ink arabesque print was divided into eight individual parts; when each was heated, the colour-changing effect created led the eye in a certain direction (Fig. 9).

![Figure 9: A colour movement illusion created by heating different parts of the thermochromic printed fabric.](image)

Using smart colours when designing a dynamic pattern challenges the principles and elements of design. In Colour, Anderson Feisner states that “colour can reflect mood, emotion, time frame, and provide the symbolism” (2006: 65). Moreover, dark compositions give “feelings of night, darkness, mystery and fear” (Ibid.: 42). The conversational pattern that was created as part of this research had a dark-brown visual expression in a non-heated state. When the temperature was increased, the temperature-sensitive colour mixtures were activated, and the textile changed from dark brown to vibrant colours (Fig. 5). Thus, the dark emotion of the inert textile changed to become a relaxed, less demanding expression. Anderson also argues that repeating hues creates rhythm and a feeling of movement (Ibid.: 66), and this links to the reversible colour-changing behaviour of the photochromic inks used in the design of the geometrical pattern: exposure to sunlight caused the pattern to exhibit a form of colour movement during the colour-changing process, and another with regard to the elements of the design (Fig. 7). This indicates that thermochromic and photochromic inks not only interact with other principles and elements of design such as rhythm, balance, proportion, scale, emphasis, and harmony, as static colours do, but suggest dynamic alternatives to them.

Many designers consider the symbolism of colours (Ibid.) when designing a surface pattern. Within this concept, black, for example, has negative connotations relating to death, emptiness, depression, etc.; alternatively, it can have positive inferences of sophistication, power, luxury, etc. These meanings and associations pose the question of how colour symbolism can be utilised in relation to smart colours – when, for example, designing a product wherein black thermochromic ink changes to white as a result of an increase in temperature.
Challenging current colour theory and practice using smart colours in textile design

Colour system
Textile designers are often visual learners, and thus learn through observing. This may be the reason why the colour circles and systems were established – to visually and verbally represent colour theory, to enable artists and designers to organise and predict colour mixtures (and their interactions), and to communicate colour choices to other artists and designers along with manufacturers and customers. This raises the question of whether these systems are able to verbally and visually describe the colour-changing effects of thermochromic and photochromic inks, and to factor in the use of heat and UV light as design variables. The answer to this question, however, is no; they are not able to visually represent the basic and complex colour transitions of thermochromic and photochromic inks. As is shown in figure 4 and 5, temperature-sensitive colour mixtures are able to change from one colour to multiple. Almost all existing colour systems or models explain the alternating relationships between primary, secondary, and tertiary colours, as well as the relationship between each of these and black and white. The fact that they are unable to describe how temperature-sensitive mixtures can change from one colour to various others, and then back again to the first (from Colour A to Colours B or C, D, E, F, etc., and back again to Colour A) indicates that there is a need to incorporate the dimensions of temperature and time into existing colour systems.

Lack of colour principles and systems that can assist textile teachers and designers in effectively communicating the possibilities of thermochromic and photochromic inks affects teaching, studying, making informed decisions, and predicting colour transitions for different environmental conditions when designing a dynamic surface pattern. Consequently, their absence affects design processes in terms of the repeatability of colour-mixing processes, as accurate printing paste recipes require colour measurement. Due to the current absence of a thermochromic and photochromic colour database with which to measure the dynamic prints using a spectrophotometer, it is impossible to put existing colour principles and systems into practice.

Terminology
One challenge when studying, teaching, and designing with thermochromic and photochromic inks is the lack of appropriate terminology with which to describe and discuss the behaviour of them in relation to external stimuli such as temperature and UV light. In The Material of Invention (1989), Manzini stresses the fact that exploring the design properties of new materials is not concerned solely with the discovery of new design possibilities; rather, the experiments should also suggest new terminology with which to discuss these design possibilities. It is near-impossible to teach and study the behaviour of thermochromic and photochromic inks by employing existing theories and practical terminology, which are intended for static colours.

As is shown in figure 1, it was observed that a blue thermochromic ink with an activation temperature of 15°C (thermochromic slurry mixed with extender in a ratio of 1:99) was invisible at ambient temperature, and changed to light blue in a cooled state. In existing colour systems or models, a light colour is made solely by adding a large quantity of white to a colour; in this case, however, no white was added to the thermochromic ink, and instead heat and time were involved. This indicates that, at present, the lack of 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. Suggested new vocabulary...
could include terms such as ‘non-activated colour’ and ‘fully-activated colour’, rather than ‘colour change from a fully saturated colour to a light one’.

CONCLUDING DISCUSSION

Over the course of the last two decades, time, heat, and UV light have become design variables, but theories and academic work have consistently failed to factor them in. In addition, the applications of these parameters are not limited to smart colours, as new technologies continually involve them further in the textile design area. Bethany Rose Coggins, a Master’s student in textile design at the Kolding Design School in Denmark, explores the design properties and possibilities of dispersive dyes in digital heat transfer printing applications by working with heat and time. ‘Transfer printing’ is the term used to describe textile and related printing processes in which the design is first printed on to a specially designed sheet of paper, then transferred onto a textile using heat.

During her research project, Coggins has explored how heat and time can transform and affect the colour of dispersive dyes. She has created more than 550 different tints and tones from four original dispersive dyes (red, yellow, blue, and turquoise), which were heated at 185, 195, 205, and 215°C for periods of between 10 and 40 seconds.

This emphasis on heat, time, and UV light needs to be added to colour models and systems in order to facilitate improved understanding and design of surface patterns in the context of textile design.

Due to their colour-changing properties and ability to be controlled, thermochromic and photochromic inks have the potential to propose new forms of communication in terms of temperature, air pollution, sound, and so on. In order to skilfully use these smart colours, however, proper design and communication tools are needed.

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Challenging current colour theory and practice using smart colours in textile design