

Design Concepts for a Temperature-sensitive Environment Using Thermochromic Colour Change

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Thermochromic dyes and pigments, of both leuco dye and liquid crystal types, offer significant potential for aesthetic and functional textile design in the area of smart materials. This paper presents an overview of some of the most important recent design applications of thermochromism, illustrating the potential they offer the designer together with a discussion of the technical features of the materials which have limited their exploitation to date. Our approach to research on thermochromic textiles at the design/technology interface is presented in terms of an illustrated discussion of the application of a specifically developed variable-temperature colour measurement methodology to inform and predict thermochromic colour change effects within design, complementing the fundamental skills of the textile design practitioner.

Introduction

Colour is generally the most immediately visible aspect of textile design and is thus an essential design consideration, for many designers the principal aesthetic concern. The physical properties of fabric that can allow colour to be enhanced through light play, surface and structural effects are also of immense value to designers. Colour is emotive; it can move us, and inspire us. Designers have their own personal take on colour and a preferred colour palette that contributes to their individual uniqueness. Current commercial ranges of dyes provide textile designers with the ability to introduce a wide gamut of colours into yarn or fabric. These dyes are required to provide a constant, predictable and reproducible colour and, as far as is technically feasible, a permanent colour in terms of exposure to external effects such as light and washing. A variation in the colour of a dyed or printed fabric, for example when exposed to temperature change or to light, would normally be regarded as highly undesirable: a defect. However, it has been recognised in recent years that there are potential commercial niche applications for dyes that exhibit a distinct colour change when exposed to an external stimulus, especially when that change is controllable and reversible. Such dyes are collectively now commonly referred to as 'chromic materials', of which there are a variety of types [1,2]. For example, photochromic dyes acquire a colour when exposed to UV radiation and revert to their original colourless state when the light source is removed. Photochromics find their most important commercial applications in sun-screening ophthalmics (sunglasses, ski-goggles), security printing and in high-technology applications, such as optical data storage.

The focus of this paper is on thermochromic dyes and pigments that change colour in a controlled way when the temperature is varied [3,4]. The colour change is used to indicate temperature variation, for example in plastic strip thermometers, food packaging, medical thermography, and non-destructive testing of engineered articles and electronic circuitry. There has been commercial exploitation of thermochromic textiles, probably most notably (some would argue notoriously) the T-shirts that changed colour with skin temperature, a

transient novelty fashion item of the late 1980s. There is, however, considerable potential for functional textile applications of thermochromism associated with so-called 'smart' fabrics and clothing, which are designed to sense and react to environmental conditions and stimuli [5,6]. Smart materials are also of intense interest to artists and designers, inspired by the possibilities for the development of new creative design directions towards interaction, response and ultimate functionality. Colour change technology thus offers the designer unique and challenging design opportunities

In the School of Textiles & Design of Heriot-Watt University, we have been engaged for a number of years in research aimed at the technical development of photochromic and thermochromic materials specifically for use in textile applications, and of methods for the assessment of their performance on textiles [7–9]. The outcomes of this research have provided textile designers in the school with unique access to optimised materials, technical expertise and predictive tools to complement their creative skills in the use these materials. In this paper we demonstrate how technological understanding and specifically devised experimental methodology applied to thermochromism is now informing an AHRC-funded programme of research at the design/technology interface.

Thermochromic Dyes and Pigments

There are two principal types of thermochromic systems that may be applied to textiles. The term 'system' is used advisedly as these materials are not dyes in the conventional sense. The system which has been most commonly used is referred to as of the 'leuco dye' type. This system relies on colour formation from the interaction of three materials, a colour former (the leuco dye), an acid (or activator) and a low melting solvent. The mode of action involves a series of physical transformations within the composite system, which induces a chemical interconversion between coloured and colourless forms based on the leuco dye chemistry. Scientific details of the mechanism may be found in the literature [3,4]. The observed thermochromic effect is usually a change from coloured to colourless (which is reversible) as the temperature is raised, although by mixing with traditional dyes and pigments an interchange between two single colours may be achieved.

The second type of thermochromic system which can be applied to textiles is based on liquid crystals. Liquid crystals, often termed the fourth state of matter, are liquid-like in behaviour but the molecules have a tendency to line-up in an ordered pattern, unlike normal (isotropic) liquids in which there is random orientation. The thermochromic effect provided by certain types of liquid crystals is quite different from the leuco dye types in that they commonly provide a continuously changing spectrum of colours over a range of temperatures (referred to as 'colour-play'). The colours arise from physical changes in the orientational structure of the liquid crystal rather than from the chemical conversion involved with leuco dye types. The colour changes result from the way light interacts with the liquid crystals to produce coloured reflection by interference, and from the variation of the liquid crystal structure with temperature [7,8].

There are two broad groups of liquid crystal thermochromics: cholesteric (chemically modified natural products) and chiral nematics (purely synthetic products). Of these, the chiral nematics show a more dramatic colour-play, but are more expensive. By careful formulation, each of the thermochromic systems can be fine-tuned to give colour changes in different temperature ranges, although commonly the requirement is for systems that change colour around ambient room temperatures or at human skin temperatures.

A feature of both thermochromic systems applied to textiles is the requirement for

microencapsulation, a process by which the ingredients are wrapped in a tiny hard shell. This is necessary to ensure that the materials are contained and provides them with protection against their environment to which the materials may be sensitive. Since they are applied as discrete solid particles, they are often considered as pigments rather than dyes. There are relatively few manufacturers of thermochromics. Manufacturers include TMC (Thermographic Measurements), UK, Color Change Corporation, USA, and Matsui, Japan.

Thermochromics in Art and Design

The concept of smart textile materials is currently having a significant impact on the design world, through the convergence of the disciplines of science, engineering and design. However, the fascination of artists and designers with the ability to create entities capable of transformation, for example by changing appearance in an interactive environment, is not new. Forward-looking art movements have perennially been inspired by the cross-fertilisation of science and art. As early as the 1920s, the Hungarian artist László Moholy-Nagy was profoundly influenced by the new technologies of his time. He had a particular fascination with light, colour and the developments in technologies such as photography and advertising displays, which informed his conceptualisation and creative activity in a form of art which he termed 'kinetic optical composition' [10]. One of his contemporary Bauhaus artists, Ludwig Hirschfeld-Mack contributed to the new artistic genre in his 'reflected colour displays', which employed the projection of coloured lights from freely-movable sources through opening and shutting apertures of a variety of shapes, his dynamic multicoloured creations being set to rhythmic musical accompaniment [10].

Today, the development of these technologies into the digital era and the introduction of smart materials continue to make available a range of new media for creative exploitation. The use of thermochromics to express colour change on a textile surface fits comfortably into the area of smart design.

Thermochromism has been exploited by a few designers who have been stimulated by a recognition of the potential for novel design directions. An overview of some recent relevant design research is presented in this section. A thermochromic design requires a means of application of the thermochromic dyes or pigments to a substrate, in conjunction with a heat-generating system, which may, for example, involve simple human skin contact or electronic circuitry. The latter combines the creative design process with the technologies of coloration and electronic engineering.

Linda Worbin has successfully employed thermochromic colour-change technology in her practice-based research, using traditional fabrics and printing processes, to develop dynamically changing and responsive textile patterns in the area of smart and interactive textiles [11,12]. In an interesting demonstration, she illustrates how a thermochromic fabric reacts to spillage of a cup of hot water. The colour disappears in the regions in contact with the hot water. In some prototype designs, she used thermochromic printed fabric with laser-cut heating elements beneath the fabric. When connected to a power source, the heat generated reveals the printed pattern on the fabric surface. She also produced thermochromic designs with carbon fibre woven into the fabric, producing a colour and pattern change on the fabric surface when connected to the power supply [11,12].

Zane Berzina's paper entitled 'Skin stories: charting and mapping the skin' collects together the results of her practice-led multidisciplinary research, which adopted multiple approaches to design [13]. Her interests in the human skin and its biology from a textile designer's perspective provided the inspiration to use thermochromic textiles to act as a metaphor for

a 'living membrane' capable of sensing environmental change. An interesting feature of her work is Touch-Me Wallpaper, a prototype multisensory interactive wallcovering triggered by contact with the human hand. A temporary handprint appears on a thermochromic surface, aromatherapeutic fragrances are released, and the incorporation of phase-change material allows storage and controlled release of heat, prolonging the thermochromic effect and allowing control of room temperature. Berzina has also experimented with 'drawing' using electricity. In her work *Sensory Screen*, semiconducting threads are incorporated between layers of thermochromic non-woven fabric. As a circuit connection is switched on and off intermittently, the thermochromic effect produces a line that appears and disappears [13].

A further important contributor to designing with thermochromics is Maggie Orth, who was the founder of International Fashion Machines (IFM), a company with a focus to produce flexible electronic art that incorporates new technological concepts into consumer products. IFM has produced an electronically activated colour-change textile, *Electric Plaid*, which combines thermochromic printed textiles with electronic circuitry. The circuits are woven into the surface of the fabric and activate the thermochromic effect when connected to a power supply. IFM's current direction appears to be leading towards products integrating electronics with textiles that can be used in the home, for example in interior applications where the products function within the context of the home environment [14]. Joanna Berzowska, a co-founder of IFM, has developed *Shimmering Flower* which deploys thermochromic technology, conductive yarns and computer-controlled electronic circuitry to create a non-emissive colour-change textile display. The thermochromic effect is activated in areas of the design with individually addressable pixels, the colour change being programmed or controlled in real time [15]. *Shimmering Flower*, a highly poetic design piece, was woven on a Jacquard loom, which allowed the creation of soft-woven circuitry through complex weave structures. *Krakow* is a further piece produced by Berzowska combining thermochromic and Jacquard weave technologies. In this case, human figures in the woven image change from black to transparent when the temperature rises. The connection to the power source is visible and adds to the aesthetic value of the design [16].

Research into the use of thermochromic materials in architecture has demonstrated inventiveness using unconventional material combinations in response to significant technical and design challenges. This has introduced the concept of interactive architecture, which allows aspects of a building to sense, respond and adapt. Glaister, Mehin, and Rosen have incorporated thermochromic materials into concrete with a system of nickel-chromium wires linked to a power source. The thermal energy activates the thermochromic effect at the surface of the concrete to allow, in principle, the display of graphics and information [17]. A climate-control tile has been developed by Johnson. The tile combines phase-change material and thermochromic technology on its outer surface. The ability of phase-change material to store and control release of heat in combination with the thermochromic technology makes it possible to produce a visual thermograph or heat map [18]. These tiles might be used, in principle with appropriate integrated control technology, to change colour throughout the course of the day, and to provide temperature regulation.

There are recurring themes in the commentaries from designers who are making use of thermochromics, providing some explanations for the relatively limited exploitation of the technology to date. The materials are limited in scope and availability, and they are relatively expensive. The dyes cannot be used in exactly the same way as traditional dyes and pigments, and there is generally limited access to technical expertise, information and support for their use in the range of media with which designers would wish to experiment. As a result, practitioners commonly resort to the inevitable trial-and-error approach. The dyes may also show limited stability in certain environments, leading to questionable longevity of

textile designs produced. Another factor that may have limited their exploitation in textiles is the ingrained memory of their use in the past for novelty effects, presenting a barrier to more intelligent and creative use in complex design systems. It has been acknowledged that, compared with other markets, the textile sector lags behind in the exploitation of thermochromic materials and that continuing research in the chemistry and technology of dyes for textile applications will be important to widen the range of materials and to improve their performance [19]. At the same time, it is important for designers to recognise not only the potential of this colour-changing technology but also the technical limitations, and to embrace the challenges within design. The approach to the concept in the School of Textiles & Design of Heriot-Watt University is reflected in our parallel programmes of research on technical aspects of chromic materials and in textile design using the materials, informed by our acquired technological expertise.

An Interdisciplinary Approach to Textile Design Using Thermochromics

Thermochromics are most conveniently applied to textiles by screen printing using pigment printing formulations. It cannot be assumed necessarily that the materials will behave as normal pigments because they do not have comparable levels of stability. In the case of



Figure 1 Thermochromic printed textiles (a) before and (b) after heating

leuco dye types, traditional pigment printing binder formulations and curing conditions generally can be made to work reasonably well [20]. Examples of the colour change behaviour of textiles printed with leuco dye thermochromics are shown in Figures 1–3.

Figure 1(a) illustrates a textile sample screen-printed separately with green, magenta and blue leuco thermochromics in a transparent binder, showing the bright individual colours that can be obtained at ambient temperatures. Figure 1(b) shows the same samples with the temperature raised using a hair dryer, which causes the disappearance of the pattern. The designs re-emerge when the samples cool back to room temperature. Figure 2 shows a design

inspired by electronic circuitry and demonstrates a different colour-change function. The background was printed with an open screen using an orange thermochromic together with an opaque white pigment to produce a more subtle, muted colour effect. The permanent design was overlaid using a brown pigment. On heating with the hair dryer, the background disappears leaving the image of the permanent design. Figure 3 illustrates a textile printed with thermochromics incorporated into a puff binder, using magenta and blue in different

Figure 2 shows a design

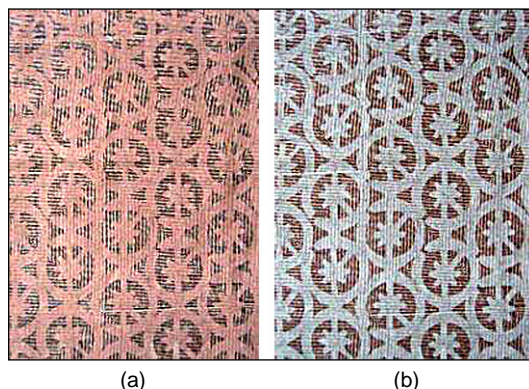


Figure 2 Thermochromic printed textiles (a) before and (b) after heating



Figure 3 Thermochromic printed textiles (a) before and (b) after heating

regions of the design. The thermochromic effect of three resistant nickel-chromium wires connected to a power source and located under the print is evident as lines in which the colour has disappeared.

We have previously reported our investigations of the colour change-properties of thermochromic pigment-printed textiles using a system developed in our laboratories to measure colour as a function of temperature [7,8]. The measuring system makes use of a traditional reflectance spectrometer to which is attached a hot-stage, which is computer-controlled to provide accurate temperatures in contact with the textile fabric. Details of the methodology have been reported previously [7]. An important feature of these studies was the exploration of the ways in which the data may be presented and interpreted. Since colour is itself a three-dimensional property, introducing temperature as a further variable adds a fourth dimension to the complexity. The methodology we have established provides a unique tool for designers to establish the exact form of the colour changes and the temperatures at which these changes occur. The technique may be applied usefully to determine the temperature ranges over which leuco dye thermochromics change colour, and the interpretation in such cases is relatively straightforward as it involves simple interchange between two colours.

The design illustrated in Figure 4(a) was printed with a blue leuco thermochromic dye as the predominant component, mixed with a magenta thermochromic and with permanent yellow and opaque white pigments in smaller quantities. Figure 4(b) illustrates the print blown with a hair dryer in such a way that there is a temperature profile across the print, the top of the print at the lowest temperature and the bottom at the highest. At the top there has been no colour change, while at the bottom there has been complete loss of thermochromic colour leaving a visual colour effect due only to the yellow and white pigments. In the centre it is apparent that the blue has decolourised, but the colour of the magenta thermochromic remains (providing a mauve colour when combined with the yellow and white), because its response temperature is evidently higher than that of the blue. The thermochromics were reported by the suppliers as having similar temperature-change ranges, but it is clear that there are differences possibly due to the rates of change, or indeed to batch variation in the commercial samples. While in this case the interesting effect was discovered serendipitously, it is of interest that our colour measurement method offers the facility to predict such effects for use as a design tool.

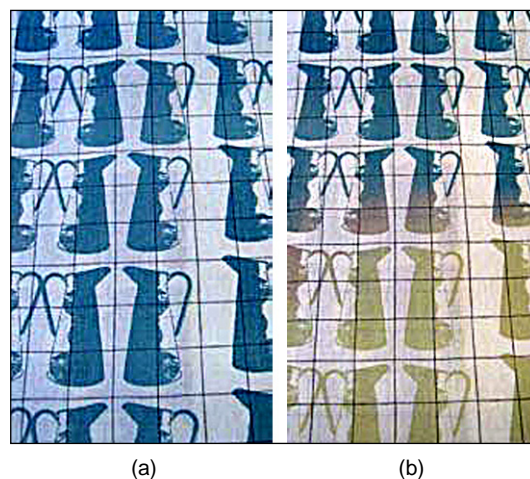


Figure 4 Thermochromic printed textiles (a) before and (b) after heating

We have applied the methodology more extensively on liquid crystal thermochromics, where the colour change phenomena are more complex and, arguably, create a wider range of exciting possibilities for design applications. Thermochromic liquid crystals are rather sensitive materials, requiring extreme care in formulation and presenting technical limitations in textile applications. These features, together with their relatively high cost, may explain why they have been less extensively exploited by designers. The designer needs to understand and work within these parameters for maximum impact. A particular deficiency, which may limit application for manufactured articles requiring longevity when exposed to a demanding environment, may not be so important for a set of exhibition artefacts that can have a reasonable lifetime if stored and used carefully. However, we have demonstrated that fabrics printed with thermochromic liquid crystal can show reasonable fastness to washing under mild conditions [8].

It is commonly stated that thermochromics are sensitive to light, especially to the damaging UV radiation in sunlight, and we have demonstrated this from our quantitative measurements [8]. Nevertheless, we have examples of these thermochromic prints made up to 15 years ago that have been exhibited and used as conference lecture illustrations on numerous occasions over that period in venues around the world with minimal apparent deterioration in thermochromic performance. The prints thus have reasonable longevity if stored out of light but with no other special precautions.

In our previously published reports of the various ways in which thermochromic colour variation with temperature can be expressed numerically and graphically, we have made use of three-dimensional CIELAB colour space, an accepted standard method of colour representation, as illustrated in Figure 5. The human eye can distinguish millions of colours and any one of these is represented as a single point in this colour space. The attribute of lightness (L^*) is given in the vertical axis. An ideal white would give an L^* value of 100, with $L^* = 0$ for an ideal black. Hue is represented by the parameters a^* (redness/greenness) and b^* (yellowness/blueness) values. Chroma (C^*) is the distance from the origin and describes the saturation (or richness) of colour, often described as 'colourfulness'. Thus strong bright colours give high chroma values, while neutral colours (white, grey and black) give chroma values close to zero and hence they are commonly termed 'achromatic'. Because of the complexity in attempting to use three-dimensional representations, we have found two-dimensional a^*b^* diagrams, such as those given in Figures 6–8, useful to represent the colour changes. In our previous publications we have separately illustrated appropriate reflectance curves, lightness and chroma values to provide a complete characterisation of the colour changes as the temperature is varied [7,8].

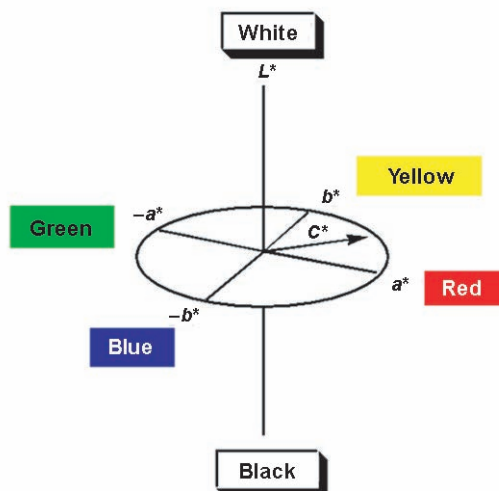


Figure 5 CIELAB colour space

It is commonly stated that in order to produce the most striking thermochromic effect from liquid crystals, it is necessary to apply the prints to a black background. This is commonly cited as a factor that restricts the versatility of their application to textiles. The physical reason is that, for optimum visual effect, a black background is required to absorb the transmitted light so that the reflected colours are displayed to their full effect. Figure 6 shows an a^*b^* diagram obtained from measurements for a print formulated to show colour-play at temperatures just above room temperature printed onto substrates with black and grey backgrounds over the temperature range 26–47 °C. Each of the individual points constitutes a measurement at a particular temperature, a few of which are indicated on the curve for the black print. Initially, the film is essentially colourless and the measured colour is given by a point close to the origin, characteristic of the background. As the temperature is raised, the colours pass rapidly through red and yellow shades and progressively more slowly through green and blue shades. The shape of the curve demonstrates that the system produces richer (higher chroma) colours in the green and blue regions, than in the red region, in agreement with visual observation. At a sufficiently high temperature the print becomes colourless as the liquid crystal converts to a normal liquid and the curve thus returns essentially to its original point. As shown in Figure 6, the print on the grey background, because of its lower light absorption properties, provides generally lower richness of reflected colour compared with the print on black.

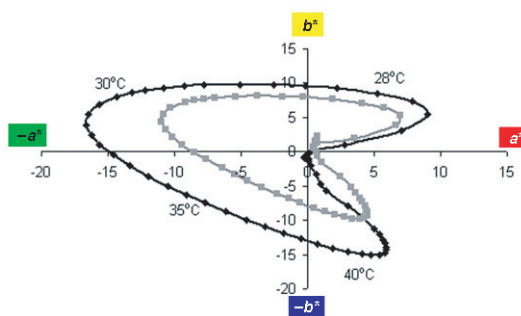


Figure 6 a^*b^* diagram illustrating the colour-play of a thermochromic liquid crystal print over black and grey backgrounds; the colours used to illustrate the curves have been selected to indicate the colour of the background

Video 1 shows a design derived from a thermochromic ink containing microencapsulated chiral nematic liquid crystal printed on to black nylon-spandex fabric. Initially, at ambient temperatures, the design is essentially colourless, although weakly visible because of the slight opacity of the print. It is then subjected to blowing with a hair dryer. Because of the rapid



Video 1 A demonstration of the reversible thermochromic effect obtained from liquid crystal prints on textiles [Click on the image to view]

heating rate, the reds and yellows are transient and the green rapidly develops, converting to deep blue as the temperature rises. After a heating period of about one minute, the hair dryer is switched off and the colour changes are seen to reverse as the print cools. This time, a colour commonly described as red-tan is more clearly observed due to the slow rate of cooling.

Thermochromic colour-change technology offers designers the ability to create both subtle and dramatic effects. By using different background colours it is possible to explore a range of colour-play effects, offering immense design potential when used in conjunction with the range of fabric types available today. To illustrate the possibilities, measurements were made of the same ink printed onto different coloured backgrounds. The graphical representations of the data are shown in Figures 7 and 8 and allow an interpretation of the way in which the colours change as the temperature is varied. For clarity, the colour of the background is indicated in the colour of the curve and the individual measurement points are omitted. In each case, similar curve shapes are obtained, offset to a position on the a^*b^* diagrams defined by the background colour. Figure 7 shows the curves provided by prints onto relatively dark background colours, namely brown, navy-blue and olive-green, with the curve for the black background included for comparison. The curves show that highly chromatic colours can be achieved on such backgrounds. The reddish-brown background gives marginally stronger yellowish hues, but with reduced chroma greens and blues. The blue and green backgrounds give stronger colours when the light reflected from the liquid crystal is the same as, and thus reinforces, the background colour, but there is reduced intensity in other colour regions.

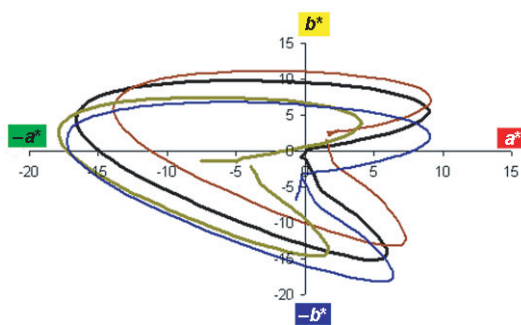


Figure 7 (left) a^*b^* diagram illustrating the colour-play of a thermochromic liquid crystal print over black, brown, navy blue and olive-green backgrounds; the colours used to illustrate the curves have been selected to indicate the background colour

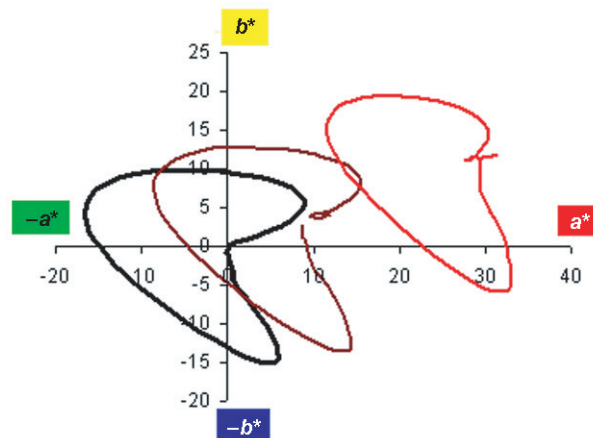


Figure 8 (right) a^*b^* diagram illustrating the colour-play of a thermochromic liquid crystal print over black, burgundy and red backgrounds; the colours used to illustrate the curves have been selected to indicate the background colour

Figure 8 shows the curves obtained from the thermochromic print on two red backgrounds, a burgundy and a bright yellowish-red, with the black again reproduced for comparison. The burgundy background, as the temperature is raised progressively, provides stronger chromatic reaction than over black in the red and yellow regions, weak greens, but a reasonably chromatic reddish-blue. The thermochromic outcome of the print on the bright red is a subtle change of properties within the red to yellow colour regions. As the temperature is raised, the red hue becomes initially yellower, losing chroma, but later transforms to a bluer shade of red with

increasing chroma. It is our opinion that there is significant scope for the designer to make creative use of such subtle colour changes.

Conclusions

The textile designer has a unique set of fundamental skills, which include the ability to select, combine and transform colour. Designers are also continuously influenced by external trends and market demands. Developments in the emerging area of smart materials are providing access to new and innovative fabric and yarn types and coloration systems that offer the designer a set of exciting new opportunities, together with significant creative and technical challenges. The unique features of colour change technology, such as thermochromism, allow design skills to be embedded as a function within textiles. Our approach, exemplified by the results described in this paper, combines research in colour-inspired design, research in colour technology and research at the design/technology interface. An important aspect of this set of parallel programmes is an AHRC-funded programme of textile design research, based on fundamental design skills, supported by the technical capability to measure and predict colour changes on printed thermochromic textiles, in combination with specifically designed electronic circuitry, to provide controlled and regulated temperature profiles, with the aim of producing dynamic and responsive textile designs and artefacts.

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