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An Investigation of the Activation of Multi-Colour Changing Photochromic Textiles

Çoklu Renk Değiştirebilen Fotokromik Tekstillerin Aktivasyonu ile İlgili Bir Araştırma

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AN INVESTIGATION OF THE ACTIVATION OF MULTI-COLOUR CHANGING PHOTOCROMIC TEXTILES

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ABSTRACT: Recent development in chemistry, fibres and electronic technology provides new material directions for designers to develop dynamic textiles that can change colour and pattern as a response to external environmental stimuli. Such dynamic textiles create many opportunities including novel surface decorations, development of flexible displays that can express emotions or signals and textiles for safety and camouflage. The photochromic material can be used to design textiles embedded with reversible multi-colour changing effects that can be experienced in daylight conditions. The activation of the colour changing effect of photochromic textiles is mainly influenced by the ultraviolet radiation that has a wavelength below 400 nm. One of the limitations of using photochromic colourants for the development of multi-colour changing textiles is the inability to control the activation of individual colours that have been applied to the textile surface. As such, the resulting visual experience has the tendency to become predictable for observers, thus, restrict the creative product design possibilities. The research conducted in this paper aimed to address this by exploring the possibility of handling different activation methods to control the kinetic behaviour of photochromic textiles. Three different activation methods including; sunlight, artificial UV lights and SMD UV LEDs were examined, and the possibilities to use each of these activation methods for the excitation of controllable multi-colour changing photochromic effects was highlighted. The paper concludes with a discussion on the creative design possibilities that can be exploited with such controllable multi-colour changing photochromic textiles, and appropriate visuals have been referred to justify the findings.

Keywords: Dynamic aesthetics, Multi-colour changing textiles, Non-emissive colours, Printed textile design

ÇOKLU RENK DEĞİŞTİREBİLEN FOTOKROMİK TEKSTİLLERİN AKTİVASYONU İLE İLGİLİ BİR ARAŞTIRMA

ÖZET: Kimya, lif ve elektronik teknolojisindeki son gelişmeler, tasarımcıların dış ortam uyarılarına cevap olarak renklerini ve desenlerini değiştirebilen dinamik tekstiller geliştirmeleri için yeni malzeme yönelimleri sağlamaktadır. Bu tür dinamik tekstiller, yenilikçi yüzey süslemeleri, duyu ve sinyalleri ifade edebilen esnek ekranların geliştirilmesi, güvenlik ve kamuflaj tekstilleri gibi birçok fırsat yaratmaktadır. Fotokromik malzemeler, gün ışığı altında çift yönlü çoklu renk değiştiren özelliklere sahip tekstilleri tasarlamak için kullanılabilir. Fotokromik tekstillerin renk değiştirme etkisinin aktivasyonu, temel olarak dalga boyu 400 nm'nin altında olan ultraviyole ışınımından etkilenmektedir. Çok renk değiştiren tekstillerin geliştirilmesi için fotokromik renklendiricilerin kullanılmasının sınırlamalarından biri, tekstil yüzeyine uygulanan bireysel renklerin aktivasyonunun kontrol edilememesidir. Bu nedenle, ortaya çıkan görsel deneyim gözlemciler için öngörülebilir eğilimindedir. Dolayısıyla bu, yaratıcı ürün tasarımı olanaklarını kısıtlamaktadır. Bu çalışmada, fotokromik tekstillerin kinetik davranışını kontrol etmek için farklı aktivasyon yöntemlerinin kullanılma olasılığı araştırılmaktadır. Güneş ışığı, yapay UV ışıklar ve SMD UV LED'ler olmak üzere üç farklı aktivasyon yöntemi incelenmiş ve bu aktivasyon yöntemlerinin kontrol edilebilir çoklu renk değiştiren fotokromik etkilerin uyarılması için kullanım olanakları ortaya konmuştur. Bu çalışma, kontrol edilebilir çoklu renk değiştiren fotokromik tekstillerle oluşturulabilecek yaratıcı tasarım olanakları üzerine bir tartışma ile son bulmaktadır ve bulguları açıklamak için uygun görsellere atıfta bulunulmuştur.

Anahtar kelimeler: Dinamik estetik, Çoklu renk değiştiren tekstiller, Işıma yapmayan renkler, baskılı tekstil tasarımı

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1. INTRODUCTION

Photochromism is a chemical process where a compound undergoes a reversible change between two states having separate absorption spectra [1]. This change occurs due to the influences of the ultraviolet radiation. The forward colour change is facilitated by UV light, and the change in the reverse direction occurs either thermally when the UV source is removed (T-type photochromism) or photochemically induced with an irradiation of a different wavelength of light (P-type photochromism) [2]. The colour change in photochromism is generally 'colourless to coloured' and the materials undergoing this change called 'photochromic materials'.

Photochromism was first reported in the 19th century by Fritzsche, who observed a colour change in tetracene in the presence of light [3-5]. Interest in photochromism increased around the 1940s, but the commercial awareness of photochromism has been identified during 1960s due to the development of photochromic lenses, which darken in sunlight converting glasses to sunglasses [6]. Since then, this phenomenon was studied in much greater depth, and most of the research literature have been reported in the areas of chemistry, physics, material sciences, crystallography, optics and polymer sciences [4]. There is also a growing research interest in photochromic textiles and considerable research has been published in the areas of application technologies including exhaust dyeing of synthetic fabrics [7,8], measuring the photo coloration of printed photochromic textiles [9,10] and the assessment of the technical performance of photochromic textiles prepared with screen printing method [11,12].

The non-emissive reversible colour changing properties of photochromic colourants can offer numerous design opportunities to significantly enhance the aesthetics of textile products. Despite the scientifically oriented research attempts in photochromic textiles, the ability to utilise reversible colour changing properties of photochromic colourants as a means of producing novel visual effects for textile application has only been exploited to a lesser extent [13]. One of the fundamental reasons for this lack of design research is the difficulty of controlling the activation of individual photochromic colours that have been applied onto the textile surface. For example, when a textile printed with four different photochromic colours, the respective colours of the print activate simultaneously upon exposure to UV light. As such, the dynamic visual experience facilitated through this material has the tendency to be predictable for observers. The research reported in this paper aimed to address this by exploring the possibility of handling different activation methods to control the overall kinetic behaviour of printed photochromic textiles. This research paper attempted to examine sunlight and artificial UV light sources as activation methods. The ability to control the photochromic colour changing effect was investigated by considering the following features;

- I. Controlling the colour changing visual effect by altering the colourfulness (colour strength or depth of colour) of the activated photochromic print design.
- II. Controlling the colour changing visual effect by changing colours in specific (designated) areas of the photochromic print design.

The research highlighted a number of decisive parameters associated with sunlight and artificial UV light sources. The observational visual data was presented in order to describe the ability to use these parameters to make an impact on the dynamic visual characteristics of printed photochromic textiles. In addition, the paper also examined the possibility of electronically controlling the colour changing functionalities of printed photochromic textiles. To realise this, regulated UV radiation was reflected onto the reverse side of the photochromic textile using small-scale Surface Mounted Device UV LEDs. The experimentation indicated the ability of instantly activating a larger area of a print design with strong, deep multiple photochromic colours. Two decisive parameters that can be used to electronically activate and control the dynamic colour changing characteristics of printed photochromic textiles were highlighted. The paper concludes with a discussion on the creative design possibilities of each activation method when complemented with printed photochromic textiles.

2. EXPERIMENTAL SET-UP AND PROCEDURE

Author's design practice and design thinking was considered as the main method of investigation, and the data (visual, textual, numerical) was generated by directly experimenting with the photochromic material, screen print processes, activation methods and related technologies. The progress of this research was mainly monitored by 'observing' the colour changing effect of the printed samples and evaluating them with relevant activation procedures that had been used to produce those effects. These observations were captured under consistent visual data capturing settings with three different activating methods. This form of structured and directed observational data collecting procedures enabled to considerably reduce the subjective nature of the observational data and also to achieve high validity and reliability of the research outcomes. The activating methods and associated data capturing settings are;

- Capturing setting 01: Activating printed photochromic textiles with solar UV radiation (sunlight)

The textile samples printed with multiple photochromic inks were photographed before and after sunlight exposure. The images collected from this approach visualised the different types of effects that the printed textile designs can have when they were placed in indoor or outdoor conditions. The photographic procedure and the equipment used during this setting can be seen in Table 1.

- Capturing setting 02: Activating printed photochromic textiles with an artificial UV light (UV torch)

In capturing setting 02, visual data were collected by using a UV torch with two LEDs with a capability of emitting a consistent 365 nm UV wavelength profile. The technical specification of the torch and photographic procedure of this setting can be seen in Table 2.

- Capturing setting 03: Activating printed photochromic textiles with SMD UV LEDs

A Surface Mount UV emitting LEDs (SMD UV LEDs) were used according to the following procedures in order to collect the observational visual data.

Table 1. The description of data capturing setting 01

Capturing Setting 01		
1	Photographic procedure	<i>Photographed before the sunlight exposure. Photographed after approximately 10 seconds of sunlight exposure. Different angles and zooming lenses were used to capture the larger areas of the activated photochromic colour of the printed textile surfaces.</i>
2	Equipment used	<i>Canon DSLR camera with 18-135 mm focus lenses</i>
3	Image type	<i>Camera Raw Images</i>

Table 2. The description of data capturing setting 02


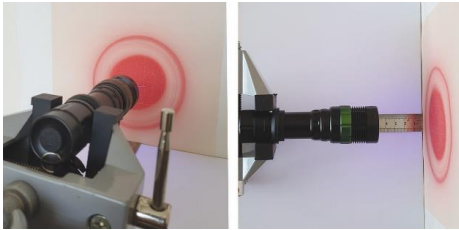
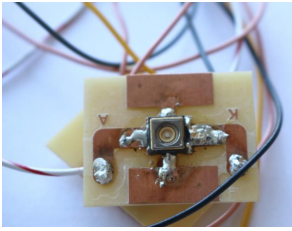
Capturing Setting 02			
		Description	
		Model	<i>3 modes zoomable UV torch</i>
		Weight	<i>130g</i>
		Working voltage	<i>4.5 V</i>
		Output power	<i>5 W</i>
		No. of LEDs	<i>2</i>
	UV wavelength	<i>365nm</i>	
1	Photographic procedure	<p><i>Photographed before UV exposure.</i></p> <p><i>The UV torch was directed onto the printed photochromic textile sample and switch on for approximately 10 seconds. The photographic evidence were recorded as soon as the UV torch was switched off.</i></p> <p><i>In order to examine how the printed photochromic colours react to variable UV radiation intensity, the visual data can also be recorded by altering the operating distance between the printed textile surface and the UV torch. To achieve this, the UV torch was held onto a table clamp and placed on a stationary position. The printed photochromic textile samples were mounted onto whiteboards/wall and exposed to UV torch in variable distances.</i></p>	
			
2	Equipment used	<i>Canon DSLR camera with 18-135 mm focus lenses</i>	
3	Image type	<i>Camera Raw Images</i>	

Table 3. The description of data capturing setting 03

Capturing Setting 03			
		Description	
		Model	<i>Surface Mount UV LED</i>
		Dimension	<i>6.8 (L), 6.8 (W), 2.1 (H) mm</i>
		Radiant flux	<i>590 mW maximum</i>
		Forward voltage	<i>3.2 V to 3.9 V</i>
		Forward current	<i>Variable</i>
	Peak wavelength	<i>365 nm</i>	
1	Photographic procedure	<p><i>As an approach to regulate the UV radiation intensity that is reflected onto the reverse side of the printed textile surface, the SMD UV LED was activated for variable time intervals and the photographic evidence was recorded as soon as the SMD UV LED was switched off.</i></p> <p><i>As an approach to regulate the UV radiation intensity that is reflected onto the reverse side of the printed textile surface, the operating distance between the printed textile surface and the SMD UV LED was also altered. In order to accurately change the operating distance, a milling machine base equip with measurable XY axis was employed.</i></p>	
2	Equipment used	<i>Canon DSLR camera with 18-135 mm focus lenses</i>	
3	Image type	<i>Camera Raw Images</i>	

The photochromic textile samples examined in this research paper were produced by screen printing (a screen made out of 90T monofilament polyester mesh) commercially available water based photochromic inks as a pigment printing method.

The water based photochromic inks visualise a colourless effect once printed onto textiles. When exposed to UV radiation, the inks change colour from colourless to coloured (colourless → coloured). When removed from the UV exposure, the inks gradually return to their original colourless state (colourless ← coloured). The water based photochromic inks are commercially available in different reversible colour changing options including; Clear (colourless) ⇌ blue, clear ⇌ red, clear ⇌ yellow, clear ⇌ green and clear ⇌ purple. In order to produce the multi-colour changing textiles, primary photochromic colours of blue, red and yellow were screen printed onto medium weight plain cotton white (PCW) fabric. (Clear (colourless) blue symbolize the reversible colour changing effect of photochromic blue colour which changes from clear or colourless to blue upon UV exposure and returns back to colourless when remove from the UV radiation). To expand the colour changing options, some textile samples were also printed with the combination of photochromic and static pigment inks. An important technical properties associated with the commercially available water based photochromic inks can be referred in Table 4.

3. ANALYSIS

The observational visual data collected from consistent data capturing settings were used as the main sources of analysis. Throughout this research, the visual data analysis was made by comparing the degree of activated photochromic colour against the relevant activation method that had been experimented. This process was also complemented with critical reflective practice that enabled the author to obtain an original insight into the behaviour of the material as well as the impact of individual activation method for the excitation of controllable colour changing effect on photochromic textiles.

4. RESULTS AND DISCUSSIONS

4.1. Sunlight (Solar UV radiation) as an activation method

According to Lucas, et al. (2006), the Ultraviolet radiation that was emitted by the sun can be classified into three main bands; UV A (315 nm – 400 nm), UV B (280 nm – 315 nm) and UV C (100 nm – 280 nm). When sunlight passes through the atmosphere, 100% of UV-C and approximately 90% of UV B radiation are absorbed by the ozone layer. Thus, the solar UV radiation mainly consists of UV A and a small component of UV B [14]. Commercially available photochromic colourants change colour upon exposure to any UV wavelength, therefore, exposing the printed photochromic textiles to sunlight can be considered as the most convenient method of activation.

In response to incident sunlight, the textiles printed with photochromic colour changing inks ‘rapidly’ change colour from colourless to coloured. The intensity of solar UV radiation is determined by many environmental factors such as time of the day, time of the year (season), latitude and cloud cover [14]. Depending on these environmental factors, a subtle variation on the activated effects can be observed on the printed photochromic textiles. For example, the images in figure 1 demonstrate how the different outdoor conditions could change the colourfulness of the activated multicolour photochromic textiles. It is not possible to predict the environmental factors that influence the outdoor conditions. Therefore, sunlight can be considered as an uncontrollable activation method that could trigger an unpredictable multi-colour changing effect on the printed photochromic textiles.

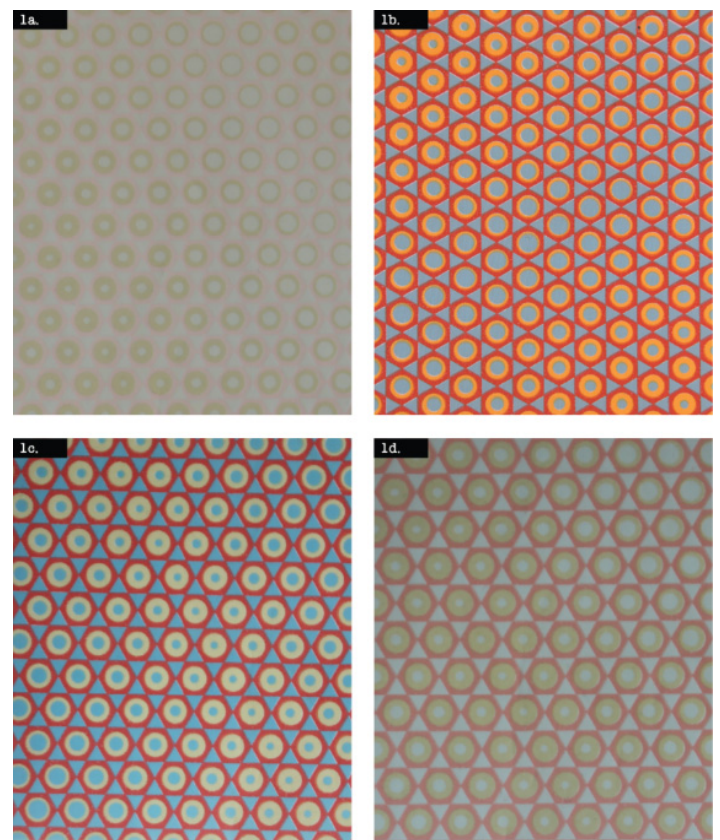


Figure 1. The images demonstrate the different activated multi-colour effects of a photochromic pattern (Capturing setting 01). 1a. Multi-coloured photochromic pattern before UV exposure. 1b. The photochromic pattern was activated by direct exposure to solar UV on a sunny day (UK Summer) at 12.30 pm. 1c. The photochromic pattern was activated by direct exposure to solar UV on a cloudy day (UK Winter) at 10.30 am. 1d. The photochromic pattern was activated by direct exposure to solar UV on a cloudy day (UK Winter) at 4.30 pm.

Table 4. Technical properties of the commercially available water based photochromic inks

Water based photochromic ink properties	Description
Ink composition / Printing paste	50% photochromic pigment slurry + 50 % water based textile acrylic binder
Pigment content of the ink (%)	24 ± 2 %
Pigment size	95% of the pigments are less than 8 microns (μm)
Solvent	Water
Ink viscosity (cps)² (Viscosity of the mixture of slurry and textile binder measured on a LVT Brookfield viscometer at 25 °C)	> 5000
Recommended mesh size for screen printing	90 T (Number of threads per 1cm)
Finishing parameter	The printed ink should be dried at 130 °C for 2 to 3 minutes
Storage	Do not store in temperature in excess of 25 °C. Do not freeze.

Although it was difficult to predict how strong the photochromic colours activate under sunlight, it was still possible to create a subtle variation on the activating area of the printed photochromic design. As can be observed in figure 2, the activation of the multiple photochromic colours can be temporarily altered by interrupting the interaction of sunlight with the printed photochromic textile surface (The effect is temporal since the inactive photochromic colours activate as soon as they expose to sunlight).

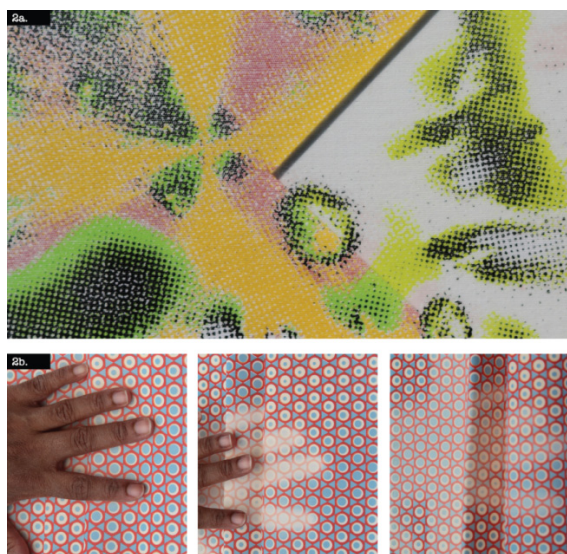


Figure 2. Images show the possibility of activating a temporal effect by interrupting the sunlight exposure of the printed photochromic textile surface (Capturing setting 01). 2a. The image shows a design printed with multiple photochromic colour-changing options. Upon exposure to direct sunlight, photochromic colours activated (left). When the interaction of the sunlight was interrupted with a transparent UV absorbing acrylic sheet (right), the area printed with photochromic colours remained inactive. 2b. Our physical movements can also trigger temporal effects on the activated photochromic design.

Moreover, the interaction of the sunlight can also be disrupted by manipulating the printed photochromic textile surface with different methods such as folding, pleating or layering. For example, as can be seen in figure 3 (image 3a), the printed photochromic area, which was directly exposed to sunlight, remains with activated photochromic colours as long as it was

exposed to sunlight. However, the activation of the fabric beneath the pleat was reduced due to obscuration by the top fabric layer. When the pleat was unfolded and was exposed to direct sunlight, the inactive photochromic colours started to rapidly change colour to match with the surrounding activated effect of the photochromic design.

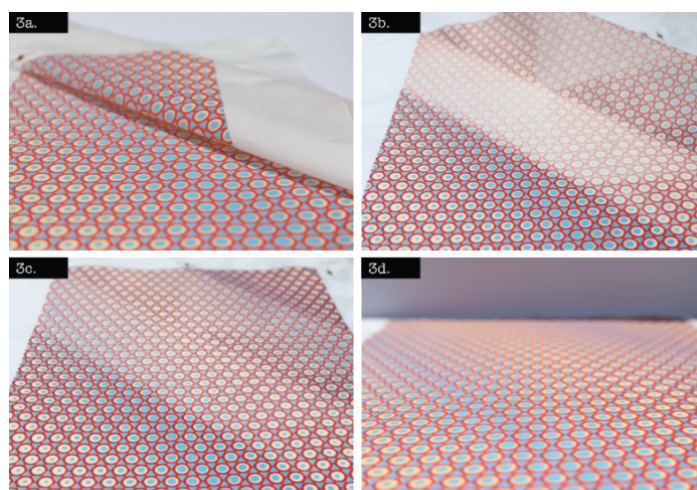


Figure 3. The images demonstrate the potential of manipulating the photochromic textiles in order to obtain a temporal variation on the activated multi-colour photochromic effect (Capturing setting 01).

As highlighted above, exposure to direct sunlight can result in rapid activation of strong photochromic colours, and the colourfulness of the activated print remains as long as the surface was directly interacting with strong/bright sunlight. Therefore, in order to observe slow changes of subtle hues, the printed photochromic textile has to be kept away from sunlight exposure (indoor) so that the activated photochromic colours could deactivate gradually into their original colourless state. Depending on the photochromic colour-changing options integrated into the printed image or pattern, the subtle variation of transitional hues can also be observed in an indoor environment. Therefore, regularly changing the surrounding environment of the printed photochromic textile surface from indoor to outdoor enable the observer to experience a dynamic printed effect where a decorative design appears, change colour and disappear with different colourfulness.



Figure 4. The images show the dynamic visual effects that can be activated by changing the surrounding environment from outdoor to indoor.

Sunlight (Solar UV radiation) as an activation method: Decisive parameter that can be used to activate a temporal multi-colour effect on printed photochromic textiles

Since the commercially available photochromic colourants simultaneously activate to UV radiation, it is difficult to control the changes of individual colours of a photochromic design. Therefore, as an approach to control the overall dynamic visual characteristics of photochromic designs, the following features have been considered.

I. Controlling the colour changing photochromic effect by altering the colourfulness (colour strength or colour depth) of the activated photochromic print design (The colourfulness of a photochromic print can also be determined by the colorant concentrations on the ink formula. However, as described in section II of this paper, a consistent pigment slurry concentration was maintained for the preparation of the inks for each photochromic colour).

Or

II. Controlling the colour changing photochromic effect by changing colours in specific (designated) areas of the photochromic print design.

Sunlight, as an activation source, triggers an instant colour change on the entire imagery or pattern printed with photochromic inks (As soon as the photochromic textile is exposed to sunlight, the color changing effect can be observed). Moreover, the intensity of solar UV radiation can change the colourfulness of the activated multiple photochromic colours, however, this could be highly uncontrollable and unpredictable since it was determined by many environmental factors. Even though the dynamic visual characteristics of photochromic textiles could not be 'controlled' under sunlight (in terms of




colourfulness and activating area of the design), the interruption of sunlight exposure may create a subtle and temporal effect on the activated photochromic surface (as can be seen in figure 2 and 3). Such temporal effects can differ depending on the type of interference. For example, the presence of external objects or surface modification methods such as folding, pleating or gathering can facilitate a different level of interference for the sunlight exposure of printed photochromic textile. Therefore, the interruption of sunlight exposure can be considered as a decisive parameter that can only trigger a subtle and temporal effect on the textile printed with multiple photochromic colours.

4.2. Artificial UV emitting light sources as an activation method

An alternative method of activating a printed photochromic textile would be to use an artificial light source that has the capability to emit UV radiation at various intensities. There are many types of UV light sources commercially available, and some of the general information is summarised in the following table.

Compared to solar UV radiation, the artificial UV emitting light sources can be handled to supply a consistent UV radiation onto the printed photochromic textile surface. It is also important to understand, how the consistent UV radiation emitted by these light sources could be used to control the overall dynamic visual characteristics of printed photochromic textile designs. As indicated in the previous section of this paper, altering the colourfulness of the activated multiple photochromic colours or changing colours in designated areas of the printed design can be considered as potential features to control the visual effects of photochromic designs. The following section investigates the possibility of achieving such controllable features when using artificial UV lights as an activation method.

Table 5. Commercially available UV light sources.

UV light source	Technical Specifications
 <p><i>UV LED torches</i> Source: Various suppliers</p>	<p><i>Commercially available UV LED torches offer a different level of output power ranging between 5W to 8W.</i></p> <p><i>Emit peak wavelengths in the ranges of 365nm, 375nm, 385nm, 395nm.</i></p> <p><i>Most torches are equipped with one to several numbers of UV LEDs</i></p> <p><i>Generally, supply UV radiation in an angle ranging between 10° to 140°</i></p>
 <p><i>Handheld or large format UV lamps</i> Source: Ultra-violet products Ltd. (www.uvp.com)</p>	<p><i>Equip with one or two UV tubes with a power of 4W, 15W, 25W or 40W.</i></p> <p><i>Generally available in different wavelengths in the regions of UV-A, UV-B, and UV-C.</i></p> <p><i>Variable UV radiation angles.</i></p>
 <p><i>High intensity UV spot / flood lights</i> Source: Advanced NTD LTD (www.advanced-ndt.co.uk)</p>	<p><i>Generally equipped with a UV bulb with a power of 35W or 50W.</i></p> <p><i>The beam profile can be selected from spot beam to flood beam. At a distance of 38cm, the UV intensity of a 50W bulb is 60000µw/cm² (Spot beam) or 5800 µw/cm² (Flood beam).</i></p> <p><i>At a distance of 38cm, a 50W bulb covers an area that has a diameter of 14 cm (Spot beam) or 29 cm (Flood beam).</i></p> <p><i>The bulb achieves full power within 5 to 15 seconds of operation. After that, the bulb provides a constant UV intensity.</i></p> <p><i>Peak wavelength 365 nm.</i></p>

Artificial UV emitting light sources as an activation method: Decisive parameters that can be used to activate and control the multi-colour changing characteristics of photochromic textiles

As highlighted by Viková, Christie and Vik (2014), exposing the photochromic print to a higher UV radiation intensity can result in a strong, deep photochromic colours activated on the printed textile surface [15]. The simplest method of regulating the UV radiation intensity supplied by a particular UV light source (that has a specific output power) would be to alter the operating distance between the printed textile surface and the UV light source. Furthermore, the exposure duration of the photochromic print (operating duration of the artificial UV light source) can also increase the colourfulness of the activated photochromic colours until it reaches to its maximum level.

Since the adjustment of *operating duration of the UV light source* or *operating distance of the UV light source* can change the colourfulness of a photochromic effect, they can be considered as decisive parameters that can be used to control the dynamic visual characteristics of printed photochromic textiles. These variable parameters can be implemented with any

commercially available UV emitting light sources. Depending on the technical specification of the selected light source (output power, radiation angle) the above parameters can activate and control the multi-colour changing effect of the printed photochromic textile surface. Some of the examples of such controllable photochromic effects can be seen in figures 5 and 6 below.

Commercially available UV emitting light sources can also be handled to control the dynamic aesthetics by changing colours in specific (designated) parts of the printed photochromic textiles. For example, a UV torch or a high-intensity UV spotlight can be focused onto a specific area so that the printed areas of the design change colour according the photochromic ink/colour option that had been printed on the textile surface. Depending on the requirement, the observers could change the focus of the UV source to another area of the printed surface. This allows the printed design of the focused area to be activated while previously activated areas are transforming into their original appearances. An example for such controllable colour changing effect can be seen in figure 7.

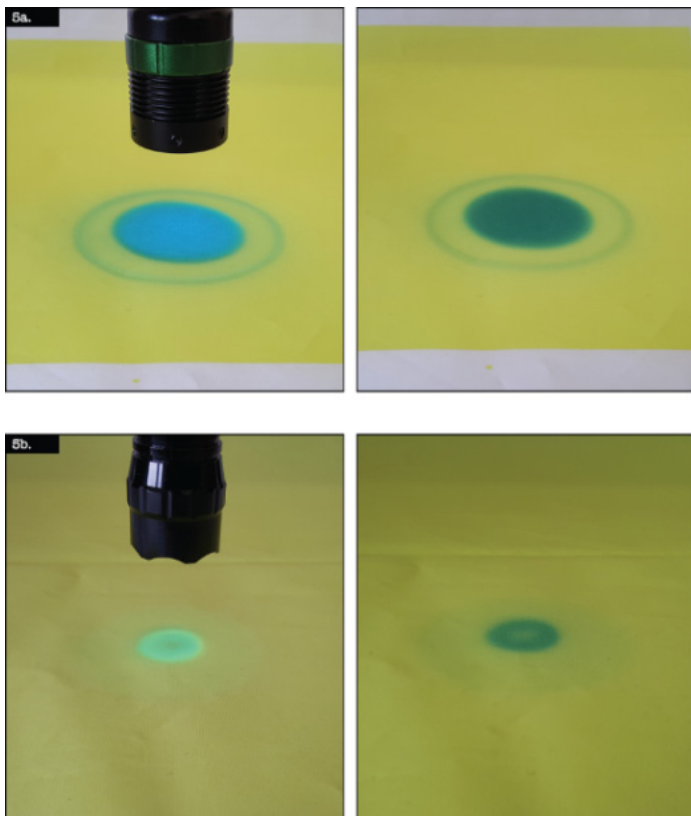


Figure 5. Images show a textile printed with a combination of photochromic and static pigment colours. Different levels of activated photochromic colours can be observed when using UV torches with different technical specifications (Capturing setting 02).

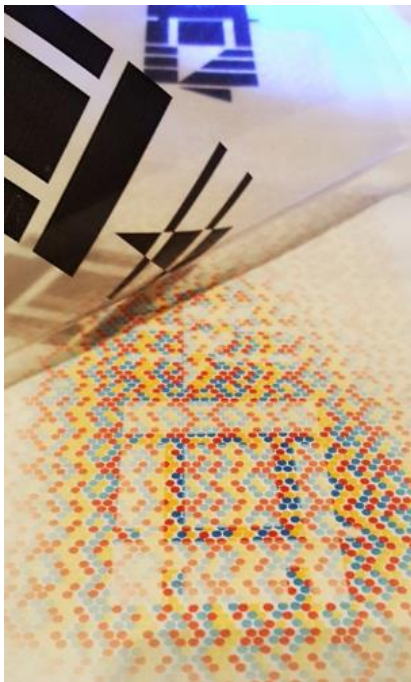


Figure 6. When an artificial UV light is transmitted through a stencil, an imprint of the stencil can be transferred onto the printed photochromic textile surface. By altering the operating duration or operating distance of the light source, the colourfulness of the activated multiple photochromic colours can be accurately controlled.



Figure 7. Using a UV light source to control the colour changing effects in different areas of the printed design.

Although the artificial UV lights can be used to control the dynamic aesthetics of photochromic designs, they, however, present some limitations. The artificial UV lights (UV torches, UV lamps or high-intensity UV spotlights) are larger in size, and the emission of UV radiation has to be directed either to the printed photochromic textile surface or the reverse side of the photochromic surface. The operating duration, operating distance or even the direction of UV emission of the light sources can be physically or mechanically controlled. However, these mechanisms tend to occur externally to the printed photochromic textile surface. Moreover, repeatedly pointing an artificial UV light source towards a particular area of a photochromic design may create a predictable activation of a multiple colour changing effect. The operating duration or distance of the UV light source may change the colourfulness of the activating photochromic colours. However, the repeating flashes of the UV light on a particular printed area could give life to photochromic elements to appear or change colour repeatedly in a similar way. (i.e. Once the observer experience an effect, they can expect the same effect when repeatedly reflect the UV light).

Due to such limitations, the creative applications of dynamic photochromic textiles could be restricted to a certain extent. In order to expand the boundaries and to locate new application scenarios, it is important to identify a versatile activation method to support the multiple colour changing functionalities of the printed photochromic textiles. Moreover, if there is an ability to complement an electronically controllable activation method alongside with fine decorative multicoloured photochromic prints, visually stimulating experiences can be obtained since the activation method can conveniently control the colour changing functionalities of the decorative features of photochromic printed designs. As an approach to instantly activate a larger area (territory) of printed design with stronger photochromic colours, Surface Mount Device UV emitting LEDs (SMD UV LEDs) can be used to reflect UV radiation to the reverse side of the printed photochromic textile surface. The description of the activation method, the parameters and the potential of electronically controlling the activation of stronger photochromic effects were discussed in the following section of the paper.

4.3. SMD UV LEDs as an electronically controllable activation method

Compared to conventional artificial UV sources such as lamps or bulbs, UV emitting LEDs offer a number of advantages. For example, UV emitting LEDs consume less power to operate, and the output beam can be focused directly onto a targeted area. Unlike conventional artificial UV sources, UV LEDs do not require any warm-up times and the emission of UV radiation can be switched on and off within a few tens of nanoseconds or even faster [16]. The UV LEDs can be operated at moderate DC voltages, and the emission wavelength of UV LEDs can be designed to cover any wavelength in the UV spectral range of UV-A (400nm - 320nm), UV B (320nm – 280nm) and UV C (280nm – 200 nm).

When attempting to use SMD UV LEDs to activate and control the kinetic behaviour of printed photochromic textiles, it was important to consider a device with higher output power (radiant flux) value. Thus, an SMD UV LED that can emit a peak wavelength of 385nm with a considerably higher radiant flux (590 mW) was used, and the reflected UV light was regulated by altering the parameters of operating duration and operating distance of the SMD UV LED. In order to understand how the visual characteristics of photochromic textiles respond to the regulated UV light, a geometrical pattern consisted with different sizes of squared shapes was designed and screen printed onto medium weight plain cotton white (PCW) fabric with water based photochromic red inks.

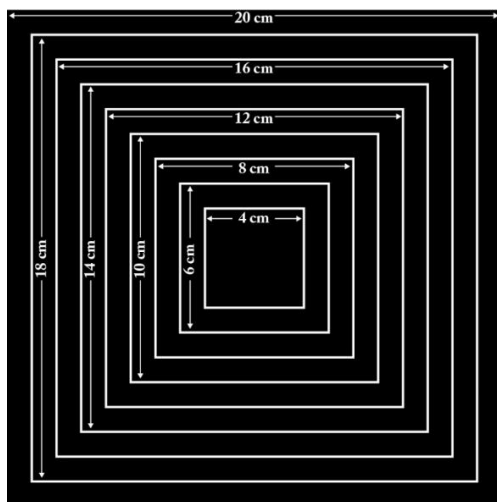


Figure 8. The photopositive artwork of the geometrical pattern that was printed onto the PCW fabric.

As indicated in figure 9, the printed PCW fabric was mounted onto a thick whiteboard frame and placed in a stationary position. Fine copper wires were soldered onto the SMD UV LED according to the manufacturer’s recommended conditions and connected to laboratory DC power supply. The laboratory DC power supply also offered the flexibility to input a constant electrical power at different time intervals. The soldered LED chip was attached to a whiteboard and then mounted onto an adjustable milling machine base (equipped with a measurable X, Y axis) which was placed behind the printed PCW fabric surface.

By maintaining the input electrical power (forward voltage 3.5 V, forward current approximately 550 mA) and the operating distance between the SMD UV LED to the printed PCW fabric surface (30 mm), the LED device was switched on for 2 seconds, 5 seconds, 10 seconds and 15 seconds respectively. After activating the printed fabric, the LED was switched off, and the resulting colour changing effects were captured photographically and can be seen in figure 10.

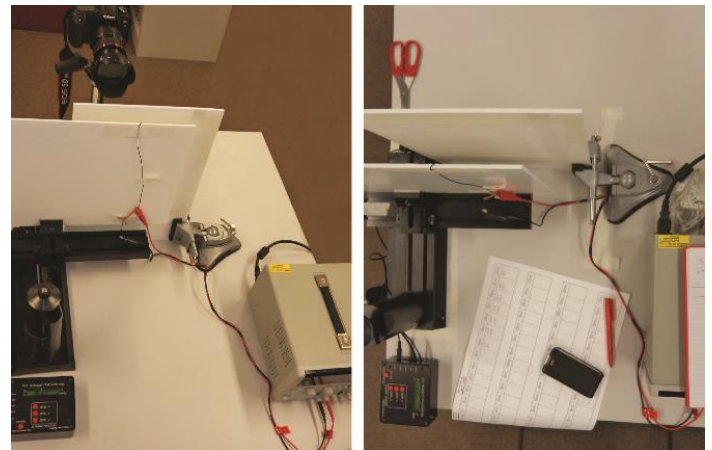


Figure 9. Experimental apparatus.

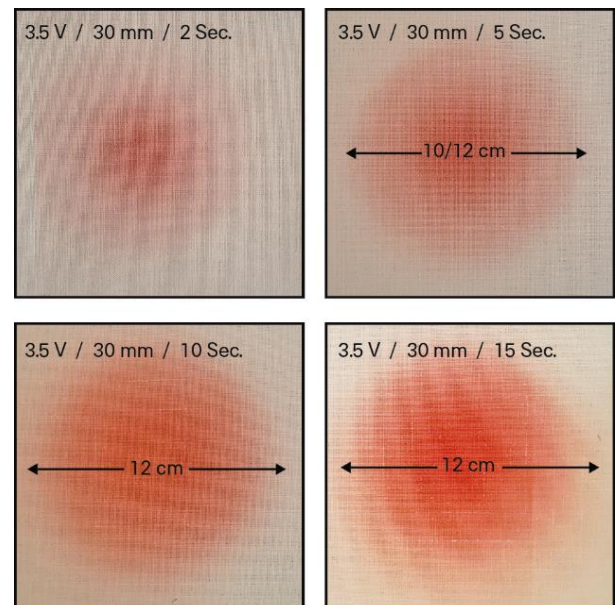


Figure 10. Changes to the photochromic effect when switch on the SMD UV LED for variable time intervals (Capturing setting 03).

As can be seen in the above images, increasing the operating duration of the SMD UV LED could increase the colourfulness of the photochromic pattern until it reaches its maximum level. The recorded visual data also provided an indication of the measurement of the activating territory (colour spot) that could be achieved by placing a small SMD UV LED from the reverse side of the photochromic textile. For example, when the LED was switched on for 2 seconds, a spot that has a diameter of 4 cm (approximately) can be activated. When the operating time of the

SMD UV LED was increased to 10 seconds, the diameter of the activated spot was increased (12 cm) and a much stronger photochromic red colour spot can be observed.

The ability to change the colourfulness of the photochromic print by altering the operating distance of the SMD UV LED was also examined. The adjustable milling machine base equipped with measurable X/Y axis, allowed the gap between the photochromic textile and the LED device to be set precisely. The SMD UV LED was switched on for 10 seconds (with voltages of 3.3V, 3.4V and 3.5V) and the gap between the printed PCW fabric and the LED device was accurately adjusted for various distances. After 10 seconds of activation, the SMD LED was switched off, and the activated photochromic effects of the PCW fabric were visually recorded in figures 11 and 12.

Different photochromic effects resulted as a response to the variable operating distances of the SMD UV LED. According to the visuals presented in figures 11 and 12, it was evident that the operating distance between the textile surface and the SMD UV LED clearly determining the colourfulness as well as the measurement of the colour changing spots that can be observed

on the PCW fabric. For example, having a gap of 5 mm to 10 mm between the fabric and the LED can activate a strong, deep photochromic spot that has a diameter of 4 cm. When the gap is increased to 30 mm, the colourfulness of the activated spot was decreased; however, the diameter of the activated spot was significantly increased up to 12 cm. When the gap between the fabric and the SMD UV LED was further increased, a larger spot with lighter photochromic red colour can be observed. Supplying higher electrical power to the operation of the SMD UV LED can also enhance the colourfulness of the activated spot; however, this factor can only become significant when there is a larger gap between the fabric surface and the SMD LED device.

This experiment was conducted with the latest SMD UV LED device that was available at the time of the experiment. However, due to the rapid development of the LED technology, there can be superior SMD UV LED devices that can operate with the lower electrical power to emit stronger UV radiation (higher radiant flux) in larger emission angle. Having such devices could significantly enhance the resulting visual characteristics of the activated photochromic textiles.

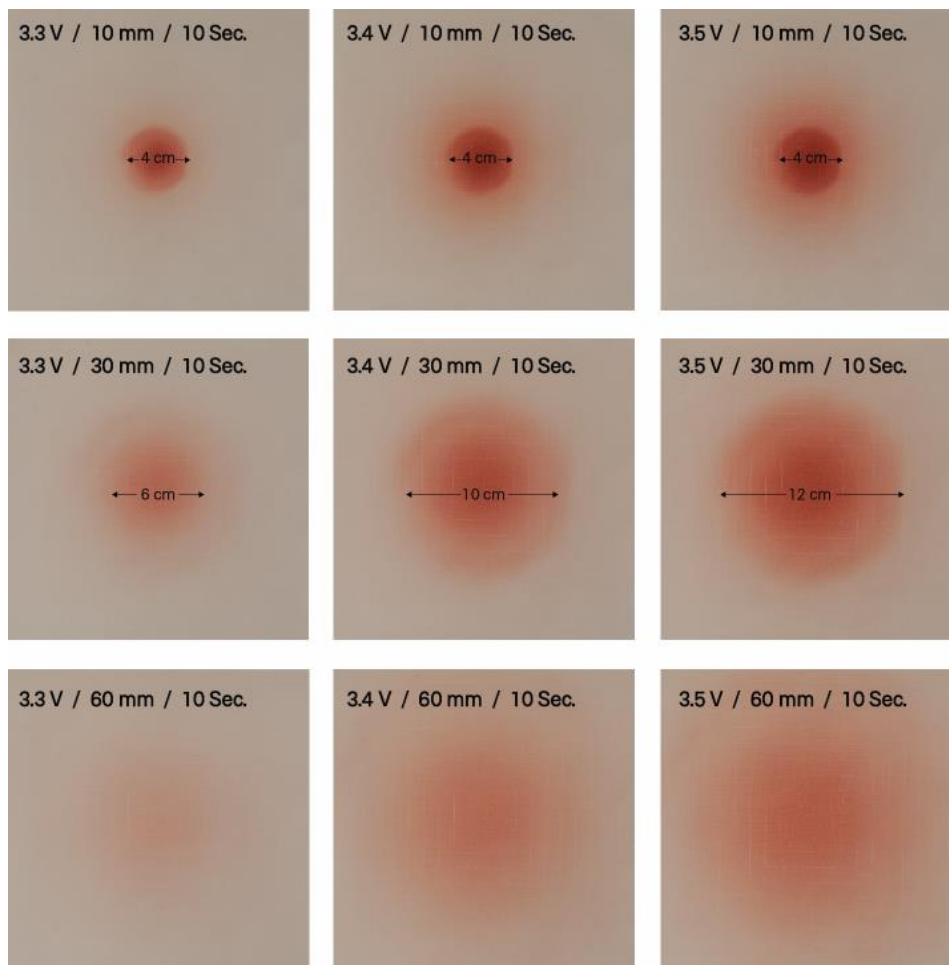


Figure 11. The dependence of the photochromic effect on the gap between the PCW and SMD UV LED.

OPERATING DISTANCE	VOLTAGE VALUES		
	3.3 V	3.4 V	3.5 V
2 mm			
5 mm			
10 mm			
20 mm			
30 mm			
40 mm			
50 mm			
60 mm			
70 mm			
80 mm			
100 mm			
120 mm			

Figure 12. The dependence of the photochromic PCW fabric surface on voltage values and operating distances.

SMD UV LEDs as an activation method: Decisive parameters that can be used to electronically activate and control the dynamic visual characteristics of printed photochromic textiles

As indicated in the previous section, the dynamic visual effects of printed photochromic designs can be controlled by altering the colourfulness of the design or changing colours in specific

(designated) areas of the design. One of the advantages of using SMD UV LEDs as an activation method is the ability to connect the operation of the individual SMD UV LED to an electronic circuit so that the functions of the LED can be controlled electronically. For example, a circuit can be designed to switch on the SMD UV LED for a specific time duration and this system can be used as a method to supply controllable UV radiation to the reverse side of the photochromic design. As shown in figure 9, an electronically controllable SMD UV LED activation of 2 seconds, 5 seconds, 10 seconds or 20 seconds could trigger photochromic colours to be observed in different colourfulness. The larger spots can give life to a number of photochromic colour changing options. This would allow a multi-coloured spot to be appeared in variable colourfulness and disappear according to the operating duration of the SMD UV LED. An example of such electronically controllable effect is given in figure 13.

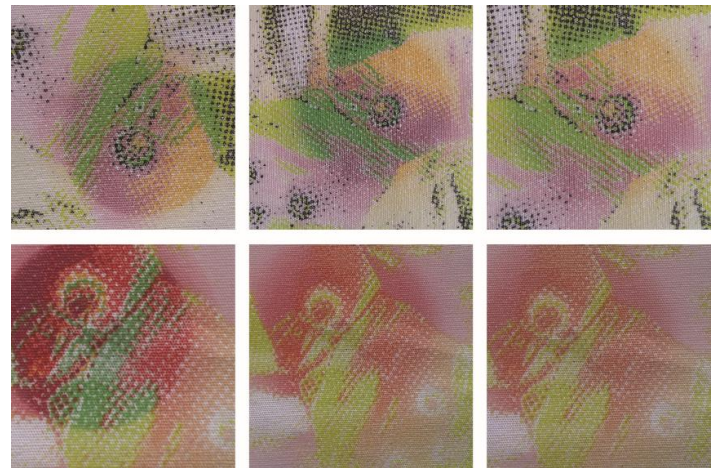


Figure 13. Images show the activation and deactivation of a multi-coloured circular spot for the regulated operation of SMD UV LED (Capturing setting 03).

According to the findings reported in figures 11 and 12, the alteration of the operating distance of SMD UV LED can significantly change the measurement of the colour changing spot while creating an impact on the colourfulness of the photochromic textile surface. However, attempting to electronically control the gap between the fabric surface and the SMD UV LED could be an impractical option since it requires development of a complex mechanism.

As an approach to simultaneously activate a number of larger circular zones in designated areas of a printed photochromic design, a number of SMD UV LEDs could be used on a grid panel and positioned from the reverse side of the printed surface. Electronic circuitry designed with a programmable sequence could activate the individual SMD UV LED to specific sequences and variable time of operations. Such programmable electronic activation of the SMD UV LED grid can influence an instant activation of photochromic spots in different areas of the design in various colourfulness. By considering this potential, it was evident that the *operating duration* and *operating sequences* of the SMD UV LEDs can define the visual effect of multi-

coloured photochromic prints, thus, they can be considered as the decisive parameters that can be used to 'electronically' activate and control the dynamic visual characteristics of printed photochromic textiles.

5. CONCLUSIONS

Three methods for the activation and controlling of multi-color photochromic effects on textiles were examined, and main research findings in relation to these methods were summarised in the following section.

The textiles prepared with commercially available water based photochromic inks instantly and uniformly changed colour upon exposure to sunlight. The intensity of solar UV radiation changes according to many environmental factors, thus, sunlight as an activation source triggers an uncontrollable and unpredictable colour changing effect on the photochromic designs printed on textile surfaces. It was evident that the photochromic design remains active as long as the textile is exposed to sunlight. However, the research suggested that *the interruption of sunlight exposure* can be used as a decisive parameter in order to activate a subtle and temporal effect on the printed photochromic designs. The design practitioners could apply this parameter innovatively to enhance the visual appearance of a textile product. For example, the ability to dynamically change the surface appearance of a garment without using any external power sources (batteries) or integrating conductive material could open up new design opportunities in fashion designing. Further experimentation could result in innovative garments or textile accessories with the ability to animate the appearance in an indoor or outdoor environment.

Artificial UV lights including UV torches, UV bench lamps or high-intensity UV spotlights can also be used as activation methods for the textiles printed with water based photochromic inks. According to Viková, Christie and Vik (2014), the UV radiation intensity can determine the colourfulness of a photochromic textile, thus, the *operating duration* or *operating distance* of the artificial UV lights can be used as decisive parameters in order to make an impact on the visual characteristics of printed photochromic textiles [15].

The paper also examined the potential of using SMD UV LEDs as an electronically controllable activation method to instantly trigger a larger area of printed design with stronger photochromic colours. In order to obtain strong photochromic spot that has a diameter of approximately 12 cm, the SMD UV LED had to be positioned 30 mm away (from the reverse side of the printed PCW fabric) and should be switched on for 10 seconds under 3.5 V. It is also possible to further enhance the colourfulness of the activated spot, however, that require a longer operation of the SMD UV LED (i.e. switching on the LED for 15 seconds). As an approach to activate circular zones in designated areas of a larger printed photochromic design, a number of SMD UV LEDs can be used as a grid panel and can be complemented with electronic circuitry. Different *operating durations* and *sequences* of the SMD UV LED would enable the different spots of the photochromic design to activate in variable colourfulness.

The ability to electronically control the photochromic effects with small-scale SMD UV LEDs would create new application scenarios for multi-colour changing printed photochromic textiles. For example, this technology can be applied to design large scaled smart textile displays or textile hangings to enhance the visual experiences within a built environment. Since the SMD UV LEDs can influence an instant activation of a larger circular zone, minimum numbers of LEDs are required to activate a complete decorative imagery or pattern screen printed with photochromic inks. The printed textile designers could consider the positioning of the SMD UV LEDs and the measurement of the activating circular zones to design decorative images or patterns. Depending on the photochromic colour changing inks being used to screen print the image or pattern, the decisive parameters of *operating duration* and *operating sequences* of the SMD UV LEDs could be programmed. This would enable the observer to experience a dynamic visual effect where larger spots in different areas of the printed design simultaneously appear with multiple colours, change into totally different colours and gradually return to their original state while visualising multiple transitional hues. Moreover, it is also possible to develop complex electronic circuitry that can sense external information (i.e. distance, voice levels) and control the decisive parameters of *operating duration* and *sequences* of the SMD UV LED grid panel. Such features could invite the observers to interact with the photochromic textile display/hanging and consequently, facilitate an unpredictable activation of dynamic visual effects on printed photochromic textile surface.

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