Self-deStaining Textiles: Designing Interactive Systems with Fabric, Stains and Light

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Figure 1: We explore the interplay between fabric, stain and light to create an interactive slow display. (a) We use programmable LEDs to pattern (b) a phone case stained across the full surface (c) for aesthetic purposes.

ABSTRACT

This work introduces "destaining" as an interactive component for the HCI community. While staining happens unintentionally (e.g., spilling coffee), *destaining* can be used as an *intentional* design tool that selectively degrades stains on textiles. We explore the design space using silver doped titanium dioxide (TiO_2/Ag), stains and light as a set of design primitives for interactive systems. We then developed replicable and accessible fabrication and testing methods that enable HCI researchers and designers to upgrade various fabrics to *self-destaining textiles*. Next, we demonstrate a Self-deStaining textile interface with embedded Light Emitting Diodes (LEDs) and moisture sensors that activate cleaning. Lastly, we showcase how the textile can be used in everyday objects such as self-cleaning clothes, a patterning station for phone cases, and accessories that change patterns and colors based on the user's experiences.

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CHI '21, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8096-6/21/05…$15.00
https://doi.org/10.1145/3411764.3445155

CCS CONCEPTS

• **Human-centered computing → Displays and imagers**; **Ambient intelligence**.

KEYWORDS

Smart Textiles; Self-Cleaning; LEDs

ACM Reference Format:
Fiona Bell, Alice Hong, Andreea Danielescu, Aditi Maheshwari, Ben Greenspan, Hiroshi Ishii, Laura Devendorf, and Mirela Alistar. 2021. Self-deStaining Textiles: Designing Interactive Systems with Fabric, Stains and Light. In *CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3411764.3445155

1 INTRODUCTION

When people stain their clothing or their furniture, it is typically unintentional and unwanted—as the term "stain" has a negative connotation. Thus, the response to staining is typically discomfort and a strong desire to reduce the stain (what we call "destain") immediately. This paper explores techniques for automating this process upon textiles by coating textile fibers with nanoparticles that destain when the fabric is exposed to Light Emitting Diode (LED) lights.

Through our explorations, we came to see multiple perspectives on staining within design research and began to study staining/destaining as a design tool. On the one hand, a stain is a mark that our technology can interactively remove. On the other hand, a stain is another form of dying or textile patterning that emerges from chance, rather than designer intent. To explore the intrinsic design value of both perspectives, this paper proposes *destaining as a tool for designing interactive textiles*. Specifically, we propose a *Self-deStaining* interactive textile that degrades organic matter through an LED interface controlled by the user and/or triggered by environmental factors such as light exposure (Figure 1). We describe them as "self" destaining because all of the components for stain degradation are inherent within the material and structure of the textile itself, rather than requiring the use of an external system such as a washing machine.

Over the past decade, interactive (or "smart") textiles have grown as an important area of study within HCI. Researchers have proposed interfaces that use thermochromic inks [20], photochromic inks [32], and liquid crystals [71] to turn textiles into soft displays. Furthermore, other work integrates piezoresistive materials [30] into textiles to embed sensing. Our work contributes to this growing body of work by focusing on the process of destaining (or "undying" — the opposite of the traditional dying) that can be triggered by light. Specifically, we interact with stains on cotton fabrics with a combination of photocatalytic nanoparticles (TiO_2/Ag) and LEDs. We then experiment with several ways in which these materials can be used within an interaction life-cycle: from removing a food stain to creating a fabric whose pattern can be changed on a daily basis.

Our *Self-deStaining* textile is designed using *light* and *stain* as materials for interaction. We explored the potential of our Self-deStaining textile for *passive interaction* (using sunlight, and desk lamps) and *controlled interaction* (using embedded LEDs). In terms of *passive interaction*, we used our Self-deStaining textile to create photograms and to sew everyday accessories. We observed how these accessories degrade in color uniquely to the experiences, movements, and environments of the user. In terms of *controlled interaction*, we first built an LED patterning station that we use to customize everyday accessories, such as a phone case (Figure 1). We also demonstrate a generic Self-deStaining textile interface with embedded LEDs and moisture sensors for real-time feedback. In the future we envision a complete closed-loop textile architecture, where the liquid stains can automatically activate the embedded LEDs for programmed destaining and adjust real-time according to environmental factors.

Thus, in this paper, we provide a set of tools for the HCI researchers to use *destaining* for interaction design. We present in detail the fabrication methods that we use to embed self-destaining and interaction in the fabric. We provide a design space for our textile that compares how different fabrics, coating methods, stains and light sources impact the design of our textile interface. Within our design space we provide technical evaluations of the design parameters, through comprehensive experiments and measured data. We demonstrate a generic textile architecture and showcase several applications that interact with it. Lastly, we present the limitations of our work, and discuss its implications for the future of design research.

2 RELATED WORK

2.1 Interactive Textiles in HCI

Over the last two decades, and in the previous few years especially, e-textiles (i.e., textiles that can embed electronics) have become a core focus area for interaction design [11, 53, 56], as most textiles can be wired electrically by merely sewing, weaving or knitting conductive yarns into their structure.

Recently, Project Jacquard brought interactive textiles into the spotlight by exploring inexpensive fabrication and demonstrating the potential of interactive textiles for wearable computing [57]. Researchers have also proposed textiles as a medium for communication by integrating passive communication protocols that enable information exchange between humans and spaces [16]. Other recent work demonstrates the potential for textiles to support common forms of sensing [7, 27, 30, 45, 70].

Researchers have also explored integrating other non-traditional materials into textiles (e.g., optical fibers [35], and flexible diodes [34]), thus enabling them to act as interactive displays [28]. One of the most intriguing HCI design space revolves around the creation of non-emissive displays by using thermochromic threads, first demonstrated by Maggie Orth in the late 90s [53]. Since then, thermochromic pigments have been utilized within smart textiles to create a wide range of textile displays and interactive wearables [9, 10, 20, 33, 55]. Similarly, photochromic pigments have also been incorporated into interactive to create soft displays [32]. A different approach was taken by the Mosaic textile that utilized liquid crystals rather than ink to create a flexible display [71].

In our work, we combine textiles with LEDs (both integrated into the textile structure or interacted with through external devices), and a light-reactant nanocoating to create novel slow displays and programmable material patterns. We present our textile in conjunction with stain as an aesthetic material and destaining as a design tool. The nanocoating we use has a non-reversible effect, i.e., unlike prior work using pigments, our destained textile does not revert to its original color once it stops being exposed to light. Yet, the material can always be re-stained and reprogrammed with patterned light when desired.

2.2 Bio-textiles

Our work is placed at the intersection of textiles and biomaterials, a recent focus of the HCI research [42, 54, 76]. Examples of recent works include BioLogic that uses natto cells as an actuator for shape-changing interfaces [76], Living Color that explores the possibilities of bacteria as a pigment [15] and Semina Aeternitatis that use genetically-engineered biofilm as data storage [4]. Worth mentioning is the important role that the DIYbio community has played in making biological tools and procedures accessible to HCI researchers [24, 36].

Our work perceives stain, an organic compound, as a natural dye and contributes by discussing the design workflow for HCI researchers, designers, and non-biologists to fabricate Self-deStaining textiles in an accessible studio setting, using off-the-shelf materials.

2.3 Cleaning Textiles

As mentioned, in this paper we propose *destaining* as a design tool and *stain* as an aesthetic material. However, traditionally, destaining is associated with cleaning and a certain perception of cleanliness.

The typical methods for cleaning most textiles involve washing [26] and dry cleaning [8]. While these methods are do-it-yourself (DIY), there are cases when professional dry cleaning needs to be used (e.g., for textiles sewn onto furniture). Ultraviolet (UV) light is an alternative that significantly reduces the labor-intensity of cleaning [74]. Due to rising concerns in sanitization, UV light has now been integrated into a variety of daily objects from hand-held wands [72] to ceiling fans [41], to automatic robots that sterilize hospitals [61], or systems that sterilize airplanes [65]. Unfortunately, the germicidal properties of UV are also carcinogenic and cataractogenic, which means that humans must not be present when the light does their cleaning. However, scientists have recently discovered that far-UVC light (207-222 nm wavelength) may not be harmful to humans and will still kill microbes [74]. Because UVC is such a new cleaning technology, and its full-range effects on humans are still studied [1], we chose to work with a technology that is activated by visible light — photocatalytic nanocoatings. Unlike other cleaning methods, photocatalytic nanocoatings can clean non-removable textile surfaces (e.g., couches), and are safe for humans to interact with, commonly being found in daily products, e.g. toothpaste [22].

Moreover, the photocatalytic nanocoatings we use in this work are self cleaning, i.e., the cleaning is triggered by merely exposing it to light and thus does not require any input from users. Once the nanocoating is applied to a surface and exposed to light, the nanoparticles automatically begin to degrade the organic matter present on the surface. This process is depicted in Figure 2, where the input energy (light) causes an electron to jump from the valence band to the conduction band. The negatively charged electron (e^-) then causes a reduction reaction in the conductive band, and the positive hole left behind (h^+) in the valence band causes an oxidation reaction. These reduction and oxidation (redox) reactions produce oxide ions (O_2) and hydroxide ions (-OH), which break down organic matter (typically made up of carbon and hydrogen) into harmless byproducts such as CO_2 and H_2O [78].

While photocatalysts are toxic to a wide range of organisms (fungi, algae, bacteria, and viruses), they do not attack human cells making them safe to interact with [25, 73]. So far, the most cost efficient, non-toxic, and effective photocatalytic coating is titanium dioxide (TiO_2) doped with silver to accommodate visible light (we denote it TiO_2/Ag) [46, 47, 77, 78]. To make our work as accessible as possible to other designers and HCI researchers we did not manufacture the coating ourselves, but rather used a commercial TiO_2/Ag from USA Nanocoat [49].

As mentioned, in our work, we combine textiles with LEDs, and the TiO_2/Ag nanocoating to create Self-deStaining textiles that suggest new directions for interaction design with stain and light.

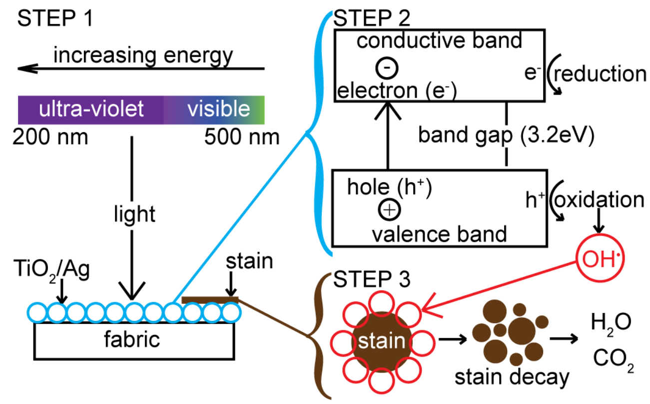

Figure 2: Schematic representation of the photocatalytic destaining triggered by TiO_2/Ag nanocoating. (Step 1) light hits the coated and stained textile; (Step 2) energized electrons in the nanocoating jump from the valence band to the conductive band, causing redox (reduction and oxidation) reactions; (Step 3) hydroxide ions (-OH) surround the organic stain and break it down into harmless byproducts (CO_2 and H_2O).

3 DESIGN PROCESS

In Figure 3 we sketch our proposed design process for self-deStaining textiles, which contains five main steps: (1) coating, (2) staining, (3) LED integration, (4) programming the textile and (5) light exposure.

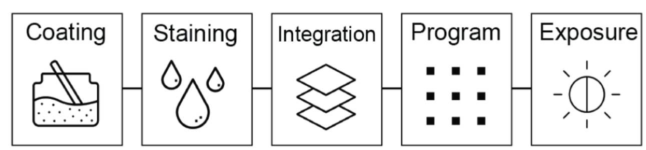

Figure 3: Schematic representation of our proposed design and fabrication process for Self-deStaining textiles containing the following main steps: coating the fabric with TiO_2/Ag, staining the fabric with common food and drinks, integrating the LEDs into the fabric, programming the Self-deStaining textile, and exposing it to light.

(1) Coating - The base material for our Self-deStaining textile is *woven cotton* that we coated in photocatalytic nanoparticles (silver doped titanium dioxide or TiO_2/Ag) though a similar process could be applied to *knitted fabrics* as well. When exposed to light for several hours, the TiO_2/Ag nanoparticles degrade organic matter, including food stains and microbes. Using commercial materials and easy to access tools, we first investigated various techniques to coat the cotton fabric with TiO_2/Ag. Specifically, we tested three methods: painting, immersing, and spraying. In Section 4.2 we provide a direct comparison of these methods and discuss the design implications for each of them. Our tests showed that destaining (i.e., reducing stain) is best achieved when using the *painting* method, rather than immersing or spraying.

For that reason, we demonstrated all of our applications (Section 5) using painting. Once the fabric was coated, we dried it and let it cure for one week. Both the TiO_2 particles and the byproducts of the chemical reaction are classified as non-hazardous (found in toothpaste, paint and cleaning products [22]). When working with the wet coating, we wore gloves to prevent skin oils from contaminating the coating. Once the coating is dry, the coated fabric is safe to touch and its effectiveness does not significantly change with interaction. The coating can be washed up to 10 times according to the manufacturer [49].

(2) Staining - Once the Self-deStaining textile is fully cured, we further stained it with common unintentional food stains (tea, cola, coffee, turmeric). Similarly to coating, we discuss different types of staining in Section 4.3 and their implications for the design process.

(3) LED integration - After the Self-deStaining textile is ready, we then integrate sensors and actuators including LEDs onto the textiles. The LEDs can be sewn into the textiles using conductive yarns. To add *controlled* interaction to our textile, we embedded programmable LEDs in double-woven (e.g. two layer) coated fabric, thus creating a Self-deStaining textile interface that can be controlled by the user (details in Section 5.2). After 20hrs of LED-light exposure, the textile destaines as desired. We further demonstrate an embedded moisture sensor that turns on an LED when stained. This feature enables automatic destaining, i.e., at the time when the stain has occurred, which may happen long before the stain dries out and can be observed with the naked eye by the user.

(4) Programming the textile - This step is straightforward and its ease highly depends on the type of programmable LEDs that are embedded into the textile. We have successfully controlled our LEDs with both Arduino and Metro boards that have an integrated programming environment to support LEDs (i.e., they have dedicated libraries and plenty of support for strand and control tests).

(5) Light exposure - The destaining process is triggered when the Self-deStaining textile is exposed to light. The wavelength and intensity of the light, the exposure duration, all these parameters play an important role in the destaining process as presented in Sections 4.4 and 4.5. Moreover, different light sources, such as sunlight or programmable LEDs, can add either passive or controlled interactivity to our textile. In Section 5 we present the applications we made to explore designing using *light* and *stain* as materials for interaction. For example, we sewed everyday accessories (a hair scrunchie and a face mask) that were worn outside (i.e., exposed to sunlight) for seven sunny days. We also created photograms by layering a negative stencil on our Self-deStaining textile, and then exposing it for a day to sunlight and a desk lamp.

4 DESIGN SPACE AND STUDY IN DESTAINING MATERIAL PROPERTIES

As mentioned, our *Self-deStaining* textile is designed using *light* and *stain* as materials for interaction. In this section, we sketch the design space by presenting the parameters that have the most influence on designing the textile, namely: fabric, coating methods, stains and light. When programming the destaining, the user can vary these main parameters to get desired results. We explore the design space by testing three or more examples for each parameter. We structured this section so that we discuss these parameters separately, while emphasizing the interdependencies when necessary.

4.1 Fabric

One of the goals of this work is to make our Self-deStaining textile accessible to researchers and designers at large. Thus, we explored commercial fabrics that can commonly be found in studio settings (we purchased all our fabrics from JOANN Fabric and Craft [30]). Specifically, we tested four types of fabrics: (1) 100% cotton, (2) 100% polyester, (3) a blend of 65% polyester and 35% cotton, and (4) 100% nylon.

We found that all four fabrics can be easily coated using the three coating methods described in the next subsection. However, after a series of experiments we learnt that there was a significant difference in the amount of destaining among the four fabrics. For that, we stained the four fabrics with 500 µl coffee and exposed them to ambient light inside (~700 Lumens) for 72 hours. The results showed that stain degradation differs in between fabrics for the same method of coating. As can be seen in Figure 4, we used the standard root mean square equation in colorimetry [68], (Equation 1), to calculate the composite RGB values of coffee stains on each fabric coated using the painting method. Larger RGB composite values indicate lighter colors (white composite value = 441.67, black composite value = 0).

$$CompositeRGB = \sqrt{(R^2 + G^2 + B^2)} \tag{1}$$

The results in Figure 4 show that the stain that degraded the most was the cotton sample that was painted on both sides (composite value = 354.0). We observed that cotton is significantly better at degrading the stain, regardless of the coating method used (the results for spraying and immersion are presented in Figures 1 and 2 in the supplementary material).

4.2 Coating Methods

We then explored how different coating methods impact stain degradation. To do so, we applied the nanocoating to cotton fabrics using 3 different ways: painting, immersing, and spraying. We used the multipurpose photocatalytic coating LumaClean Multipurpose from USA Nanocoat [49], shown to not have harmful effects on human skin or the environment [22]. The coating is liquid, consisting of nanoparticles of titanium dioxide doped with silver (denoted TiO_2/Ag). As shown in Figure 5, the coating does not alter the original fabric in visual or textural/haptic ways. Thus, even when coated with TiO_2/Ag, the fabric can be used for the same purposes as usual.

We chose the three coating methods based on related literature. Zahid et al has used high pressure air brushing [77], other researchers coated by immersing the fabrics in a sonication bath of nanocoating [40, 78], and the instructions from USA Nanocoat recommend painting [49]. To make these methods more accessible,

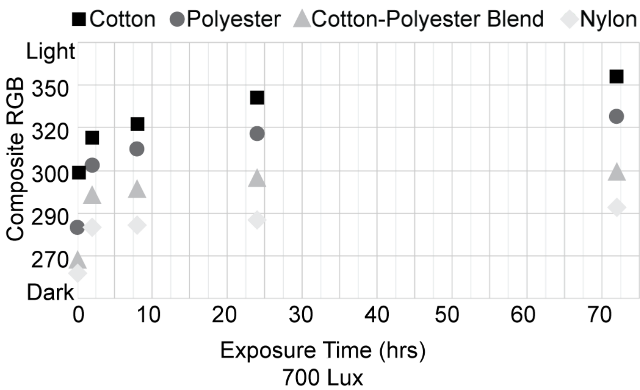

Figure 4: We compared the destaining effectiveness between four different fabrics (cotton, polyester, cotton-polyester blend and nylon) painted with TiO_2/Ag on both sides. The destaining is measured as the composite RGB values of coffee stains after light exposure for the shown time interval. As observed, cotton is significantly more effective at degrading the stain (the larger composite RGB values, the lighter the stain).

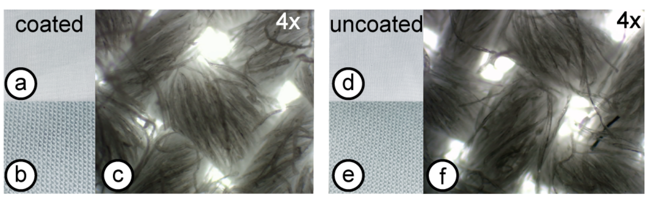

Figure 5: Images of the coated woven cotton fabric (left) versus the uncoated fabric (right) as seen through (a,d) the naked eye, (b,e) a macro lens for the phone camera and (c,f) a 4x magnification microscopic lens. The texture of the original fabric is not affected by the coating visually or haptically, thus the coated fabric can be used for the same purposes as usual.

we substituted lab equipment for off-the-shelf tools, such as a shallow plastic tub for immersing (Figure 6b) and a misting bottle for spraying (Figure 6c).

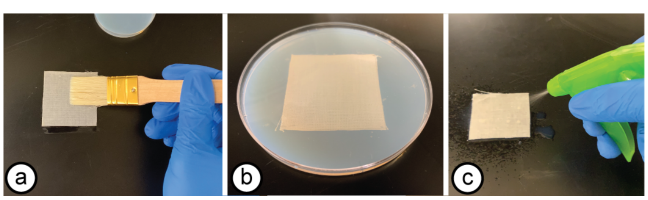

Figure 6: We coated fabric swatches with TiO_2/Ag using three different methods: (a) painting, (b) immersion and (c) spraying.

- Painting — As shown in Figure 6a, we applied the nanocoating (~5 ml) to each side of the fabric sample with a paint brush at room temperature (~22 °C). After one side was coated, the sample was dried on the table for 3 hours, flipped, and then coated again with another 5 ml of nanocoating. The samples were left to cure (air-dry) at room temperature for 7 days.
- Immersing — As shown in Figure 6b, fabric samples were immersed in a shallow bath containing 30 ml of nanocoating for 30 minutes, then removed and dried on a table at room temperature. The samples were left to cure (air-dry) at room temperature for 7 days.
- Spraying — As shown in Figure 6c, 50 ml of nanocoating was placed in a spray bottle, and each sample was misted with four squirts of nanocoating (~5 ml), dried for 3 hours, flipped, misted on the other side, and then dried again. The samples were left to cure (air-dry) at room temperature for 7 days.

Similarly to our textile test, after coating and curing the samples, we stained them with 500 µl of coffee and exposed them to ambient light (~700 Lux) inside for 72 hours. The results are presented in Figure 7. We observed that the painted cotton provided the best results in terms of stain degradation, at any time of the light exposure, while the sprayed cotton degraded the least. Based on these results, we decided to use this combination (cotton coated via painting) for this work. All the following images and examples in the paper use cotton painted with TiO_2/Ag, unless specified otherwise.

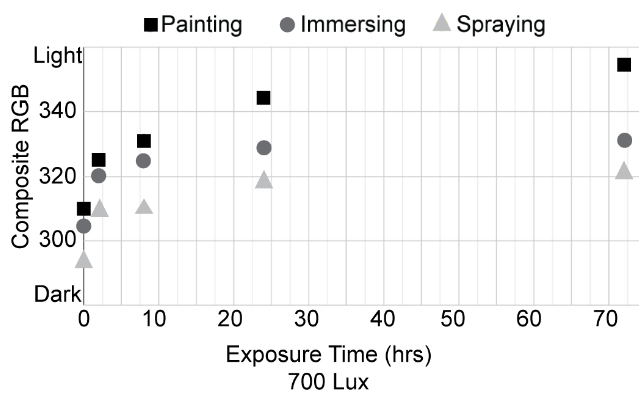

Figure 7: Composite RGB values of coffee stains on cotton fabric coated with TiO_2/Ag by painting (blue), immersing (red) and spraying (yellow). The composite values were calculated using Eq. 1. The painted cotton provided better destaining than sprayed and immersed cotton.

4.3 Stains

As mentioned, in this paper we think of stains as a design parameter, rather than something only to be removed, and of destaining as a creative design tool, rather than a chore. Thus, we explored stains that are commonly unintentional, such as food and drink stains. Specifically, we stained our fabrics with coffee, cola, hibiscus tea, black tea, peppermint tea, curry sauce (turmeric based), and methylene blue, all bought from nearby stores such as Costco [64]. The staining methods depend on whether we performed quantifiable tests (in which case we poured 500 µl of stain in the middle of the swatch like shown in Figure 9a), or whether we wanted to stain a larger surface (in which case we dipped the swatch).

As seen in Figure 8, the nanocoating degrades only the stain but does not change the color of the dyed fabric. This happens because most fabrics are dyed using synthetic compounds (i.e. chemicals that set the color permanently). We envisioned stains made of organic matter (i.e. natural pigments without chemical fixatives), which is why we chose a coating that degrades only organic matter.

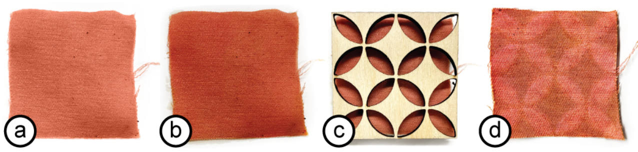

Figure 8: (a) Cotton fabric swatch synthetically dyed pink and coated with TiO_2/Ag. (b) Dyed swatch uniformly stained with coffee. (c) Swatch exposed to light with a stencil placed on top. (d) Swatch after exposure indicates degradation of coffee stain, but no degradation of pink dye.

As stated previously, applying coating on the textile does not change the visible texture or haptic feel of the fabric. However, its nanostructure is changed, specifically by making the fabric more hydrophilic. Figure 9 shows swatches of coated and uncoated fabric stained with methylene blue. Immediately after staining (i.e., before light exposure), the stains form a more circular shape on the coated fabric (more hydrophilic).

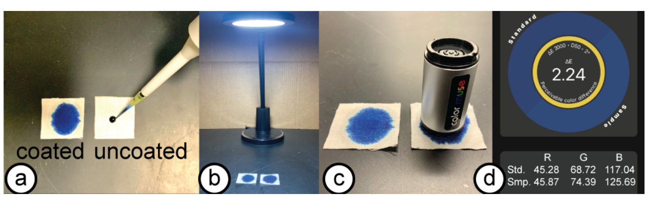

Figure 9: (a) Staining swatches of coated fabric (left) and uncoated fabric (right). (b) The coating increases the hydrophilic properties of the fabric leading to more circular stains on the coated fabric (left) than the uncoated fabric (right). After staining, we exposed the swatches to light. (c) We use the Color Muse instrument to measure the RGB values of the stains after exposure. (d) The color muse connects to a phone application that displays the RGB values.

After we stained the fabrics, we exposed them to light, testing with different light intensities and exposure times (Figure 9b). Then, as shown in Figure 9c, we measured the degradation using Color Muse, an RGB value indicator instrument [43].

In terms of creating a Self-deStaining textile, we did not observe significant differences between these types of stains. As we present in Section 5, our applications alternate through different stains and staining methods. However, for very dark stains (e.g., methylene blue) or light stains (e.g., peppermint tea), the degradation can only be measured with the RGB meter, as it is barely observable with the naked eye.

4.4 Light

The user can decide between different light sources (e.g., LEDs, lamps, sunlight), and vary the light intensity and exposure time, thus programming specific stain nuances or even fully destain to give the effect of negative space in patterns. The choice of light source impacts the interactive properties: either controlled (programmed LEDs) or passive (sunlight).

Since the source of light is very important to the interactivity part of our Self-deStaining textile, we were interested to learn how much light intensity we need for an effective stain degradation on our textiles. We exposed our samples to light illuminance ranging from 127 to 2365 Lux, for up to 24 hrs, taking measurements periodically. To generate the needed light intensity, we used a 12 Watt LED desk lamp from JUKSTG [38] and we measured the illuminance using the BT-881D Digital Illuminance Light Meter from BTMETER [13]. The lamp includes 10 brightness levels and 5 lighting modes (3000-6000K temperatures) [38].

In Figure 10 we present the results of the tests using cola. The results show that as light intensity increases, so does the degradation of the stain. In Figure 3 of the supplementary material, we present the results for methylene blue (a common dye to test for destaining in prior work). The light intensity needed for destaining falls in an accessible range, thus, as we present further in the paper, we obtained good destaining results using embedded LEDs (~2000 Lux) and sunlight.

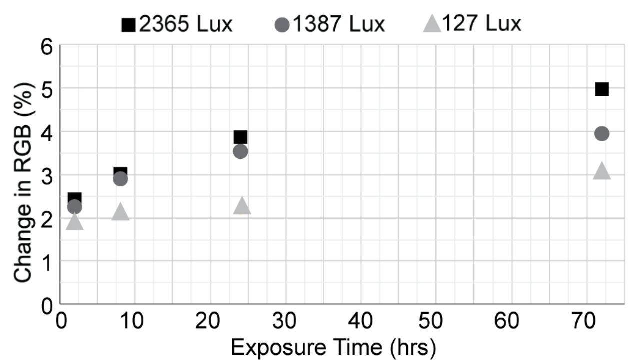

Figure 10: Light intensity impact on destaining cola stains on TiO_2/Ag cotton. Destaining is measured as percent decrease in composite RGB values. As observed, de-staining increases with light intensity and time exposure.

4.5 Light Exposure Time

Another important aspect for interaction when designing with our Self-deStaining textile is the reaction time, or in other words the exposure time needed until visible changes can be perceived in the textile. Figure 11 shows the change in the stains over time when exposed to a high intensity light. Our sample was stained by submerging the cotton in coffee for 5 minutes and then exposing it to 2365 Lux of light over the course of 36 hours. As expected, the more exposure to light, the better destaining.

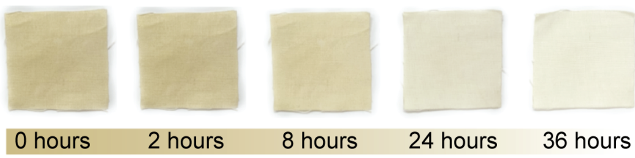

Figure 11: Destaining coffee on coated cotton exposed to 2365 Lux light over 36 hours. The destaining is more effective the longer the fabric is exposed to light, however there are visible changes within the first 8 hours of exposure.

4.6 Light Diffusion through the Fabric

As shown in Sections 4.4 and 4.5, the activation of the nanocoating highly depends on the light intensity, and its effectiveness increases with time. So far, we have done all our exploration using external light sources (a desk lamp). However, in the context of embedding LEDs for interaction design and destaining our textile, there is another parameter to consider: that is the light diffusion rate through fabric which may impact the destaining process as follows. Firstly, the fabric acts as a diffuser for light, thus reducing its intensity and overall, the effectiveness of destaining. Secondly, when interacting with our textile to program the destaining, the light diffusion may result in less sharp destaining than desired (in terms of its resolution). In this section we investigate how the light diffuses through the surface of the fabric, by sewing an LED sequin and then measuring its change in illuminance at different points across the textile. The measurement gives an understanding of how the LED placement in rapport with the fabric, and by expansion with the textile architecture, affects destaining.

We embedded an LED on the textile in three different ways: LED on top of the fabric, LED with a hole cut, and LED behind the fabric (see Figure 12). We used warm white LED sequins from Adafruit (4 x 9mm, 2mm thick including the LEDs 100-ohm resistor) [62]. When powered by 3.3V and connected to a Metro board [12], the LEDs draw about 5mA. To measure the maximum impact on light diffusion and minimize the light refraction we used black 100% cotton fabric instead of white, purchased from Coupang [52]. The LEDs are hand-sewn with a conductive thread as instructed on the Adafruit website [5]. Specifically, after the LED is stitched a few times, the thread is tied in a knot at the back and a running stitch is made to extend the connection to the edge of the fabric so the tip of the jumper wire can clip on to it. Another conductive thread is used for the - pin repeating the steps. Then, the + and - pins are connected to the 3.3V battery and controlled using a Metro board [12].

As shown in Figure 12a, we first embedded an LED on top of the fabric. Next, we embedded the LED with a hole cut (Figure 12b), i.e., the sequin was placed face down on the fabric and a cut out was made that matches the size of the diode on the sequin. Lastly, we embedded the LED behind the fabric (Figure 12c), i.e., that the sequin was placed down on the fabric to understand how the effect of fabric has on the measured illuminance. Next, we discuss how the different LED placements affect light diffusion through the fabric.

To guide our measurements we created a grid of 17.5 by 17.5 cm with cells of 3.5 cm diameter, and took measurements every 0.5

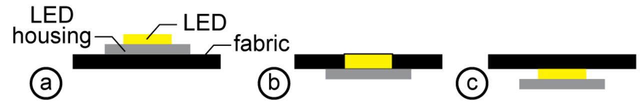

Figure 12: We investigated three methods to integrate LED sequins into fabric: (a) LED on top (b) LED with cut-hole (c) LED behind the fabric. The LED sequins were stitched to the fabric using conductive thread, and powered using a 3.3V battery.

cm (Figure 13a). The illuminance (lux values) is measured from the central LED to the edge of the fabric. The grid was positioned 10 cm below the LED on the fabric with 180 viewing angle which gave us a constant z value from the fabric to the tabletop (Figure 13b). The light meter sensor was wrapped with a cone to ensure localized measurements. All measurements were taken inside a cardboard box (25 cm x 25 cm x 10 cm), and in a dark room to avoid interference from ambient light.

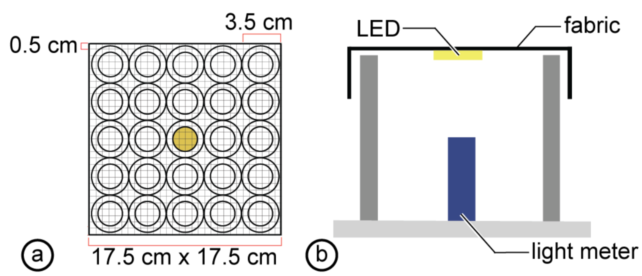

Figure 13: (a) Grid of 3.5 cm cells that guides the placement of the light meter (b) Test set-up that gives a constant z value from the fabric to the table top

In Figure 14, we present the results after measuring light illuminance for all three different LED placements (on top, cut-hole and behind the fabric). The results show that the highest illuminance is measured for the LED placed on top of the fabric, followed by the LED with cut-hole, and the lowest values are measured for LED behind the fabric. The LED behind the fabric shows very small variations in illuminance across the surface of the fabric (in average 0.1 lux decrease in each sample data). In spite of lower light intensity emitted and thus high light diffusion, we chose this configuration (i.e., LED behind the fabric) for our proposed architecture, because of its even light dispersion, which makes it easier to control. We observed that once we have the required threshold for the light intensity to activate the nanocoating, embedding LEDs behind the fabric will evenly distribute the light across the surface of the fabric for an effective stain degradation process.

5 APPLICATIONS

So far, we explored the interplay between fabric, stains and light and presented how they can be used for textile design. In this section, we go beyond that and use destaining to create both aesthetic, enjoyable and functional slow displays. We define "destaining" as the procedure of staining coated cotton with unintentional stains,

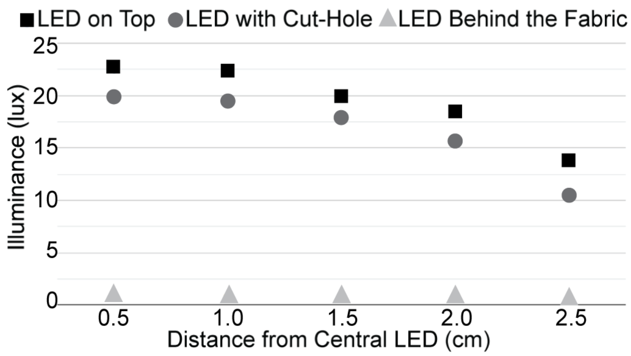

Figure 14: Results after measuring light illuminance of embedded LEDs in the fabric. The measurements were taken for all three different LED placements (on top, cut-hole and behind the fabric). The results show that the LED sewn behind the fabric distributed uniformly the light across the fabric.

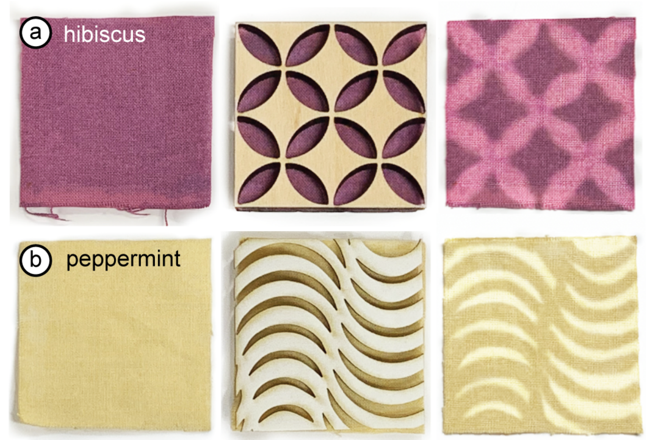

Figure 15: *Un-dyed* photograms. We obtained these photograms using Self-deStaining textile stained with (a) hibiscus and (b) peppermint tea. The photograms were obtained after 24 hrs exposure to 2365 lux light.

Figure 16: Hair scrunchy made using our Self-deStaining textile and stained with hibiscus. (a) initial textile unraveled; (b) textile sewn as a hair scrunchie; (c) the patterned scrunchie after it has been worn outside for seven days. The pattern reflects the user's unique experiences, movements, and environments, and enables imprinting the memory of special days (e.g., wedding) into tangible objects.

and then intentionally exposing parts of the textile to light so that the stain degrades to reveal creative designs. Traditionally, *dying* is used for such purposes; in this work we propose destaining as an *"un-dyeing"* technique, however used for the same purposes. In the following subsections we introduce several applications that we developed using our interactive Self-deStaining textile.

5.1 Passive Interaction

5.1.1 Solar Printing. We then go beyond using the photocatalytic coating as a method of self-cleaning (i.e., simply removing unwanted stains from clothing or furniture), by *intentionally* using our "un-dyeing" technique for creating photograms, traditionally used in camera-free photography by layering patterns on top of a light-sensitive material [21]. This idea stemmed from the desire to utilize stains and light as more traditional craft material. To create these photograms, we placed laser cut stencils on top of our Self-deStaining textile stained with hibiscus and peppermint tea. As shown in Figure 15, once exposed to light, the stains degraded according to the location of the cutouts in the stencil. In this perspective, we use stained fabric as an empty canvas, light as our paint, and stencils as our paintbrushes.

We furthered the concept of creating patterns with environmental light by creating accessories, such as hair scrunchies and face masks. As shown in Figure 16, as the user wears these items around outside, the stain degrades in ways unique to their experiences, movements, and environments. These items enable sunlight to encode the memory of special days (e.g., wedding day, the "firsts" of a newborn) into tangible objects.

5.2 Controlled Interaction

We then explored how to actively control the destaining via programmable LEDs. For that, we built a patterning station that we used to customize a phone case. We then demonstrated individual components of our potential Self-deStaining textile interface, which includes LEDs embedded into a woven textile and a moisture sensor that provides real-time feedback. In the future we aim to combine these components into a complete closed-loop textile architecture, where the stains automatically activate the embedded LEDs for programmed destaining.

5.2.1 LED Patterning Station. We built an interactive system using programmable LEDs that enable the user to control destaining. To do this, we stained coated cotton with hibiscus across the entire surface, and then exposed it to a programmed LED matrix (Figure 17). After 20 hours of exposure to the LEDs, the stain successfully degraded to match our programmed pattern. By using light to manipulate the stain, we created a slow display. As shown in Figure 17, we used the station to pattern a phone case (priorly stained with hibiscus tea) for aesthetic purposes. The user can then re-stain the textile, program a different pattern, and re-expose the textile for a new design.

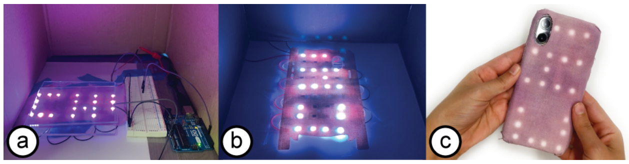

Figure 17: To interact with our Self-deStaining textile, (a) we use LEDs programmed with an Arduino. (b) The coated textile is placed on top of the LEDs and then exposed to their light for 20 hrs in a closed box to avoid interference from the ambient light. (c) After exposure, the textile is adhered to a phone case.

5.2.2 Woven LEDs. We demonstrate a component of our potential Self-deStaining textile interface, that is LEDs embedded into textile. As shown in Figure 18a, we first used double weaving [19] to make a swatch with tubes large enough for LED strips. For our swatch, we used cotton in the warp direction and wool in the weft direction. Next, we coated the woven sample with TiO_2/Ag, stained it with coffee. Then we placed the LED strips into the woven pockets (the LEDs we used were not waterproof, when using waterproof LEDs they can be embedded in the textile before coating and staining). Each LED strip had three LEDs creating a 9 by 9 matrix within our textile. We then activated our programmed LED matrix for 20 hours (Figure 18b). After exposure the stain had degraded in our programmed shape (an x). Degrading stains with internally embedded LEDs can be used to activate cleaning in specific regions of a textile, and it can also be used to programmatically reveal a pattern over time. For instance, revealing data about the use of a particular product in a form that would be lasting beyond the lifespan of the product, similar to the concepts shown in the Patina Engraver project [39].

Figure 18: Embedding controlled interaction in our Self-deStaining textile. (a) We first weaved a swatch made of cotton tubes with embedded LED strips (b) Then we coated and stained the swatch. Last, we programmed the LEDs to display a X shape (bottom middle). After 24 hrs exposure, the swatch was destained accordingly. In the bottom right picture, the LEDs are off, the light dots are the direct result of destaining.

5.2.3 Closed-loop Textile Architecture. Lastly, we explored the potential of using our Self-deStaining textile as part of closed-loop architecture with real-time feedback. Inspired by the Crying Dress project [14], we demonstrate a moisture sensor embedded in the textile (Figure 19). For that, we weaved two conductive silver yarns in the weft direction of the swatch, and then used LilyPad parts [63] to create our LED circuit. As shown in Figure 19, when water is poured onto the textile a bridge is created between the two silver yarns, the circuit closes, and the LED activates.

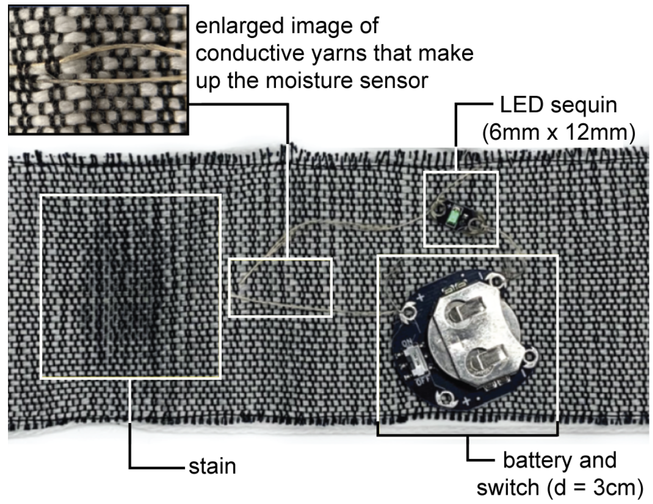

Figure 19: The conductive yarns are woven into textiles and act as a moisture sensor.

For our textile architecture we propose integrating various sensors (including moisture, capacitive and pressure sensors) and a larger array of LEDs. This will allow for a closed loop system to be embedded in the Self-deStaining textile. Such a textile architecture can detect the stain (spill of the liquids) real-time, sometimes even before the users can see it with the naked eye. Based on the feedback from the moisture sensor, this textile can activate the destaining process automatically, by turning on the preprogrammed LED patterns on the specific areas. Another potential use of this architecture is as a textile ambient display: patterns can be displayed with the different gradients of colors and negative space in the dyed area like tie-dye and batiks. Thus, the matrix of LEDs can be used to present information by blinking the light or displaying instruction for the users to follow. Furthermore, if capacitive and pressure sensors are embedded, then the textile can monitor the physiology of the body and activate the LEDs on the areas that are in the most contact with the surface. Such features are desired for scenarios where common objects are shared (e.g., cinema seats, library couches).

6 DISCUSSION AND FUTURE WORK

6.1 Constraints of our Self-deStaining textiles

While our proposed textile degrades stains in general, the effectiveness of destaining depends highly on the type of stain. Thus for tougher stains such as curry sauce or methylene blue (these stains contain pigments that adhere strongly to the fabric), destaining can be unsatisfying or not visible to the naked eye (e.g., methylene blue, see Figure 4 in the supplementary material). We also learnt that applying a uniform coating to already made garments that have an uneven surface can be challenging. Our textile also needs relatively long exposure time (over 12 hrs), which limits real-time interaction with the textile. However, for applications that aim to capture memories or experiences throughout the course of a day, this extended exposure time is beneficial. Finally, although LEDs provide enough illuminance for destaining, they can only be placed so close together as they need space for wires and resistors between them. This results in a low resolution destaining, and directly impacts the aesthetics of the design. In the future, we plan to explore weaving diode fibers [59] directly into the textile rather than embedding LEDs in woven tubes. We expect the diode fibers to create more uniformly distributed light than LEDs which will improve the efficiency of destaining. In spite of these limitations, our Self-deStaining textile still provides a creative design space (presented in Section 4) that can be used to customize textiles, or capture memories and experiences within textiles.

6.2 Self-Cleaning Challenges and Opportunities

Microbes are everywhere around us and are especially prominent in public places [3] such as movie theaters and ride-share vehicles. Despite the presence of bacteria and viruses everywhere, we have been happily living in cities without significantly worrying about cleanliness. However, with the increased frequency of epidemics (e.g.. zeka, ebola, H1N1, etc.) and even pandemics (covid-19), humans have become increasingly aware of how their public spaces are used (and possibly contaminated). In other words, our perception of cleanliness has shifted from naked eye evaluation (e.g., a surface is not stained, thus clean), to standards that now require written information about when and how a surface has been cleaned (e.g., a surface had been disinfected, thus there are no germs) [17]. The significant difference in the perceived and actual cleanliness of objects is likely to shape our interaction with them for years to come. This health issue is also an important HCI problem, since concern about exposure to infection is becoming a key consideration in the design of interactive products (e.g., touchless interfaces [2], wearable sanitizer [37]), especially those designed for use in public spaces, or by multiple users.

Studies have shown that visual cues help change the perception of cleanliness, which could then influence people's behaviors in public spaces. For example, people may infer from well stocked hand-washing supplies and emptied trash bins that the area is properly maintained and regularly cleaned [51]. One of these visual cues is *lighting*: previous studies have shown that lighting conditions change people's perceptions of cleanliness of littered areas in a simulated metro environment [48]. Moreover, lightning can be used as an effective visual cue to control the mood of the environment (e.g., in cinemas) or to help people navigate (e.g., following the exit sign). For example, specific types of LEDs are typically used in HCI to create ambient environments that provide a sense of comfort [18, 29, 67].

Our proposed textile packs both aspects mentioned earlier: it has self-cleaning properties and embeds programmable light. As explained in Section 2.3 and Figure 2, when exposed to light, the coating covering the textile is activated and degrades organic matter. In this paper we have explored the destaining properties of our textile, however research has shown that the coating can effectively degrade microbes, such as bacteria, fungi, algae and viruses [73]. The embedded LEDs can be used functionally to communicate the cleanliness of the textile, such as turning red when dirty, yellow while the cleaning process is active, and green when clean. They can also be used playfully to enhance the user's experience by adjusting dynamically according to the user's current activity (e.g., providing visuals on the seats in a movie theater that correspond to the movie that is playing). In the future, we plan to explore the potential of our textile for self-cleaning applications.

6.3 Stains as Aesthetic Materials

Materiality in interface design is becoming more and more important in HCI [58, 60, 69, 75] as it has been suggested that designers can take inspiration from materials themselves, as opposed to a predetermined design concept. By introducing destaining textiles we aim to widen the material toolbox used by HCI designers and researchers. Specifically, in this work, we note the blurriness between the terms *stain* and *dye*. While dye has a rich history in art, crafts, and design, stain typically has a negative connotation, especially when it comes to our interactions with our textile products. The negative perception of stains have resulted in the destaining process being thought of as a solution to a frequent problem for everyday users. The general tendency is to have a strong response to damage or repair, especially when it is about clothing that embed a dear memory or personal experience [23].

On one hand, destaining can be framed as the solution to a design problem, embracing the materiality of a stain as a common material that leaves permanent marks on textiles. On the other hand, destaining is an inspiration for new perspectives: stain as an opportunity for playful intervention in a similar way that certain outdoor art that only appears in the rain [6]; or the stain as a method for coating a surface such that imagery can be erased out, such as drawing with a scratchboard; or deStaining as method for making lasting solar prints upon textile material. Within this framing, we see deStaining as another method of resistive dyeing methods such as batik [31] or along the same trajectory of trends in using bacteria-based or natural dyeing on fabric to save water. Our design examples show multiple opportunities for emergence and control in the fabric: processes exploring emergent markings from sun and everyday life embrace impermanence and emergence as design values (e.g. [66]) while our LED patterning station shows how such textiles can allow for multiple instances of customization (through redyeing and patterning) as well as cleaning on items that might not otherwise be washed.

Our textile communicates its temporal status by destaining more the longer it is exposed to light, which provides an opportunity for the continual creation or revealing of new designs. Thus we describe our textile as a slow display: it functions on its own, performs destaining in the background, but it is still open to interaction, as the user can stop and reprogram it. Moreover, similarly to the olly and slow game [50], the slowness of the destaining fosters a longer-term relationship between the user and the textile. Coupled with other aspects of the technology, this could open up a whole new interaction between people and their textiles. For example, the coating can be even selectively applied to hide messages within soft objects that are slowly revealed or a surface that emphasizes time in a non-numerical fashion.

Future explorations into the stain as aesthetic may focus on the specific encounters that users want to mark through processes of destaining or a wider array of material tests to understand if such a method could be applied upon other fiber or non-fiber base products, such as 3D prints (in a similar fashion as [44]). Also, future work might explore how designers use such a method to programmatically redesign items that they love and like to change the look often (e.g. using stain to erase and light to reprogram the graphic on a t-shirt for instance).

7 CONCLUSIONS

In this paper we present Self-DeStaining textiles that control light to selectively destain materials. Our destaining textiles interface uses TiO_2/Ag nanoparticles, and LEDs to creatively interact with stains. We presented the design space for our textile – taxonomizing the design parameters such as fabric choice, coating methods, stain and light intensity and exposure. We then detail the design process such that it can be followed by HCI researchers and designers in a studio setting with easily accessible products. Lastly, we demonstrate the potential of our textile through various applications: aesthetically patterned phone cases, and wearable accessories that change their color and pattern based on the user's unique experiences. We also showcase a proof of concept for a woven closed-loop sensor, and for self-cleaning clothing. We are excited to see how the HCI community will leverage the materials in this design space in the future.

ACKNOWLEDGMENTS

We would like to acknowledge Netta Ofer and Ella McQuaid for helping with photos and Jack Forman, Alex Kass, Ken Nakagaki, and Shanel Wu for feedback.

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