"I don't want to wear a screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing

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ABSTRACT

This paper explores the role dynamic textile displays play in relation to personal style: What does it mean to wear computationally responsive clothing and why would one be motivated to do so? We developed a novel textile display technology, called *Ebb*, and created several woven and crochet fabric swatches that explored clothing-specific design possibilities. We engaged fashion designers and non-designers in imagining how Ebb would integrate into their design practice or personal style of dressing. Participants evaluated the appeal and utility of clothing-based displays according to a very different set of criteria than traditional screen-based computational displays. Specifically, the slowness, low-resolution, and volatility of Ebb tended to be seen as assets as opposed to technical limitations in the context of personal style. Additionally, participants envisioned various ways that ambiguous, ambient, and abstract displays of information could prompt new experiences in their everyday lives. Our paper details the complex relationships between display and personal style and offers a new design metaphor and extension of Gaver et al.'s original descriptions of ambiguity in order to guide the design of clothing-based displays for everyday life.

Author Keywords

Clothing-based display; dynamic textiles; style; ambiguity; weaving; crochet;

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

When people choose what to wear, they are making conscious and unconscious choices about how they want to be in the world, what they want to accomplish, and how they want to be perceived by others. These choices, which we use the term "style" to define, are driven by personal and social considerations. They are personal in the sense that people use them to craft their identities. They are social in the sense that they are crafted in relation to a broader set of cultural assumptions [13]. Cultural theorist Dick Hebdige describes style as "a visible construction, a loaded choice. It directs attention to itself; it gives itself to be read" [17]. In Hebdige's view, every detail in a garment, like the choice of a particular collar or cuff, does discursive work, speaking on behalf of the wearer. The combinations people create with their clothes signal complex identifications with particular groups, make particular experiences more or less available, and shape the way people relate to their social worlds more broadly [13,17]. As technology becomes increasingly wearable, leaving the domain of smart accessories and entering the very fabric of our clothing, it is important for HCI to consider the personal meanings and social functions technological displays foster within personal style.

In order to probe these meanings, we developed a novel textile display technology, called *Ebb*, and asked fashion designers and non-designers to describe how they might (or might not) integrate it into their practice or personal style (Figure 1). Ebb emerged from creative and technical collaboration with Google Jacquard [19,41], which was developing materials for weaving electrical conductivity into textiles at scale. The core technology of Ebb consists of conductive threads individually coated with thermochromic

Figure 1: a) Ebb consists of conductive thread coated with thermochromic paint. b, c) We created several swatches showcasing color-changing effects using weaving and crochet techniques. d) We invited fashion designers and non-designers to see and feel the swatches in order to ground a conversation about potential meanings of color-changing textiles in their design practice or personal style.

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paint. When electricity is supplied to the threads, they heat up and gradually change color over a few seconds. We named the system "Ebb" because the color change conjured images of the ebb and flow of the tides rather than the rapid changes of traditional screen based media. We created seven woven and crochet swatches with Ebb to explore its unique technical and aesthetic capabilities.

Participants' impressions of our fabric swatches revealed a desire for clothing-based displays to function differently than smart phones or watch-based displays. Namely, participants did not want to wear "screens" on their clothing and felt that the slowness, low-resolution, and rich texture of the swatches created with Ebb fit better with their personal sense of style. Additionally, they described scenarios in which abstract, ambient, and ambiguous representations of information on clothing could provoke intrigue, playful and serendipitous social interactions, calming experiences of personal information, or ironic commentaries on cultures of technology.

Reflecting on our findings, we contribute a new design metaphor of the textile display as an artistic canvas rather than a screen, and extend Gaver et al.'s original description of ambiguity within the context of clothing based displays. Both contributions can be engaged to guide the design of future clothing-based displays that seek to respect the complex, multi-layered, and even contradictory nature of expressing oneself through personal style.

MOTIVATION AND RELATED WORK

A growing interest in wearable technology and quantified self among researchers and everyday people has given rise to numerous explorations at the intersection of fashion and technology. Within consumer markets, the popularity of accessories like Nike's Fitbit or smart watches signals a desire to integrate technology within one's personal style of dress. Our paper joins existing work exploring *clothing* as a site for computational display. Existing work in this space explores provocative visions where garments react to the wearer's environment [39], emotional state [10,34], or physiology [16]. Others have explored how clothing-based displays can be used to enhance social interactions [22], motivate fitness behaviors [25], or give rise to increased environmental awareness [24].

Our work takes a more general approach. Rather than exploring a particular instantiation or context-dependent use of clothing-based displays, we produced several clothing-based display options in order to foster a conversation with individuals about how they envision the technology functioning within their daily life, (i.e., what data do they display, what representations do they use, how do they see other people engaging with them?). Davis et al. [8] use a similar approach to explore the emotional characteristics of physical/visual textures in fabrics. We investigate meaning through a lens of style, rather than emotion, to explore a wider range of ways for technology to function meaningfully within one's personal style.

Thermochromic Display Technologies

While a wide variety of technologies have been engaged to imbue textiles with display capabilities [3–6,30,32,34,36], our work joins others that use thermochromic pigments to create non-emissive textile displays [4,22,23,27,29,32]. We chose to work with thermochromic pigments because of the aesthetic contrast they offered to screen based technologies like smart phones and watches.

Most existing work in the technical space of thermochromic textiles uses heating elements to actuate color change [22,29], which impacts the flexibility and feel of the fabrics on the skin. Alternatively, we use conductive threads to actuate color change. Karpati [23], Nilsson [27], and Orth [28] also coat conductive threads with thermochromic paint to create dynamic textiles. In their approaches, conductive fibers are woven into fabrics and later coated with thermochromic inks through techniques like painting or silkscreen. Our approach is unique in the sense that we coat individual conductive threads with thermochromic paint *before* they are integrated into fabrics. This allows us to create subtle differences in the visual texture of the fabrics since variations in thread coating create "heathered" textures on the fabrics, similar to yarn-dyed fabrics. Additionally, it allows us to utilize a wider range of fabric production techniques, such as woven inlay, double weaving, and crochet.

Materialist Approaches to Smart Materials Research

Perhaps best typified by the term "computational composites" [35], new materials, like textile displays that blend digital and physical properties into a composite material, may benefit from materials-centric modes of development and analysis. In the words of Fernaeus and Sundström, "What [HCI] needs…when working with new forms of interactive materials, is to devise ways of bringing the materials into the explorations earlier in the design process, and also make them a shared resource for everyone involved, e.g., designers, developers, engineers, HCI-experts, dancers, psychologists and end users" [9].

We engage materials-centric modes of design and analysis [9,20,21,38] in order to *draw out* meanings that become associated with technology in the context of everyday personal style. In terms of design, our explorations of thermochromic textile displays began at the level of the material itself with open-ended explorations into the electrical properties of conductive thread, behavior of thermochromic inks, and various fabric production techniques. By "allowing material properties to guide our design" [9], we are able to probe the design space of wearable textile displays in order to identify new opportunities and challenges that might not have come into focus in context-specific or needs-driven design approaches. In terms of analysis, we engage designer and non-designer perspectives at a phase when our designs are developed enough to communicate several possibilities but not so developed as to suggest one particular usage

scenario. Engaging "user" feedback at this early phase is particularly useful for exploring questions of meaning, since several different design directions can be compared and contrasted in order to reveal underlying themes and symbolic associations.

DESIGNING EBB

Our design process consisted of developing a core technology, a computationally controllable color-changing thread called Ebb, and exploring design possibilities in the form of fabric swatches made using the core technology.

Electrical Characteristics

Ebb consists of conductive threads coated with thermochromic fabric paint. The conductive thread is made from cotton thread wound with copper. The copper has a thin enamel coating for electrical insulation. These cotton-copper threads were developed in an early iteration of the Google Jacquard project and were specifically engineered for use in large scale garment manufacturing [19,41]. We coated the threads with thermochromic fabric paint to explore their potential for non-emissive display. Supplying power to the conductive thread creates heat, which changes the pigments in the fabric paint from an opaque to transparent state and results in a visual effect of the thread fading to its uncoated white color. Removing power has an inverse effect, changing pigments from transparent to opaque as they cool due to exposure to ambient air temperature. Thus, maintaining the threads in the color of the thermochromic pigment requires no power, while activating the thermochromic pigment to reveal the color beneath requires power. The most feasible display functions are those that turn threads on for limited amounts of time, creating moments of dynamism in otherwise static fabrics.

Thread Construction

The construction of Ebb is unique in that we coat individual threads with thermochromic paint *before* they are integrated into fabrics rather than applying thermochromic paints to conductive fabrics after the fabric is produced (e.g., via silkscreen). Working at the thread-level allowed us to explore intricate textile production methods, like crochet (Figures 3a and 3b), as well as detailed color combinations within woven fabrics (Figure 3c). Additionally, controlling individual threads within a weave allowed for increased computational control of the dynamic fabric patterns. We developed patterns that leveraged the physical structure of fabrics to obtain particular aesthetic effects as well as power efficiency, which we describe in more detail in the Design Explorations section.

We prepared thread in three colors: blue, magenta, and yellow (Figure 1a). Our fabric paint was created by mixing TurnThermo thermochromic pigment (which activates color change at 86°F/30°C), Utretch Acrylic Gel Medium, and Golden Acrylic Fabric Medium in a ratio of 1:2:1 respectively. This recipe offered sufficient color vibrancy while being thin enough to easily coat the threads. We coated the threads by filling small plastic palette cups with fabric paint, puncturing the cup with a needle, and rapidly feeding the thread through the paint using the bobbin winder on a sewing machine. This approach allowed us to make quantities of thread (~100 yards) in a relatively short amount of time. In practice, each color of thread exhibited very different heating and cooling behaviors, which are outlined in Table 1.

	voltage (V)	current (mA)	rise time (s)	fall time (s)
magenta	1.0	426	4.0	7.0
yellow	1.6	515	2.5	4.0
blue	2.5	653	4.0	3.0

Table 1: Summary of voltage and current required to induce color change on a 20 inch string of thread. Rise and fall times refer to the amount of time it took for the thread to completely change color when current is applied or removed, respectively.

Ebb threads are volatile in the sense that they respond to heat generated from any source, not just electricity. For instance, a cold wind could blow a computationally generated pattern off of the fabric or body heat could induce change in particular locations. The pigments also have a limited life span and the transparent state becomes permanent after the threads has been heated a particular, but unpredictable (more than 500 short headings in our study) number of times. Longevity of the threads depends on the amount of power supplied and the duration of the heat application. While typically regarded as technical limitations, these aspects of Ebb have been strategically engaged to create aesthetic expressions. For instance, Maggie Orth leverages the limited lifespan of thermochromic pigments to reveal patterns over time [27].

Fabric Construction

We used weaving and crochet to explore the technical and aesthetic potentials of Ebb as a clothing-based display. Members of our design team produced crochet swatches in-house and we collaborated with a craft weaver to produce woven swatches. In the following subsections, we offer high-level descriptions of each technique in order to give the reader a sense of the structural properties of each fabric, which we leveraged to produce specific effects in our design explorations.

Crochet

Crochet is a technique where a single thread is continually looped around itself with a hooked needle. From combinations of relatively few basic stitches, endless patterns are possible. Crocheting with thread, rather than thicker yarn, produces lace-like fabrics with varying regions of densely and loosely packed stitches. Some crochet patterns (or "motifs") are created by combining regions made by separate threads. This is often used to produce regions of different colors within a single crochet fabric, with each color made from stitches on a single thread.

Weaving

Weaving is a common technique used in industrial fabric production. To produce a basic or "plain" woven fabric a

weaver threads several individual threads along the length of a loom. These are the warp threads. A weaver then joins warp threads into a fabric by running a single thread over and under alternating warp threads (called "sheds") and working back and forth across the width of the loom to produce rows (called "shots") in a direction perpendicular to the warp. The thread used to join warp threads together is called the weft of the fabric (Figure 2a).

We used plain weaving, inlay, and double weaving techniques to create custom patterns in woven fabrics. Inlay was used to create patterns atop a base fabric (Figure 2b). To create an inlay, a weaver adds an additional thread that runs parallel to and in between each shot, which results in a pattern that is woven in and out of the warp threads but sits atop the weft. In double weaving, a weaver works multiple layers of fabric at once. We used double weaving to create patterns along the warp of the fabric (Figure 2c). While double weaving produces visible patterns on the top surface of the fabric, the bottom of the fabric reveals the inverse pattern with columns of warp threads spanning regions in between surface patterns.

Design Explorations

We created several woven and crochet fabric swatches to explore possible options for clothing-based displays. We selected seven of these swatches to explore in detail in our study. All selected weaves were woven at a density of 60 ends per inch (i.e. 60 warp threads per inch) and used silk as a non-conductive base thread. We found visual quality and electrical efficiency to be optimal when there was one silk thread separating each Ebb thread along the warp and no threads separating Ebb threads along the weft. Patterns created using inlay produced better visual results than patterns woven along the weft of the fabric.

In order to actuate color change in the swatches, we soldered the copper wire from Ebb threads to thicker gauge wires and connected them to microcontrollers. Each swatch was controlled by a 5V Arduino Pro Mini and powered by a 3.7V lithium ion battery. An Adafruit Power Boost 500C module was used to supply 5V to the threads. Power to each thread was pulse width modulated. For swatches with many control threads, we used an Adafruit 16 channel, 12-bit PWM/Servo Driver to specify pulse width for up to 16 threads using I2C for communication. For demonstration purposes, we created boxes with the woven swatch placed on the lid and electronics housed inside the box. Voltage levels could be adjusted in real-time by turning knobs on the box.

Density Crochet

We observed how densely packed regions of stitches heated and changed color more quickly than loosely packed regions due to cross heating effects. In light of that observation, we designed a crochet pattern to emphasize contrasts between dense and sparse regions to explore how color change would "animate" across the fabric (Figure 3a). Applying power to the crochet created a bleeding effect,

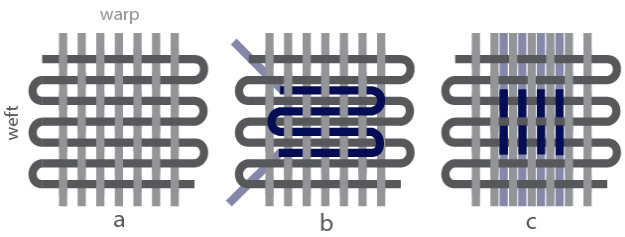

Figure 2: Weaving techniques explored with Ebb. a) plain weave b) inlay c) double weaving.

where color change slowly moved from denser to less dense regions. The resistance across the swatch was 21Ω. Dense regions changed color at a 13% duty cycle, and the entire swatch changed at a duty cycle of 100%. Full color change took roughly 30 seconds.

Multicolor Crochet

Our multicolor crochet swatch explores how colors could be controlled individually in order to produce different visual states on a single swatch (Figure 3b). Due to cross heating effects we could activate change on the magenta regions of the crochet without affecting blue regions but we could not change blue regions without affecting magenta regions. Thus, the swatch can take one of three states: magenta and blue both visible, magenta invisible and blue visible, and blue and magenta both invisible. We measured 14Ω and 16Ω resistance across the magenta and blue threads respectively. Magenta color change was induced at a 44% duty cycle and blue at 100%. It took roughly 20 seconds to change the color of the entire swatch.

Woven Color-Mixing Gingham

Gingham is a classic woven pattern created by running colored stripes along the warp and weft directions of a fabric (Figure 3c). We created stripes of Ebb thread along the warp with a double weave technique and stripes along the weft using inlay. The visual result is a pattern where only the overlapping sections of the stripes are visible, highlighting color combinations created by weaving different hues of Ebb thread along the warp and weft (Figure 1b). Since each row and column is controlled by a unique power source, the tint of each stripe be adjusted individually. We soldered individual warp threads together to make them function electrically as though they were one continuous thread. Each warp stripe had a resistance of 11Ω and at duty cycles ranging from 40%-75%, took roughly 5-10 seconds to fully change colors. Each weft stripe had a resistance of 5Ω and at duty cycles ranging from 15%-60%, took roughly 10-20 seconds to fully change colors.

Woven Graphic Element

We used inlay to explore activating color change on large graphic elements like logos or shapes (Figure 3d). We produced a large circle using a single continuous strand of Ebb thread. We programmed the swatch so that color would slowly appear and disappear, creating a "breathing" effect. The swatch had a resistance of 7Ω and at a 40% duty cycle, took roughly 7 seconds to fully change color.

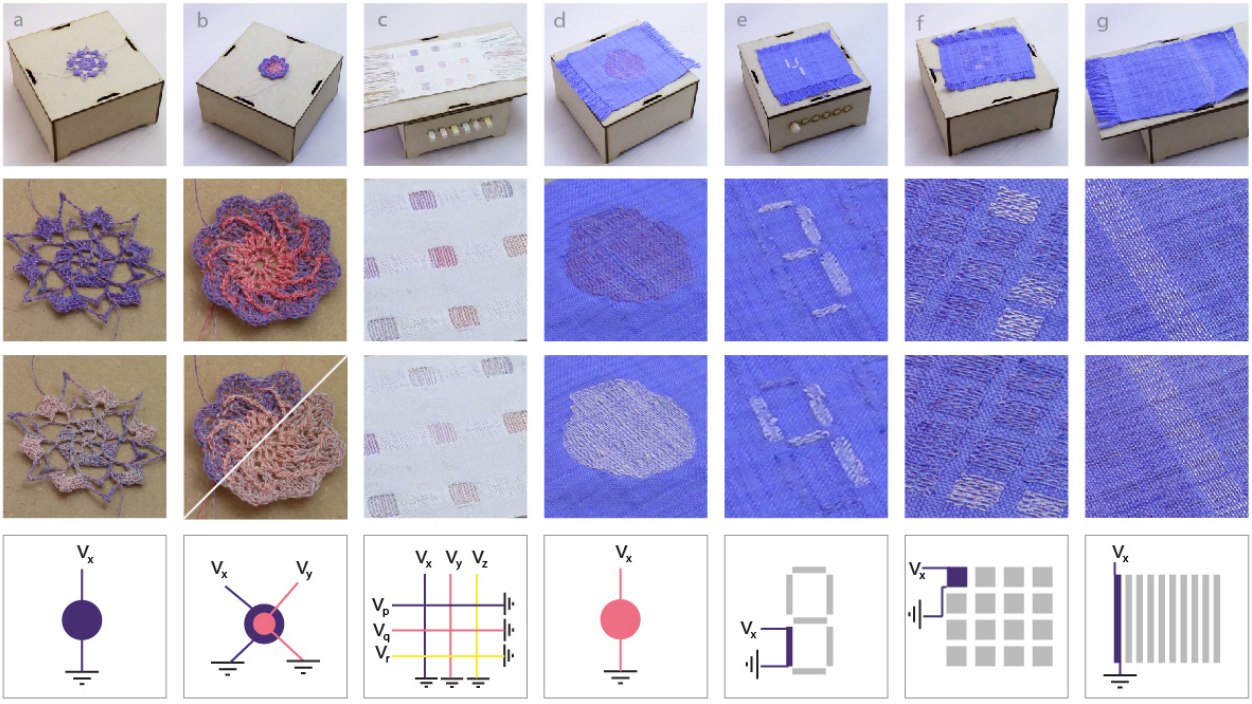

Figure 3: Swatches created from Ebb. a) density crochet, b) multicolor crochet, c) woven color-mixing gingham, d) woven graphic element, e) woven seven-segment, f) woven grid, and g) woven stripes. The bottom row shows the wiring diagrams for each swatch. On schematics e-g, grey elements each utilized identical wiring as the featured blue element.

Woven Grid

We also used inlay to create squares arranged in a four-by-four grid (Figure 3f). We controlled each square individually, which opened a space to experiment with dynamic spatial patterns and animations. When displaying the grid, we showcased a pattern that randomly turned one grid cell on at a time. The effect was a slow "shimmering" across the fabric. Each square had a resistance of 2Ω and at a 70% duty cycle, took roughly 2 seconds to fully change color.

Woven Stripes

Stripes are a common fixture in fashion as well as informational displays. We created stripes with Ebb by weaving ten separate Ebb threads into the weft of the fabric. Each stripe could be turned on an off individually (Figure 3g). Our display animation turned each stripe on and off in series, creating the effect of a single activated stripe moving down the length of the fabric. Each stripe had a resistance of 7Ω and at a 100% duty cycle, took roughly 14 seconds to fully change color.

Woven Seven-Segment

In order to explore how traditional display elements might be perceived differently with Ebb, we created a woven version of a seven-segment display (Figure 3e). Each segment was created using inlay and could be controlled independently of the other segments. For display, we showed an animation that slowly cycled through numbers from zero to nine. Each segment had a resistance of 2Ω and at a 70% duty cycle, took roughly 6 seconds to fully change color.

RESEARCH QUESTIONS

While HCI has explored domain specific and conceptual proposals for clothing-based displays, very little is known about the way such displays would be perceived and utilized within everyday life, beyond runways and outside of galleries. On a high level, we are interested in exploring why someone would choose to wear a garment with display capabilities. We approach this question through the lens of personal style, which foregrounds how self-identity shapes clothing choices [13,17]. From this perspective, a person's choice about how she might wear a clothing-based display is linked to the symbolic meaning she thinks it communicates, bringing two specific questions into focus:

What associations shape one's perceptions of a clothing-based display? According to Hebdige, the meaning of something is established among a web of associations with other meaningful things [17]. For instance, within the United States, a stovepipe may be strongly associated with former president Abraham Lincoln. When introduced into one's wardrobe, such a hat could form a bold statement: First, because the style is uncommon within the present day fashion landscape; and second, because the hat represents many of the characteristics culturally associated with Lincoln. As a new technology, Ebb lacks a distinct historical lineage of its own and must be understood in relation to things with similar function, visual appearance, or feel. Understanding what comes to mind when people see a clothing-based display can help designers understand how those perceptions could be leveraged to create spaces for particular kinds of experiences and interactions.

Second, **how do people envision clothing-based displays shaping their everyday interactions and experiences?** Drawing from Barad [2] and Balsamo [1], we argue that meaning is actively constructed and reconstructed within activities. While our first question takes a historical perspective to understand meaning, this question is future focused, exploring how people envision clothing-based displays performing within their daily lives. In addition to helping designers explore new territories of everyday clothing-based displays, investigating this question can provide insights on how specific meanings are put to work to produce particular social, personal, functional, and/or aesthetic effects.

ENGAGING DESIGNERS AND WEARERS

We presented fashion designers and wearers with our swatches in order to probe symbolic and social implications of Ebb. For clarity throughout the section we will refer to fashion designers as designers and other participants as wearers. We engaged wearers in order to unpack the factors that shaped how everyday people might bring Ebb into their wardrobes. We engaged designers as "expert" users whose understandings of the symbolism of clothing would be grounded in their practice of designing for clients.

Session Structure

We conducted 90 minute semi-structured sessions where participants were introduced to the fabric technology and asked to imagine how they would integrate it into their wardrobe or design practice. We began each session with swatch demonstrations to show how the fabrics changed color and invited participants to touch and feel the fabrics.

Next, we asked participants to select the swatches that they would be interested to integrate into their wardrobe or design practice. Focusing on their selected swatches, we asked participants to address more details about how they would design/wear it (e.g., on a scarf, shirt, inner wrist cuff, etc.), the contexts it was designed for or would be worn in, the kind of information it could display, how the participant imagined interacting with the display personally and socially, and how issues of sustainability affected their perception or ideas of use. Since the symbolism of one artifact often emerges in contrast to other artifacts, we frequently presented participants with alternatives to Ebb that could serve similar functions (i.e., woven fiber optics or flexible LED screens) and asked them to compare and contrast the technologies.

Throughout the sessions, we allowed participants to talk at length about aspects of Ebb they found personally interesting or uninteresting. To provoke discussions on topics that the participant found personally important, we based many questions on the unique responses of the participants. All sessions were video recorded and later transcribed for analysis. We analyzed video and transcripts using a grounded theory approach [7] in order to reveal common associations and themes that shaped perceptions and envisioned uses of Ebb. Audio from each interview session was transcribed and coded in two passes by the first and third authors to identify recurring themes within the data.

Figure 4: Fashion designers and wearers engaged with Ebb and discussed how they envisioned it within their style.

FINDINGS

17 total individuals: 12 wearers (aged 23 to 56, 3 male, 9 female) and 5 designers (aged 22 to 52, all female), participated in our study. The designers had a range of experience and worked for large brands, as independent and freelance designers, or in costume design. 3 designers had knowledge of dynamic textiles and had used them within their design practice. 3 wearers had experience wearing some kind of dynamic textile or jewelry, most often with LEDs.

The range of responses, associations, and experiences from participants varied as much as their individual styles. Participants described many types of garments that could integrate the display, from dresses and shirts, to handkerchiefs and scarves, and had very different thoughts about how the garment would play into their personal styles. Designers and wearers had similar imagined uses of the technology. Yet, designers tended to address the physical texture of the fabric and used it to ground the garments they imagined.

The designer perspective also helped us contextualize our results. For one, designers did not find Ebb to be fundamentally different from other materials they engaged in their practice—design constraints based on electrical capacities were not seen to be different than constraints based on available materials or customer preferences. They saw Ebb as a new kind of material with a certain set of affordances and meanings that could be crafted in their design practices. Additionally, they were able to address the broader fashion landscapes within which color-changing clothing would be understood. Molly, for example, spoke of San Francisco having highly diverse "fashion micro-climates" and Gemma noted how "San Francisco is all about leather and feathers, where New York is very sleek and streamlined."

Among designers and wearers, themes emerged in relation to how they associated Ebb and the role they imagined it playing in their lives. We present our results in two sections in accordance with our earlier research questions: the first explores past experiences that gave rise to how designers and wearers saw Ebb and the second describes how participants thought those symbols could provoke particular kinds of experiences within the wearer's daily life.

The Symbolism of Ebb

As Hebdige notes, the symbolism of a clothing item is established among a web of symbolic historical, experiential, and material associations [17]. These associations can be multi-layered, relating to aspects like material properties as well as functionality. As we talked with participants about how they imagined integrating Ebb into their wardrobe, particular associations emerged more frequently than others.

Screen or Canvas

Participants' past experiences with dynamic displays often took place on computer or tablet screens. They tended to describe Ebb as a kind of screen and discussed how it was similar and different than other experiences with screens. Most participants had negative associations with screens: Diego, a wearer, described his phone screen as the entryway into "a world of hurt." Peter, a wearer, said "there is enough glare in my life as it is." While Ebb was seen as a kind of screen, most felt that its material qualities (lack of light emission, gradual changes, and low resolution) prevented it having the same negative effects as other screens in their life. Gemma, a designer, offered an alternative description of Ebb as a "canvas" since it offered more "painterly" uses of computation in garments.

The quality participants most disliked about typical screens was light emission. They described light emitting devices as "jarring" and distracting, like billboards or neon signs. Associations with light emission also extended beyond descriptions of screens. Participants recalled past memories of light emitting clothing: like blinking Christmas sweaters, children's sneakers that lit up when they walked, or light-up visors they might get at carnivals and amusement parks. Additionally, many referenced existing cultures of LED-enhanced clothing at clubs, large theatrical events, and Burning Man. In summary, clothing with light-emitting displays tended to be associated with parties, kids, and novelty. These associations were not strictly good or bad, but they did shape how participants imagined using textile displays in their life. For instance, Satia, a wearer, felt that LEDs in clothing were "tacky" but enjoyed wearing them to "take tacky to the extreme." For most participants, including Satia, the non-emissive quality of Ebb made it a better fit for everyday life and daytime situations.

Ebb was further differentiated from a screen because of its texture. Participants felt the patterning and the visual evidence of our swatches being made by hand gave Ebb a "warmer" appeal than traditional screens. Many participants ran their hands over the fabric and playfully draped the swatches in order to get a richer sense of its feel. The stiffness of woven fabric and its fairly coarse texture led Janet, a wearer, and Marie, a designer, to comment on its "heirloom"-like quality. In Janet's words, "[Ebb] seems a lot more tactile and something like cloth rather than plasticky…I think it's just more intimate and easier to like." The hand-crafted nature of Ebb had particular appeal for Elle and Gemma, who were concerned about the consumption and waste of textile displays. They felt that wearing clothing that was hand crafted increased its lifespan and signaled a commitment to quality and care.

The gradual color change of Ebb was also seen as an asset that made it less like a computer screen and more like a canvas. Diego, a wearer, expressed, "it's really hard to make a bad [design] decision with this kind of technology. It's really easy to make a watch, or fitness tracker, that's just the worst thing. Even the worst decision you make within the constraints of this design system would still make a really classy, nice thing." Diego attributed this observation to, "…the slowness, it has a latency that's way too high for advertising." For Diego, associations with advertising colored his impressions of our textile display. He felt that Ebb's slowness necessitated an investment of attention that sheltered it from being used for things that screens were typically used for and opened up a space for a more personally pleasurable experience of technology.

Many participants felt that Ebb could elicit different kinds of readings and interactions than other kinds of displays. They used terms such as "beautiful," "elegant," and "subtle," to describe their impressions of Ebb. Gemma, a designer with e-textiles experience, expressed how she "loved the ghostly in and out of thermochromics." Adelaine, a wearer, felt that the swatches were "more ambient than attention grabbing." Diego described Ebb as "trustworthy" because it felt more like fabric than a screen. When comparing Ebb to flexible screens he commented, "nothing is fabric but fabric." These impressions, and underlying associations, were based in past as well as imagined future experiences. While some participants felt that Ebb conjured up associations with beloved heirloom objects, others found its appeal precisely in what they felt Ebb *could not* become associated with, namely, advertising and wasteful consumption.

Envisioned Interactions & Experiences with Ebb

In this section, we focus on various ways that participants imagined leveraging the symbolic qualities of Ebb to prompt specific personal experiences and social interactions in their daily lives. Within each section, we describe how participants imagined integrating Ebb into their wardrobe.

Provoking Intrigue

Beth, Tammi, and Patrick, all wearers, liked the idea of using Ebb to mystify others, prompting interactions that began with lines such as, "Wasn't your dress blue a minute ago?" or "Wasn't that stripe on your shoulder before?" Like an inside joke, this quality of Ebb was seen to bring enjoyment, delight, or a shared sense of "being in the know" to wearers and their everyday audiences. The perceived audience for these kinds of intrigue-based interactions shifted with duration. For instance Peter imagined wearing a t-shirt with a graphic element that moved across his chest according to the time. In the morning, it would be on his left side, and as the day

Figure 5: Envisioned uses of Ebb. Participants described various ways that abstract displays of information (circles and stripes as opposed to arrows or numbers) could be strategically engaged in social scenarios.

progressed, it would move in an arc to his right side. The change would be too slow to be noticed immediately but could be discovered by people who interacted with him over the course of a day. Specifically, he imagined friends looking at his Facebook feed and discovering that his shirt had been changing in a way they had not been aware.

The gradual color change and non-emissive quality of Ebb were seen to foster a very specific kind of encounter with the public that was not explicitly attention grabbing, but a more nuanced and modest attention seeking that came from noticing and discovery. In this sense, the dynamism of Ebb was able to integrate within and represent complex personal characteristics like the ability to be cunning yet easily discovered or playful yet secretive. These statements are difficult to make with static clothing but may be too obvious when displayed through light emitting technology. The form of communication Ebb offered was not literal, but symbolic: signaling particular propensities and preferred modes of being within broader social worlds.

Data-Driven Serendipitous Encounters

Maxine, Beth, and Diego described ways Ebb could respond to their physical states or online activities. Maxine, a designer, envisioned clothing that responds to physical state in communicative, but non-literal, ways. She described how responsive garments with dynamic displays could have grammars of their own, adding a new dimension of expressivity to everyday life. Over time, she felt that users would be able to learn to control these seemingly abstract expressions and audiences may be able to read them.

Beth and Diego, wearers, imagined garments that connected their digital and physical lives. For instance, by responding to their physical proximity to someone they interacted with online. Beth imagined a shirt where a mark on her shoulder could become visible when she was near someone that she "swiped right" (a gesture to indicate potential interest) on in Tinder, a popular dating application (Figure 5a). Her choice of the shoulder as a display location signals an interest in having this information be visible to others (as opposed to wrist where only she would see). While she liked the idea of being able to connect with someone through the shirt, she also preferred the indication to be non-obvious. When asked if she would prefer an arrow pointing to the person rather than an abstract circle, she noted a preference for the circle in order to maintain a sense of not knowing, to keep her cover so to speak. Her use of Ebb was not intended to explicitly connect two people but to set up an awareness of an opportunity to potentially connect, something she felt might be more exciting, private, and comfortable. There would be a chance that the other person might notice her shirt and recognize her, or a chance that she could notice the indication and recognize the other person, or finally, a chance that both parties may not recognize the indication at all. Beth felt that chance was an asset that could infuse daily life with an element of playfulness and opportunity.

Both of the described interfaces embrace ambiguity in the display of event driven information. In the case of garments that respond to physical stimuli, Ebb was seen to support ambiguous representations that could foster multiple interpretations. Participants felt that this quality of Ebb could support playfulness and also allowed the wearer to make decisions about whether or not they would pursue particular social encounters. The slowness and subtlety off Ebb were seen to be well suited for ambiguous representations of information.

Beautiful Functional Things for Personal Enjoyment

Janet and Elle, wearers, wanted to enjoy Ebb privately instead of using it to prompt new kinds of interactions with others. They appreciated the aesthetic of Ebb but were concerned about attracting unwanted attention. Elle feared people "leering" and Janet described how she was afraid of "being at the [subway] station and waiting and sitting and wanting to just read my book and someone starring at [my] shirt and saying 'its changing colors – that's crazy!'"

Instead, Janet wanted to use Ebb as a watch located inside the wrist on her shirt because she felt it would be unexpected and beautiful, yet mundane enough to limit attention. Her interest in a fabric watch was rooted in an appreciation for the material qualities of Ebb. She was particularly fond of the unusual textured patterns created by woven inlays on the seven-segment swatch (Figure 3e). She also thought the limited lifespan of a thermochromic watch made it more interesting: "With something like clothes or functional objects, they are always so meticulously thought about that it might be nice and refreshing to add an element of chance. You'll just have to deal with how it looks [when the pigments become inoperable] and that would be part of its appeal, I think."

Ebb's physical texture, the slowness of its change, and its susceptibility to forces outside of the wearer's control combined in a way that offered Janet personal aesthetic pleasure. As a watch, it also served a functional purpose. Ebb suggested a poetic opportunity to combine new and old technology in unexpected ways.

Many Garments in One Garment

Sam, Larry, and Gemma saw Ebb as something that could increase the utility of a single garment by allowing it to change its appearance. They each imagined uses that involved waking up, setting the pattern of the garment for the day, and then having the pattern remain static throughout the day. Gemma, a designer, imagined a shirt where different kinds of collars could dynamically appear

based on the wearer's preferences for the day: "A shirt completely changes its look when it's all white, including the collar, and then the collar turns into an accent color, or maybe just the tips of the collar turn bright red…like a western shirt. [Collars] all have different connotations and associations so you can say a lot with a simple, subtle change." Her personal design philosophy aimed at fostering long-term engagements between people and their clothes through the creation of garments that could be adapted and mended as the wearer's preferences changed over time. Gemma felt that Ebb increased the lifespan of a garment by offering aesthetic utility, the ability to integrate many different meaningful looks into a single garment.

Humane Information Access

Sharon and Sarah, both wearers, and Maxine, a designer, imagined Ebb offering information they typically accessed on their phones through a soft, clothing-based interface. Sharon imagined a striped scarf that could communicate real-time bus information (Figure 5b). When activated through an app on her cell phone, the stripes at the end of the scarf could change to reflect the number of minutes before her bus arrived. She preferred to represent the time information with stripes, rather than numbers, so it would not distract people she might be interacting with. She commented, "our brains are wired to recognize letters and numbers, we can't not see them." She typically accessed bus information on her phone and felt that the slowness of the information represented on the display could support a relaxing "zen-like" experience of information. Even though she imagined activating her scarf with her phone, she felt that her scarf interface would ameliorate stress by providing a slowly shifting dedicated information stream that would allow her to direct her attention to the world, interacting with others, rather than frequently checking her phone.

Most descriptions of information displays using Ebb resonated with descriptions of peripheral, calm and ambient computing [12,18,33,37] in which limited amounts of abstracted information reside in one's peripheral awareness. The information could be easily referenced or ignored on the end of a scarf or the sleeve of a shirt. The uses of Ebb as an informational display highlight how it could reduce cognitive load while also serving a social function. For instance, by allowing the wearer to maintain a sense of privacy over their data even when it is clearly on display in public spaces or allowing them to maintain conversations while staying aware of important information.

Commenting on Technology and Culture

Diego, a wearer, and Marie, a designer, felt that displaying information publicly on their clothing could be used towards critical effects. Diego described a shirt that could display his Klout score, a numeric value that is computationally derived to describe how influential a person is. For Diego, an artist who frequently explored themes of culture and technology, clearly displaying his Klout score in an outward facing position on his shirt was meant to act as an ironic commentary on our relationship with technology.

Marie, a designer, also saw clothing as a place to provoke commentary and reflection. She described a dress with accents along the bodice, which could respond to Facebook data. She saw clothing and Facebook as artificial surfaces onto which people project their ideal selves. "I think about Facebook as this curated hologram of our lives. It is very much not representative of who we are as full and complicated people…fashion is a surface too…so it feels like an appropriate comparison."

Information used towards ironic or critical affect served a much "slower" function, as Hallnäs et al. use the term [14], in the sense that it is presented for reflection and contemplation rather than efficiency or awareness. The symbolism of particular information streams represented on clothing through Ebb were seen as a way to express one's perspective about technology and culture and signal a particular orientation within those cultures.

DISCUSSION

While the variability and uniqueness of participant preferences limits the generalizability of our study to other populations and contexts, the particular body of users we studied reveals new design territories for wearable displays and new questions for designers to consider while creating such displays. The individuality of each participant and their unique perspectives of Ebb highlighted the complexity of personal style. Each aspect of the display, from the physical feel to the data represented, dramatically changed a participant's impressions and envisioned uses of Ebb. The expressions made through clothing-based displays did not have a single intended meaning, but contained many layers of sometimes contradictory meanings to produce specific effects like intrigue or irony. This poses a future design challenge for HCI, how do we go about designing clothing-based displays that can mesh well with the complex tastes and lifestyles of an individual wearer? Reflecting on the findings from our study, we suggest a new metaphor and extend Gaver et al.'s original descriptions of ambiguity in order to expand future research of clothing-based displays for everyday life.

Shifting Metaphors: From Screen To Canvas

The metaphor of a screen is an easy fit with the dynamic changes in appearance supported by textile displays. However, if designers think of these displays as "screens" they may be inclined to base their design on existing heuristics for evaluating screens (i.e., "better" screens offer higher resolution, fast switching times, and high visibility). Within the context of personal style, a very different set of heuristics was evoked. Our participants expressed value for displays that offered aesthetic pleasure and utility. In the shifting contexts of everyday life, participants described a variety of situations in which slow, specific, low-resolution displays were preferable to high fidelity display options. In many cases, the slowness, low-resolution, and volatility of

Ebb were seen as assets and opened up spaces for wearers to imagine mysterious and meditative encounters with the technology.

Drawing from the observations of our participants, we suggest that the metaphor of a *canvas* may offer designers a mental representation that expands the role of clothing-based displays within everyday life. The idea of an artistic canvas brings values for textured materials and abstraction to the foreground. Where screens might be understood in terms of their use, canvases are better understood as things that become "present" [15] within a broad spectrum of everyday life experiences. The experience of such canvases could be framed as aesthetic [31,40], enchanting [26], and slow [14].

Our study highlights how clothing-based displays can foster aesthetic and slow experiences for wearers and their publics simultaneously (e.g., Peter's slowly moving graphic t-shirt offered a personal aesthetic experience and an opportunity for surprise for others). Participants felt these kinds of shared experiences could potentially give rise to serendipitous social interactions and bring a particular kind of attention to the wearer that he or she desired. The complex and nuanced experiences provoked by the clothing reflected back on the wearer, signaling their own complexity as people.

Revisiting Ambiguity in the Context of Clothing

Ebb was seen to promote intriguing interactions through ambiguous representations of information. According to Gaver et al., ambiguity emerges from uncertainty within the "interpretative relationship linking person and artefact" [11] and can be engaged to make artifacts and situations, "evocative rather than didactic, and mysterious rather than explicit […] the artefact or situation sets the scene for meaning-making, but doesn't prescribe the result." The usage scenarios described by participants resonate with Gaver's et al.'s descriptions of ambiguity in the sense that it was seen to create potentials for various kinds of interactions and interpretations to occur without forcing those interactions. Yet, we found that ambiguity, as it was described by participants, was difficult to understand without reconfiguring the relationship between person and artifact offered in the original description.

When interactive displays enter the fabric of clothing, the artifact (i.e., the display) and the person (i.e., the wearer of the display) become tightly coupled. The person, their histories, ways of being, and other aspects of their style, contribute to the meaning of the artifact and vice versa. Thus, in the context of clothing, ambiguity might be better understood as emerging from the interpretive relationship linking the wearer and artifact *as well as* the relationship linking wearer-artifact and their publics. If we understand ambiguity in clothing through this lens, we are better able to grasp, for example, how Diego's own personality contributes to the ambiguity that emerges from his wearing of the Klout score t-shirt. As an artist whose work explores ironic uses of technology, Diego's shirt may be interpreted by his personal "audiences" along very different lines than, perhaps, a businessperson wearing the publicly displayed score at a networking event. Diego *becomes part of* the contextual discourse that shapes the interpretations others might draw from his clothing. In other cases, like Sharon's use of stripes instead of numbers on her scarf to represent transit information, ambiguity of information was pragmatically engaged to allow Sharon to maintain a level of informational awareness while remaining socially present to her friends. Ambiguity served a practical function while also reflecting Sharon's own care and value for her peers. In both cases, ambiguity between the wearer-artifact and his or her publics was strategically engaged by wearers to shape the range interpretations others might have of them, while leaving room for their publics to formulate their own meanings. Ebb uniquely allows this ambiguity to flourish in the context of clothing.

FUTURE WORK

While all envisioned uses were feasible in terms of the display capacity of Ebb, some would require significant advances in wearable power supplies in order to be comfortably worn in everyday contexts. In order to probe the everyday wearability and social implications of Ebb, we are developing sensor-driven prototypes for participants to wear throughout their daily life. Through these studies, we hope to provide richer experiential accounts of Ebb while also exploring how ambiguous displays of information affect how such signals are interpreted by the wearer and their publics.

CONCLUSION

Our study shed light on ways that clothing-based displays can function within the complex and meaning-laden landscapes of personal style. By employing a materials-centric perspective that embraces materials as meaningful communicators, we were able to draw out associations that shaped perceptions of technology in clothing. From these perceptions, we suggest that the metaphor of canvas, rather than screen, could expand the design space of clothing-based displays for everyday use. Furthermore, participants in our study envisioned scenarios in which the slowness and low resolution of Ebb could be engaged to foster serendipitous social encounters, ironic commentaries, and meditative experiences of personal data. Ambiguity played a central role in many of these scenarios. We revisit and extend Gaver et al.'s descriptions of ambiguity in the context of clothing based display in orders to highlight how ambiguity can function strategically when integrated within the complex personal and social landscapes of style.

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