# Knitting Access: Exploring Stateful Textiles with People with Disabilities

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**(a) "I flipped a bubble every time I gave myself a compliment."** **(b) "I rated the intensity of my anxiety from low to high … in the morning, noon, and evening."** **(c) "I looped a cord through the hole if I took a break from work … skipping a hole meant I skipped the break that hour."**

**Figure 1: Examples of stateful textiles being used to track and reflect on self-care practices.**

## ABSTRACT

Wearables are often a primary means of collecting data on the body and in-situ. The data collected upon wearables can shape or record interactions in real time, prompting practices like self-care and reflection. In this work, we became intrigued by textile structures that were non-digital but in themselves "stateful". We explored how these textile interfaces can fit meaningfully into the lives of people with disabilities as sensors and display. Our study revealed interesting practices that emerged for self-tracking that were qualitatively unique in their close relationship to the body and deeply physical modes of engagement. Our findings offer insights into (1) qualities of textile interfaces that are important to people with disabilities, (2) new forms of data that people found to be worthwhile in tracking, and (3) knitted interfaces for sensing and display.


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## CCS CONCEPTS

• **Human-centered computing → HCI design and evaluation methods**; **Interactive systems and tools**.

## KEYWORDS

textile inputs/outputs, sensors, knitting, disability, inclusion, personal informatics

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## 1 INTRODUCTION

Textiles as a medium for wearable assistive technology (AT) have great potential because garments are versatile, mobile, adaptable, and are always available to provide support. They are a natural extension of our bodies and personalities, and transcend places and activities (e.g., [7, 29, 30]). Garments also already embody multiple kinds of inputs. Textile accessories such as buttons, zippers, and drawstrings can and have been transformed into computational inputs [45, 46], and can offer alternative means to traditional inputs.

In addition, researchers across HCI have looked towards the potential of transferring concepts such as sliders, dials (e.g., [18]), and trackpads (e.g., [20, 70]) to the textile domain. These dimensions of textile-based wearables present new opportunities to improve the usability, comfort, and appearance of wearable AT. Until now, little research has considered people with disabilities for these emerging interfaces, and the contexts and practices these interfaces might facilitate.

In our research, we explore the potential of textile inputs and outputs to support the unique social, cognitive, and embodied experiences of individuals with disabilities. While there is a great deal of work in transferring digital sensing technologies to textiles (e.g., [44, 64]), there has been less exploration of the emergent phenomenon that could be sensed arising from people's particular context and practices. There is an opportunity to explore how textile structures themselves can serve as user interfaces that offer unique, tactile inputs and outputs, and how people with disabilities perceive, appropriate, and adapt their physical and computational characteristics.

In order to explore these possibilities, we developed a speculative probe comprising three non-digital, *stateful textile swatches* that react to and remember inputs, and asked adults with different (dis)abilities to experiment with integrating them into their everyday experiences (Fig. 1). Our swatches emerged from creative and technical explorations of freeform, shape knitting. Each swatch consists of a variety of shapes, textures, and moveable pieces that can be manipulated, combined, and deformed to encode interactions and represent information. We chose not to add electronic sensing or actuation to our swatches as we wanted them to be open-ended and felt that electronics would limit possible interactions by making their inputs and outputs too specific. Our swatches can be electronified[1] and our findings have implications for digital textile practices and designs.

## 2 MOTIVATION AND RELATED WORK

There is a growing interest in wearables that provide alternative means to engage with others and environments (e.g., [7, 35]). Textiles, in particular, present opportunities to engage the wearer's senses in diverse and subtle ways (e.g., [7]), and to leverage movement capabilities (e.g., [72]) and meanings of the body. Our work joins existing research exploring clothing as a site for sensing and display. Work in this space has explored the design of sensors to enable textile-based control elements (e.g., [19, 33, 44]) and to sense physiological signals (e.g., [14, 47, 57, 72]). Research efforts have been made to capture inputs through textile affordances like folding, crumpling, stretching, and caressing (e.g., [19, 33, 36, 44, 53, 62]), and by adapting garment features like buttons, zippers, and drawstrings (e.g., [44, 46]). Others have explored the design of textile-based outputs through fabric movement, shape-changing structures, and color-changing yarns (e.g., [6, 7, 38]). In addition, researchers are leveraging textile practices like weaving, braiding, and knitting to augment garment features without compromising aesthetics. For instance, StretchEBand [64] focuses on optimizing sewing stitches on elastic backings to sense elastic stretch as input and I/O braid [44] leverages multistrand interlacements of braids to add interactivity to ropes and cords.

Our work takes a more material-oriented approach. Rather than figuring out how to add interactivity to textiles by integrating conductive material, we explore how the material itself can provide interactivity and computational power. We use craft as a way of thinking through material [42, 43] and let the material properties guide our design [11] to identify opportunities in the design space of textile-based inputs and outputs that we may not have imagined in context-specific or needs-driven design. In doing so, we further narratives about what is a sensor [25, 35] and investigate the unique roles tactility and physicality play in the experience of data collection and sharing.

In addition to asking what is a sensor, we also examine how sensing technologies can function meaningfully within people's lives. Prevalent sensing technologies make judgements about people's physical un/fitness, mental un/wellness, and other physiological conditions in terms of discrete categories extracted from context [24, 25]. These data representations claim to know people's state and suggest what they should do about it [24]. The normative values of helping individuals be fitter, happier, and more productive that these sensing technologies promote have been called into question [10]. Researchers are beginning to identify opportunities for sensing that encourage humans to take a more active role in meaning making and self-knowledge (e.g., [39, 51, 68]) and move beyond individuality and optimizations. Our work joins existing work exploring alternative desires for sensing and display (e.g., [23]). Rather than seeking to build on-body sensors and display that provide unambiguous data- and algorithmic interpretations of people's state, we aim to leverage ambiguity as a resource that encourages people to take a more active role in sensing. By making our sensors non-electronic we cut the link of data surveillance and judgement, giving give rise to sensors and display that foster awareness and reflection of the self and others.

### 2.1 From Digital to Material

HCI is re-imagining the material interfaces through which interactions take place under the banners of "computational composites" [63] and "hybrid craft" [16, 60, 61, 73]. A range of everyday materials like felt [50], paper [71], and clay [49] have been envisioned as substrates that can be endowed with computational properties. Researchers are considering how these materials suggest different kinds of interactions and relationships than screen-based interfaces and how material properties can give rise to new forms of sensing and display (e.g., [7, 38, 71]), and new practices of design (e.g. [8, 15, 31]). For example, in explorations of material surfaces, Jung et al. demonstrates that the physical properties of surfaces are "no mere superficial design feature sitting on top of the 'real interactions'" but can be essential to the "generation of different meanings and experiences" [28]. Wiberg further suggests that computation can occur through the material itself [66].

Our work engages material practices to explore knitting as a method to discover and study emergent forms of accessible inputs and outputs. Our explorations started at the material level with investigations into the properties of knitted structures and different knitting techniques. We tapped into a growing space of research

[1]Examples of techniques for integrating conductive materials into knitted textiles can be found at https://www.kobakant.at/DIY/

on both designing with and fabricating knitting objects to probe the design space. In terms of designing with knits, Albaugh et al.'s explorations of actuation highlight the potential for knitted multi-layer structures [2] and shape changing interfaces [1]. Combined with open-source resources such as Kobakant [46], the structures suggested in this paper can be adapted by others to perform new forms of sensing and interaction. Work on machine knitting suggests ways that these structures can be fabricated more quickly and at larger scales (e.g., [37, 41]).

## 2.2 How We Understand Disability

When developing AT, we are often tempted to frame disability as discrete and isolated impairments to scope our research. However, disabled experiences rarely fall into discrete categories. Instead, lived experiences evidence that disability is interactional [54], contextual [56], sometimes temporary, progressive, and/or variable [22]. By designing AT one impairment category at a time, we may "make the problems we need to solve more tractable, but inflexibility may create new ones in the process" [21]. Researchers are beginning to recognize that AT will be more robust and useful if it can operate in contexts where disabled people are not always recognized as disabled [21], may have more than one functional impairment [69], and/or where more than one disabled person exists [56]. To understand experiences with technology across different ability levels and contexts, researchers have suggested including groups of people with different disabilities and/or people with multiple disabilities (e.g., someone who is autistic and blind) in the same study. In doing so, we may anticipate complexity and conflict, and design for its negotiation (e.g., [48, 52]) making our access technology more accessible and useful to a wider audience.

We brought this perspective to our work in two ways. First, we recognize that it may not be possible to create technology that is universally accessible or even technology that is accessible to all people. Instead, we consider how our technology is flexible and enables resources to disabled people to modify it to meet their needs [69]. We therefore used a speculative probe as first step to imagine assistive textile interfaces. Our probe allowed participants to explore how textile-based sensors and display may fit into their everyday lives, support their existing practices, and meet their individual needs. Second, we included groups of people with different disabilities and people with multiple disabilities in our study. We used self-reports of demographics to avoid excluding people as others have recommended (e.g., [52]).

# 3 DESIGNING STATEFUL TEXTILES

Our design process consisted of exploring the characteristics of knitted structures, developing deformable and reformable knitted structures that could react to and remember inputs, called *stateful textiles*, and exploring the design possibilities for inputs and outputs using these stateful structures.

## 3.1 Characteristics of Knitted Textiles

Knitting has many valuable attributes as a medium for physical interfaces. It can be leveraged to create seemingly infinite dimensionality (e.g., [2, 27, 41, 55]) and endless possibilities for deformations (e.g., [67]). It is a flexible structure that can be made to stretch in all directions or to hold a particular shape, it can be constructed to be bulkier or lighter, to be billowing or compressing, and it can be knitted into seamless 2D and 3D shapes, geometric (e.g., sphere, triangle) or organic (e.g., zoomorphic, xenomorphic). The shapes can be integral to the structure or appear on the surface as textures such as bumps, ridges, and dimples. Knitwear's elastic nature allows these shapes and textures to be deformed, affording both gentle and aggressive manipulations like stroking and bending or punching and poking [3]. This creates endless input and output possibilities as deformation supports many different gestures: squeezing, stretching, bending, pushing, pulling, and more [3]. A limited set of these imagined interactions have been explored (e.g., [19, 33, 36, 53, 62]).

## 3.2 Constructing Deformable and Reformable Knits

**Shape Knitting.** Shape knitting techniques are a well-recognized method of constructing three dimensional physical, textile structures. We leveraged these techniques as a means for exploring the design of shapes and surfaces that could be deformed and reformed through direct manipulation. We explored several different options for knitting shapes: partial knitting wherein stitches are suspended to isolate different segments of the knit, segments may be knitted to different lengths, and reconnected to cause specific areas of the knit to form dome-like structures; tubular knitting which produces tube-like shapes by knitting in a cylindrical configuration rather than in a flat configuration; adding and removing stitches to expand or contract the width of segments; casting on and off stitches to create holes or openings; and knitting with varying tension to create segments with differing elasticity[2]. Each of these techniques can be used to produce simple, generic 3D forms and combining several techniques allows complex shapes to be knitted integrally that would otherwise require extensive labor of cutting, stitching, and molding of textiles.

**Freeform knitting.** While shape-knitting can be done on the machine, knitting by hand gave us a closer intuition to the shapes and textures during the development process. It also allowed us to explore the design possibilities by way of freeform knitting, which is difficult to do on machines as these cannot easily switch between different knitting patterns. Freeform knitting is a method involving incrementally making small additions in different sections of the knit and combining small pieces of knitting to create unique forms. This method required using multiple knitting needles to be able to work on separate segments of the knit. Thinking about knits as disparate segments (rather than one piece) that could each grow on their own in length and width offers opportunities to create complex structures beyond shape primitives. With this method, we were able to make exaggerated geometries (e.g., billowing bubbles), unique shapes (e.g., zigzags), and combine softer and stiffer yarns to create more or less pliable surfaces.

**Tension.** Through our design exploration, we discovered that tension is a key factor in creating shape-retaining and non-shape-retaining structures. Tension refers to the number of stitches and rows knitted for a given length or width. Differences in tension can

[2]Underwood presents a lexicon of shape knitting techniques and preforms in "The Design of 3D Shape Knitted Preforms"


**Figure 2: Our explorations making a deformable bubble structure: (left) exploring ways to shape knit a bulging structure using freeform knitting; (middle) experimenting with size, material, and structure; (right) making the structure reactive (giving a sensation of snapping or popping) by varying the tension in different places.**

be achieved by knitting more tightly or loosely and by combining or introducing new loops and material. Differences in tension can bring about interesting material behavior as it makes the deformation space inhomogeneous. We noticed that areas knitted more tightly became stiffer and held their shape whereas areas knitted loosely remained slack and were drapable. Both areas could be deformed when acted upon, though shape-retaining structures could spring into new configurations or spring back into their original shape. By combining areas of high and low tension we were able to create reactive controls that could actuate (see Fig. 2).

## 3.3 Design Dimensions

In designing our stateful textiles, we considered what elements of design might invite exploration, creativity, and playful interactions. We found our inspiration in fidget widgets: handheld objects that support spontaneous movements of the hands ranging from squeezable stress balls to bendable sticks to malleable putty. Fidgeting is an integral component of everyday experiences, provides delight, satisfaction, and pleasure through somesthetic of stimulating materials and tactile experience [32]. Therefore, fidgeting is a valuable lens through which to consider the design of user interfaces that offer unique, tactile inputs and outputs, and satisfy functional as well as more personal and emotional needs.

Taking inspiration from fidget widgets, we constructed different textile structure to provide pleasurable somesthetic experiences. We explored structures that provide resistance to movement and structures that exert pressure or provide compression when wrapped around the arm, hand, or fingers. We also explored structures that might be manipulated with the thumb, index finger, or the whole hand, and considered structures that provided different movement, like sliding, stretching, or pressing. This provided a great starting point for creating textile interfaces that were dynamic, stimulating, and invited playful interactions.

In addition to playfulness, we also considered ambiguity, temporality, and materiality as design dimensions. We differentiate between simple and complex states, short-term and long-term availability of state, and the sensory effects of different materials.

**Ambiguity.** Ambiguity, a well-known resource for design [12], can create potential for various kinds of interactions and interpretations without forcing those interactions. It can serve as a practical function in that it pushes people to imagine how they might personally use designs and what their lives would be like in consequence. It can also compel people to explore and make sense of a system and its context.

We introduced ambiguity by creating shapes and surfaces that do not prescribe specific interactions and do not have a clear concept. We chose to make designs symmetric to avoid indicating orientation and made the base of each textile sample rectangular to avoid indicating how the textiles are to be worn.

**Temporality.** Ephemerality reflects human life in our different stages of aging (e.g., childhood, teenage years, adulthood) and in special moments we might experience. It can serve as a motivation to appreciate the present and act in the moment. In design, it can create potential for fluidity: inputs and outputs that are not absolute or discrete, cannot be precisely controlled, and can be interpreted and interacted with anew. This offers opportunities to design for engaging and meaningful interactions.

We thought of two ways our textiles could support ephemerality: temporary encodings and momentary interactions, and considered how mechanics and materials could support these. For example, we explored ways in which our textile might represent progress through gradual deformation instead of discrete states, and fleeting emotions and thoughts through surfaces imbued with thermochromic inks (dyes that change color when temperatures increase or decrease e.g., touching with warm finger). In the end, we designed out textiles so that they cannot display past encodings of data and new interaction will change the data display.

**Materiality.** We considered materiality as a way to make designs informal, comforting, and personal. Rather than choosing a smooth yarn like silk, we chose wool, a coarse-textured yarn that is springy, and slightly fuzzy. We felt that its properties mimic the soft qualities yet subtle texture of our skin.

## 3.4 Speculative Probe

Speculative design is an approach that allows individuals and groups to imagine future configurations of technology and society [34, 58, 59]. Design probes are objects whose materiality and form are designed to pose questions through provocative and creative means [65], invite critical reflection, and afford participation by prompting


**Figure 3: The three swatches that emerged from our design explorations: (a) bubble swatch, (b) stranded swatch, (c) corded swatch. Each swatch offers a range of interaction possibilities and body placements.**

considerations of individual lived experiences [13]. Within speculative design, design probes have been used to provide context for ideas and to provoke experiential encounters of alternate futures that engage people at the emotional, physical, and sensorial (as well as intellectual) levels [35]. These experiential encounters are important for exploring how technology can fit meaningfully into people's lives. Our probes are speculative probes [4] which combine the investigative engagement of design probes [17] and the imaginative predictions of speculative design [13, 40]. In addition, our textile swatches, in their intriguing materiality and graspable transformability, offer a means of involving non-experts in envisioning future self-tracking technology and practices that have personal value.

We started with several initial swatches for potential speculative probes. These included tubes, twisted coils, foldable origami-like structures, and multilayer structures. After reviewing these with fellow researchers and individuals from an arts and crafts community workshop, we selected three concepts that were most dissimilar to each other and offered the most interaction possibilities different from those of existing textile inputs and outputs. We also specifically selected concepts that could be integrated into a flat, flexible surface so that the probe could be pinned to different parts of the body and accessories.

Our final speculative probe consisted of three different swatches that communicate several different input and output possibilities and are open to different options for wearing or attaching to the body (Fig. 3). All three swatches were knitted with worsted wool yarn and roughly 9 in. x 9 in. in size. We found that this size worked well to offer the most freedom for manipulating, carrying, and integrating the swatches on the body. They were small enough to fit in pockets and also large enough to wrap them around different body parts.

*3.4.1 Swatch 1: Bubble swatch.* The "bubble" swatch mimics bubble wrap and consists of a 3x3 grid of bubbles that can be "popped" to one side or the other (see Fig. 3a). The bubble swatch harvests the springiness of knitted structures to imbue textile bubbles with a "snapping" sensation and to make it sensitive to a small amount of force; a gentle poking gesture rather than a push or press. We created the bubble effect by increasing the number of stitches across a small section of the knit such that the excess textile billows from the knit in the shape of a bubble. The knitted bubble is more dense (and therefore more rigid) than the flat knit which creates tension and lends the bubble its "pop". Each bubble can be popped in or out independently of the others allowing one to make different patterns (see Fig. 4a). This swatch exemplifies textile mechanisms that are reactive and deform into specific target configurations.

*3.4.2 Swatch 2: Stranded swatch.* Fabric draping is the process of positioning and fastening fabric in place to create structure and patterns. We were intrigued by how this process can transform a flat fabric into a three-dimensional surface with pronounced surface shapes (e.g., ridges and folds). Instead of fastening draped fabric in place, we created a swatch with the ability to gain, retain, and loose shapes by way of draping fabric through holes. The swatch consists of three columns, each with three holes, through which rectangular strands are pulled through and draped (see Fig. 3b). The holes constrain the drape to a specific area of the knit and hold it in place until the fabric is pulled through other holes to drape it anew (see Fig. 4b). We saw this interaction, pinching a fold of fabric between one's fingers and pulling it away from the body, as a more conventional means of interacting with textiles.

*3.4.3 Swatch 1: Corded swatch.* I-cords, thin tubular knits, are a common and versatile fixture in clothing and accessories. Their application ranges from drawstrings on a hoodie or pants, to shoelaces, hair ties, and wrist bands. We saw this as an opportunity to explore how i-cords could be further integrated into textile surfaces and manipulated to form distinct inputs and outputs. In contrast to i-cords typically found in garments, we created a set of disconnected cords that can be twisted, knotted, and woven together freely as well as into a flat knit with a set of 3x3 holes (see Fig. 3c). We matched up the size of the cords and holes such that the cords stayed in place in the holes regardless of how they are positioned or how far they are pulled through the holes. This afforded continuous, gradual deformation (e.g., sliding the cords back and forth in the holes, weaving them through multiple holes) as a way to represent a continuous range of states rather than discrete states (see Fig. 4c).

## 4 ENGAGING WITH STATEFUL TEXTILES

We presented our speculative probe to a diverse group of wearers to explore how their material properties and form factors (e.g., tactile qualities, open-ended design, and playfulness) can support interactivity, and to explore the design space for accessible inputs and outputs. We wanted to understand how stateful textiles might benefit people with different embodied capacities and unpack the factors that shape how they might bring textile sensing and display technology into their lives. To situate the speculative probe in the context of people's everyday lives, we invited people to experiment with the swatches in their homes, with their families, as part of their daily routines, and in other situations that reflect daily living.

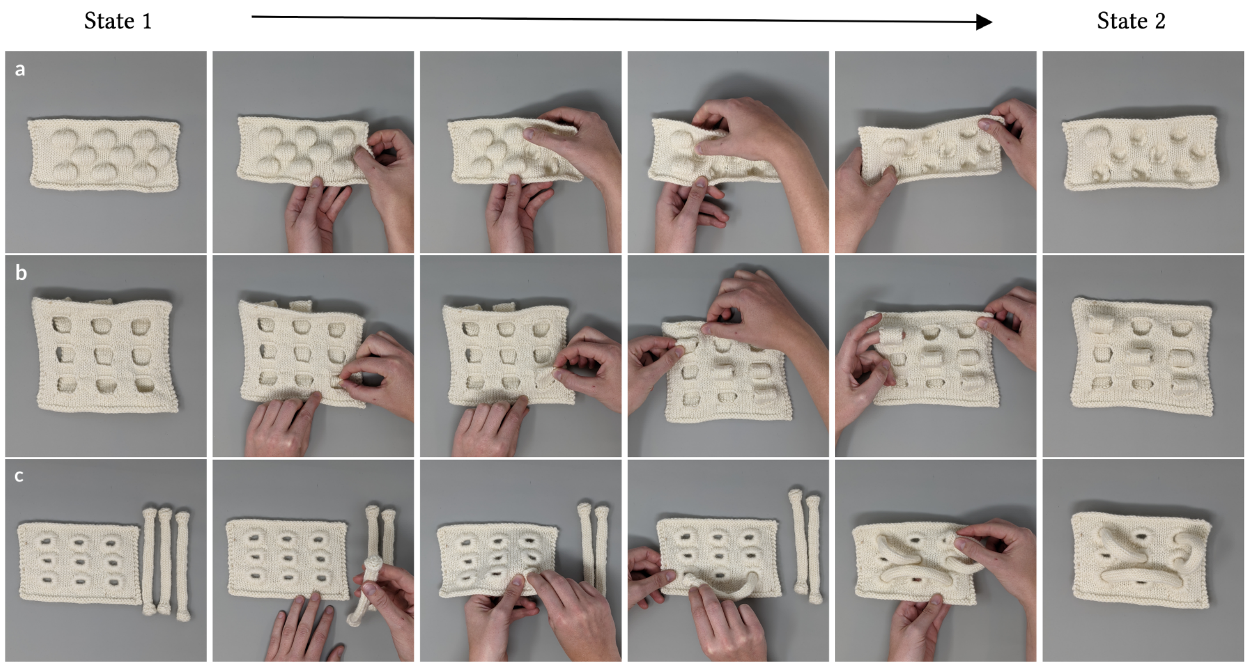


**Figure 4: Data can be encoded into the swatches by changing their physical state.**

Participants revealed interesting practices that emerged for self-tracking. We embraced how people decided to incorporate the stateful textiles into their daily experiences and encouraged participants to explore and discuss these practices with us.

## 4.1 Participants

We recruited 10 participants who were interested in exploring how they might engage with stateful textiles in their day-to-day lives. In addition to inviting people with disabilities, we sought out individuals who reported engaging in fidgeting behavior or having heightened sensitivity to stimuli. We also invited fashion designers who might contribute ideas for new 3D textile forms, new techniques for creating these, and ways to integrate these into existing garments.

Three people identified as having visual impairments, four identified as neuro-divergent (e.g., ADHD), one person identified has having a learning disability (e.g., dyslexia), one individual identified has having psychological disabilities (e.g., anxiety, depression), and two people reported having different capacities for dexterity. Participants had diverse backgrounds, working in different domains (e.g., Mathematician, Artist/Designer, Music Studio Manager, Software Developer, College Student), having different levels of experience with wearables, and different levels of interest in fashion (e.g., preferring aesthetics or functional/comfortable clothing, different fashion styles, sensitive to certain textures, etc.). Two participants identified as fashion designers with a range of textile expertise and two participants had families with small children. Participants demographic information is summarized in Table 1.

## 4.2 Method

Our probe protocol consisted of three steps which participants completed in order: becoming familiar with stateful textiles, engaging with the probes, and sharing and discussing their experiences.

*4.2.1 Introduction to Stateful Textiles.* We conducted a 30-minute session where participants were introduced to our speculative probe and allowed to ask questions about the textile attributes and functions. We began the session with a swatch demonstration to show how the different textiles can be deformed and to encourage participants to experiment with the swatches freely. At the end of this session, we asked participants to fill out a short survey about their self-care practices, self-tracking practices, daily routines, wearable device and technology uses, and preferences for clothing. We used participants answers to our survey questions as context and to ground our discussions in people's daily experiences (Section 4.2.3).

*4.2.2 Activity.* After the introduction, participants were tasked with experimenting with our probe kit for 3 consecutive days and to document their interactions and experiences. The probe kit consisted of our three swatches, several safety pins, and an instruction sheet detailing how to engage with the swatches. In the instructions, we asked participants to keep the swatches on them in some way throughout the day (e.g., attaching or placing the swatch on their garments or accessories). We instructed participants to engage with each swatch for at least half a day but let participants decide which swatch(es) to wear when and for how long.

We instructed participants to record their interactions and experiences by taking pictures/videos and notes every time they engaged with a swatch. As participants had different abilities to use technology, we provided several options for capturing pictures/videos

**Table 1: Participants' demographic information**

| Participant | Age | Gender | Self-reported disabilities and differences | Background |
|---|---|---|---|---|
| P1 | 36 | Male | Visually impaired | Principle Accessibility Engineer |
| P2 | 51 | Female | Visually impaired | Web Accessibility Tester |
| P3 | 31 | Non-binary | Attention Deficit Hyperactivity Disorder (ADHD) | Artist; Fursuit Designer; Music School Studio Manager |
| P4 | 28 | Female | Attention Deficit Hyperactivity Disorder (ADHD); Anxiety | Artist; Business Owner |
| P5 | 27 | Non-binary | Attention Deficit Hyperactivity Disorder (ADHD) | Graduate Student; Research Assistant |
| P6 | 37 | Female | Visually impaired | Accessibility Consultant |
| P7 | 69 | Female | Age-related conditions: decreased dexterity and strength | Retired Mathematician and Professor |
| P8 | 68 | Male | Age-related conditions: decreased dexterity | Retired Mathematician and Professor |
| P9 | 20 | Female | Attention Deficit Hyperactivity Disorder (ADHD); Dyslexia | College Student |
| P10 | 29 | Male | Anxiety | Software Developer |

(e.g., mobile device, disposable camera), taking notes (e.g., voice recordings, pencil on paper, electronic documents), and sharing this data (e.g., Google Drive, texting, USB key), and let participants choose their preferred methods and tools.

*4.2.3 Interview.* We invited participants to share their experiences and discuss which aspects of stateful textiles they found interesting, useful, and delightful. The semi-structured, remote interview lasted 60 minutes. Participants had the swatches during the interview to demonstrate their interactions. We also used participant's documentation from the probe kit activity as discussion points. To provoke in-depth discussions about experiences, we based many questions on the unique responses of the participants. All interviews were video recorded and later transcribed for analysis.

*4.2.4 Data Analysis.* Our participants provided a wealth of unstructured qualitative data including text, photos, videos, drawings, their own renditions of stateful textiles, and interview responses. We analyzed video, transcripts, and artifacts using a grounded theory approach [5] to reveal common associations and also to tease apart unique envisioned interactions and futures possibilities. The data was coded in two passes by the research team to identify recurring themes within the data.

## 5 FINDINGS

Participants enjoyed using the swatches and were enthusiastic about integrating them into their everyday experiences. They saw the stateful textiles as a new kind of non-digital wearable with a unique set of affordances. Participants described the swatches as "versatile", "open-ended", "adaptable", "mobile", and "carriable". P2, for example, highlighted that there were "many possibilities to attach it to the body", to clothing, or to accessories and P4 noted how it could easily be "arranged in different ways to support different interactions". The analog nature of the swatches appealed to participants in the way of providing infinite possibilities for inputs and outputs and opportunities to engage in personally pleasurable experiences with technology.

While participants explored a range of uses, from Braille learning to mnemonic devices, themes emerged in relation to how participants appropriated the textiles for encoding and tracking daily activities and the role physical modes of engagement played in enriching these practices. In the following sections we describe how participants associated with the material, adapted the design for their different bodies and practices, and how the unique qualities of the material provoked particular kinds of experiences within the participants' lives.

### 5.1 Material Associations and Requirements

The quality participants most liked about the material was the softness: a feeling resulting from the supple, rich, and marshmallow-like properties of the textile. Participants described the softness as "more pleasant to hold and touch", "feeling warm and inviting", and "giving a sense of calm".

Metaphorical associations also extended to experiences a person might have of the body. P9 explained that touching the textile "feels sensual like touching the skin" and P10 expressed that "the way the hands connect to the soft fabric feels intimate". In addition, P2 noted that the soft nature of the material made it so it "wasn't intrusive", instead, feeling like an extension of the body. The close relationship to the body could be more widely leveraged in design.

The softness of the material not only brought physical comfort but emotional consolation as well. The physical and visual texture evoked a sense of deep familiarity; impressions of having been brought newly into contact with beloved garments. P4 associated the swatches with an old, knit sweater and related it to feelings of "remembrance and comfort". The hand-crafted nature also appealed to P2, P3, and P4 who associated it with familial traditions. They saw knitting as a representation of the times when they felt comfortable and secure. For most participants, these impressions and associations made the textiles "approachable", "safe", and "personal", and a good fit for embodied interactions.

One participant did not like the material. P1 appreciated that the material was soft and flexible but felt that knitted textiles are often "feminine" gendered. P1 (male; visually impaired) could not see the swatches and was worried about how he might look and be perceived by others when wearing and using them.

Several other participants also had reservations about the material. P1, P6 and P9 reported having sensitive skin and while they appreciated the softness of the material, they found the texture to be less pleasant. P6 raised concern about the texture "causing friction and feeling rough" when moving her hands across the surface of the swatches. For P1, P6 and P9 the texture made the textile less "approachable", and all three participants wished for a smoother fabric. This suggests that knitted interfaces for AT should use knitting patterns that create smooth textures or small stitches that make textures less perceivable.

Experiences with materials are subjective and individual, and individual requirements of people with disabilities regarding materials may be much more diverse than for people without disabilities (i.e., materials that are suitable for some, may not be suitable for others, and requirements for materials can sometimes be contradicting).

## 5.2 Interactions and Adaptations

The probe was intended to last 3 days, but participants wanted to explore the use of the swatches for longer (min. 3; avg. 7; max. 10 days). All participants reported trying each swatch for at least one whole day. Nine participants had a favorite swatch and reported using it for several additional days. P2's and P8's favorite was the corded swatch, and P3, P4, P5, P6, P7, P9, and P10 enjoyed the bubble swatch the most. P1 did not have a favorite swatch, and no one preferred the stranded swatch. While participants did not dislike the stranded swatch, they did not enjoy interacting with it and reported that they would not use it beyond the probe. Participants reported that they would use the bubble and corded swatches in their daily life in their current form as self-tracking and self-care tools and several participants asked if they could keep the swatches.

In the following subsections, we focus on how participants interacted with the swatches: what guided their interactions, accessibility challenges they encountered, and what and how did participants encode information. We also describe emerging values for physical inputs and outputs.

*5.2.1 Function followed form.* The swatches invited and conditioned many different interactions. P3, P4, P5 let the appearance and structure of the swatch guide their interactions, responding to the different shapes and movements. For instance, P3 liked inverting the bubbles by pressing on their puffy exterior. She enjoyed manipulating the topography of the swatches to explore the interaction it affords. Instead, P2 (visually impaired), P6 (visually impaired), and P9 let the material properties guide their gestures and were drawn to the ability to deform the flexible material to explore new, unpredictable shapes. For example, P2 (visually impaired) twisted, folded, and tied the structure into knots. She liked that she could "almost mold the material in a way" and that she "didn't have to worry about breaking it". This openness to a diversity of interactions appealed to the participants, inspiring playful and expressive interactions.

While we designed the swatches to afford a range of inputs and outputs, we were surprised by the different ways in which people interacted with the swatches and the patterns that they created. For example, P3, P4, and P8 enjoyed sticking their fingers through the different opening in the swatches and threading holes in the swatches onto their fingers in different arrangements. P6 and P9 created unexpected patterns with the *corded swatch* by weaving the cords through multiple holes, crisscrossing cords, and tying multiple cords together. Many of these interactions included combination of gestures like pulling, twisting, and rolling fabric onto itself. The spatial dimensions of the textiles afforded many different patterns. Examples of these interactions are shown in Figure 5.

**Figure 5: Examples of ways in which participants wore and interacted with the swatches during the study. Participants physically adapted the swatches to fit their bodies, certain interactions, and different contexts.**

*5.2.2 What and how people tracked activities.* As participants engaged with the swatches throughout their daily lives, they discovered ways to encode and represent different experiences. In particular, participants found enjoyment in recording activities and behaviors. These recordings quickly emerged as self-tracking practices and, over timer, participants wholly embraced the stateful textiles as a tool to support these practices.

There are many different activities and behaviors that people wanted to track quantitatively and qualitatively. Some of these were objective measures. For example, P7 tracked how much water she drank throughout the day by encoding the number of water bottles she finished. P9 tracked her night-time routine, checking off each step by inverting a bubble on the *bubble swatch*. Other measures were subjective. For instance, P4 (ADHD; Anxiety) liked to track her emotional wellbeing and represented the momentary intensity of her anxiety as a numeric rating. P8 tracked his progress towards cleaning the house in terms of progress made towards organizing and putting items away. He assessed his progress qualitatively and looped a cord through a new hole on the *corded swatch* whenever he felt he had made progress towards his goal.

Some of the participants encodings represented quantities such as a count or rating. For instance, the number of bubbles inverted or the number of holes with a strand draped through. Other encodings were symbolic. For example, P10 (Anxiety) created different smiley faces with the cords on the *corded swatch* to represent his different mood. P5 used the swatches as a mnemonic device for her to-do list and associated items on her list with unique patterns, creating a symbolic representation for each item. Example data encodings are shown in Figure 6.

*5.2.3 Physically adapting the design.* Many participants physically adapted the swatches to fit their own bodies, for certain interactions, and contexts. P8 wore the swatches on his upper arm because he could "get to it without much effort". He liked having "immediate and controlled access" to it during his activities. P2 (visually impaired) liked to carry and interact with the swatches inside sweater pockets so that she had access to them, but they weren't available to her children. On the other hand, P3 and P4 preferred to integrate the swatches in ways that supported habitual body postures. They pinned the swatches to their pant legs because "when sitting, the lap is a comfortable and natural position for the hands." The flexible nature of the textile made it possible to customize them to the different preferences of an individual body.

Participants also realized that placement affected the range of interaction possibilities. For instance, P8 discovered that with the *corded swatch* the cords stayed in place in the holes regardless of how far he pulled the cord through the hole or how he positioned them. This prompted him to reposition the swatch as a shirt pocket so that he could access and pull on the cords from both sides (the "inside" and "outside" of the pocket). P3 incorporated the *bubble swatch* as a "kangaroo pouch" (like the pocket features on the front of a hoodie) so that she could manipulated the bubbles with both hands as well as from both sides. These adaptations suggest opportunities for dual-sided textile inputs and outputs that can further expand the range of interaction possibilities on garments.

P3, P5, P7, and P9 explored ways to integrate the swatches that would match their style. For instance, P5 integrated the swatches as elbow patches so that they fit "into the aesthetics of [her jacket] and looked like they were designed to be there". She felt that the swatches could contribute positively towards the visual perception of the garment, making it "look cute" and "interesting". P3 imagined integrating them along the zipper and P7 suggested incorporating them as a hem or a cuff "to make them look like an intentional design detail".

Other participants felt that the swatches would look "too eccentric" on the outside of garments. P4 (Anxiety) feared people "starring" and hid the swatches in her pockets in public settings. She imagined integrating the swatches on the inside of jackets and other outerwear so that she could interact with them privately whenever she pleased. P1 (visually impaired) also didn't want to elicit attention from strangers. He thought that a scarf, gloves, and other accessories may be more appropriate for unique shapes and textures. This is a reminder that textiles, like other AT, may also be stigmatized. In contrast to other AT, aesthetics may be a central stigmatizing features for textile-based AT (rather than function and use).

*5.2.4 Emergent values in physical tracking.* The encoding of interaction into physical representations seemed to be meaningful and enjoyable for participants. In particular, participants saw physical engagement in their self-tracking practices as a benefit that offered more "control", "awareness", "mindfulness", "satisfaction", and "motivation".

Many participants noted that the swatches engaged them explicitly in selecting and representing information. Choosing how to record and represent data was seen as having more control over collecting personal data. P7 explained: "I have control over how I am doing it. You have control and you know if it is screwed up. Whereas sometimes when you are using your phone, you want to record that you are standing enough, then you get distracted, and then an hour later, you need to see if you got up enough but you find out that the [smart watch] didn't correctly record it". The act of manually and directly engaging with the inputs and outputs further this view. P8 asserted that "it's not a matter of how it works is hidden; I can look at it and figure out what states I want to have and what they symbolize for me". Direct control also engendered trust in the data. Participants perceived their encodings on the swatches to "more accurately" and "more meaningfully" represent activities and emotions.

P2 (visually impaired) noted that there were a few occasions when the bubbles on the bubble swatch inverted on their own as a result of being bumped against other surfaces. She expressed that when this happened without her knowledge, it created confusion, and made it so she could not interpret the encodings on the swatch. This further illustrates that people in the study wanted explicit control over states and that textile-based AT must be robust against unintended manipulations caused by random movements (further discussed in Section 5.3).

Figuring out how to encode interactions in the swatches also prompted participants to reflect on their tracking practices. Participants gave active consideration to what information would allow them to gain knowledge about the activities and the self. For instance, P8 questioned if he should "record the activity because [he] didn't do it very well". He felt that counting the activity would be misleading and give him a false sense of accomplishment. It also prompted him to think about the value of tracking data qualitatively rather than quantitatively and question whether some activities should be tracked at all. Participants felt that these reflections allowed them to be "more intentional" about the activities in their lives. P7 further expressed that the impermanence of the data allowed these reflections to be on-going. This was demonstrated by participants re-evaluating and renegotiate their practices and ways to encode these in the swatches. Participants discussed that the act of encoding and self-reflection made them more accountable to complete meaningful tasks and to do them well.

The act of physically encoding the interaction and materializing the stimulus also prompted participants to become more aware of their activities. P9 noted that "the act of recording something imprints it more in your brain". Increased awareness helped some participants focus on the task at hand. For others, the physical representation of the data on the body served as a reminder, both tacitly and visually. P3 (ADHD) explained that "the textile itself, its presence, feeling it, reminds me to focus". Even passively the stateful textiles were seen as offering increased awareness and serving a purpose.

P8 and P10 also described ways in which wearing the swatches provided awareness of one's body. P8 wore the swatches on her chest, near her heart, to connect more intimately with her heart rate. She explained that the presence of the swatch made her more aware of the pace of her heartbeat. In this way, the swatches increased people's perception of the state and properties of her body.

Many of the data encodings can be interpreted as a materialization of achievements rather than data about activities or behavior. Participants used the swatches to reward themselves for completing activities or for certain behaviors. For instance, P9 rewarded herself for completing a juice cleanse by inverting a bubble on the *bubble swatch*. Using the textiles as a reward mechanism motivated people to complete activities that they did not want to do. P7 explained that "it was nice to have this visually pleasing, fun reminder to do [activities]" and P9 expressed that "it was rewarding to record the data in this fun way, but it was also satisfying to see the data displayed". Participants who wore the swatches around family viewed the swatches as a display of their achievements.

*5.2.5 Peripheral interactions and self-regulating behavior.* Participants also used the swatches as a tool to support self-regulation behavior: conscious and subconscious movements of the body to help increase or decrease attention, either calming or energizing the mind. For instance, P2 liked to engage with the swatches "in times when I just needed to take a breathing break, to get my mind off of something". P3 described fidgeting with the swatches "to help divert unneeded energy elsewhere, to focus". She also used the swatch when she felt anxious and explained that "looking at and exploring all of the different textures and structures allowed [her] to calm down".

While fidget objects are often designed for small repetitive movements, the swatches range of interaction possibilities was seen as an asset. P2, P3, and P9 liked that the swatches afforded simple gestures but also puzzle-like engagement. P2 explained that "the bubble swatch was good for fidgeting and focusing because it was simple [. . . ] the corded swatch was better for disengaging and taking a break because you could do more with it". Some participants felt that the texture of the knit in itself was stimulating. Other participants received the most satisfaction from the movement and tactile experience of the 3D shapes.

Participants compared fiddling with the swatches to past experiences with fidget objects like fidget spinners, cubes, and other small widgets (e.g., binder clips, bracelets, pens). P4, P6, and P9 expressed that fiddling with the textile elicited less negative attention than other objects. In particular, P6 and P9 were concerned about the social perceptions and stigma associated with fidget toys (e.g., "white boys have fidget spinners"). P4 explained that the swatches "don't make noise" and don't have the appearance of fidget objects. P9 felt that fiddling with the swatches was "less noticeable" to others. Both participants liked the idea of having "fidget spots integrated into their clothes" and felt that the textiles offered opportunities to design "versatile" fidget objects.

## 5.3 Accessibility Challenges

Participants' interactions with swatches highlighted a number of accessibility challenges.

**Clear orientation.** Visually impaired participants found it difficult to determine the orientation of the swatches which made it difficult to interpret their state and the data already encoded. P2 (visually impaired) mentioned: "I had to figure out which side of the swatch was the top and which was the bottom and like they are the same". P1, P2, and P6 (all visually impaired) suggested adding additional textures to each side of the swatch or varying the structure to be able to determine the orientation.

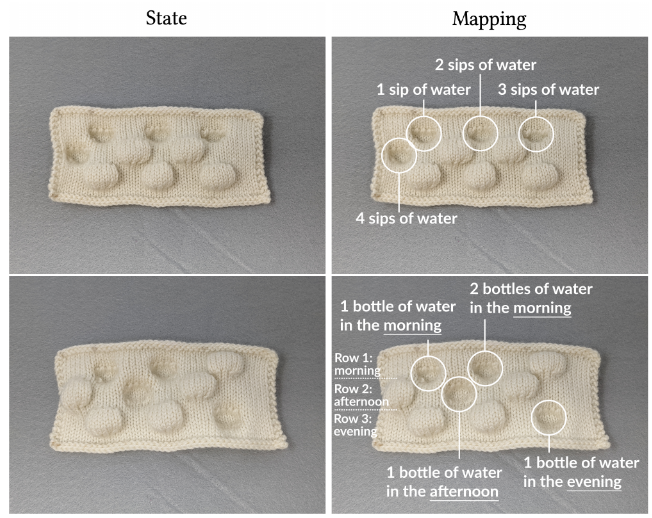


**Figure 6: Example of two ways to track hydration using the bubble swatch, revealing that "state" can be a combination of orientation, location, and form.**

**Explicit control.** Visually impaired participants also faced challenges with accidental manipulations and changes to the swatches which caused data to be lost without participants' knowledge. For example, when reading the state of the stranded swatch by touch, the strands sometimes fell out of the holes changing the pattern of the swatch and therefore the data encoded within it. Participants did not always notice these unintended manipulations and became confused when the swatch did not exhibit the pattern that was previously encoded. This interaction suggests that textile-based AT should provide users explicit control over inputs and outputs.

# 6 DISCUSSION

We engaged a diversity of participants as a generative starting point to explore how stateful textiles may enrich peoples' daily live. Participants' experiments and discussions about stateful textiles illustrated unique characteristics of non-digital, physical modes of sensing and display: (1) enriching the experience of data collection and (2) offering ways to collect new forms of data that people found to be worthwhile tracking. It also gave us insights about what factors are important to consider in designing sensors. In addition, we highlight new opportunities for inputs and outputs, and body placements in the context of assistive wearables.

## 6.1 Mapping Sensing to Textile Expressions

Our stateful textiles gave us insights into the various dimensions of textile expressions and the role these play in communicating data. In exploring how people used our swatches in their tracking practices we observed how participants mapped data to textile features. We observed that state can be a combination of several factors including orientation, location, and form (see Fig. 6). Different combinations of these factors (i.e., different patterns) can communicate a range of different data (e.g., a specific point in time, an interval, quantities, ratings, etc.).

## 6.2 Data Beyond Biometrics

Our stateful textiles suggest new kinds of data that people found to be worthwhile in tracking. For instance, participants wanted to track their performance not by some quantitative metric but qualitative means; rather than tracking if they had done something or for how long, they were interested in tracking if they had done it well. This prompted participants to create symbolic representations rather than quantitative encodings. Furthermore, participants wanted to track things that could not be easily defined as a single activity or behavior, or broken down into metrics (e.g., success or failure, feelings of anxiety). These kinds of data engendered encodings of complex patterns. This suggests opportunities in creating inputs and outputs that allow a wider range of representations beyond measurements.

## 6.3 Broadening the Definition of Sensors

Stateful textiles allowed participants to collect and represent data through physical manipulations of open-ended designs. In doing so, they reasoned about what information to track and how to represent it as an encoding through patterns. These practices combine stages of collection and reflection [31]. Furthermore, the "short-term memories" of the textiles placed the act of reflection in the moment which allowed people to interpret the data in context and brought awareness between the associations of actions and data. The transient nature of the encodings fostered on-going reflection of activities and behaviors as participants had to encoded data anew, bringing attention to the information once more and prompting participants to re-evaluate their practices. Thus, stateful textiles as a means of tracking are not just about knowing oneself; they demand both knowing and re-negotiating oneself. Building on the narratives of physicality and self-reflection, we bring attention to the potential to explore and support ephemeral data representations as these may have positive impacts on people's data tracking practices.

## 6.4 On-Body Interactions with Clothing

Our work suggests that the scope of "natural gestures" for on-body interaction [9] may change depending on individual bodies, activities, and context. The range of integrations showed that no specific placement is necessarily better than another. Body positions anticipate habitual possibilities of movement, impacting reachability and comfort. Therefore, different body positions invite different interactions. For example, in our study, body placements beyond the wrist were more comfortable for seated positions and when working with the hands.

Participants' different integrations of the swatches suggest that people with disabilities might want wearables with "all over" inputs and outputs, placements beyond the wrist, convenient or habitual spots, visible and non-visible locations, and non-watch form factors. It also highlights opportunities for interfaces with dual-sided inputs and outputs, and for two-handed interactions.

Our work further suggests that preferences for on-body interactions may be influenced by social roles. In our study, we found that parents have different preferences for body placements that consider both the parent and the child's ability to interact with the wearable.

Finally, our findings suggest that on-body interactions do not need to be hidden or made less explicit. The visual properties of our stateful textiles were seen as an aesthetic feature and participants reported being comfortable wearing and interacting with them in public. Future textile-based wearable designs might prioritize aesthetics over other design dimensions.

# 7 LIMITATIONS AND FUTURE WORK

Stateful Textiles present our first attempt at creating accessible textile inputs and outputs for assistive wearable interfaces. Based on our work to date, we identified several opportunities for future work. First, participants imagined application ideas beyond sensing and display. For example, one participant appropriated our swatches for Braille learning. This suggests that there are many different assistive functions textile inputs and outputs can serve.

At the moment, our stateful textiles do not work well if the context of sensing is to collect and communicate data for someone else. This is in part a limitation of how we structured our speculative probe and we see opportunities to conduct further research to understand how stateful textiles can be used in a social context.

In addition to improving stateful textiles ability to sense and display information, we see the potential for do-it-yourself (DIY) assistive technology [26]. What would it be like if participants knitted their own idealized interfaces? As our methods for crafting stateful textiles do not require high-end knitting machines, we see this as a viable way to explore future wearable textile interfaces with people with disabilities as designers and makers.

# 8 CONCLUSION

In this paper, we presented stateful textiles as inputs and outputs in and of themselves to explore alternative ways of interacting with data and self-tracking. Our work suggests that the act of materializing data in the moment allowed people to interpret the data in context and brought awareness between the associations of actions and data. We contribute the notion of transient states and transient data as a way to foster on-going reflections and re-negotiating of the self. Furthermore, we highlight an interest in collecting and representing unstructured data and abstract metrics through symbolic representations. Our work shows that non-digital modes of sensing and display can provide empowering self-tracking tools for users with disabilities.

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