VISMOCK: A Programmable Smocking Technique for Creating Interactive Data Physicalization

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ABSTRACT

Data physicalization is a research area that explores representing data attributes through manipulating the geometric and physical properties of tangible objects. We introduce VISMOCK, a data physicalization approach that leverages a fabric manipulation technique called "smocking". VISMOCK supports the creation of interactive and dynamic data physicalizations by extending the smocking technique with programmable components such as thermochromic pigments and shape memory alloys. Using a research-through-design methodology, we develop an initial design space for VISMOCK that shows how data can be represented using visual and tactile variables, as well as the affordances of VISMOCK. We demonstrate the generative power of our design space through four exemplars, created using VISMOCK. We use these exemplars to discuss the advantages and limitations of VISMOCK as a tool for data physicalization.

Authors Keywords

Data Physicalization; E-textile; Interaction Design

CSS Concepts

• Human-centered computingVisualization~Visualization techniques • Human-centered computing~Visualization~Visualization systems and tools

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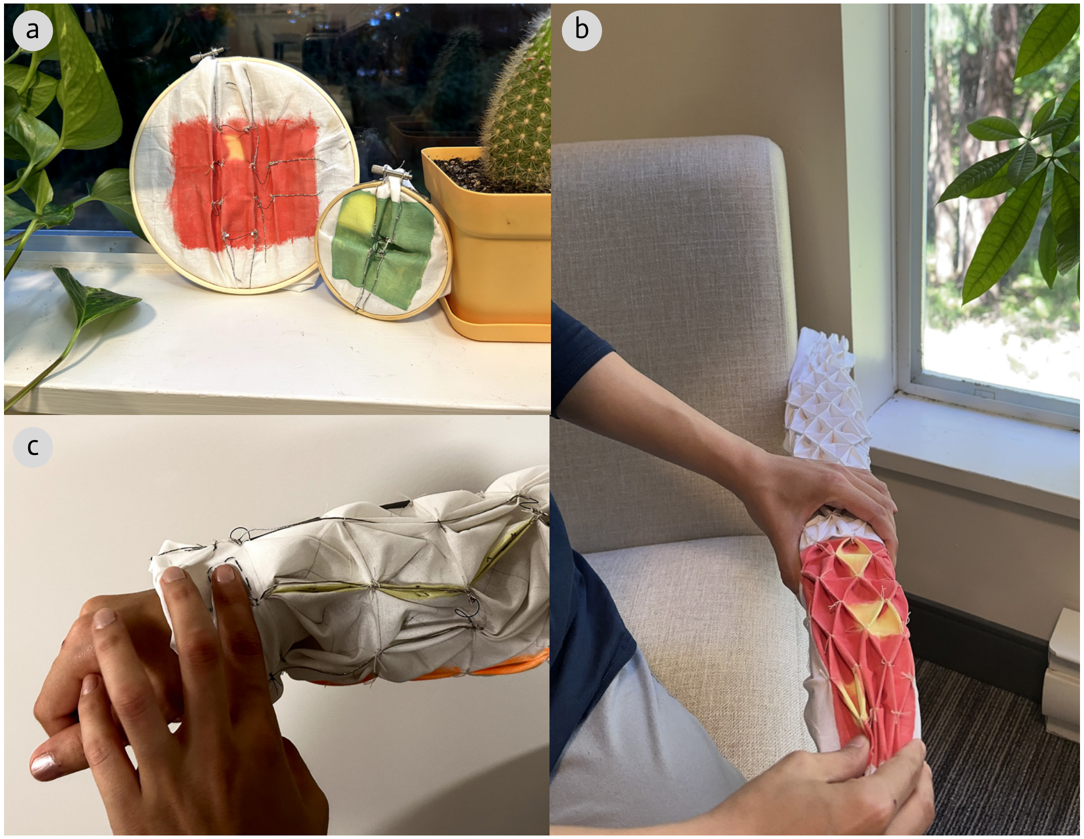


Figure 1: Three data physicalization examples created using VISMOCK technique.

INTRODUCTION

Data physicalization research is concerned with designing and studying approaches to encode data in the "geometrical shape or material properties" of physical artifacts [27]. Representing data in a physical form can offer advantages such as improved cognitive, spatial and perceptual understanding [11, 27, 72], lowered technical skills threshold for engaging with data [27, 72], and multisensory experiences that can provide richer understanding of the data [22].

However, to design new data physicalizations, a number of challenges must be first addressed [27]. For example, there is a need for identifying and studying new physical mediums whose properties can be leveraged for representing data [9, 37]. Similarly, we must identify how interactions with such mediums can be designed to facilitate understanding of the encoded data [19, 43, 57]. To this end, researchers have proposed new systems and techniques for data physicalization, such as using actuated objects to support data analysis [39, 41], and using mediums such as paper with kirigami techniques to facilitate interactive operations like retrieving and sorting data values [9]. Building on these works, we explore the potential of e-textiles (textiles combined with computational materials [35]) as a medium for representing and interacting with data (See Figure 1).

E-textiles have been used for conveying information in a variety of contexts (e.g., [6, 10, 23, 31, 76]). Past works have highlighted the potential of e-textiles to become an ambient display [76], to employ personal meanings and social functions [10, 31], to offer seamless integration of computing into everyday objects [61], and to provide less focus-demanding interactions [33]. However, no previous work has focused on the development of novel interactive data physicalizations by leveraging the geometric and material properties of textiles, combined with the benefits of programmable electronics, to map data to visual and tactile variables.

We present VISMOCK, a technique that integrates electronics within textile-based smocked patterns, to create a programmable display for representing and interacting with data (see Figure 1). Smocking is a sewing technique that creates three-dimensional shapes on fabrics [46]. The resultant 3D shapes can be utilized to display a number of visual variables such as position and size, or the area occupied by a data point [4]. Additionally, smocked patterns have an inherent elastic quality and can have different textures, which can be used to convey tactile variables such as roughness, lay, and compliance [25, 70]. We combine these visual and tactile variables afforded by smocked patterns with off-the-shelf electronics such as thermochromic pigments and shape memory alloys to create an interactable display for data representation. Although the individual components of our technique (smocking, thermochromic pigments, and shape memory alloys) are not new, how we combine them to develop interactive data physicalizations is novel.

We designed and developed VISMOCK using the research-through-design methodology [82]. We iteratively developed a design space which shows how visual and tactile variables, together with the affordances of VISMOCK can be used to represent and interact with data. Using the evaluation-by-demonstration method [42], we demonstrate the generative power of VISMOCK's design space via four exemplars that show potential applications in personal and group settings (see Figure 1). These exemplars demonstrate three main capabilities of VISMOCK. First, the technique can be utilized to represent different types of data and data visualization idioms such as bar charts (Exemplar 1a), heat maps (Exemplar 2), and line charts (Exemplar 3). The technique can also dynamically update the data representation based on new data gathered from an activity such as running (Exemplar 3). Second, supported via manual and computationally triggered interactions, operations such as filtering and zooming can be performed (Exemplars 1-3). Third, leveraging the properties of thermochromic pigments, the technique can modify visual variables such as the color of data points dynamically.

In summary, we make the following contributions:

(1) We introduce the VISMOCK technique and present a corresponding design space, which shows how a sewing technique (smocking) can be adapted for physicalizing data; specifically by controlling visual and tactile parameters.

(2) We showcase VISMOCK's ability to create different interactive visualizations to demonstrate the generative power of the VISMOCK design space.

RELATED WORKS

Our work is informed by literature from the areas of data physicalization and e-textiles. In this section, we briefly explain the recent efforts in data physicalization research, and research in the space of interactive e-textiles for communicating data (e.g., [51, 55, 61]).

Interactive Data Physicalization

In non-physical visualization, data is represented using graphical marks such as lines and points. The data values for each data point are represented by varying visual variables (also called visual channels) of the corresponding mark such as its position, size and color, in accordance with the type of data value (e.g., position for quantitative values, size for ordered values and color hue for categorical values) [53]. Data physicalizations also leverage graphical marks and visual variables, however, they are different in that they also represent data values by varying the geometrical and material properties of physical objects [27].

In the field of data physicalization, much of the research focus has been around adapting digital visualization idioms such as barcharts (e.g., [65, 71]), line charts (e.g., [71]) and node-link graphs (e.g., [12]) to the physical world in a static way. The topic of interaction for data physicalization, although not new (for example, Bertin's reorderable matrices [5] were already being used half a century ago), is only beginning to be explored in academia. Notable interactive, dynamic data physicalization examples include using actuated rods to create 3D bar charts [72], micro-robots to create scatterplots [41], and touch-sensitive 3D printed material to create 3D networks [2].

A different approach consists of exploring what data physicalization possibilities are enabled when starting from the material, rather than the visualization idiom to create. For example, KiriPhys [9] explores a new type of data physicalization based on kirigami, a traditional Japanese art form that uses paper-cutting. Investigating such a technique makes it possible to identify and explore the potential of new physical variables (such as elasticity and density of the kirigami pattern) that can be used to communicate data. We follow a similar approach with VISMOCK: by utilizing the smocking technique on fabric, we explore new physical variables and interactive capabilities that can be used both to recreate existing visualization idioms and to propose new types of data physicalizations.

Smocking

Smocking is a fabric manipulation technique [68] that can be used to create different shapes on fabric. There are three variations of the smocking technique: English, American, and Italian smocking. While English and Italian smocking are created based on embroidery stitches on top of gathered pleats, American smocking is created by sewing regularly-spaced stitches on a grid structure [29, 50]. Different stitching patterns result in different 3D shapes [48, 50]. Smocked patterns like the Honeycomb pattern also introduce certain affordances such as an elastic property, and therefore are commonly used in clothing such as swimsuits [48]. In architecture, smocked patterns have been created using different grid sizes, topological variations, and deep volumetric folds to create highly complex structures [63]. In HCI, a few studies have explored smocked patterns as a crafting technique for interactive interfaces. For instance, Efrat et al. [14] investigated how a catalog of different kinds of smocked patterns can be combined using a parametric design CAD tool to assist makers in creating artifacts. GesFabri [28] is another study in which researchers investigated interaction gestures with textile patterns by studying a set of interactive textile interfaces, including smocked patterns as systematic folding textures. However, interactivity and affordances of smocked patterns have not yet been explored to represent data in the context of data physicalization.

Interactive E-textiles for Communicating data

Researchers have demonstrated how e-textiles can be used to build interactive interfaces (e.g., [19, 21]). For example, Nabil et al. showed through a set of design fictions how artifacts used in interior design, including some fabric-based artifacts such as a tablecloth and couch, can be used as mediums to represent and interact with personal data [55]. A study of Emotocouch, an interactive furniture that conveys emotions, revealed that personalization and complementing with existing accessories and furniture in the home is a crucial aspect of interactive furniture [52]. In the Social Fabric Fitness project [51], researchers studied the potential for using glanceable wearable e-textile-based displays to improve awareness, cohesiveness, and motivation for group running scenarios. FabriCar [33] explores e-textile-based interactions incorporated in the steering wheel, seat-belt pad and headrest cover of a vehicle; they showed that users feel safer and less distracted using e-textile prototypes for non-driving tasks like media control, in comparison with screen-based interactions.

While these past projects describe interactions with data, they do not explicitly consider how to leverage the geometrical and physical properties of the textile and computational materials to represent data. Therefore, they do not fall within the realm of data physicalization. In this work we focus on how data can be visually and physically mapped to e-textiles and how interaction with such data representations can be facilitated.

RESEARCH METHODOLOGY

We used the research-through-design methodology [81, 82] to explore the use of fabrics, the smocking technique, and the incorporation of electronics, for representing data. This method is an iterative design process wherein researchers engage in designing prototypes and through such design explorations construct knowledge about a design opportunity. Following the steps outlined by Zimmerman and Forlizzi [81], the lead researcher engaged in the process of creating different smocked patterns and integrating different types of electronics. Informed by these samples we discussed and created an initial design space for how smocked patterns can be used for building multisensory visualizations. To demonstrate the versatility of VISMOCK and its initial design space, we used the evaluation-by-demonstration method [42] and developed four prototypes for three scenarios. These design exemplars highlight how VISMOCK can be used as a technique for creating data physicalizations that engage visual and tactile senses.

VISMOCK IMPLEMENTATION

In this section, we provide implementation details of VISMOCK.

Smocking Display

The primary component of VISMOCK is an augmented smocked pattern, which we refer to as a smocking display (see Figure 1). To create a smocking display, we combine American smocked pattern [48, 68]) with programmable electronics to actuate textile shape [36, 56] and color [10, 76].

To create a smocked pattern, small stitches are sewn into the fabric using specific designs (see Figure 3, step 5). Such stitching can be done either manually or using a sewing machine. A smocked pattern can be developed using different types of fabrics such as cotton and linen. To demonstrate VISMOCK, we created our displays with a medium weight white cotton fabric. We chose this fabric because it could i) show the details of the pattern, ii) be shape-actuated with a reasonable amount of energy consumption, and iii) have the weight and color that would lend itself well to both integrating electronics and to displaying actuated changes in color and shape.

In our implementation, a smocking display is composed of a number of cells as shown in Figure 2. A single cell within the smocking display can be described as follows:

A cell corresponds to a square grid of a specific dimension that has a stitch design, and can be connected to a circuit to control its color and shape.

Circuit Design

We use a composite technique to create a smocking display. This involves compositing a separate fabric layer, which we refer to as the heater layer, containing the electronics and the circuit, with a smocked pattern layer (see Figure 3).

Our heater layer has two faces. On the front face, we sew conductive thread patterns that act like heating elements. The back face of the heater layer acts as a breadboard and connects to different parts of that heater layer using copper tape. Regular cables can also be used instead of the copper tape connections (see Figure 2). To power and control our heater layer, we use an off-the-shelf microcontroller, Arduino Mega. MOSFET is used to control the current flow from an external power source to the circuit. To power our circuit, we use 3.7 volt rechargeable Li-Ion batteries with capacities higher than 1000mAh (see Figure 4).

Programming Color Change

Color actuation has been explored in textile-based user interfaces through combining heating elements such as silver ink [74], Peltier element [47], and fluidic channels [79]. Researchers have utilized color-changing elements such as liquid crystal displays [17], and thermochromic paints [47, 73, 79]. In VISMOCK, we mix thermochromic pigments (with a variety of activation temperatures: Black-Colorless (38 C), Red-Yellow (31 C), and Green-Yellow (25 C))[1] with white dye and paint the mix on the fabric surface. The thermochromic pigment is then actuated using the heater layer. Thermochromic pigments typically enable a material to have two states – an original base color, and a changed color when applying heat over a certain threshold. When the material cools to a temperature below the threshold, it returns to its base color.

1 https://www.colorchangingdeals.com/product-page/thermochromic-powder-pigments

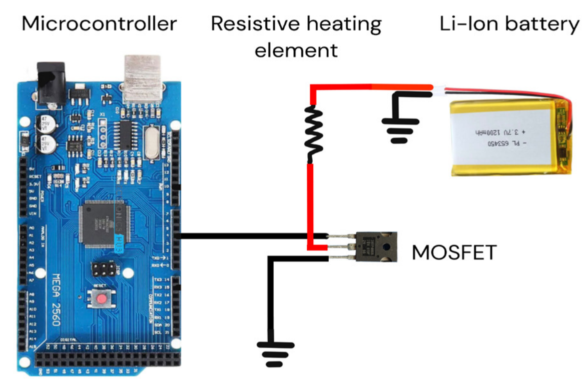


Figure 4: circuit design.

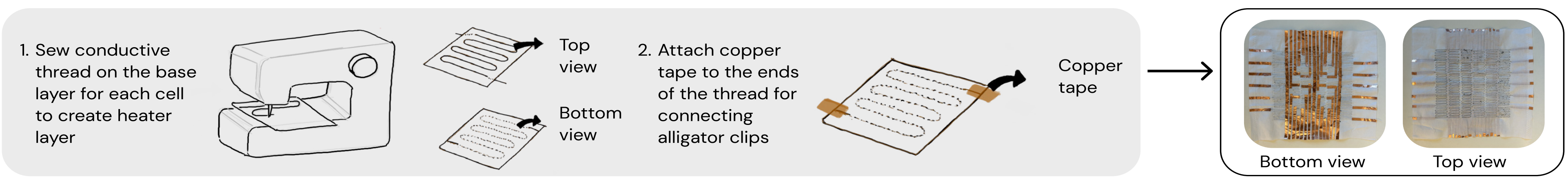


Figure 2: Steps to create a heater layer.

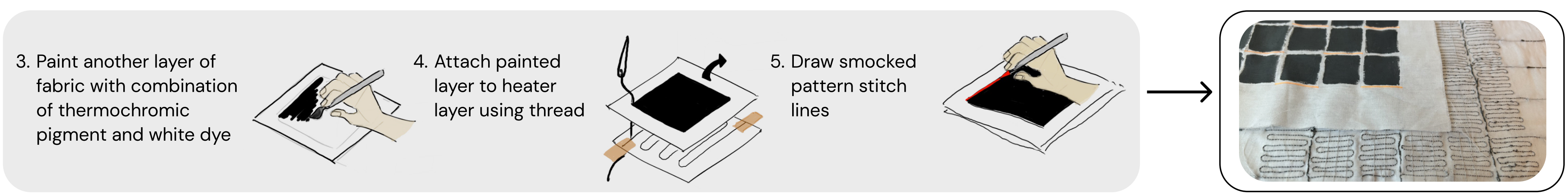


Figure 3: Steps to create a composite of heater layer and smocked pattern layer.

For example figure 6a shows the color of an actuated cell changes from one color state (black) to another (white) within 60 seconds when using a 3.7 volt battery and conductive thread with relatively low resistance. Over a given time (60s in our case) by manipulating the on and off duration for passing current we can have different color intensities. This makes it possible to apply non-binary color changes to cells (See Figure 6b).

Programming Shape Change

Shape actuation has been proposed in user interfaces in many different ways such as using shape memory alloys (SMAs) [36, 54, 56], fluidic shape changing [49, 62, 80] and magnetic effects [78]. Among these, SMAs are most frequently used in e-textile user interfaces because of their light weight and relative flexibility to integrate into fabrics. In VISMOCK, we use shape memory alloys (SMAs), such as shape memory wires and springs. These types of SMAs have a trained state. Applying current and heating the wires above their activation temperature causes these wires to go back to their trained state.

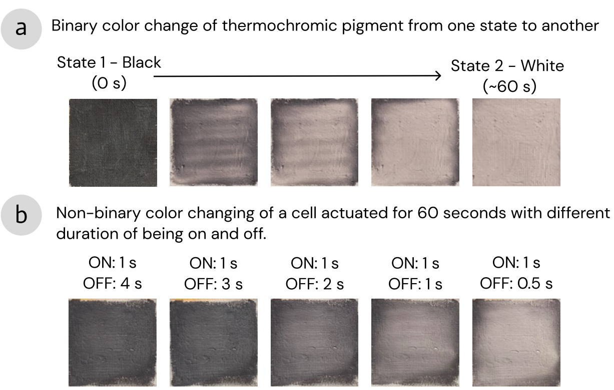


Figure 6: Binary and non-binary color actuation.

In our implementation (see Figure 5), to expand, we use NiTi shape memory alloy with wire trained state, of size 0.5mm, and transition temperature of 45C[1]. To compress, we use NiTi shape memory alloy with helical spring trained state, of size 0.5mm, a mandrel size of 8mm, a pitch of Wire size*4, and a transition temperature of 45C[2]. By setting the state of current flow to 'on' or 'off', or by controlling the time interval during which the current flows, we can either reach a specific shape state or animate an expansion or compression sequence. Figure 7 shows a cell of 3*3 cm size fully expanded or compressed by shape memory alloy within 2 and 8 seconds appropriately.

1 https://www.kelloggsresearchlabs.com/product/round-wire/
2 https://www.kelloggsresearchlabs.com/product/helical-spring/

Using shape memory alloys and thermochromic pigments comes with challenges that are opportunities for future research. First, in our implementation the SMAs are one-way actuators that can be used either for compression or for expansion. Investigating two-ways SMAs would make it possible to actuate both expansion and compression via heating and cooling of a single kind of SMA [45, 69]. Second, as shape memory alloys and thermochromic pigments activate by heat caused by passing current, in wearable applications it is important to use thermal protection to prevent thermal discomfort [66].

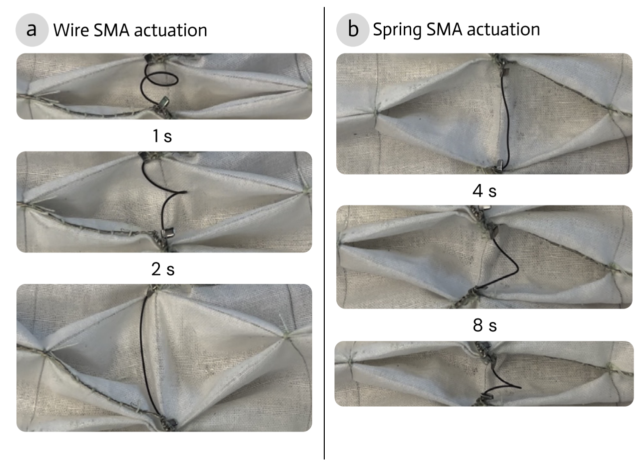


Figure 7: Compression and expansion shape actuation.

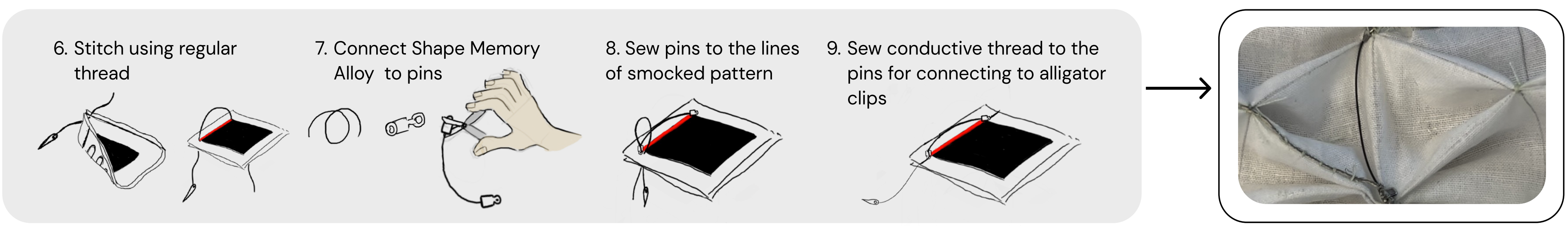


Figure 5: Steps to implement shape actuation and example of shape actuation.

VISMOCK DESIGN SPACE

In our exploration, we developed the VISMOCK design space shown in Table 1 that consists of three parts: independent variables, dependent variables, and affordances. We selected to explore an initial set of visual and tactile variables that are both relevant to textiles and relevant to data physicalization. Our selection, guided by the multisensory visualization design space by Hogan et al. [23] and the design space for data physicalization by Bae et al. [3], includes variables that are fundamental to visualization design and that support as a whole both quantitative and qualitative data attributes [4].

Independent variables are aspects of smocked patterns that can be modified independently from other parameters. They can be visual (cell size, number of cells, pattern kind and cell color) or tactile (cell stitch state, and cell temperature). Each independent variable can be controlled either manually while making the smocking display, or by manual interaction or using electronics within the fabricated smocking display.

Dependent variables are aspects of smocked patterns that are modified by varying independent variables.

The dependent visual variables we explored are shape, shape size, shape position, and dynamic cell color. Shape in VISMOCK corresponds to each repeating unit of the smocked pattern and depends on the pattern kind (see Figure 8). Shape size and position correspond to the characteristics of that unit within the entire pattern. Dynamic cell color corresponds to the current color of the thermochromic pigments applied to the cell's surface and depends on cell temperature. Shape depends on pattern kind and cell stitch state, while size and position depend on pattern kind, cell stitch state, and the size of the grid structure that the pattern is made from.

The dependent tactile variables we explored are roughness, lay, and compliance [25, 70]. Roughness in VISMOCK is modified through variations in the fabric caused from changes in shape. Lay depends on the orientation of the rows and columns of the pattern kind. Compliance refers to the capability of the pattern used to be compressed and expanded, which can range from high compliance like honeycomb, to relatively rigid like the flower shaped pattern, and depends on pattern kind and cell stitch state.

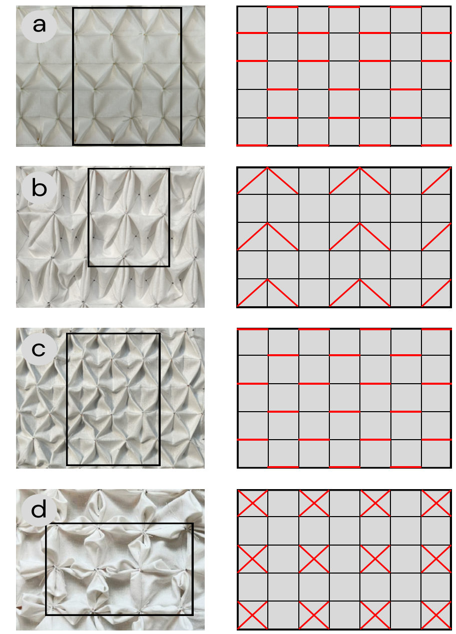
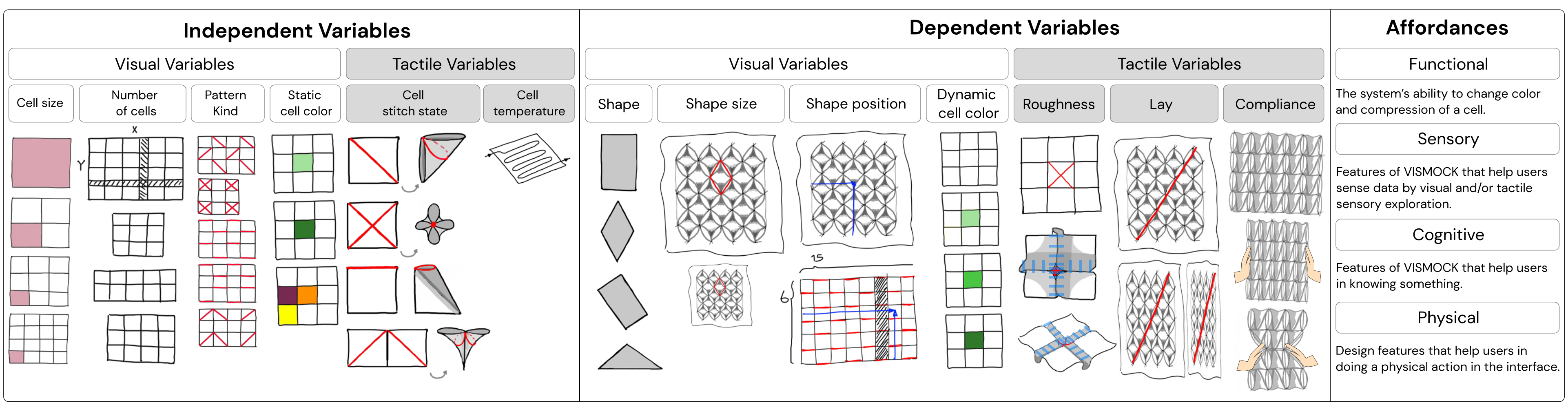


Figure 8: a) Lozenge, b) Wave, c) Honeycomb, d) Flower pattern.

Table 1: VISMOCK design space.



Affordances in VISMOCK refer to the functional, sensory, cognitive, and physical affordance categories described by Hartson [20]. These categories are not entirely distinct, but taken together correspond to how data represented using VISMOCK is being perceived, sensed, and used as a function of independent and dependent variables that represent data (see Figure 9).

Functional affordances are design features that help users accomplish tasks. Functional affordances in VISMOCK encompass the ability of the system to close or open the stitches and to map the color value of a cell to a range of data values, which enables users to visualize quantitative, categorical, and ordinal data.

Sensory affordances are design features that help users sense something in support of cognitive or physical affordances. Sensory affordances in VISMOCK relates to temperature changes that pertain exclusively to the tactile sense (e.g., feeling data value changes), color changes to the visual sense (e.g., seeing trend), and compliance, lay, and roughness to both tactile and visual senses (e.g., extent of roughness could indicate differences in data values).

Physical affordances are design features that help users in doing a physical action. Physical affordances in VISMOCK are about compliance as it helps users compress and expand the smocking display to perform operations such as zooming in and out.

Cognitive affordances are design features that help users in knowing something. Cognitive affordances in VISMOCK relate to lay, compliance, and roughness as they help users in knowing the characteristics of the smocking display. For example, high compliance can enable users to know that the pattern can be compressed and expanded or lay can communicate that there is a trend in the visualized dataset.

Next, we demonstrate through a series of exemplars how VISMOCK might help users to sense, understand, and interact with data. Together, these exemplars demonstrate the usefulness of the VISMOCK design space to generate new types of interactive data physicalizations.

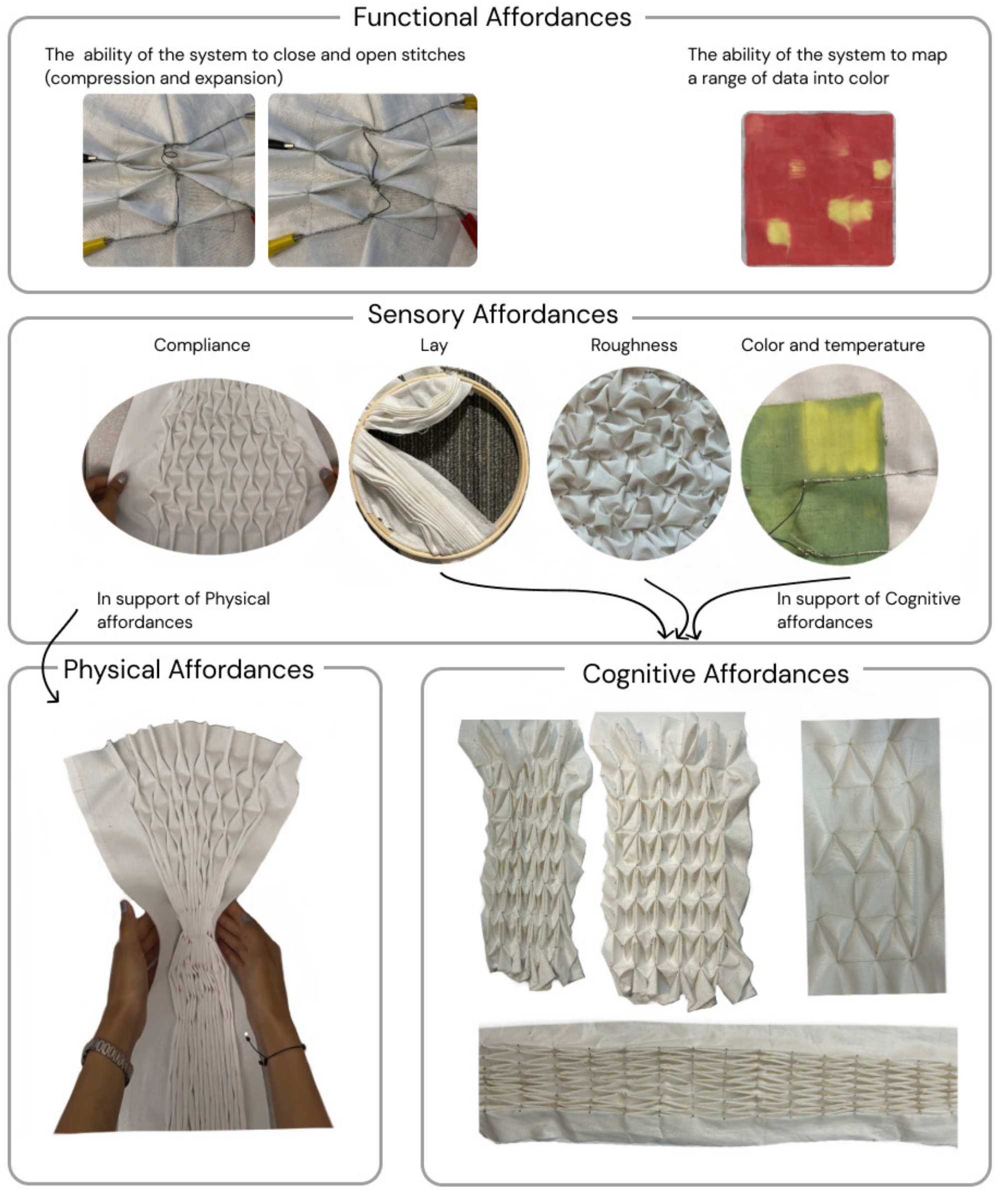


Figure 9: Examples of functional, sensory, physical and cognitive affordances.

EXEMPLAR 1A AND EXEMPLAR 1B: SHAREABLE AND PORTABLE DATA VISUALIZATIONS

Researchers have demonstrated data physicalizations can facilitate sharing data with others in contexts such as: education to support learning abstract concepts [75]; family life to create a sense of community and shared understanding [40, 59]; health to communicate the state of a patient with biometric monitoring over a distance [7]; and decision making [41].

In this scenario, we demonstrate how VISMOCK can also be utilized for sharing data with others. Unlike past works, which primarily comprise of systems that are placed at a fixed location, VISMOCK supports creating mobile [38] physicalizations. Physicalizations made with VISMOCK are made using fabric, a flexible material, and therefore they can be integrated into portable garments and accessories as shown in Figure 10. Such portability can be useful for data monitoring when individuals want to learn about others while going about their routine activities for example [38]. Because VISMOCK physicalizations do not look like standard visualization idioms, it is not obvious that these represent data and therefore can be used to maintain data privacy even if the data physicalization is carried around as a publicly visible wearable.

We created two data physicalizations for family members to share data with each other at a distance. Each physicalization represents i) how busy a family member is during a day and ii) if the person is currently busy with an ongoing task. Sharing such insights with family members can be useful for providing support and coordinating activities.

Figure 10: Shareable and portable physicalizations integrated into accessories.

Table 2: Exemplars 1a and 1b described using the VISMOCK design space.

Independent Variables						Dependent Variables						
Visual Variables				Tactile Variables		Visual Variables				Tactile Variables		
Cell size	Number of cells	Pattern Kind	Static cell color	Cell stitch state	Cell temperature	Shape	Shape size	Shape position	Dynamic cell color	Roughness	Lay	Compliance
3*3 cm	3*5	Lozenge	No static color	Horizontal stitch	Rises (passing current)	Hexagon	Change in 1D size (width)	Change in position	Red to Yellow	Pattern Compression	No change in lay	Pattern Compression
3*3 cm	3*3	Flower	No static color	Diagonal stitch	Rises (passing current)	Square	Change in 2D size (area)	Change in position	Green to Yellow	Pattern Compression	No change in lay	Pattern compression

Exemplar 1a (see Figure 11) is a bar-chart like physicalization that represents data about multiple tasks being performed by an individual. Each vertical bar corresponds to a task the person is scheduled to engage with on a given day - so the larger the number of bars, the busier the family member is that day. Each vertical bar is divided into three segments (for start, middle and end) that indicate the person's progress toward completing that task. Progress toward completing a task is indicated by changing the color of the three segments within the corresponding bar. As a task is being completed, its corresponding bar closes and the bar that corresponds to the next task opens up.

Exemplar 1b (see Figure 12) shows a single task. The task being performed by a person is represented by a single smocking display consisting of nine cells, and each cell corresponds to a step within the task. As the person makes progress within a step, the color of the corresponding cell begins to change, reaching its final color (here yellow) when the step is complete (see Figure 12a-c). When all steps for that task are complete, the shape of the display changes (see Figure 12c-e). In future implementations, several such displays could be assembled and organized in different ways to provide richer insights into different tasks accomplished by the same person or different people in a shared setting such as a home or an office.

These two exemplars utilize visual variables color, shape, size, and position and tactile variables roughness and compliance.

Regarding affordances, changes in temperature, size, shape, position, roughness and compliance can be perceived through tactile and visual senses; while changes in color can be perceived through visual senses only. For example, when the user looks at or touches the pattern, more roughness means that more tasks have been completed by the user. In terms of cognitive affordances, the collapsible form factor of the pattern shape communicates that expansion and compression in one spatial dimension in Exemplar 1a, and in two spatial dimensions in Exemplar 1b. Both exemplars also include functional affordances given that shape and color are actuated.

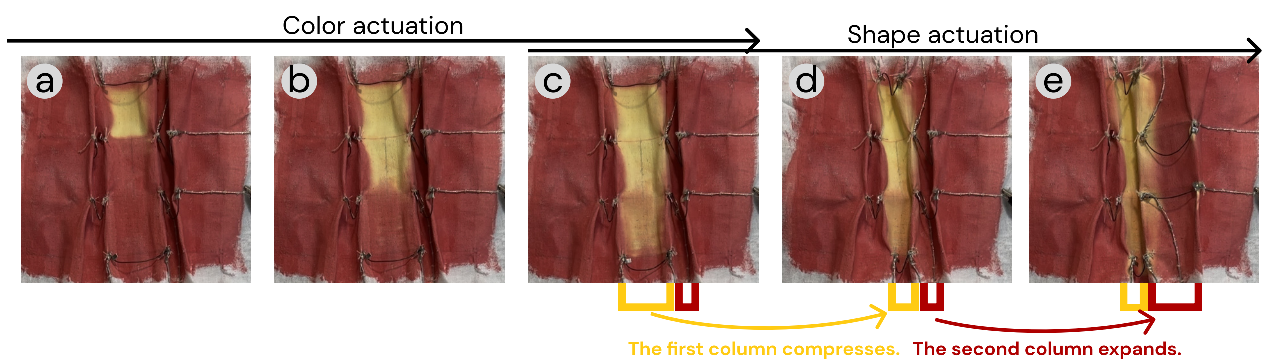


Figure 11: In Exemplar 1a, a,c) task progress is represented with color actuation, c-d) upon task completion the corresponding bar compresses, and e) the next bar expands when a new task starts.

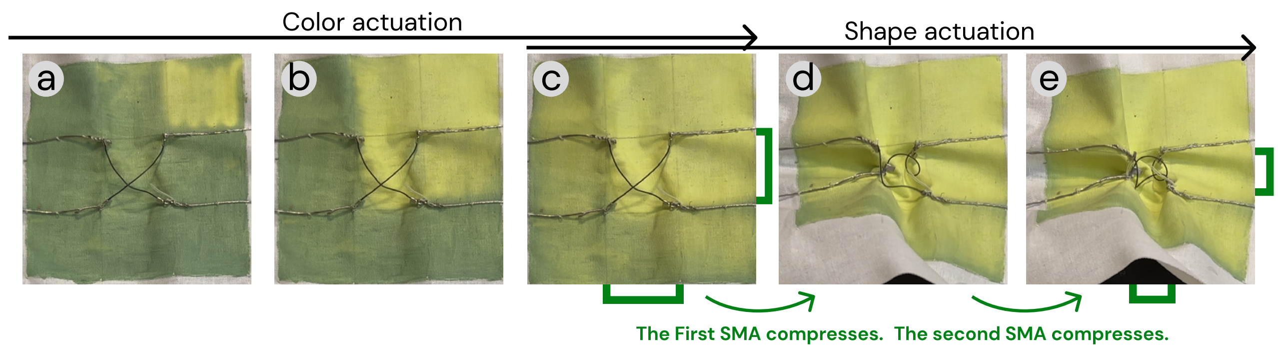


Figure 12: In exemplar 1b, a,c) task progress is represented with color actuation, and c-e) upon task completion the two SMA compress.

EXEMPLAR 2: VISUALIZING AND ENGAGING WITH PERSONAL DATA

Personal data is a common application area for data physicalization (e.g., [32, 43, 44, 60]). For example, in the domain of health, it has been shown that representing data in everyday spaces in playful ways can increase awareness of, and engagement with data that are crucial to understand one's mental health [77]. VISMOCK can be used to that end: fabric lends well to integration with everyday spaces and artifacts such as furniture in the home, and the elastic and soft characteristics of a honeycomb smocked pattern can create a playful experience, as is the case with other stretchable physicalizations (e.g., [9]). As an example of playful physicalization that can be integrated into everyday spaces, we created a stress tracker. The physicalization is integrated into a sofa arm that supports casual interactions and reflection opportunities (see Figure 1b).

The physicalization is a heatmap of a person's stress level values, where each column of the pattern represents a week, and each row represents a day of the week (see Figure 13). The daily stress level of the person is represented on a red-yellow color scale, with red meaning 'high stress level' and yellow meaning 'low stress level'. Because this physicalization represents data over a significant amount of time, performing operations such as zooming into specific weeks can be useful.

Inspired by existing focus+context [8] and distorting lens [8] visualization techniques such as 'melange' [16] for displaying large data sets on a relatively small display, we use the expansion characteristics of honeycomb to zoom in and out physically. By compressing the pattern at the beginning and end of a desired time interval and expanding the interval area, we can zoom in on the data in that area (see Figure 14a,b). The zooming as currently implemented in our exemplar is closer to a focus+context technique [8] than to a magnification of the material that would improve resolution. Other types of implementation are possible with VISMOCK to reveal information at a different level of detail. For example, Figure 14c shows how opening up the fabric and expanding cells can reveal another level of stitched patterns and corresponding level of data.

This exemplar uses visual and tactile variables to communicate through both visual and tactile senses. It utilizes the functional affordance of actuating color, and the physical affordance of providing manual compression and expansion as a result of using a honeycomb pattern that has high compliance. As the temperature rises and the color changes, the user understands the increase in stress level through both touch and visual senses.

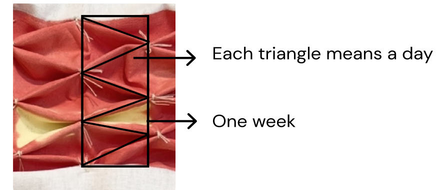


Figure 13: Meaning of cells individually and as a group.

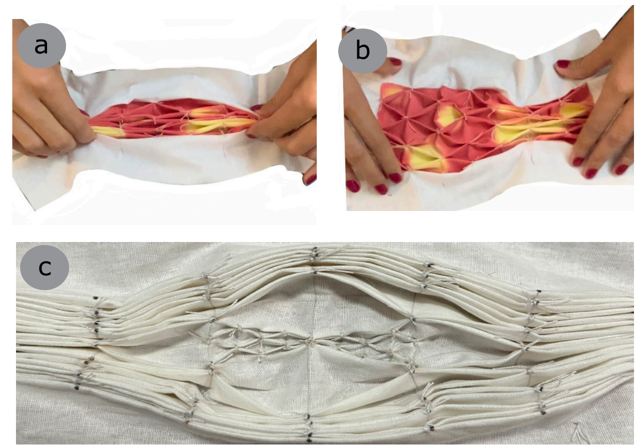
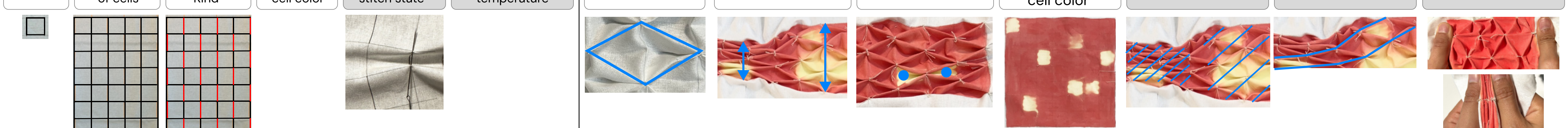


Figure 14: Manual zoom interaction to see- a,b) cell colors, and c) nested cell level patterns.

Table 3: Exemplars 2 described using the VISMOCK design space.

Independent Variables						Dependent Variables						
Visual Variables				Tactile Variables		Visual Variables				Tactile Variables		
Cell size	Number of cells	Pattern Kind	Static cell color	Cell stitch state	Cell temperature	Shape	Shape size	Shape position	Dynamic cell color	Roughness	Lay	Compliance
												
3*3 cm	7*number of weeks	Honeycomb	No static color	Vertical stitch	Rises (passing current)	Diamond	Change in 1D size (length)	Positions of each cell	Red to Yellow	Pattern Compression	Pattern Compression	Pattern compression

EXEMPLAR 3: VISUALIZING GROUP DATA

Previous work has demonstrated positive effects of physicalizing activity data to increase motivation for maintaining healthy habits in both individual and group activities. For example, Bookly [30] and LOOP [64] support continuous self-reflection through a data physicalization of reading time and physical activity data. It has also been shown that digital visualizations of group data can help forming communities [1 , 51]. Building on this research, Exemplar 3 is a physicalization of progress toward group activities that offers continuous exposure to data about individuals in the group to motivate and provide peer support. It can be worn as a sleeve attachment to enable in-situ interactions (see Figure 1c).

The physicalization, shown in Figure 15, is a `small multiples' physicalization of time series line charts, where color hue, shape, position, roughness, lay, and compliance represent data. Each color-coded line (i.e. each small multiple line chart) represents the running distance of an individual for several days. The frames for each small multiple are created by adding two buffer rows on the bottom and on the top of the line. This way, updating one of the line charts does not accidentally affect the shape of the other line charts. To get an update on a friend or family's running performance, the person can update the positions of the points of a line chart with updated data using a touchpad sewn at the end of each small multiple (see Figure 1c).

This exemplar can be perceived through visual and tactile senses. Shape actuation provides a functional affordance. Sensory affordances are being used as support for cognitive affordances. For example, the rectangular shape of the pattern that is communicated through both visual and tactile senses supports the idea of compression and expansion of pattern and facilitates the connection of the pattern with the line chart structure. Lay of each line can also be perceived by tactile and visual senses and supports the cognitive affordance of understanding trends.

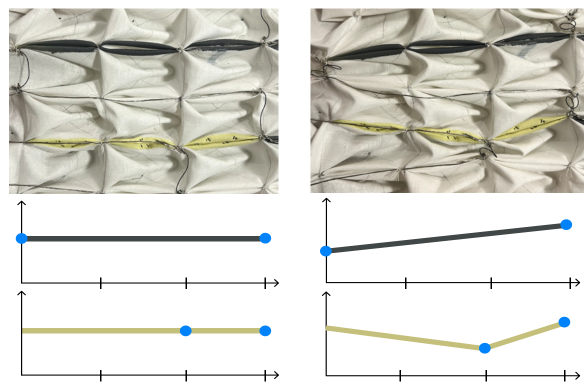


Figure 15: Actuated line charts of running distance

DISCUSSION AND FUTURE WORK

We discuss the insights we gained from developing the exemplars we presented.

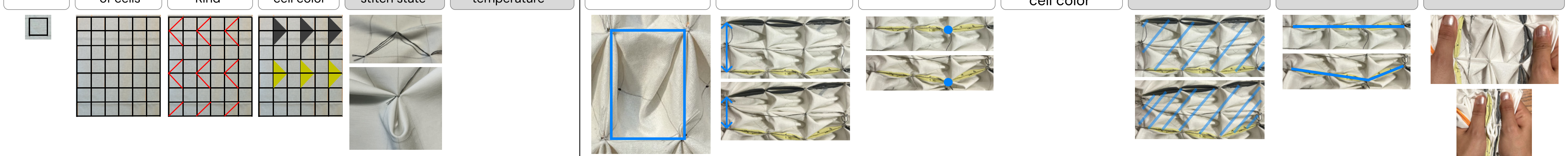
Representing Data Points

Unit visualizations represent each data point using a unique visual mark [13, 58] -- for example, a scatterplot where each data point represents a student. In contrast, aggregate visualizations summarize collections of data points [15, 58] -- for example, a barchart where each bar represents the aggregate value for all students of a given research group. Our exemplars cover both unit and aggregate visualizations. For instance, Exemplar 1a is a unit visualization because each bar (visual mark 'line') represents one task. But when the bars collapse they form a stack of collapsed bars whose size represents the number of completed tasks, much like what is done in visual sedimentation [26], and this visualization is an aggregate one.

Within both unit and aggregate visualizations, VISMOCK supports tracking items during animated transitions [58] (Exemplar 1a, 1b and 2) and supports interactions (Exemplar 3). In our implementation, the modifications of unit and aggregate visualizations are achieved using SMAs and thermochromic pigments -- materials that are difficult to scale due to their high power consumption.

Table 4: Exemplars 3 described using the VISMOCK design space.

Independent Variables						Dependent Variables						
Visual Variables				Tactile Variables		Visual Variables				Tactile Variables		
Cell size	Number of cells	Pattern Kind	Static cell color	Cell stitch state	Cell temperature	Shape	Shape size	Shape position	Dynamic cell color	Roughness	Lay	Compliance
3*3 cm	16*13	Wave	Partially colored	Diagonal stitch	No change	Rectangle	Change in 1D size (length)	Positions of each cell	No dynamic cell color	pattern compression	pattern compression	pattern compression



To address this limitation, research in electrical engineering is required to explore new ways to power the circuit (e.g., [34]). Nonetheless, manual actuation of smocked patterns is a useful alternative as the 3D structure of a smocked pattern can be utilized to represent individual or aggregate data points. For instance, a VISMOCK unit visualization can represent each student by using techniques such as coloring individual cells and constructing individual cells using different fabrics. Similarly, a VISMOCK aggregate visualization can represent the number of students in each research group with a bar chart whose implementation leverages the grid structure of smocked patterns (as shown in Exemplar 1a).

All the exemplars we designed are about a single individual or a small group of people, such as runners or a family. In such contexts, only the individual or group of individuals is expected to be able to decode and understand the data, and one would imagine that the decoding key would be explained to whoever should be able to read the data. Other people outside the group might not even realize that some data is being represented, and it is an advantage for obvious considerations of privacy. However, there are other scenarios in which it is desirable that anyone can understand the representation, typically in public settings such as a museum. Even though this could be addressed by providing a decoding key or a legend besides the physicalization, in the future we plan to look into how to integrate labels, axes and legends into VISMOCK. Similarly, retrieving exact values is difficult (as is the case with many physicalizations) and future work should investigate interactive techniques that support getting details on demand.

Enabling Operations and Transformations

Our work addresses the challenge to "integrate input and output modalities into physicalizations by concurrently considering form and interactivity" [2], by combining textile and electronics for the purpose of representing data physically. Notably, compliance is one of the primary characteristics of many smocked patterns. For example, we leverage the high compliance of some patterns such as honeycomb to compress and expand a physicalization. Similarly change in roughness as a result of shape change is an inherent part of using actuated smocked patterns. Such affordances unlock interaction possibilities such as updating, filtering and zooming. Manual zooming was demonstrated in Exemplar 2 and automated adjustment was demonstrated in Exemplar 3. In exemplar 1 updating data is visible by changing roughness. Similarly perceiving roughness change could be utilized in specific application areas such as accessibility [73].

Supporting Color Schemes and Scales

Digital visualizations support different color schemes and color scales [67]. To achieve similar flexibility with data physicalization is much more challenging [27]. One could simply add color-rich LCD screens and LEDS, but these are known to conflict with aesthetic requirements [56], and their rigidity would also hinder the manipulation of fabric.

We explored the use of thermochromic pigments to encode categorical data with color hue and quantitative data with color value Yet, the number of available color options is limited by the number of available thermochromic pigments. The visual resolution of the color ranges is also limited by the difficulty to accurately control thermochromic actuations. Lastly, color ranges are limited to interpolations of values between two colors and thermochromic pigments do not support multi-hue color scales. In the future we will explore materials that provide multiple hues such as liquid crystal inks [18].

Computational fabrication and ideation tools

Through the development process of VISMOCK, we faced many ideation, scenario development, and fabrication challenges — as is the case with most data physicalizations. For example, combining different smocked patterns while having color- and shape-changing capabilities is promising. However, it is hard to imagine what a set of design decisions will result in without actually creating physical objects, and we had to prototype by hand any idea we wanted to explore. This ideation process is therefore difficult, resource-intensive and time-consuming. Fabricating and testing VISMOCK samples also results in non-negligeable energy consumption and waste of electronics and chemicals that have a negative environmental impact. Much like toolkits, libraries and frameworks have bolstered research and practice for digital visualizations, similar toolkits are needed for data physicalizations (only a few research prototypes have been proposed [2, 71]) to support faster, cheaper and more environmentally sustainable ideation and prototyping solutions.

CONCLUSION

In this work, we introduced VISMOCK, a programmable smocking technique for creating interactive data physicalizations. We showcased four exemplars that illustrate the technique's potential across three scenarios. Using our examples, we demonstrated and discussed how this approach can be used to represent data with both visual and tactile variables, and to support both manual and computational interactions like updating data and zooming in and out. Through this work we contribute an understanding of how sewing and e-textile techniques can be leveraged to create interactive data physicalizations.

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REFERENCES

[1] Noor Ali-Hasan, Diana Gavales, Andrew Peterson, and Matthew Raw. 2006. Fitster: social fitness information visualizer. In CHI'06 Extended Abstractson Human Factors in Computing Systems. 1795–1800.

[2] S Sandra Bae, Takanori Fujiwara, Anders Ynnerman, Ellen Yi-Luen Do, Michael L Rivera, and Danielle Albers Szafir. 2023. A Computational Design Pipeline to Fabricate Sensing Network Physicalizations. IEEE Transactions on Visualization and Computer Graphics (2023).

[3] S Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. 2022. Making data tangible: A cross-disciplinary design space for data physicalization. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. 1–18.

[4] Jacques Bertin. 1983. Semiology of graphics. University of Wisconsin press.

[5] Jacques Bertin. 2011. Graphics and graphic information processing. Walter de Gruyter.

[6] Joanna Berzowska and Marcelo Coelho. 2006. Smoks: the memory suits. In CHI'06 Extended Abstracts on Human Factors in Computing Systems. 538–543.

[7] Alberto Boem, Kai Sasaki, and Shori Kano. 2017. Vital+ morph: A shape-changing interface for remote biometric monitoring. In Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction. 503–509.

[8] Andy Cockburn, Amy Karlson, and Benjamin B. Bederson. 2009. A Review of Overview+detail, Zooming, and Focus+context Interfaces. ACM Comput. Surv. 41, 1, Article 2 (jan 2009), 31 pages.

[9] Foroozan Daneshzand, Charles Perin, and Sheelagh Carpendale. 2022. KiriPhys: Exploring New Data Physicalization Opportunities. IEEE Transactions on Visualization and Computer Graphics 29, 1 (2022), 225–235.

[10] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. " I don't Want to Wear a Screen" Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems. 6028–6039.

[11] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. 2020. Data physicalization. Handbook of Human Computer Interaction (2020), 1–51.

[12] Adam Drogemuller, Andrew Cunningham, James A Walsh, James Baumeister, Ross T Smith, and Bruce H Thomas. 2021. Haptic and visual comprehension of a 2D graph layout through physicalisation. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems.

[13] Steven Drucker and Roland Fernandez. 2015. A unifying framework for animated and interactive unit visualizations. Microsoft Research 1 (2015).

[14] Tamara Anna Efrat, Moran Mizrahi, and Amit Zoran. 2016. The hybrid bricolage: bridging parametric design with craft through algorithmic modularity. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems. 5984–5995.

[15] Niklas Elmqvist and Jean-Daniel Fekete. 2009. Hierarchical aggregation for information visualization: Overview, techniques, and design guidelines. IEEE transactions on visualization and computer graphics 16, 3 (2009), 439–454.

[16] Niklas Elmqvist, Nathalie Henry, Yann Riche, and Jean-Daniel Fekete. 2008. Melange: space folding for multi-focus interaction. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. 1333–1342.

[17] Shreyosi Endow, Mohammad Abu Nasir Rakib, Anvay Srivastava, Sara Rastegarpouyani, and Cesar Torres. 2022. Embr: A Creative Framework for Hand Embroidered Liquid Crystal Textile Displays. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. 1–14.

[18] Marinella Ferrara, Murat Bengisu, Marinella Ferrara, and Murat Bengisu. 2014. Materials that change color. Springer.

[19] Ebba Fransén Waldhör, Pauline Vierne, Paul Seidler, Berit Greinke, and Katharina Bredies. 2017. E-textile production of wearable ambient notification devices. In Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems. 309–312.

[20] Rex Hartson. 2003. Cognitive, physical, sensory, and functional affordances in interaction design. Behaviour & information technology 22, 5 (2003), 315–338.

[21] Anja Hertenberger, Barbro Scholz, Beam Contrechoc, Becky Stewart, Ebru Kurbak, Hannah Perner-Wilson, Irene Posch, Isabel Cabral, Jie Qi, Katharina Childs, et al . 2014. 2013 e-textile swatchbook exchange: the importance of sharing physical work. In Proceedings of the 2014 ACM international symposium on wearable computers: Adjunct program. 77–81.

[22] Trevor Hogan and Eva Hornecker. 2013. In touch with space: embodying live data for tangible interaction. In Proceedings of the 7th international conference on tangible, embedded and embodied interaction. 275–278.

[23] Trevor Hogan and Eva Hornecker. 2017. Towards a design space for multisensory data representation. Interacting with Computers 29, 2 (2017), 147–167.

[24] Michael Holroyd, Ilya Baran, Jason Lawrence, and Wojciech Matusik. 2011. Computing and fabricating multilayer models. In Proceedings of the 2011 SIGGRAPH Asia Conference. 1–8.

[25] Eva Hornecker, Trevor Hogan, Uta Hinrichs, and Rosa van Koningsbruggen. 2023. A Design Vocabulary for Data Physicalization. ACM Transactions on Computer-Human Interaction (2023).

[26] Samuel Huron, Romain Vuillemot, and Jean-Daniel Fekete. 2013. Visual sedimentation. IEEE Transactions on Visualization and Computer Graphics 19, 12 (2013), 2446–2455.

[27] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and challenges for data physicalization. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. 3227–3236.

[28] Mengqi Jiang, Vijayakumar Nanjappan, Hai-Ning Liang, and Martijn ten Bhömer. 2022. GesFabri: Exploring Affordances and Experience of Textile Interfaces for Gesture-based Interaction. Proceedings of the ACM on Human-Computer Interaction 6, EICS (2022), 1–23.

[29] Ruby Joseph, Kaur Prabhjot, Mehtab Shazia, et al . 2011. Lattice smocking techniques: an innovative approach to smocking. Asian Journal of Home Science 6, 1 (2011), 5–11.

[30] Somi Ju, Kyung-Ryong Lee, Subin Kim, and Young-Woo Park. 2019. Bookly: an interactive everyday artifact showing the time of physically accumulated reading activity. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. 1–8.

[31] Viirj Kan, Katsuya Fujii, Judith Amores, Chang Long Zhu Jin, Pattie Maes, and Hiroshi Ishii. 2015. Social textiles: Social affordances and icebreaking interactions through wearable social messaging. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction. 619–624.

[32] Maria Karyda, Danielle Wilde, and Mette Gislev Kjærsgaard. 2020. Narrative physicalization: Supporting interactive engagement with personal data. IEEE Computer Graphics and Applications 41, 1 (2020), 74–86.

[33] Pouya M Khorsandi, Lee Jones, Vandad Davoodnia, Timothy J Lampen, Aliya Conrad, Ali Etemad, and Sara Nabil. 2023. FabriCar: Enriching the User Experience of In-Car Media Interactions with Ubiquitous Vehicle Interiors using E-textile Sensors. In Proceedings of the 2023 ACM Designing Interactive Systems Conference. 1438–1456.

[34] Sang Jin Kim, Sang Un Kim, Chi Cuong Vu, and Joo Yong Kim. 2023. Improved heating method for shape-memory alloy using carbon nanotube and silver paste. Fashion and Textiles 10, 1 (2023), 16.

[35] Abiodun Komolafe, Bahareh Zaghari, Russel Torah, Alex S Weddell, Hamideh Khanbareh, Zois Michail Tsikriteas, Mark Vousden, Mahmoud Wagih,Ulises Tronco Jurado, Junjie Shi, et al. 2021. E-textile technology review–from materials to application. Ieee Access 9 (2021), 97152–97179.

[36] Pin-Sung Ku, Kunpeng Huang, and Cindy Hsin-Liu Kao. 2022. Patch-O: Deformable Woven Patches for On-body Actuation. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. 1–12.

[37] Carine Lallemand and Maud Oomen. 2022. The Candy Workshop: Supporting Rich Sensory Modalities in Constructive Data Physicalization. In CHI Conference on Human Factors in Computing Systems Extended Abstracts. 1–7.

[38] Ricardo Langner, Lonni Besancon, Christopher Collins, Tim Dwyer, Petra Isenberg, Tobias Isenberg, Bongshin Lee, Charles Perin, and Christian Tominski. 2021. Mobile Data Visualization. Chapman and Hall/CRC, Chapter An Introduction to Mobile Data Visualization.

[39] Mathieu Le Goc, Lawrence H Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. 2016. Zooids: Building blocks for swarm user interfaces. In Proceedings of the 29th annual symposium on user interface software and technology. 97–109.

[40] Mathieu Le Goc, Charles Perin, and Sean Follmer. 2018. Embedded Personal Physicalizations. In Toward a Design Language for Data Physicalization, IEEE VIS.

[41] Mathieu Le Goc, Charles Perin, Sean Follmer, Jean-Daniel Fekete, and Pierre Dragicevic. 2018. Dynamic composite data physicalization using wheeled micro-robots. IEEE transactions on visualization and computer graphics 25, 1 (2018), 737–747.

[42] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation strategies for HCI toolkit research. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. 1–17.

[43] Kyung-Ryong Lee, Somi Ju, Temirlan Dzhoroev, Geonil Goh, Moon-Hwan Lee, and Young-Woo Park. 2020. DayClo: an everyday table clock providing interaction with personal schedule data for self-reflection. In Proceedings of the 2020 ACM Designing Interactive Systems Conference.1793–1806.

[44] Kyung-Ryong Lee, Beom Kim, Junyoung Kim, Hwajung Hong, and Young-Woo Park. 2021. ADIO: An interactive artifact physically representing the intangible digital audiobook listening experience in everyday living spaces. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. 1–12.

[45] Christian Lexcellent, Sylvain Leclercq, Bertrand Gabry, and Gilles Bourbon. 2000. The two way shape memory effect of shape memory alloys: an experimental study and a phenomenological model. International Journal of Plasticity 16, 10-11 (2000), 1155–1168

[46] Malin Lind. 2019. Smocked patterns: An exploration of jacquard woven patterns and smocking techniques for a spatial textile design context.

[47] Guanhong Liu, Tianyu Yu, Zhihao Yao, Haiq-

ing Xu, Yunyi Zhang, Xuhai Xu, Xiaomeng Xu, Mingyue Gao, Qirui Sun, Tingliang Zhang, et al . 2022. ViviPaint: Creating Dynamic Painting with a Thermochromic Toolkit. Multimodal Technologies and Interaction 6, 8 (2022), 63.

[48] Sarah Ljungdahl. 2018. smock x knit: Exploring the possibility of shape in knitwear by looking at theaesthetic properties of smocking, drawing inspiration from sportswear. University of Borås. https://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Ahb%3Adiva-14890.

[49] Qiuyu Lu, Haiqing Xu, Yijie Guo, Joey Yu Wang, and Lining Yao. 2023. Fluidic Computation Kit: Towards Electronic-free Shape-changing Interfaces. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. 1–21.

[50] Olfat Mansour. 2020. Aesthetics of Smocking Stitches in Zero-Waste Innovative Fashion Design. International Design Journal 10, 1 (2020), 381–399.

[51] Matthew Mauriello, Michael Gubbels, and Jon E Froehlich. 2014. Social fabric fitness: the design and evaluation of wearable E-textile displays to support group running. In Proceedings of the SIGCHIConference on Human Factors in Computing Systems. 2833–2842.

[52] Sarah Mennicken, AJ Bernheim Brush, Asta Roseway, and James Scott. 2014. Finding roles for interactive furniture in homes with EmotoCouch. In Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication. 923–930.

[53] Tamara Munzner. 2014. Visualization analysis and design. CRC press.

[54] Sara Nabil, Aluna Everitt, Miriam Sturdee, Jason Alexander, Simon Bowen, Peter Wright, and David Kirk. 2018. ActuEating: Designing, studying and exploring actuating decorative artefacts. In Proceedings of the 2018 Designing Interactive Systems Conference. 327–339.

[55] Sara Nabil and David Kirk. 2019. Interactive Interior Design and Personal Data. People, Personal Data and the Built Environment (2019), 103–122.

[56] Sara Nabil, Jan Kučera, Nikoletta Karastathi, David S Kirk, and Peter Wright. 2019. Seamless seams: Crafting techniques for embedding fabrics with interactive actuation. In Proceedings of the 2019 on Designing Interactive Systems Conference. 987–999.

[57] Leyla Norooz, Matthew Louis Mauriello, Anita Jorgensen, Brenna McNally, and Jon E Froehlich. 2015. BodyVis: A new approach to body learning through wearable sensing and visualization. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. 1025–1034.

[58] Deokgun Park, Steven M Drucker, Roland Fernandez, and Niklas Elmqvist. 2017. Atom: A grammar for unit visualizations. IEEE transactions on visualization and computer graphics 24, 12 (2017), 3032–3043.

[59] Jesse Pepping, Sarah Scholte, Marnix Van Wijland, Milan De Meij, Günter Wallner, and Regina Bernhaupt. 2020. Motiis: Fostering Parents' Awareness of their Adolescents Emotional Experiences during Gaming. In Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society. 1–11.

[60] Charles Perin. 2021. What Students Learn With Personal Data Physicalization. IEEE Computer Graphics and Applications 41, 6 (2021), 48–58. https://doi.org/10.1109/MCG.2021.3115417

[61] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E Robinson. 2016. Project Jacquard: interactive digital textiles at scale. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems. 4216–4227.

[62] Purnendu, Sasha M Novack, Eric Acome, Christoph Keplinger, Mirela Alistar, Mark D Gross, Carson Bruns, and Daniel Leithinger. 2021. Electriflow:Soft Electrohydraulic Building Blocks for Prototyping Shape-changing Interfaces. In Designing Interactive Systems Conference 2021. 1280–1290.

[63] Andrew Saunders and Gregory Epps. 2016. Robotic lattice smock: a method for transposing pliable textile smocking techniques through robotic curved folding and bending of sheet metal. Robotic Fabrication in Architecture, Art and Design 2016 (2016), 78–91.

[64] Kim Sauvé, Saskia Bakker, Nicolai Marquardt, and Steven Houben. 2020. LOOP: Exploring physicalization of activity tracking data. In Proceedings of the 11th nordic conference on human-computer interaction: shaping experiences, shaping society. 1–12.

[65] Kim Sauvé, Argenis Ramirez Gomez, and Steven Houben. 2022. Put a Label On It! Approaches for Constructing and Contextualizing Bar Chart Physicalizations. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. 1–15.

[66] Yingli Shi, Chengjun Wang, Yafei Yin, Yuhang Li, Yufeng Xing, and Jizhou Song. 2019. Functional soft composites as thermal protecting substratesfor wearable electronics. Advanced Functional Materials 29, 45 (2019), 1905470.

[67] Samuel Silva, Beatriz Sousa Santos, and Joaquim Madeira. 2011. Using color in visualization: A survey. Computers & Graphics 35, 2 (2011), 320–333.

[68] Ruth Singer. 2013. Fabric manipulation: 150 creative sewing techniques. David & Charles.

[69] AYN Sofla, DM Elzey, and HNG Wadley. 2008. Two-way antagonistic shape actuation based on the one-way shape memory effect. Journal of Intelligent Material Systems and Structures 19, 9 (2008), 1017–1027.

[70] Simon Stusak, Andreas Butz, and Aurélien Tabard. 2018. Variables for Data Physicalization Units. Toward a Design Language for Data Physicalization, IEEE VIS. (2018).

[71] Saiganesh Swaminathan, Conglei Shi, Yvonne Jansen, Pierre Dragicevic, Lora A Oehlberg, and Jean-Daniel Fekete. 2014. Supporting the design and fabrication of physical visualizations. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. 3845–3854.

[72] Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring interactions with physically dynamic bar charts. In Proceedings of the 33rd annual acm conference on human factors in computing systems. 3237–3246.

[73] Anne Theurel, Arnaud Witt, Philippe Claudet, Yvette Hatwell, and Edouard Gentaz. 2013. Tactile picture recognition by early blind children: the effect of illustration technique. Journal of experimental psychology: Applied 19, 3 (2013), 233.

[74] Cesar Torres, Jessica Chang, Advaita Patel, and Eric Paulos. 2019. Phosphenes: Crafting resistive heaters within thermoreactive composites. In Proceedings of the 2019 on Designing Interactive Systems Conference. 907–919.

[75] Annemiek Veldhuis, Rong-Hao Liang, and Tilde Bekker. 2020. CoDa: Collaborative data interpretation through an interactive tangible scatterplot. In Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction. 323–336.

[76] Akira Wakita and Midori Shibutani. 2006. Mosaic textile: wearable ambient display with non-emissive color-changing modules. In Proceedings of the 2006 ACM SIGCHI international conference on Advances in computer entertainment technology. 48–es.

[77] Weiyun Wang, Xianghua Ding, and Ilyena Hirskyj-Douglas. 2023. Everyday Space as an Interface for Health Data Engagement: Designing Tangible Displays of Stress Data. In Proceedings of the 2023 ACM Designing Interactive Systems Conference. 1648–1659.

[78] Kentaro Yasu. 2022. MagneShape: A Non-electrical Pin-Based Shape-Changing Display. In Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology. 1–12.

[79] Tianyu Yu, Weiye Xu, Haiqing Xu, Guanhong Liu, Chang Liu, Guanyun Wang, and Haipeng Mi. 2023. Thermotion: Design and Fabrication of Thermofluidic Composites for Animation Effects on Object Surfaces. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. 1–19.

[80] Yijun Zhao, Yong Shen, Xiaoqing Wang, Jiacheng Cao, Shang Xia, Fangtian Ying, and Guanyun Wang. 2021. PneuMat: Pneumatic Interaction System for Infant Sleep Safety Using Shape-Changing Interfaces. In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems. 1–7.

[81] John Zimmerman and Jodi Forlizzi. 2014. Research through design in HCI. In Ways of Knowing in HCI. Springer, 167–189.

[82] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through design as a method for interaction design research in HCI. In Proceedings of the SIGCHI conference on Human factors in computing systems. 493–502.