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Towards Performative Woven Textile-form Interfaces

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In this paper, we explore how textile-form thinking, i.e., the simultaneous design and construction of the textile and form, can be leveraged as a strategy to embrace and unlock the performative potential of woven interactive textiles to building towards more intuitive interactions with woven interactive textiles in our everyday. First, we designed and wove five textile-form interfaces, working as contact switches and sensors, with sensing capabilities and diverse performative qualities. Then, we investigated the action possibilities of the interfaces in an exploratory study. Grounded on the study's outcomes, we identified three design themes relative to the performativity of our woven textile-form interfaces. Finally, we derived practical design tactics that designers can apply to design for the performativity of woven textile-form interfaces.

Keywords: Woven Textile-form Interfaces; performativity; textile-form thinking; e-textiles

1. Introduction

Textiles offer design and Human-Computer Interaction (HCI) practical potential in embedding responsive technologies in fibres, yarns and their interlacements, enabling casual gestures in interactions with everyday artefacts (Jiang et al., 2022; Mlakar et al., 2021; Olwal et al., 2020; Parzer et al., 2017). However, the majority of approaches to designing textile interfaces translated elements of traditional user interfaces (UIs) from the digital world onto textiles in the form of buttons (Dementyev et al., 2019; Mlakar & Haller, 2020), sliders (Nowak et al., 2022), keyboards (McDonald et al., 2022; Strohmeier et al., 2018), and flexible displays (Lepinski & Vertegaal, 2011). In these examples, the textile is treated as a flat surface (Jiang et al., 2022; Mlakar et al., 2021; Poupyrev et al., 2016; Wicaksono et al., 2022) and used as a substrate to be manipulated (e.g., (Lepinski & Vertegaal, 2011)) and host other components. Textiles' intrinsic material qualities that mediate the experience of textileness (Gowrishankar et al., 2017) and textiles' performative potential (Giaccardi & Karana, 2015) have been investigated in a few studies towards intuitive and engaging interactions

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(Gowrishankar et al., 2017; Olwal et al., 2020). Greinke et al. (2022) investigated folding textile construction and manipulation techniques to design e-textile sensors that leverage three-dimensional shapes rather than planar surfaces. Mikkonen and Townsend (2019) demonstrated that frequency-based signals could detect various intuitive interactions on textiles, broadening the possibilities for designers to combine textile qualities with new forms of interfaces.

Building on and as an attempt to contribute to this existing body of work, we aim to detach interactive woven textiles from preestablished user-interaction heuristics and flattened expressions by expanding specifically on weaving. We propose textile-form thinking, i.e., the simultaneous design (Townsend, 2003) and construction of the textile and form (McQuillan, 2020), as a strategy to unlock the performative potential of woven interactive textiles. We argue this approach generates unexplored interaction possibilities from woven textiles' complex and interconnected material system (Tandler, 2016) beyond stable and predictable 2D interfaces.

To instantiate our approach, first, we reflected on our material-driven design process to obtain five woven textile-form interfaces. The interfaces present electronic sensing capabilities and diverse performative qualities, namely: Foldable, Rollable, Compressible, Deployable and Expandable. Second, we conducted an exploratory study to investigate the performativity of these interfaces and how design can enhance their performativity further. Finally, grounded on the analysis of the study results, we identified design themes and tactics to facilitate the design for performativity with and through woven textile-form interfaces.

2. Interacting with woven textiles

Weaving is one of the most ancient and common textile production methods consisting of perpendicularly interlacing vertical and horizontal yarns. Because yarns in woven textiles are not exposed to elevated levels of strain as, for example, in knitted fabrics, e-textile research has explored how to integrate conductive yarns in woven textiles for interaction (e.g., Devendorf and Di Lauro (2019); Sun et al. (2020)). The possibility of multilayer weaving, i.e., weaving simultaneously multiple layers of fabric on top of each other, has appealed to many scholars who developed electronic wiring and circuits (e.g., Mikkonen and Pouta (2015)), sensors (e.g., Wu et al. (2020)) and actuators (e.g., Sun et al. (2020)), and interactive artefacts for exhibitions (e.g., Wood et al. (2020)). Despite the efforts to take advantage of complex textile construction techniques specific to weaving (Bredies, 2017; Greinke et al., 2022), most research to date has emphasised the commonly understood 2d-structure of woven cloth, which may then be applied to a 3D form or not. 3D structures and forms that extend from woven textiles as the means for interaction have been indicated as an interesting unexplored domain for HCI (Pouta & Mikkonen, 2022).

2.1. Performativity of textiles and woven textile-forms

The concept of performativity in interaction design is strictly related to the concept of affordance, presented by Gibson (1979) in cognitive psychology and later adopted by Norman (2013) in the design of physical products and their interaction. Introduced by Giaccardi and Karana (2015), the performativity of materials concerns the actions elicited by materials through their unique material qualities in everyday encounters. The performativity of textiles has been leveraged across architecture (e.g., Agkathidis and Schillig (2011); Thomsen and Pišteková (2019)), fashion design (e.g., Lamontagne (2017)), and conceptual (e.g., O'Neill (2016)), interactive (e.g., Wood (2022)), and performing arts (e.g., Skach et al. (2018)). Schneiderman and Coggan (2019)'s concepts of performative curtains for residential use let users perform new practices, such as framing their window views, using them as unfolding shelves, and adapting to different spatial and climatic conditions. The "wall chair" by Lefferts and Gerayesh (2015) unlocks novel ways of sitting, inviting people to use their entire body weight to extend the stretchable textile attached to a wall. The Dynamic Folding Knits by Salmon (2020) are playful knitted textile-forms intentionally designed to encourage interaction.

A limited number of studies in HCI explored the performativity of interactive textiles. For example, Wicaksono et al. (2022) presented a large-scale installation hosting a dance performance on an interactive carpet. Other HCI researchers explored actions elicited by textiles as input for activation, such as stretching (Vogl et al., 2017), pinching and twisting (Olwal et al., 2018) or grasping and deforming (Karrer et al., 2011). Soft Radio by Gowrishankar et al. (2017) is a knitted interactive textile-form whose interface logic builds on the relationship between intuitive textile interactions and the digital functions of the radio embedded into it.

The performative capacity of woven textile-forms as a means to facilitate long-term relationships with users through the engaging experiences elicited by them and their multi-situatedness (Karana et al., 2017) has been discussed by McQuillan and Karana (2023). Through woven textile-forms, entire textile artefacts (e.g., garments, furniture) can be fabricated in one step on a loom, and they can be produced with heterogeneous qualities across their 3D form. McQuillan and Karana (2023) discussed the benefits of using woven textile-form methods, such as reducing textile waste and seamlessly integrating technologies into textiles. Woven textile-forms present two (or more) configurations, which we call states. The *resting state* is the initial configuration of the textile-form presented to the user before interaction. The *active state* is the configuration of the textile-form during the interaction. We call *activation* the transition from resting to an active state, while *recovery* the return process from the active to resting state. Sometimes, the textile-form in the resting state is two-dimensional and transforms into a three-dimensional form upon activation. In other cases, the textile-form in the resting state might be three-dimensional, but it flattens during the activation. Users perceive the transition between resting and active states (and vice versa) as a state change, which in most cases is reversible, and creates opportunities for unforeseen action possibilities, i.e., performativity. This performative potential of woven textile-forms has not been explored to date. In the next section, we will present our design journey in which we take advantage of the two possible states of woven textile-forms to create performative woven textile-form interfaces.

3. Designing Performative Woven Textile-form Interfaces

We carried out a material-driven design process in a multi-disciplinary team consisting of an interaction designer, a jacquard designer, and a textile design researcher across three main phases. First, we started with a designerly exploration of textile-form samples from the jacquard designer's library. We identified five textile-form types to be turned into textile-form interfaces with integrated conductive yarn (Fig. 1a). Second, over two design iterations, we fabricated the five textile-form interfaces (Fig. 1b). Lastly, we conducted an exploratory study with designers to investigate the performativity of the textile-form interfaces (Fig. 1c).

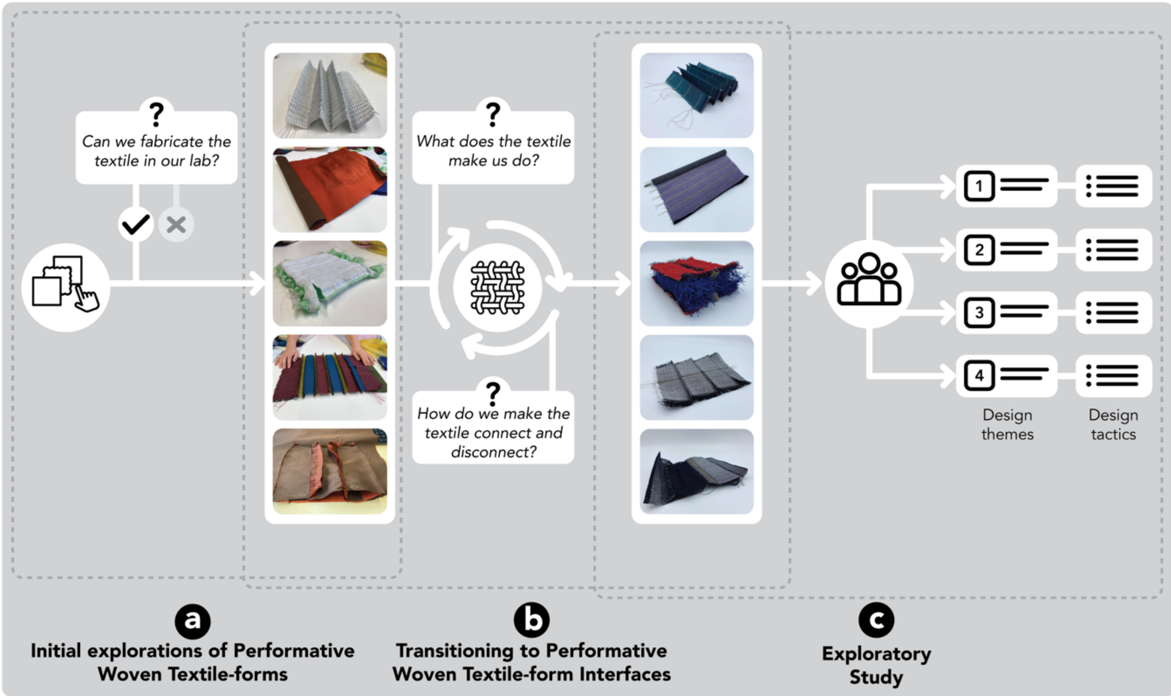

Fig. 1 – Methodology of the work presented in this paper.

3.1. The Making of Performative Woven Textile-form Interfaces

We interacted with woven textile-form samples from the designers' libraries in multiple inspiration sessions. From the pool, we eliminated samples that we could not manufacture[1]. Then, we selected five textile-forms based on their potential for performativity and how this could enable connectivity. The textile-form interfaces were designed following an iterative process which asked, *"How can we make this sample even more performative?"*. The performative qualities of the textile-forms emerged from their capability to change between a resting and active state (see Fig. 2). Simultaneously, we asked ourselves, *"How do we make the textile connect and disconnect?"*. Aware of basic electronic sensing principles, we envisioned the path of conductive yarn to be woven in the weft direction of the samples to create switches and sensors. By observing how the different layers or sections of textiles would move during the interaction, we could identify if and where (across which layers and in which location) conductive yarn could be used to create switches or sensors. For example, when a textile-form needed to be cut to be expanded (e.g., Fig. 2d), we conceptualised it could work as a contact switch: the stretching of the textile-form would cause the conductive yarn to be interrupted, opening the electrical circuit; whereas, the release and closing of the textile-form would allow the conductive yarn to be re-connected, closing the electrical circuit. In other cases, when two layers of textiles would overlap (e.g., Fig. 2b), we envisioned a capacitive sensor. The opening of the textile-form would cause the distance between two stripes of conductive yarn to increase, decreasing the capacitance of the electrical circuit.

[1] To improve the scalability of our work, we also deliberately excluded samples achieved with techniques that could not be woven on industrial (shuttleless) jacquard looms (e.g., supplementary and discontinued weft).

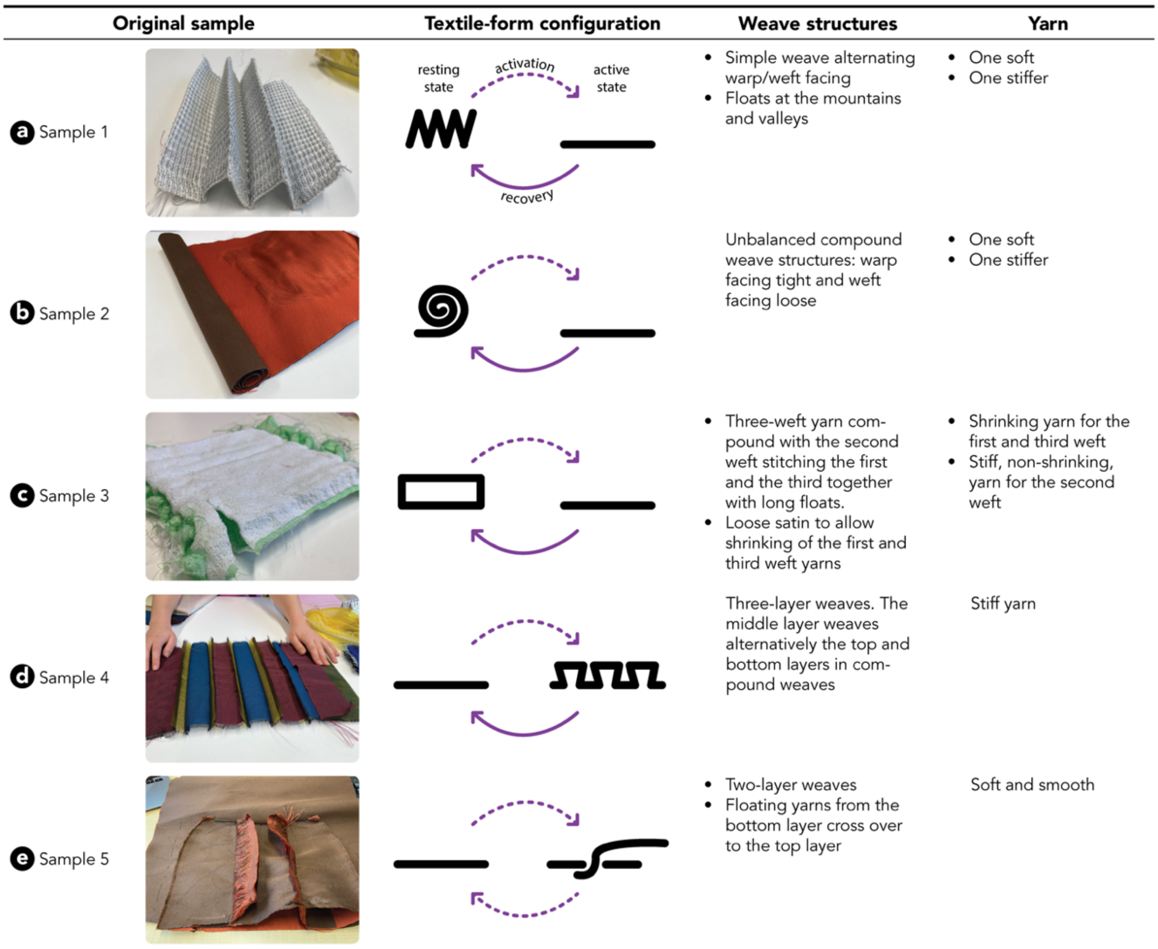

Fig. 2 - Overview of the original samples of woven textile-forms. The 'Textile-form configuration' shows the two states of each textile-form, resting and active, and the transition between the two. In this study, the activation for all samples is manually operated by the user (dotted arrows). The recovery is always automatic (continuous arrows) except for Sample 5 (e), which requires manual recovery.

We programmed the five textile-form interfaces in NedGraphics software and wove them on a digital jacquard TC2 loom. All samples presented in this study are functional and computationally activated when connected to a processing unit. Apart from visualisation tools commonly known among the weaving community (e.g., weave draft), in this study, we utilised layer relationship diagrams, a layer notation system, and Maps of Bindings (MoB) (see Appendix A for extensive explanation). Details on fabrication and materials used are available in Appendix B. Videos of interactions with the working samples of the interfaces are available in Supplementary Materials.

3.1.1. Developing Sample 1 into the Foldable Textile-form Interface

We created horizontal stripes by weaving the conductive yarn in the weft. The yarn was programmed to float on top and at the bottom of valleys and peaks, respectively. After weaving, the floating yarn was cut to create a disconnection of the conductive traces, creating an on/off switch. When the pleats are folded onto each other, the conductive floating yarns touch, closing the connection (Fig. 3).

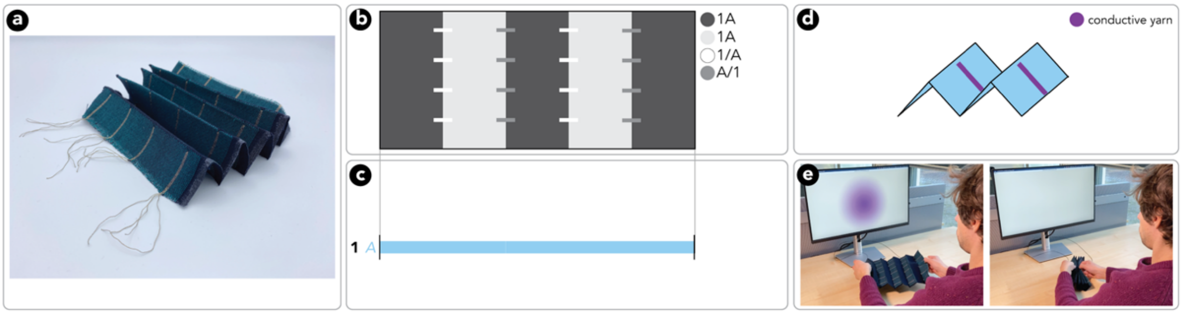

Fig. 3 - a) The Foldable Textile-form Interface uses unbalanced weave structures, stiff yarns and floats to create a foldable on/off switch, inspired by the work of Petri and Greinke (2021). b) The MoB with different colours shows the unbalanced weave structures alternating between warp-facing and weft-facing to produce a pleated textile-form in a single-layer woven textile. Off the loom, the pre-determined folding behaviour is emphasised using an iron, and the chosen yarn's stiffness allows the pleats to remain rigid. c) Layer relationship: Warp 1 weaves weft A. d) Placement of the conductive yarn. e) Interaction with the textile-form interface.

3.1.2. Developing Sample 2 into the Rollable Textile-form Interface

We wove conductive stripes on the top face of the textile at intervals of 90 mm (Fig. 4) to create a capacitive sensor. The movement of rolling and unrolling the fabric causes the distance of the conductive stripes to increase and decrease, respectively, influencing the capacitance measured between contiguous conductive stripes (Fig. 12e).

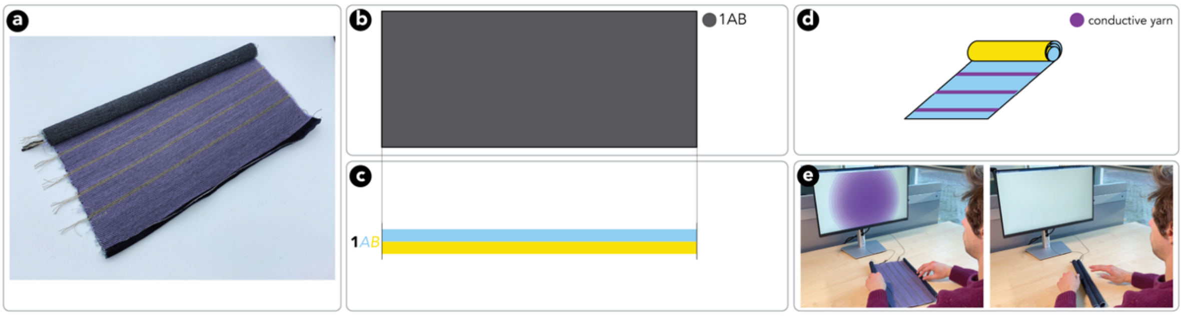

Fig. 4 – a) The Rollable Textile-form Interface is designed to curl into a tube. It consists of a single-layer compound weave structure with two unbalanced weft sets. b) The MoB shows with one colour that the same binding is applied to the entire sample. One weave structure is weft-faced (faces up), and the other is warp-faced (faces down). With the unbalanced weaves and using yarns with different stiffness, one side of the fabric tends to curl along the warp direction when released from the loom. c) Layer relationship: Warp 1 weaves weft A on top and weft B at the bottom. d) Placement of the conductive yarn. e) Interaction with the textile-form interface.

3.1.3. Developing Sample 3 into the Compressible Textile-form Interface

Sample 3 was exploited for its spongy behaviour to create an on/off switch. The stiff blue yarn keeps the two conductive stripes separated in the relaxed state. When the interface is pressed, the connection between the stripes is restored (Fig. 5).

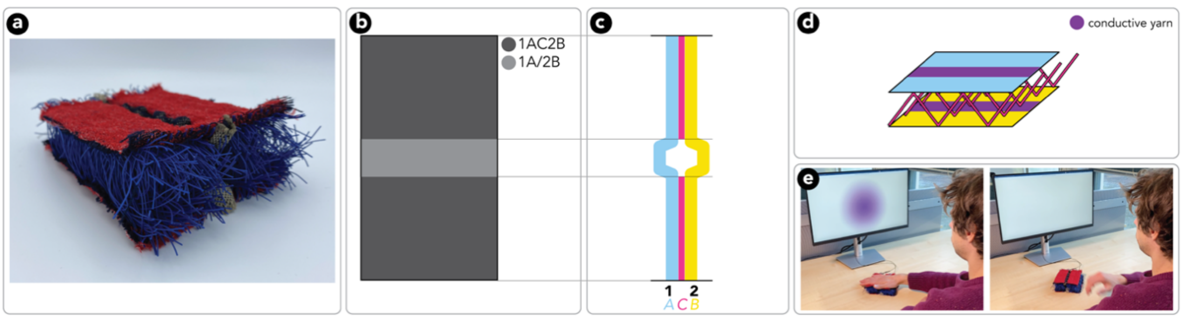

Fig. 5 - Inspired by other work in spacer fabrics and switches (Aigner et al., 2022; Albaugh et al., 2021; Balgale & Baltina,

2020), the Compressible Textile-form Interface consists of a two-layer weave with heat-shrinking yarn woven together via a stiff blue yarn. b) In section '1A/2B' of the MoB, only conductive yarn is woven at the top and bottom, creating a 'tunnel' through the fabric. When exposed to heat, the top and bottom layers shrink, causing the entire structure to expand in height. c) Layer relationship: Warp 1 weaves weft A and warp 2 weaves weft B. Weft C is inserted as a 'binder' between the two layers. d) Placement of the conductive yarn. e) Interaction with the textile-form interface.

3.1.4. Developing Sample 4 into the Deployable Textile-form Interface

This textile interface is an on/off switch fabricated by inserting conductive yarn in the weft of the top layer (Fig. 6). Because of the weft yarn used (paper yarn), when the textile is stretched and released, it retracts, returning to its initial state. The cuts to the woven structure interrupt the conductive trace that is restored when the form is closed again (Fig. 6d-e).

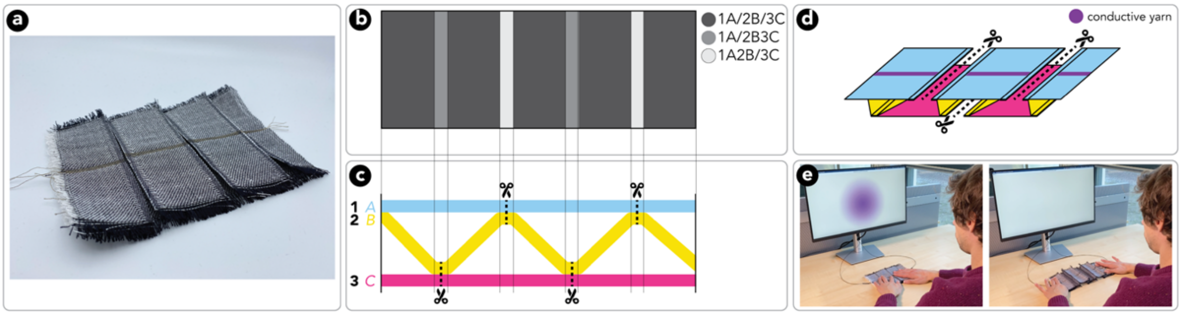

Fig. 6 - a) The Deployable Textile-form Interface leverages three-layer weaving to create an on/off switch via the connection and disconnection of conductive yarn. b) The MoB shows three different types of bindings. c) Layer relationship: In section 1A/2B/3C warp 1 weaves weft A, warp 2 weaves and warp 3 weaves weft B. In section 1A/2B3C, warp 2 and 3 weave weft B and C together. In section 1A2B/3C, warp 1 and 2 weave weft A and B together. d) Placement of the conductive yarn. The dotted lines represent the cutting lines along the locations where two layers are woven together (i.e., seams), allowing the woven structure to expand in longitudinal and vertical directions when pulled. e) Interaction with the textile-form interface.

3.1.5. Developing Sample 5 into the Expandable Textile-form Interface

Conductive yarn is woven along the weft in the stopper and in the fixed section of the textile layer, making sure that the two sides do not face each other but are insulated utilising unbalanced weaves (Fig. 7). The sensor is activated by pulling the float section outwards, thus allowing the two conductive stripes to get closer and resulting in a change of capacitance (Fig. 7e).

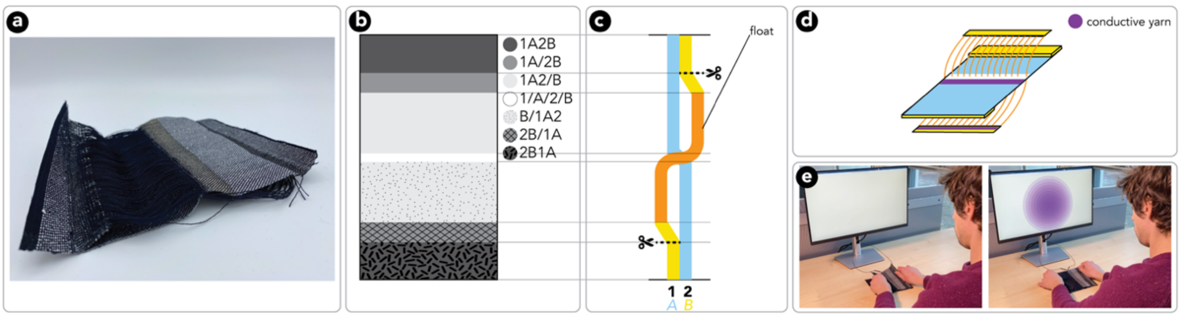

Fig. 7 - a) The Expandable Textile-form Interface consists of a two-layer weave with zones of expandable float bindings creating a capacitive sensor. b) The sections of the sample '1A2B' and '2B1A' are woven in one layer. Then, the textile splits into a two-layer structure ('1A/2B' and '2B/1A'). Weft A weaves throughout the entire length of the samples, whereas weft B weaves the 'stopper' and then it is left floating ('1A2/B' and 'B/1A2'). In the middle of the sample, weft A is left floating ('1/A/2/B') in a small section, creating the 'intersection'. c) Cuts along the two-layer construction allow the floats (orange colour) to slide through the intersection along the warp direction. d) Placement of the conductive yarn. e) Interaction with the textile-form interface.

4. Exploratory study of Woven Textile-form Interfaces

We conducted a preliminary study with six designers with prior experience in material-driven design and interaction design to map expected responses to input actions they perform with the textile-form interfaces and to discuss the mechanisms that could help augment the performativity of the five textile-form interfaces. The study was designed according to open gesture elicitation study protocols (Fig. 8). Firstly, the designers were asked to freely explore and interact with the five textile interfaces on the table in a 'think-aloud' manner (e.g., Fan et al. (2021)). Then, they were asked to complete two tasks with each interface: 1) to turn the light on and off, and 2) to vary the intensity of the light. The researcher could control the lamp's output through a smartphone according to the actions performed by the designer, simulating the connection between the textile interfaces and the light via the experience prototyping approach (Buchenau & Suri, 2000). Lastly, the researcher asked the designer how they would further design the samples to augment their performativity. Each session lasted between 50 minutes to 1 hour.

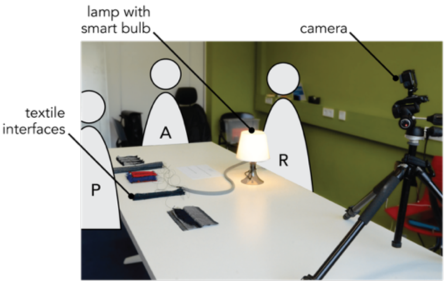

Fig. 8 - The five textile interfaces were placed in a quiet room on top of a large empty table. A connection between the interfaces and a lamp with a smart bulb was simulated so that the researcher (R) could control the bulb via smartphone. A camera was set up on the table to record the participant's (P) interactions with the textile interfaces. An assistant (A) captured the interactions with an additional camera. The sessions were audio and video recorded for analysis purposes.

Over several iterations, the video recordings and the pictures were evaluated among the authors to identify identical, similar, or varying actions between designers for each textile interface. In the case of multiple responses, multiple actions were included in the results. We defined the coupling of the designers' performed action with the expected light output as 'Input action-expected response pairing'. Transcripts of the video recordings, pictures, and quotes were analysed through thematic analysis on Miro.

4.1. Overall performativity of the textile-form interfaces

As soon as the designers understood the behaviour of the textile interface at hand after repeating simple gestures (e.g., pulling) a couple of times, they started to describe their actions and the reason behind their actions: for example, *"It's really inviting this type of gesture"*, said M2 while squeezing the Compressible Interface in their hands and pushing it on the table. We collected a total of 46 different combinations of actions performed by the designers for the given five textile interfaces. Actions often varied in terms of release, the orientation of the interface, and the use of one or two hands or other body parts. Fig. 9 shows a selection of the most frequent combinations of actions for the specific expected response performed by the designers. Even though opinions largely varied, most designers associated the opening or closing with the function of a binary switch. Designers often associated a mid-opening of the textile interface with controlling the intensity of the light. Some designers found that some textile interfaces were intuitively more suited to work as binary switches or to gradually control the output intensity in either a continuous or stepwise manner. With all textile interfaces, unexpected ways of interaction emerged (Fig. 10).

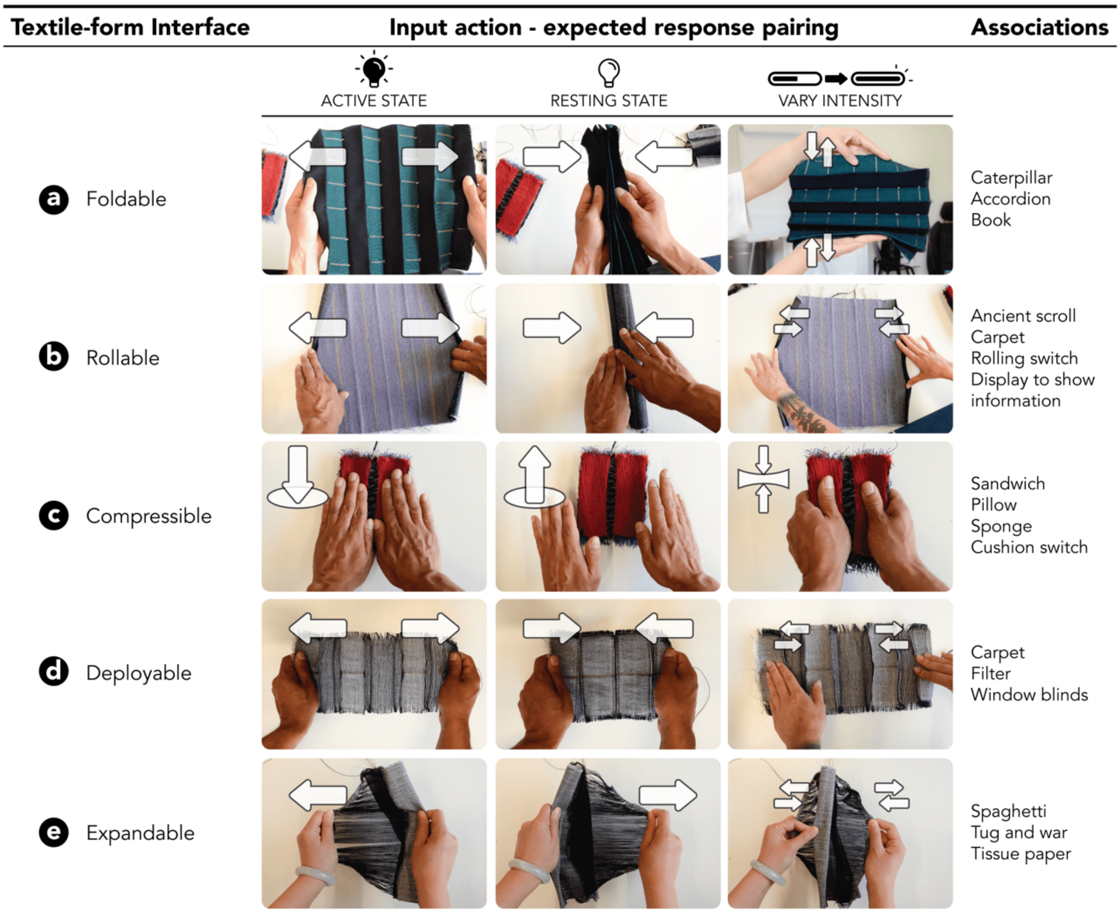

Fig. 9 - A selection from the most frequent combinations of actions performed by the designers with the five woven textile-form interfaces are: a) Stretch/release and compress; b) Unroll/roll; c) Push/release and squeeze; d) Stretch/release; and e) Pull and pinch+pull.

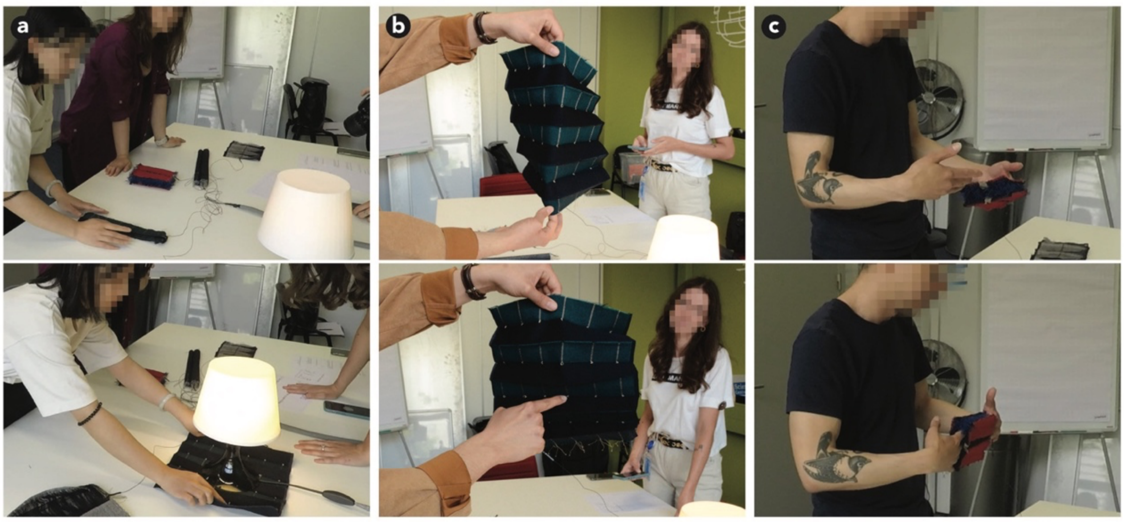

Fig. 10 - Selection of unexpected ways of interaction with the woven textile-form interfaces: a) extending and placing the textile under the lamp to turn it on; b) vertically pulling the pleats until they reach a "permanent state"; the intensity of the light is decreased by snapping each pleat one after the other; c) inserting the fingers in the gap created by the conductive stripe.

5. Design themes and tactics

From the thematic analysis, we derived three themes that summarise the designer's suggestions to enhance the performativity of the woven textile-form interfaces:

- **Consider the relationship with the surrounding environment**: The orientation and location in space, the direction of the input action and the relationship with light play a significant role in how the textile-form interface is perceived.
- **Tune the ambiguity**: Leaving ambiguous cues and slowly revealing information could be a way to engage and invite people to act.
- **Vary spatiotemporal states**: The configurations of textile-forms in their resting and active states open up opportunities to design with temporality and introduce playful elements in the interaction.

For the extended version of the themes, refer to Appendix C. Below, we present practical design tactics for designers of woven textile-form interfaces that aim to design for their performativity (Table 1). These design tactics originated from our tacit knowledge during the making and our findings from the exploratory study, and are supported by the theory and practice review on performativity (presented in Section 2.1). The following tactics should not be considered exhaustive design guidelines, but open to changes and expansion with future work.

Table 1 – Tactics to design for Performative Woven Textile-form Interfaces.

Design Theme	Design tactics
Consider the relationship with the surrounding environment	o Take advantage of **fractional density**. As an outcome of multi-layer weaving, the fabric density of each layer is a fraction of the total fabric density divided by the amounts of layers woven. Use this phenomenon to obtain heterogeneous translucency properties across the textile-forms: the higher the number of layers woven together, the less light will pass through. o Include **fixing mechanisms** through the textile-form itself or by adding extra components (e.g., magnets) to attach the interface to objects or control the transition between resting and active states. o Use **two-layer weaving** to create 'tunnels' or 'pockets' to integrate the additional materials.
Tune the ambiguity	o Hide **messages, patterns, or colours** in the textile-form sections that can be revealed only when the textile-form is activated. o Tune the **speed of response**. Once the textile-form interface is activated, it does not need to be immediate. Instead, give some gradual hints to guide the user through the discovery process. o Play with the **perceived fragility** of the textile. o Disrupt the **function**: design a textile-form that intentionally stops working to invite users to activate it. Or, for example, design the textile-form so that it is perceived as a piece is missing: users will want to complete it. o Introduce **'snapping'** during the activation or recovery of textile-form to signal step-wise gradual control.
Vary spatiotemporal states	o Consider **all states** of the textile-form to enable the interaction: which state is the user presented with and how does the recovery happen (automatically or manually).

- Investigate which state is perceived as **active** and try other configurations.
- Increase the **distance** (in time and/or space) between the resting and active state if you want to use the interface to gradually control an output. Instead, minimize the distance (in time and/or space) to create a binary switch-like interface.
- Use **automatic recovery**, perceived as a 'bouncy' effect, to invite for repetitive actions.
- Scale up or down the **size** of the interface. Sample the same textile-form at different sizes to understand how the scale influences interaction.

6. Final reflections and conclusion

Designing Performative Woven Textile-forms requires a material-driven and open-ended approach encompassing deep knowledge of textile-form thinking and textiles' material systems. Solely by skillfully engaging with textile-forms as active materials, designers can let their latent affordances emerge (Barati et al., 2018).

The interfaces were described with elements that range across an extended textile hierarchy: from yarn and weave structures to the flattened and 3D versions of the textile form, and to interaction level. When designing woven textile-forms, traversing elements and scales of the textile-forms' system is key. For example, the length of the pleats and yarn properties in the Deployable Interface was found to be strictly correlated to the springy behaviour of the textile-form. When varying the size of the pleats, changes were applied at yarn, weave structure and MoB-level to tune its springiness once off the loom and cut. In another case, the rolling behaviour of the Rollable Interface was lost when the stiffer yarn was replaced with a softer one. So, the relative density of the two weave structures constituting the compound weave was tuned to compensate for the choice of materials, and a satisfying roll-ability returned. Design choices at one level of the woven textile-forms' hierarchy impacts the rest of the levels.

The extended textile-form hierarchy can also introduce unfamiliar aesthetics and interactions not immediately associated with textile artefacts. When designers are open to unfamiliarity and instability as outcomes of interactions with woven textile-form interfaces, textiles can be celebrated for their properties, allowing for re-contextualization and new interaction scenarios to emerge. For example, the digital readings of the Expandable Textile-form showed an irregular signal because the friction between yarns was impeding a smooth sliding action. Despite the initial disappointment, we noticed how this inconsistency in the readings made the interface more playful and inviting to act. We do not suggest that reliability in these interfaces should always be discarded. Still, we urge designers to consider alternative starting points for their design beyond that of making stable and reliable textile-based UIs. This should also prompt designers to consider alternative perspectives when evaluating the performance of textile-form interfaces - a textile's organic and sometimes unpredictable behaviour could be the strength of a new design.

A designer of woven textile-form interfaces should foresee which levels of the hierarchy are affected by their design choices, identify which levels can offer potential solutions, be open to unpredictable or unfamiliar aesthetics and experiences, and carefully consider how the outcomes are evaluated. Using a material-driven design approach supports this and further enables the scaffolding of performativity in textile-form thinking, putting to the fore an approach which builds on the unique multi-faceted potential of textile-forms.

6.1. Beyond the lab: Performative textiles over different spatiotemporal scales

When we interact with textiles in our everyday life, interactions extend over different spatiotemporal scales: through the whole body, at different times of the day, for different durations, and in different locations. Most of the research on textile interfaces, including this work, has studied interaction with textiles with swatches that are usually hand-sized for a short time in laboratory settings. These aspects are also limitations of this study. Even though our study setup allowed us to identify input action-response pairings for the Woven Textile-Form interfaces, the dimensions of the samples limited the action possibilities to mostly finger and hand interactions and gestures. Furthermore, while the simulated connection of the interfaces to the lamp let the designers envision their input actions, it did not allow them to discover their use through "casual discovery", typical of performativity (Barati & Karana, 2019). Therefore, open-ended and longitudinal studies in the real world will help us discover unexpected interaction modalities and practices (e.g., Hauser et al. (2018)). In future studies, we aim to expand the scale of the artefacts, transitioning from weaving on a TC2 loom to industrial jacquard looms and from hand-based to whole-body interaction. Examples of potential application scenarios could be interactive room dividers for shared office spaces or seat covers able to record sitting data and adapt their shape.

6.2. Conclusion

This paper presented the design and investigation of five Performative Woven Textile-form Interfaces - Foldable, Rollable, Compressible, Deployable and Expandable. We have applied textile-form thinking to generate novel interactions that arise from textiles' complex and interconnected material systems beyond stable and predictable 2D interfaces. The exploratory study with designers suggested considering the relationship with the surrounding environment, tuning ambiguity, and varying spatiotemporal states as overarching themes and directions to design for performativity with woven textile-form interfaces. To this end, we provided a series of design tactics drawn from the design and use time of the interfaces, serving as examples of actionable knowledge. This work is the first endeavour to facilitate designers of interactive textiles navigating the complex design space of woven textile-forms for enriched experiences that leverage textiles' inherent qualities and performative potential. We envision future work to expand the exploration of interactive woven textile-forms by allowing users to engage with their entire bodies and move, intuitively shaping their interactions during use.

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Appendix 1

A. Basic architecture of woven textile-forms

3D woven textiles, 3D weaving, and multilayer weaving are only a few of the terms used to encompass methods and weaving techniques aimed at detaching textiles from planar forms. The use of specific terminology in the space is contested, and standardization for these terms does not yet exist. We recommend the reader refers to Devendorf and Di Lauro (2019) and Devendorf et al. (2022) to gain a deeper understanding on basic weaving process, terminology and on how to operate a loom. An extensive explanation on multilayer woven structures and how they could be used in HCI textiles is also provided by Pouta and Mikkonen (2022).

In order to design woven textile-forms, in which multiple types of weave structures and layer relationships are combined, being able to move across the elements of textiles' system is key. Apart from visualization tools common in the weaving community (e.g., woven textile rendering (Fig. 11a), weave repeat (Fig. 11b), weave draft (Fig. 11c), and yarn path (Fig. 11d)), in this study, we present layer relationship diagrams (Fig. 11e), which are drawn as an abstracted cross-section of the textile layers, in combination with a notation system that describes the relationship between warp and weft yarns across these layers. We suggest the reader refers to Buso et al. (2023), which serves as a practical introductory guide to these tools.

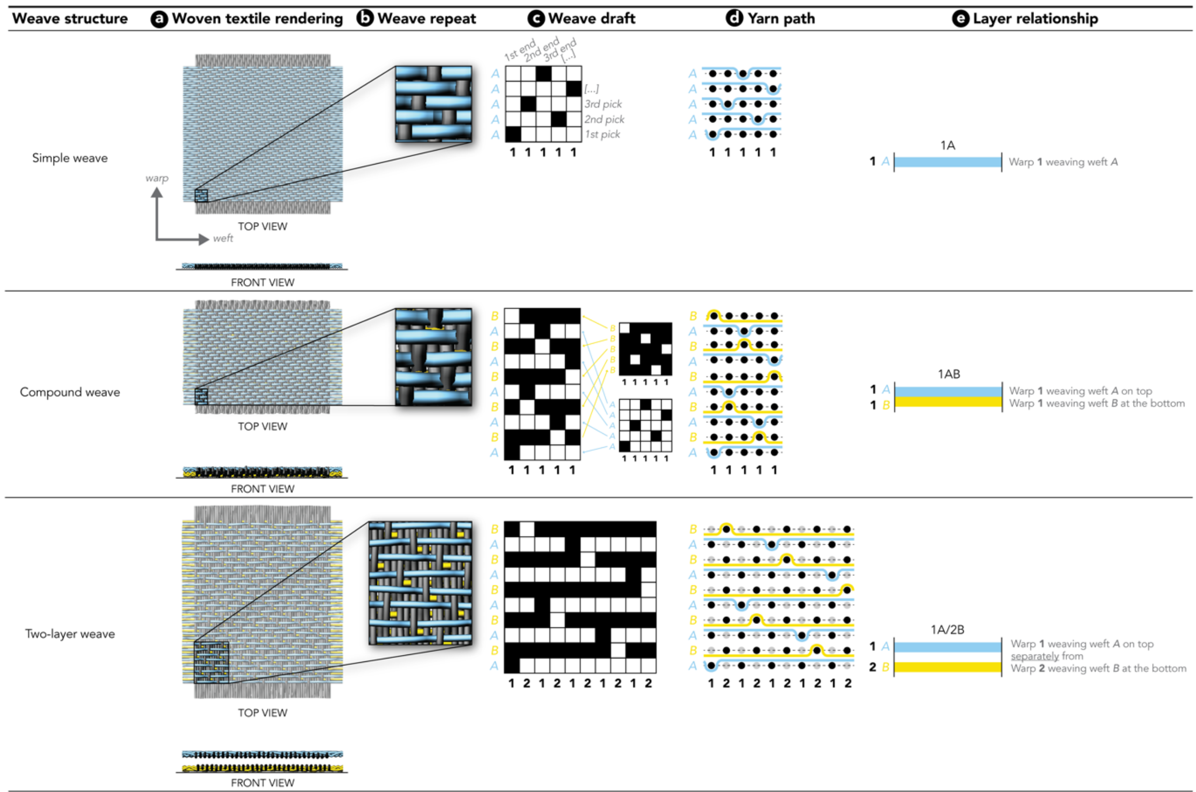

Fig. 11 - Overview of weave structure visualizations for a simple, compound and two-layer weave: a) NedGraphics generated 3D rendered top and front view of the woven textile; b) weave repeat; c) weave draft; d) yarn path; and e) layer relationship. In order to weave multiple layers, warp yarns are divided in two or more sets. We indicate different sets of warp yarns with numbers (1, 2, 3, …) and different sets of weft yarns with capital letters (A, B, C, …).

The layer relationship diagrams and notation system work in combination with a Map of Bindings (MoB) (Fig. 12b) to produce a 3D form on a digital jacquard loom. The MoB, first introduced by McQuillan, is a combination of the 'artwork' in weaving and a 'pattern' in fashion and form-making. It represents the 3d form flattened into a two-dimensional plan which arranges weave bindings in zones which enable the construction of a Woven Textile-Form. For example, the textile in Fig. consists of a 3-layer textile with a seam on the left edge where the three separated layers merge into a single layer (compound weave). The MoB and its corresponding layer relationship are illustrated in (Fig. 12b-c). In this case, the MoB includes two types of bindings: '1A2B3C' for the compound weave section (Fig.12 b-left) and '1A/2B/3C' for the three separated layers section (Fig. 12b-right). The MoB and layers relationship together enable switching between visualizing the textile from the top, in the same orientation as the weaving takes place, and visualizing the textile's layers relationship. During the programming of woven textile-forms, the layer relationship guides the designer in assigning specific weave structures (which determines 3D, cross section, yarn journey) to each zone of the MoB (which is a 2D plan for their placement). The particular shapes of the zones of the MoB contribute to the form emerging from the woven textile. As such, another useful tool for designing woven textile-forms is paper prototypes, which materialize the relationship between layers relationships and MoB, effectively representing the three-dimensional nature of woven textile-forms.

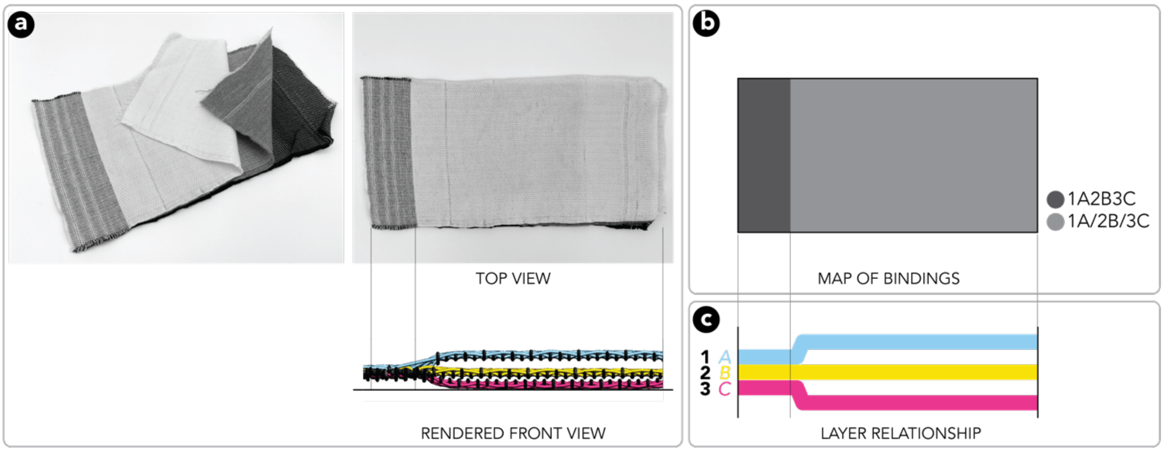

Fig. 12 - Flat woven textile form: a) NedGraphics generated 3D rendered front view; b) MoB; c) layer relationship.

B. Weaving documentation

- Loom: Digital Jacquard TC2 loom
- Warp: Black wool 2/66x2/66; warp density 36epc
- Conductive yarn: Shieldex Statex 235/36 dtex 2-ply HC+B x2

Table 2. Materials of the five Woven Textile-Form Interfaces.

Textile-form Interface	Weft materials
Foldable	A: Green coated yarn
Rollable	A: Wool Lilac merino 2/30 B: Recytex Light-blue 3000 dtex
Compressible	A, B: Districo Special Combi yarn C85-332 dtex PES red C: Recytex Blue 3000 dtex

Deployable	A, B, C: White paper yarn
Expandable	A, B: White paper yarn

C. Design themes

Table 3. Summary of the Design Themes and relative subthemes that emerged from the exploratory study.

Design theme	Subtheme	Description
Consider the relationship with the surrounding environment	Exploring light-textile relationship	Designers were attracted by the see-through woven pattern of some interfaces. For example, with the Deployable Interface, the textile consists of three overlapping layers of fabric, whereas when extended the structure unfolds revealing its single layers one by one, whose fabric density is ⅓ of the total fabric. Because of this effect, some designers held the interface towards a light source (e.g., window, lamp) and used the interface to modulate the light passing through the textile by opening and closing the folds.
	Connecting textiles with bodies and objects	A recurrent suggestion was about the scale of the samples: increasing or decreasing their size could invite novel interactions, e.g., whole-body interaction. For example, a designer (M3) suggested using his arms to keep the conductive traces of the Foldable Interface closed. Some designers held the textile interfaces in the air to simulate a wall or ceiling fixture. One designer felt the urge to place the Compressible Interface on the floor in order to step on it (F2). The direction of interaction emerged to be particularly important with the Rollable and Expandable interfaces. The opening and pulling to one side were paired with turning on or off (M1, F2). In another case, with the Expandable Interface, one designer suggested that the Expandable Interface could be connected to multiple outputs, such as light sources vertically aligned on a wall, and it could be used to control each individual light source by pulling at the top, middle, or bottom floats (M1).
Tune the ambiguity	Revealing information	Some designers mentioned that they would have been attracted to interact with the interfaces if they revealed unexpected effects during the activation. For example, the unrolling of the Rollable Interface or stretching the Deployable Interface, the textile sections that were hidden in the resting state could reveal some information or visual effect.
	Discovery	The less familiar the textile-form interface was to the designers, the higher level of confusion expressed by the designers (e.g., the Expandable Interface). Some designers even suggested strategies to limit possible unwanted interactions. Other designers instead suggested keeping the interaction more textile-driven and letting the user discover the functionality of the interface by "trial and error". For example, a designer (M1) suggested that the ripping feeling when pulling the Expandable Interface, as a result of the friction among the yarns, could indicate that something requires a careful type of interaction.
Vary spatiotemporal states	Playfulness of the textile elements	The designers were curious, engaged and in some cases surprised by the variety of textile behaviours of the interfaces. Especially the interfaces with more springy behaviour such as the

		Expandable, Rollable and Foldable Interfaces were perceived as playful and inviting for recurring and repetitive actions.
	Freedom of movement	Designers preferred types of interaction that allow for more possibility of movement, such as the Rollable and Foldable Interfaces have the highest degree of change between the open and closed states. Some designers wished that the Deployable Interface could extend more in order to have more difference between the relaxed and expanded states. Generally, when designers experienced a big change between the resting and active state, they thought they could control the intensity of the light. Instead, when a small difference was perceived between the two states, they envisioned a binary switch (e.g., Compressible Interface).
	Shape-ability	As opposed to the springy behaviour of some interfaces, designers noticed that they could configure the shape of the interface to control the output. For example, a designer played with snapping each individual pleat of the Foldable Interface to achieve the amount of extension desired. The Expandable Interface could be extended to diverse lengths. Designers expressed the need to be able to control the change between the resting and active state of the interfaces, in order to predict the type of light response desired. For example, a designer (F3) suggested flipping the Rollable Interface upside down after unrolling it, to keep it open (F3). Another designer used other objects, such as the lamp itself to keep it from folding back (F1). M1 lifted the Foldable Interface in the air and used the ability of the pleats to go in a “permanent state” when pulled completely to fix the shape of the textile in order to turn on the light.