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An exploration of woven textile-forms

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The unfolding of textileness in animated textiles: An exploration of woven textile-forms

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Abstract: Designers of textile-based interactive systems tend to treat woven fabrics as static materials and lack deeper understandings of how the textile can be designed for responsive behaviours in artefacts. As a result, in most studies across design and HCI, textiles are employed as substrates for computational, biological, or smart materials. This narrow view limits the potential of textiles that can be programmed to express responsive behaviour through their inherent material qualities. Our paper aims at bridging this gap in the design of animated textile artefacts. We present woven textile-forms where textile structures are programmed to tune the behaviour of low-melt polyester yarn that shrinks when heat is applied, resulting in complex topological and textural woven forms that can change over time. Foregrounding woven-forms as a medium for animated textiles, our work calls for design and HCI researchers to pay attention to textileness for prolonged relationships between users and animated textile artefacts while eliminating waste from production and end of life.

Keywords: animated textiles; textileness; woven textile-forms; smart textiles.

1. Introduction

In recent years, the world of textiles has become of increased interest to design and HCI communities to comply with today’s societal demands of connectedness (Choi et al., 2019; Fernández-Caramés & Fraga-Lamas, 2018), seamlessness (Nabil et al., 2019), embodied interaction (Joseph et al., 2017), and well-being (ten Bhömer et al., 2015). Studies showed diverse ways to augment textiles, for example, via responsive materials or computation, or more recently, by living organisms. Our paper explores the potential of textiles’ inherent material qualities and structures to generate novel responsive behaviour and interactions for animated textile interfaces. Grounded on the notion of Animate Materials (The Royal Society, 2021), we use the term Animated Textiles to encompass diverse biological, physical, and computational efforts in endowing textiles with animate qualities.

The first examples of animated textiles are traced back to the 1990s and are mainly framed under Smart Textiles, which originated from wearable computing (Post et al., 2000) and ubiquitous computing (Weiser, 1991) fields. Smart Textiles are “a category of fibers, yarns, fabrics, or end products that can respond to environmental stimuli in a controlled way" (ASTM International, 2020, p. 1). The advent of conductive yarns paved the way for augmenting textiles with electrical properties (Zhang et al., 2005). Over the years, scholars have introduced new terms referring to the multifaceted nature of smart textile technologies, including *intelligent textiles* (Wang et al., 2016), *smart fabrics* (Singh et al., 2012), *active textiles* (Kapsali & Vincent, 2020; Le Floch et al., 2017), *electronic textiles* (or *e-textiles*) (Ismar et al., 2020; Stoppa & Chiolerio, 2014), *interactive fabrics* (Gong et al., 2019; Olwal et al., 2020) and *robotic fabrics* (Buckner & Kramer-Bottiglio, 2018). When Smart Textiles are used to create apparel, they are also called *smart garments* or *smart clothing* (Ariyatum et al., 2005).

These projects provide a broad panorama of technological possibilities to animate textiles. However, they do not fully mobilize textile qualities as the driving element of the design. The added layer of smart technologies has taken precedence over malleability, stretchability, pliability and textiles' tactile feeling. These characteristics and many more constitute the intrinsic material qualities of textiles. We argue that only through the inherent material qualities it is possible to express the textile character in an animated textile artefact, which we call *'textileness'*, inspired by the 'materialness' notion of Nimkulrat (2009).

In Animated Textiles, embeddedness is a significant factor in the perceived textileness of a textile artefact, and temporality is a design variable. In this context, the designer is required to manage and embrace complexity. However, the increased complexity generates opportunities for holistically addressing the unsustainability of our textile and textile-based form industries (McQuillan, 2020). The ability of Animated Textiles to change can be mobilised for extending life spans in artefacts. Change can occur on different scales in the use time: it could be instantly visible, or, as designers tend to extend an artefact's life, it could appear very slowly, not being immediately visible to the human eye (see, for example, Talman's evolving textile patterns (2018)). Also, Animated Textiles are not static or inaccessibly locked behind skill barriers but open to interactions with users. With Animated Textiles, we aim to address these opportunities by proposing a holistic approach in designing textiles with responsive behaviour in their use time and to show their potential for novel interaction possibilities and experiences. Instead of adding external elements to textile artefacts, with our design case, we bring attention to the potential of textiles animated through their inherent material qualities and structural properties, hence foregrounding their textileness.

This paper presents:

- A strong concept (Höök & Löwgren, 2012), i.e., "Animated Textiles", to provide generative knowledge for design and HCI communities and help broaden the material palette in the design of interactive textile interfaces;
- Four classes of animated textiles, to help better articulate the concept, suggesting a vocabulary of practical relevance for practitioners from different backgrounds (interaction design and fashion design) who aim to introduce animated textiles into our everyday lives;

- A case of animated textiles, to further explain our approach, advancing our unique technique to open up a design space in woven textile-forms.

2. Animated textiles

Animate Materials refers to the emerging field of materials created by the human agency that "are sensitive to their environment and able to adapt to it in a number of ways to better fulfil their function" (The Royal Society, 2021, p. 10). Animate Materials brings to the attention that any material can have an animate capacity, i.e., they can be active, adaptive, or autonomous, not necessarily requiring the involvement of digital components. Building on the notion of Animate Materials, we coin the term Animated Textiles as an overarching term for textiles or textile systems that are active, adaptive, or autonomous in their use time through physical, digital and/or biological means. Animated Textiles expands the current definition of Smart Textiles, considering both the smartness of computational or biological components and the intrinsic qualities of textiles as equally significant in their final expression and function. The interaction with Animated Textiles can be one way, two ways, or continuous. We exclude from this definition textiles that might be active in their design and production time but not in their use time (e.g., BioLace series of Collet (2011) is not considered an animated textile). In the following sections, we provide examples from literature and practice to describe the main techniques and approaches used to animate textiles to date. These are not intended as separated classes but rather as a continuum of practices at the intersection of computation, biology, and materiality.

2.1 Textiles animated through computational materials

Generally known as electronic textiles or e-textiles, these animated textiles require **digital components**, i.e., sensors and actuators, connected and programmed by a processing unit (e.g., Arduino board). Sensors can be applied onto the textile substrate (e.g., via embroidering or snap fasteners) or be integrated into the textile structure using a conductive yarn (Aigner et al., 2020; Skach et al., 2021). Multiple forms of actuators responding to stimuli in a controlled and programmable manner exist. For example, smart materials such as thermochromic ink can be digitally programmed to follow algorithms (Figure 1) (Devendorf et al., 2016; Kan et al., 2015). LEDs, OLEDs, and electroluminescent materials are light-emitting actuators that are attached to textiles to design light-emitting textile displays (see, for example, Social Fabric Fitness (Mauriello et al., 2014)). Alternatively, optical fibres can be directly embedded into the textile structure during the weaving or knitting process (Yamada, 2020). Other types of actuators can apply warming & cooling effects (Wang et al., 2010), provide vibration or haptic feedback (Gay et al., 2020), or amplify sound (Stewart, 2019). A unique approach that could pave the way toward integrated computational textiles has been suggested by the recent study of Loke et al. (2021) (Figure 2), who developed a textile-based fibre with digital capabilities. This is the first example of animated textile able to be literally programmed to sense, learn, and ultimately develop contextual awareness. This approach coincides with the *Internet of Smart Clothing* (Fernández-Caramés & Fraga-Lamas, 2018)., i.e., a future vision to create intelligent and connected garments.

Figure 1. T-shirts display a message via thermochromic ink (Kan et al., 2015). Source: © 2012 Tangible Media Group / MIT Media Lab (CC BY-NC-ND 3.0)

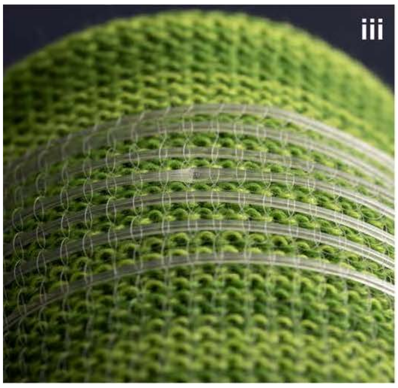

Figure 2. Digital fibre integrated in a cotton-based fabric. (Loke et al., 2021). Source: © 2021 Loke et al. (CC BY 4.0) / Part of the original image.

2.2 Textiles animated through living organisms

Living organisms capable of sensing and responding to external stimuli can endow textiles with animate qualities towards *living artefacts* (Karana et al., 2020). In 2017, a team of designers and researchers coated a dress with photobacteria extracted by a deep-sea fish, resulting in a blue, glowing effect (Figure 3) (Geaney, 2022). Another example is the project Biogarmentry (Figure 4) (Aghighi, 2018). Aghighi developed the first proof of concept of a textile embedded with microalgae, making it capable of varying colour and purifying the air around the wearer via photosynthesis. Recent studies further developed the concept of living textiles by bioprinting microalgae on bacterial cellulose (Balasubramanian et al., 2021) and textiles (Stefanova et al., 2021), showing that it is possible to create photosynthetic textile biocomposites. The nascent field of biodesign offers excellent opportunities for animated textiles, where textile's chemical components and structure should be understood at the nanoscale to be compatible with the living organism at hand, hence, provide the best habitat for their livingness (Karana et al., 2020).

Figure 3. Bioluminescent dress by Geaney (2022) in collaboration with Pollak and Kan.

Figure 4. Biogarmentry dress by Aghighi (2018).

2.3 Textiles animated through other materials

Conventional materials such as paper and polymer sheets are coupled with textiles to unlock novel responsive behaviours. For example, researchers used thermal expansion of copper and fabric laminates (Du et al., 2018), low-boiling point liquids (Sanchez et al., 2020), the compression of fluids in pneumatic actuation (Zhu et al., 2020), or tendon-based actuation with polymer yarns (Albaugh et al., 2019) to create folds or plies in textiles (Vahid et al., 2021). Using digital fabrication techniques, scholars deposited hydrogels (Rivera et al., 2020), 3d-printed patterns of inextensible polymer (Guberan et al., 2013) or spread humidity responsive dead bacterial cells to give shape-changing abilities to textiles (Yao et al., 2015).

Smart materials and their active qualities have also been paired with textiles to generate novel responsive behaviour and expressions via post-processing methods (Ruckdashel et al., 2021). For example, chromic technologies include materials that react to temperature (i.e., thermochromism) (Howell et al., 2016; Nabil et al., 2019), ambient light (i.e., photochromism) (Periyasamy et al., 2017), and electric potential (i.e., electrochromism) (Graßmann et al., 2020; Meunier et al., 2011). Also, the potentials of active nanocoatings triggered by light have been explored for novel interactions (Figure 5) (Bell et al., 2021). Functional fibres (Buckner & Kramer-Bottiglio, 2018), including Shape-Memory Alloys (Buckner et al., 2020; Granberry et al., 2019), Shape-Memory Polymers (Hu et al., 2012), composite thread actuators (Figure 6) (Forman et al., 2019) and multi-layer composite fibres (Kilic Afsar et al., 2021) have been used to endow textiles with shape changing abilities under thermal or electrical stimuli. In these examples, smart fibres are woven into the textile structure.

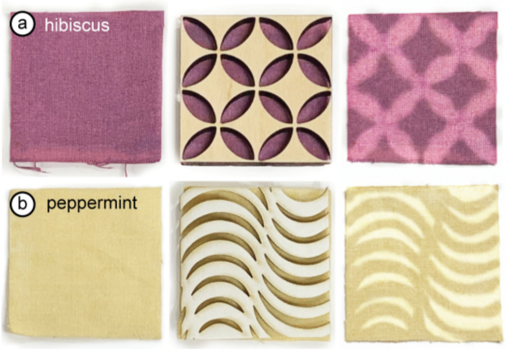

Figure 5. Swatches of Self-destaining Textiles (Bell et al., 2021).

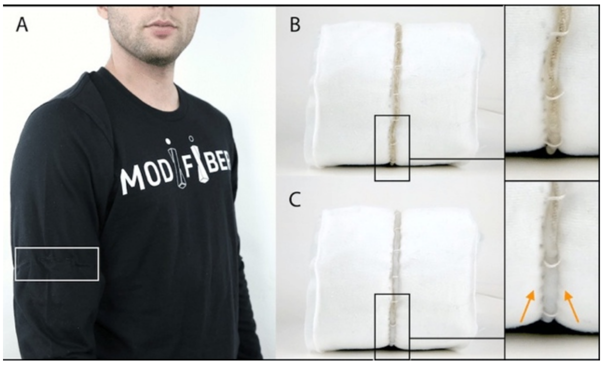

Figure 6. Composite thread actuator ModiFiber applied on a shirt (Forman et al., 2019).

2.4 Textiles animated through their inherent material qualities: An opportunity

While much attention in design and HCI has been given to animating textiles by integrating other materials into their structures, limited work explored the possibility of animating textiles exclusively through their inherent material qualities. Jane Scott's Responsive Knit project (Figure 7) is one such example in which yarn twist direction, knit structure and the hygromorphic behaviour of wool is used to create textile structures that shrink and transform shape when water is sprayed onto them (Scott, 2018). In another example, Talman (2018) utilised fibres and weave structures that accumulate discolouration at different rates to design surface patterns that emerge through use in various contexts (e.g., outdoors vs indoors) (Figure 8). Limited academic studies exploited textiles' inherent material qualities in the creative making because this approach requires a holistic view and deep knowledge of fibres and textile structures behaviour more commonly seen in craft spaces (see, for example, the complex weave structures working in symbiosis with fibre and yarn properties in Richards (2021)). In each example, the physical properties of fibre, yarn and structure work in a system to enable specific textile behavior to be expressed.

Figure 7. Knitted structure shrunk in response to cold water spray (Scott, 2018). Source: © 2018 Jane Scott (CC BY-NC-SA 4.0)

Figure 8. Changes in expression of textile artefacts after use (Talman, 2018). Source: © 2018 Riikka Talman (CC BY-NC-ND 4.0)

2.5 Our approach: Call for textileness in animated textiles

In arts and crafts, Nimkulrat introduced the concept of materialness to define the material's capacity to extend its passive and predefined qualities to "animated modes of expression of someone experiencing the material" (Nimkulrat, 2009, p. 208). Accordingly, materials do not have a fixed application or expression. Instead, they actively inform the artist through their qualities during the making of an artwork.

> "By focusing on a material, a textile artist can create the form and content of an artwork and also bring the elements of context and time to her creation in order to design an overall experience for viewers. The tangible material participates actively in the form, content, context, and time of the artwork." (Nimkulrat, 2009, p. 208)

Thus, in the making of artefacts, "the forms of things arise within fields of force and flows of material" (Ingold, 2010, p. 91). McQuillan (2020) proposed a multi-scale and multi-dimensional design method for textile-based forms, namely *Multimorphism*, calling for the holistic integration of material-form scale behaviours in the context of sustainable use and manufacture. In architecture, Menges and Reichert's (2012) work unlocks the potential of conventional materials, like wood veneer, for climate-responsive architecture with particular attention to programming structures through computer-aided design. Wood veneer flanges bend according to humidity fluctuations in the environment. Similarly, Oxman and her co-authors' work positioned between art and architecture explores how materials' potential can be unravelled with novel structures achieved through digital tools (Coelho et al., 2009). In design, Rognoli et al. (2015) proposed DIY Materials as new material expressions grounded on imperfect aesthetic qualities that show the existence of an alchemist's (i.e., designers') manual labour and craftsmanship. Introduced by Karana et al. (2015), the Material Driven Design (MDD) method suggests that during the design phase, the designer should play an active role in discovering material potentials by engaging with the material through material tinkering, reflections, and sharing with people. Likewise, in HCI, with the *"material turn"* (Robles & Wiberg, 2010), the role of materiality and material composition of computation has become of increasing importance for interaction designers and researchers (Qamar et al., 2018; Vallgårda & Redström, 2007; Vallgårda et al., 2015). Overall, materials are increasingly considered "alive, active, adaptive": open to change at both design and use time (Karana et al., 2019).

In line with this body of work across art, design, and HCI, we advocate a focus on textileness to create intuitive and engaging interactions with Animated Textiles and fully exploit their interaction potential. Valle-Noronha (2019) explored the relationship between the textilities of cloth and tactility of wearers, highlighting the need to make the agency of clothes visible for more engaging interactions. Instead of using textiles as a mere functional layer (Townsend et al., 2020) or alluding to existing artefacts (Gowrishankar et al., 2017), we see an excellent opportunity to bring materialness in the design of textile interfaces, whose responsive capacities can be ingrained in the interactions between the elements of the textile system.

3. Design exploration: Woven textile-forms as animated textiles

The use of animated textiles in the context of the garment industry has the potential to transform how we make and use garments - eliminating waste from production, generating novel aesthetics while facilitating an ongoing and changing relationship between user and product. In this section, we present a case of animated textiles in which Holly McQuillan, Karin Peterson and Kathryn Walters explored the potential of low melt polyester yarn (NSK, https://tinyurl.com/36zt8jku) through woven textile-form[1] design for programming changeability in garments (Talman, 2018). Heat shrinking yarns are often used commercially in planar woven textiles to generate surface texture (Figure 9) for applications such as 3D textiles for sound insulation (Casalis, 2020). Active Textile Tailoring by Tessmer et al. (2019) implemented heat shrinking yarn for shaping 3D knitted garments to the body. In this example, the researchers explored its use to provide greater control of form, fit and texture in woven textile-forms.

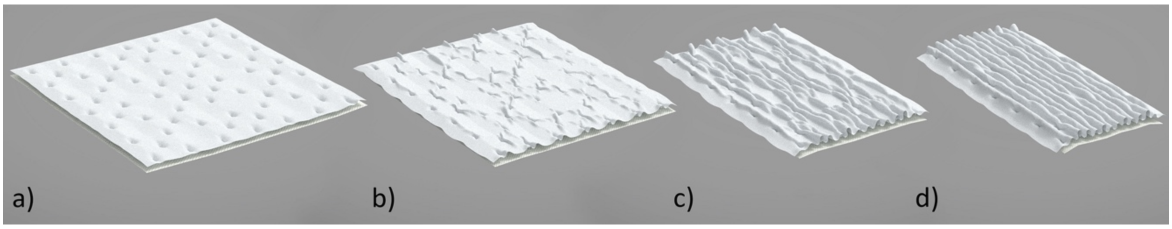

Figure 9. Digital render (CLO3D) of common use for heat reactive yarn in woven textiles. The textural expression of a planar textile (a) changes because non-shrinking yarns used in the upper surface are periodically woven to a layer interlaced with shrinking yarns. As the shrinking lower layer reduces in size (b, c, d), the texture of the upper surface transforms. Source: © 2021 Holly McQuillan (CC BY-NC-ND 4.0)

In our case, low melt polyester yarn (NSK) that shrinks when heat is applied is used in combination with programmed weave structures, woven textile-form methods and a 3D form resist, resulting in complex topological and textural woven forms that can change over time. The NSK yarn is uniform in its behaviour down its length – it shrinks up irreversibly to approximately 40% of its original length when exposed to dry heat of up to 100 °C while maintaining the pliability expected in worn textiles. However, variation in heat application and specific behaviour can be programmed via weave structures that arrest or amplify its physical response to heat. Tightly woven zones do not shrink significantly, while loosely woven, low-density zones do. The textile structure determines the textural expression that results from the shrinking. In this way, the uniform shape change behaviour of this commercially available yarn can be manipulated through specific textile structures to facilitate the expres-

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[1] In this paper, we adopt the definition of McQuillan (2020) to describe *'textile-form'*. Textile-form is made at the same time as the textile is constructed. This includes whole garment knitting, non-woven moulded forms and 3D printed garments. With woven textile-form, we refer to the 'whole garment weaving', 'composite garment weaving' and '3D woven garment', but acknowledge that not all woven textile based forms are garments.

sion of one-way interactive 3D behaviour that could support changes in form, fit, textile expression, and use over time. The zones are determined by the 2D-3D unfolding process unique to woven textile-form design methods and result in a phenomenon named 'fractional density'[2] (Figure 10).

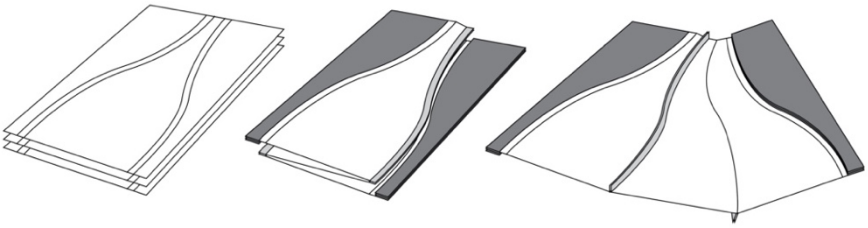

Figure 10. The way the three layer woven textile-form structure is achieved results in variation in yarn density where dark grey zones are 3 times denser than the white zones when unfolded. Source: © 2021 Holly McQuillan (CC BY-NC-ND 4.0)

Below we present our case in two steps. In the first step, we explore shape change behaviour in applying heat reactive yarn in layered weave structures where density controls the degree and type of shape change expressed. In the second step, we use the same ingredients, but we amplify change via multilayer construction particular to woven textile-forms, removing shape change yarn entirely in some zones.

3.1 Experiment 1: Tunic

In Experiment 1, all layers utilise shape changing yarn (Figure 11). The form and Map of Bindings (MoB) (Figure 12) is designed to enable the symbiotic relationship between programmed weave structure (Figure 13-14), fractional density, and the method of heat application (Figure 15). By doing so, the specific shape change expression, such as texture size and fit is determined (Figure 16). The same warp and weft density can be used to create fabric structures of varying behaviours based on the number of warp and weft interlacements controlled by the weave structure. The more interlacements, the tighter the weave and the less the heat shrinking behaviour can be expressed. For example, a plain weave has a 1x1 weave structure, resulting in as many warp and weft interlacements as the density allows. Whereas a twill weave could use a 3x1 weave structure resulting in fewer interlacements for the same density. The density of warp and weft in woven textile-forms is determined by the number of layers required to construct a 3D form (resulting in fractional density). The same weave structure (3x1 twill, or 1x1 plain weave, etc.) will express differing shape change behaviours when used in zones with different fractional densities. So, the selection of weave structures is determined by 3D form needs, intended fabric behaviour, and how, together,

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[2] Fractional Density is the total number of yarns per cm, divided by the number of layers that makes the form unfold. So, if the yarn density in a single layer were 90 epcm (ends per cm), then in a 3 layer textile on the same loom settings each layer will be 1/3 of that total (30epcm). Weft yarns do not have to be divided evenly, however each unfolded layer is always a percentage/fraction of the total weft yarns available. The same is true in the weft direction but with fewer limitations (you can more easily increase density as you are weaving).

they express shape change behaviour. Additionally, the method and extent of heat application will directly impact the result - transferring some of the design decisions to the end-user.

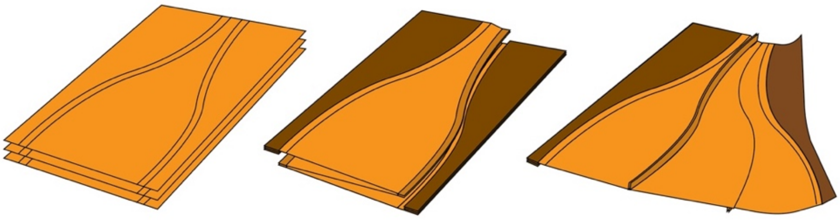

Figure 11. In this diagram all layers contain equal amounts of heat reactive yarn (left). In the middle and right, the combination of fractional density and specific weave structures enable a variety of shape change behaviours. Brown areas are high density and contain all of the heat reactive yarn, while orange is low density with ⅓ of the total heat reactive yarn used. Source: ©2021 Holly McQuillan (CC BY-NC-ND 4.0)

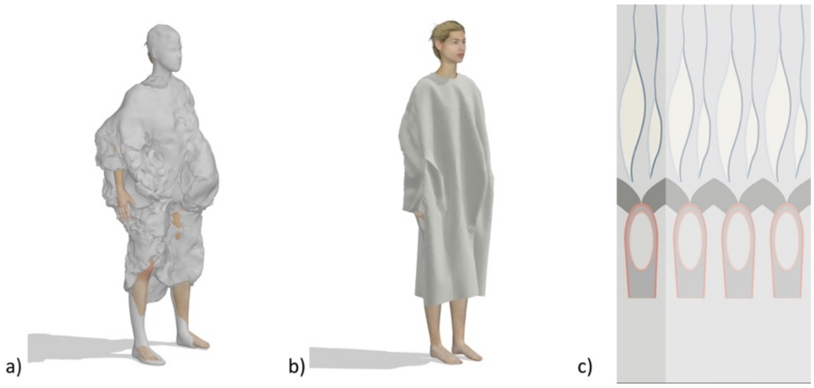

Figure 12. a) 3d scan of clay mould imported to CLO3D. b) Flattened textile shell of mould. c) Section of MoB. Source: ©2020 Holly McQuillan (CC BY-NC-ND 4.0)

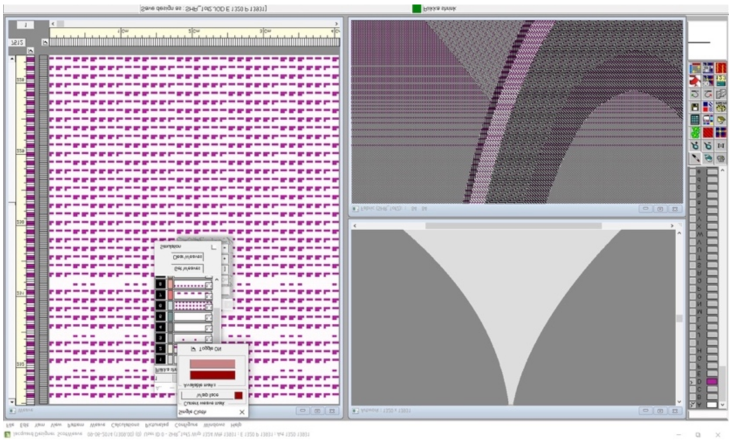

Figure 13. Programming woven textile-form in Scotweave. Left: Close up detail of warp and weft yarns (pink: heat shrinking yarn, white: cotton warp and weft) in interlacing weave structures. Top right: section of MoB being examined. Bottom right: Zoomed out view of section of weave structure. Source: ©2020 Holly McQuillan (CC BY-NC-ND 4.0).

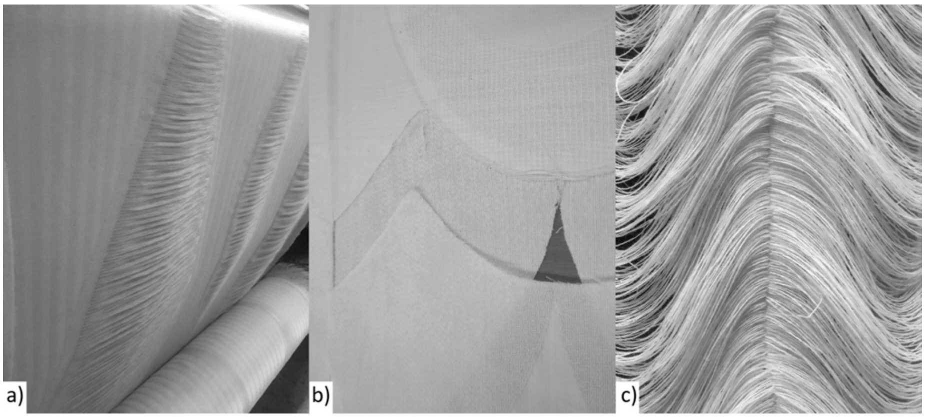

Figure 14. a) Loom state woven textile-form; b) cutting the textile-form; c) expanding textile-form (left side: unconstrained heat shrinking yarns). Source: ©2020 Holly McQuillan, Kathryn Walters and Karin Peterson. (CC BY-NC-ND 4.0).

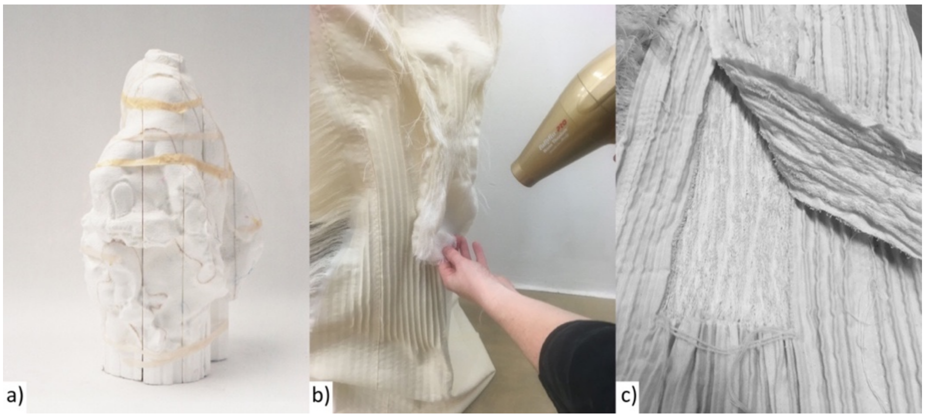

Figure 15. a) 3D mould in 1:1 scale. b) Targeted heating (using a hair dryer) on a 3D mould (or body) allows the user to control the activation of the animated textile, impacting on its texture, size, and shape. c) Uniformly heating in a domestic dryer results in 100% of the shape change potential of the animated textile to be expressed. Photograph: Amanda Johansson. Source: ©2020 Holly McQuillan, Kathryn Walters and Karin Peterson. (CC BY-NC-ND 4.0)

Figure 16. The woven textile-form in its many states: a) unshrunk; b) shrunk on mould using targeted heat application; c) uniformly shrunk in the dryer. Photograph: Amanda Johansson. Source: ©2010 Holly McQuillan, Kathryn Walters and Karin Peterson (CC BY-NC-ND 4.0)

3.2 Experiment 2: Trouser

In Experiment 2, the extremes of shape change behaviour were exaggerated further by using weave programming to remove the active yarn from zones where shrinking behaviour or textural change was not desired (Figure 17). The weave structure controlled the physical expression of the uniform heat reactive behaviour by transferring the yarn between layers and modifying the ratio of NSK yarn to static yarn (Figure 18). This approach enabled a high degree of shape change behaviour to be expressed via the weave structure even though a uniformly behaving shape changing yarn was utilised (Figure 19).

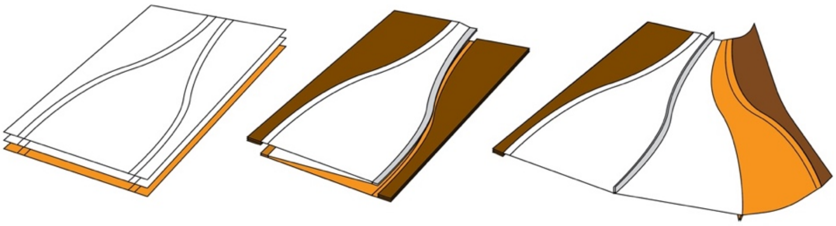

Figure 17. In this example, the orange represents layers where heat reactive yarn is located in a single layer of the multi-layered weave structure. When unfolded and heated, the variation of shape change behaviour across zones is evident. Where the heat shrinking yarn is located in low-density zones (orange) will express a high level of shape change behaviour, while in high-density zones (brown) will express a low level of shape change behaviour, and white areas will not exhibit any shrinking. Source: ©2021 Holly McQuillan (CC BY-NC-ND 4.0)

Figure 18. Yarn, weave structure and textile-form construction work in symbiosis to produce specific shape change behaviours. Source: ©2021 Holly McQuillan (CC BY-NC-ND 4.0).

Figure 19. a) Woven textile-form unshrunk. b) Woven textile-form shrunk on the mould so that the garment fits to the waist of model. c) Woven textile-form shrunk in a dryer. In this case, uniform heat is applied to the whole textile but the weave structures cause large variation in the expression of the heat reactive yarn. Photograph: Amanda Johansson. Source: ©2021 Holly McQuillan, Kathryn Walters and Karin Peterson. (CC BY-NC-ND 4.0).

4. Discussion

In recent years, researchers have been developing textiles with responsive features, making them able to sense changes in the environment or of the body and respond by showing changes in their function or expression. In this article, foregrounding animated textiles as an overarching term for such textiles, we showed how by designing a woven textile structure consisting of yarns with different thermal responses, we could program the fabric to adapt itself to the user or the user's preference when heated. The programming is done at the intersection of 3D form behaviour (in CLO3D) and yarn configuration in 2D (Scotweave), resulting in 3D shape and surface texture changes. This final section presents the key concepts that require attention in future animated textile research and practice.

4.1 Flattening the textile hierarchy

To understand textile-based form (such as garments) as a system of materials, we can start by deconstructing its components - unpicking the stitching to see the pieces of textile that make the form, teasing out yarn from the textile structure, untwisting the yarn to reveal the fibres, and lastly examining the fibre under a microscope. According to Guo et al. (2016), it is possible to view this system as a hierarchy and Tandler (2016) argues for smart textiles to be understood on a scale from fibre molecules up to the textile structure. In contrast, Albers et al. (2017) discussed the notion of textiles as an interrelated system with mutual influences where fibre and construction modulate each other “through the agency of the other, the tuning up or down of some inherent qualities, or their alteration.” (p. 59).

Animated textiles are often designed as isolated materials with technical behaviours and features. The textile hierarchy can aid in developing and understanding the degree of embedding of actuation in animated textiles. However, in practice, the relationship between materials is less hierarchical and more symbiotic. In our examples, it is no longer possible to separate the garment form from the textile structure: the form defines the textile, the textile defines the form, and the textile-form is the manifestation of complex mutual influences between fibre and construction, as suggested by McQuillan's notion of *multimorphism* (2020). This inseparability applies throughout the design and production process, where every decision has consequences for the whole. Tandler (2016) argued that no textile outcome could be considered 'smart' unless all system parts are smart. If we are to exploit the potential of animated textiles in design and HCI, we must symbiotically design all parts of the resulting textile system: from fibre and yarn level, to textile and form level.

4.2 Towards fibre-yarn programming for animated textiles

According to Vallgårda and Redström (2007), when textiles are embedded with conductive yarns and electronic circuits, the computer is "literally woven into the fabric" (p. 6), and computation becomes a material for interaction. This concept is relatable to the theory of Tibbits (2021) on programmable materials. Informed by Scott (2018), we question if it might be possible to combine complex fibre-yarn-textile-form systems to program specific behaviours from natural fibres. By utilising specialised yarn spinning software and machine[3], we speculate that it is possible to control the response of the textile by computationally determining how wool fibre is spun down its length, and combining this with multilayered weave structures to exaggerate or minimise these behaviours in 3D textile-form. Similar perspectives could be applied to a range of fibre types, both natural and synthetic, and may allow us to make better material selections specific to identified sustainable goals. For example, matching the fibre type of programmable materials with non-reactive materials to achieve complexity in monomaterials to simplify recycling efforts.

4.3 Performativity of animated textiles

According to the Materials Experience framework introduced by Giaccardi and Karana (2015), material qualities play a unique role in eliciting not only meanings and emotions but also actions, i.e., the performativity of materials. In the design of animated textiles, we demonstrated how to develop woven textile-forms that change shape when heat is applied. These novel textile-forms invite people to act upon textiles and alter their material qualities, thus generating unprecedented ways of interactions. Examples of such actions are using a hairdryer or steam generated by an iron to apply shape change to the textile-form. When these actions are repeated over time, they could potentially transform socio-cultural practices (Giaccardi & Karana, 2015). Fashion and textiles bring new materiality and a new vo-

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[3] Hilo yarn spinning machine and software is an open-source systems allowing on demand yarn production: https://www.studiohilo.com/

cabulary to interaction design (van Dongen, 2019, p. 47). Therefore, a future research direction that we aim to elaborate on in a future publication consists of developing a vocabulary to explore and discuss the performative qualities of animated textiles, i.e., what actions they elicit from people and how we can purposefully design for those actions.

4.4 Blurred boundaries in the design of animated textiles

The woven animated textile-form examples are the result of multimorphic and interdisciplinary approaches. As boundaries of categorisation are increasingly blurred, notions of 'ownership' of discrete parts of an outcome become deeply entangled. Hierarchies between technical (material science, engineering) and design (or art, craft) disciplines are flattened. Devendorf et al. (2020) argued for the benefits such collaboration and delineation will provide in the context of HCI research. Similarly, the boundaries between digital, physical, and biological are also significantly blurred. Igoe (2018) discussed new materialism and the emergence of digital-physical textile hybrids. Indeed, with our work, we highlight the conflict between the desire to strictly categorise for practical purposes and the reality in which boundaries are already blurred. In the future of animated textiles, we expect the boundaries between digital-physical to dissolve, moving towards new biological, computational, and physical entanglements for long-lasting evolving material hybrids. Hence, developing new vocabulary and design lenses that enable us to traverse these phenomena will be increasingly important.

5. Conclusions

In foregrounding woven-forms as a medium for animated textiles, our work calls for design and HCI researchers to pay attention to textileness to augment the often complex relationships between users and animated textile artefacts. With the case presented in this paper, we aim at opening up a design space that encourages new methods of design and production techniques that lean more heavily on textileness, embracing the tangible familiarity that textiles bring to our everyday lives. In doing so, we can develop novel interactions deep in the textile material system - while eliminating waste from production and end of life, which is currently one of the most prominent problems of smart and computational textile systems.

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