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Visual Materiality: crafting a new viscosity

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A re-materialisation of the visual in terms of viscosity is provided by this article. The argument is grounded in practical design processes from on-going research in the integration of archival material into AR/MR environments (Augmented Reality and Mixed Reality). This is an approach to emergent materiality not because new materials are invented but because existing visual, digital and traditional craft materials are re-configured. The archival material we use for this project is visual rather than textual, and it portrays moving bodies. The re-materialisation happens through experimentation with materials, affect and perception. Visual materialities, in this case viscosity, rely on a phenomenological approach to vision whereby design materials cannot be separated from the active perception of the designers, the participants and even the materials themselves. This article outlines the final iteration of the *AffeXity* project where glass was used as a design material to enhance viscous materiality. Viscosity is experienced as depth, layers, stickiness, reflections, motion, and an affective quality of dreaminess or the passage of time.

visual materiality, viscosity, glass, phenomenology, Augmented & Mixed Reality

1 Introduction

This article offers a particular glimpse of research processes centred on the creative integration of archival material into mobile Augmented Reality and Mixed Reality environments (AR/MR).[1] Part of the research program of the Living Archives research project at Malmö University in Sweden, the intent is not simply to present archival material in digital form but to call attention to performative practices of archiving.[2]

[1] The concepts Augmented and Mixed Reality are sometimes used interchangeably. However, in this paper, we follow the understanding of Mixed Reality as the overarching concept in which Augmented Reality technologies are understood in the context of other technologies (Billinghurst, Clark & Lee, 2014). Augmented Reality, most often understood as a way to "enhance reality with digital content in a non-immersive way" (Billinghurst, Clark & Lee, 2014: 79), is used to refer to specific software in this paper.

[2] http://livingarchives.mau.se

The goal is to open up visual archival material for an encounter with images that has a greater ability to afford perceptual depth and affective engagement. The material qualities to arise through our experimentation with AR/MR can be grouped under the term *viscosity*. This counts as an emergent material experience not because a new material is invented but because a careful re-configuration of existing design materials can produce a different qualitative experience. Viscosity has haptic, visual and affective qualities. In terms of touch, the texture can be glutinous; visually it exhibits distortion or a play between opacity and transparency; and affectively (where affect is seen to be a convergence between the emotional, pre-reflective, embodied and perceptual (Stewart 2007, Barthes 2005, Kozel 2012) it can be both enticing and disconcerting. Glass acts as a visual lens but also a catalyst for memory and imagination - this makes it powerful for designing ways to open out archival material.

Viscosity is an evocative term that might seem to be a metaphor, but it is a description of perceptual experience and reflects aesthetic choices that were implemented in the design process. Viscosity has a presence in a range of design disciplines, it can refer to how information, interaction, and communication can flow more smoothly across devices (Olsen 2008); or to the cognitive perception of effort in relation to workflow goals (Poelmans 1999), or in computer graphics, it refers to the simulation of highly viscous fluids (Kawabe & Nishida 2016). These uses of the term are not analogous with ours, however research into viscosity in computer graphics does open a range of characteristics that resonate with our sense of viscosity from a phenomenological perspective. Temporality, density, and pressure (Peer et al, 2015) are felt in the MR experience, particularly given that the archival material we use is film and video footage of dancing or moving bodies, and elasticity has a stretchy quality that is textural, temporal and spatial (Kawabe & Nishida, 2016).

This paper is structured around four sections. In the first section the phenomenology of perception as it is relevant to our consideration of visual materialities is grounded in Maurice Merleau-Ponty's reflections on the perceptual experience of the painter and Tim Ingold's reminder that the material world participates in the sentient process. In the second section an overview of the *AffeXity* project is provided with emphasis on visual strategies for using AR/MR to open archival material (Kozel 2012, Kozel et al, 2014, Engberg et al 2017). The focus of this paper is a recent design iteration of *AffeXity* that experiments with the use of hand crafted glass to provide an added layer of viscosity to the experience. In the third section the design process for creating the glass is described: the *how*, the *what* and the *why* of glass in relation to viscosity. The final section is a technical perspective on vision: how the camera and AR/MR code see, in particular what happened when we introduced 3D glass objects into the visual field.

2 Visual Perception

A phenomenology of perception is key to understanding viscosity as a visual material. For this we will rely on Maurice Merleau-Ponty's philosophical thought on the sensing of lived experience, in particular how vision works in the artistic encounter between the eye and the world. Unlike other applications of Merleau-Ponty in HCI which rely on *The Phenomenology of Perception* from 1942 (Giaccardi & Karana 2015, Svanæs, 2013), we draw on his later work, "Eye and Mind" the last work he published before he died in 1961 and *The Visible and the Invisible* incomplete at his death, where he complexified his own account of visual perception by relying less on on proprioceptive and anatomical examples and more on artistic and poetic ones (Ingold 2011, Kozel 2007). The reversible and "chiasmic" approach to visual and haptic perception from his later work is more appropriate for understanding the play of viscous materiality when designing the visual layers of Mixed Reality experiences, and for explaining how both the visual sensibilities of the human and the digital camera coincide in our process (Merleau-Ponty 1987, pp.130-155).

Merleau-Ponty's existential phenomenological approach acknowledges and even celebrates the opacity of the world, without trying to tidy up, instrumentalise, or regulate it. The body at the centre of the lived experience is not that of "an information machine", it is embedded in the world and implicitly tied to other beings, “the others who haunt me and whom I haunt” (Merleau-Ponty, 1985, pp. 160-161). Writing the essay “Eye and Mind” (with the original French title “L’Œil et l’Esprit”) on art in the early 1960s he was still operating with the model of mid-century humanism, but his deep reflections on vision evoked a sort of animism, a vitality of the natural world, objects, and other beings in it, so that the primacy of the human being gave way to “the primacy of perception,” and the ability to perceive was shared by animate and inanimate substances alike. The mountain looked back at Cézanne as he painted. It writhed and heaved. If there was a fundamental category for perception, it was that of movement.

In terms of crafting an approach to visual materiality, a phenomenological approach means that materiality cannot be considered separately from vision and touch: from the body in the very process of seeing and touching, and of being seen and touched. This implies that as designers we do not consider the visual externally as a property of the object or separate from the processes of seeing. Visual materiality is created by the way we see the material and the way the material and the devices look back at us. Materiality is not separable from the body, and the body is “an intertwining of vision and movement” (Merleau-Ponty, 1985, p. 162). Further, touch is not just the domain of the hand, vision not just performed by eyes. What Merleau-Ponty learns from the painter is that vision is “voracious,” inducing “delirium,” and the body is implicated in the world: in fact, the body is able to see precisely because it moves about in the world. Vision is never total, it is always a play between what is seen and what is not seen, touched and not touched, between the visible and the invisible; and touch is not constrained to the haptic, we touch and are touched through resonance, radiation and vibration (Nancy, 2007). With relevance to the play of layers possible with careful crafting of Mixed Reality, the essence of the visual is to have “a layer” of invisibility (Merleau-Ponty, 1985, p. 187). This partial quality of what and how we see means that we are constantly building a visual sense of the world at the same time as the picture changes and certainty is lost. “Vision is not a certain mode of thought or presence to self; it is the means given me for being absent from myself” (Merleau-Ponty, 1985, p. 186). Full transparency is impossible, just as complete archival documentation of the past is impossible.

More than just saying that perception is uncertain or unstable, a close reading of Merleau-Ponty such as that provided by social anthropologist Tim Ingold emphasises how what we see also has a sort of sentient being. There is a deep entwinement between the world and those beings who inhabit the world. The world looks back at us. When he writes that the world does not just expose “only its rigid, external surfaces to perceptual scrutiny” (Ingold, 2011, p. 12), it is possible to take inspiration for how a re-configuration of materials including AR/MR on mobile devices might escape the dominance of the flat cold surface of the screen. If each body is “irrevocably stitched into the fabric of the world, our perception of the world is no more, and no less, than the world’s perception of itself - in and through us” (Ingold, 2011, p. 12). To be sentient is to open up to a world, “to yield to its embrace” (Ingold, 2011, p.12), and to enhance the viscosity of the perception is to let oneself plunge into the visual field as if it were liquid, or to rebound, stroke it, or move through it. Designing for visual materiality in the phenomenological sense is designing for bodily resonance, not just for the eyes.

The “delirium which is vision” in Merleau-Ponty’s words (Merleau-Ponty, 1985, p. 166) can be seen as the magic of “opening one’s eyes upon a world in formation” and more than that, at seeing the world in formation *because of* and *through* our vision (Ingold, 2011, p. 128). This captures the essence of emergence in visual materiality. A deepened account of Merleau-Ponty opens for the designer for an expanded visual approach in the design process as well as his or her own visual perception in the design process. This deepened understanding of the phenomenology of perception in design will only increase in relevance as the development and proliferation of AR and MR technologies increase in coming years.

3 AffeXity

3.1 AffeXity: Passages & Tunnels (2013)

AffeXity is a Mixed Reality project that integrates dance and video experimentation with AR browsers running on mobile devices in urban spaces. The first iteration was shown in 2013 as part of the Re:New Festival in Copenhagen. Called *AffeXity: Passages & Tunnels* the goal was to use AR in conjunction with archival material in such a way as to create a sense of travel through time, or at least to a different space of memory and imagination.[3] The freely available AR application Aurasma was used to create a layered and performative engagement with archival material. The archival material was from dance, film and artist archives: film and video of bodies & objects moving in time and space is a category of archival material that is difficult to display in 2D static forms, and is often accessed through computer screens or in solitary viewing modes. We experimented with opening possible performative modes for encountering the material (Kozel et al 2014).

We modified the usual QR code triggers for launching the AR media by replacing them with still frames from the video footage of various sizes to launch short video loops. These images were attached to the outside of the Nikolai Contemporary Art Gallery in central Copenhagen. We called these images "tags" and some were quite large. They were tucked into the gothic elements of the architecture and helped to promote a thick affective quality for the performances and guided tours – most of which happened at night (figures 1 and 2).

Figure 1 A view of AffeXity: Passages and Tunnels being performed at night. Source: Jeannette Ginslov

[3] The research team for *AffeXity: Passages & Tunnels* (2013) included Susan Kozel (artistic direction & concept), Jeannette Ginslov (visuals & concept), Wubkje Kuindersma (dance), Oliver Starpov (dance), Camilla Ryd (image processing & interaction design), Jacek Smolicki (images & sound), Daniel Spikol (technical direction).

Figure 2 A view of an AffeXity target image placed on the building. Source: Jacek Smolicki

Our visual aesthetic for layering media was to play with the opacity of the video (making it semi-transparent). This feature allowed the video to be suspended in the device at the same time as the camera functioned, without blocking or replacing the camera feed. Through the video the tag image could be seen, and the space in between tag and video was also seen. This activation of the space between tag and device remains a key design component of *AffeXity* (Rouse & Barba, 2017). In the *Passages & Tunnels* iteration it became a performance space and enhanced the architecture and spatial elements, in the next iteration it is the location of glass layers and contributes to the visual materiality of viscosity.

3.2 AffeXity:Glass (2017)

The interest in glass emerged several years after the first showing with the desire to tour *AffeXity: Passages and Tunnels* to different locations. As this work is embedded in a long-term research project on archiving, with an interest in the GLAM (Galleries, Libraries, Archives and Museums) and cultural heritage sectors, we considered transforming the *AffeXity* approach to visual materiality into something that could be useful for galleries or museums for showing their visual archival material. There were two significant material developments for this second iteration: 1) shift of AR platforms from Aurasma to Argon; and 2) the introduction of glass as a material for the tags.[4]

Why glass? The idea of inserting a glass layer or object over the flat visual tag was based on the desire to escape the seeming 'flatness' of the 2D image that was used to trigger the media in the first version of *AffeXity.* For this first performance prototype, we had the advantage of embedding the 'tags' of various sizes into the crevices and nooks of the gothic architecture of the Nikolai building. The old brick walls and small arches made the tags seem less flat, producing an almost holographic effect.[5] However, once the work was removed from this specific site we could not reconcile the aesthetic qualities of the MR experience with producing simply flat tags – like photographs or posters. The quality of time-travel or passages would be lost. Glass seemed like a beautiful and evocative way to introduce a layer of density to the space between the tag and the

[4] The 2017 research iteration of AffeXity called AffeXity:Glass was by Susan Kozel (concept), Jeannette Ginslov (visuals), Maria Engberg (Mixed Reality design), Henrik Svarrer Larsen (glass design) and Colin Freeman (camera vision). See http://livingarchives.mah.se

[5] https://youtu.be/41gB7exGZGo

device that could be reduced in size and more able to tour. It also might be a way for museums or galleries to present material in fairly contained spaces with controlled lighting.

In this second iteration, the re-configuration of design materials was our focus: video, still image, mobile device, AR browser, glass and perception. The glass was intended to be experienced both directly and through the layers of visual media. Once interposed between the image and the device, the glass seemed less hard and more gelatinous, fluid or flexible. It had a sort of viscosity when layered with the opaque moving imagery.

4 Using Glass

4.1 The design process

From the perspective of the glass maker, "hot" hand-formed glass is made through the craft of glassblowing, allowing for an intimate engagement with the material as the molten glass is shaped. Paradoxically, glass in its cold form is still a liquid, a "still" liquid. The spectrum of variance in viscosity of different glass batches is what defines them as a malleable material to a blower. For *AffeXity:Glass* the optical qualities of the glass were the focus, given that the glass was combined with the trigger image for the Argon AR browser and had to work with the visual recognition software (more on this below). We limited our explorations to solid glass in rather generic shapes either clear or white with varying opacity; some with inserted bubbles or sand to give inner and outer texture (figure 3). While the shapes were constrained to basic circles, spheres, triangles and rectangles, the making involved was manifold as hand-forming included shaping solids and indenting castings, incorporating bubbles, sand, coloured patches, as well as some glass cutting (figure 4 and 5).

Figure 3 The glass objects that were made. Source: the authors


Figure 4 Shaping of glass. Source: Mads Hobye


Figure 5 Additional glass shaping to add layered qualities. Source: Mads Hobye


Figure 6 A viscous image: shaped glass with a "swoop" and a tracking image underneath. Sources: dancer: Oliver Starpov, still from video: Jeannette Ginslov, photo: the authors.

Some of the glass shapes were made to enhance visual qualities of the images acting as triggers for AR – in particular the ‘swoop’ in the glass shape that was used with one of Oliver Starpov’s dance solos (figure 5 and 6). Other glass textures more abstractly echoed the visual qualities of the movement in the video: the rounded shape picked up on the curve of the archway while the bubbles embedded in the shape added qualities to the layers of media – a watery quality the evoked time or submersion in memory (figure 7). And finally, some shapes were speculations of what might contribute to a viscous experience, emphasising the phenomenological sense of the objects being sentient, inviting us to plunge into the combination of glass and archival material, to swim in it and have it rebound on us, surprise or captivate us.

Figure 7 A round glass shape with bubbles and a tracking image underneath. Sources: dancer: Wubkje Kuindersma, still from video: Jeannette Ginslov, photo: the authors

In the digital realm, glass and glass coatings have been used in interactive products but so far primarily on flat glass (Transparent Intelligence 2017). Until recently, there have been very few efforts with three-dimensional glass, and these have focused mainly on embedding technology within the glass (Dynamic Transparencies, 2017; Olofsson, 2017; Contemporary Glass Society, 2017). Our work speaks to some of these efforts on interactive glass, yet is distinct by drawing the three-dimensionality of glass into visual digital media. *AffeXity:Glass* incorporates the temporal spectra of the moving media in the AR-application and the functions of perception and memory in the person who experiences the designs. The design interest in the layered material is not the duality of seeing an object (picture and/or glass) on its own and then seeing it on the screen overlaid with videos of dancers, but rather in the interplay between image, glass and media, closely related to small movements of the camera and its holder. These micro hand movements of the person holding the camera can include deliberate adjustments to see better or to choose different viewing angles for the 3D glass objects, but they are equally the involuntary trembles of hands and arms, and the negotiation of physical space shared with other bodies who may be using their device to access the media in close proximity. It is possible to focus on the glass placed on the photographic tags or glass with the image embedded within it as a viscous image (see figure 6), however with the *AffeXity:Glass* design research, viscosity refers to the entire material experience, including devices, people, tags and media.

4.2 *Cultural reflections*

The insertion of glass into our process provoked and inspired our design process, revealing how a material can have both significant cultural and embodied reactions. The obvious initial reactions were sensory and tactile, but also related to our imagination, childhood memories and cultural connections to the glass objects, despite their comparatively neutral shapes. Curiously, our reactions were often negative, in the sense that cultural or personal resonances arose that were not welcome: we did not want them to interfere with our aesthetic and design decisions. Various members of the design team reacted against the glass looking like ubiquitous flat screen displays, Christmas Tree baubles, candle holders, or paperweights. The more we worked with glass, the more glass we saw around us or remembered from past histories.

We wanted to design in such a way as to avoid these associations, then we realised that this was impossible or undesirable. Why design with the desire to be a-cultural, particularly when working in a culture traditionally known for working with glass? The cultural references are unavoidable, a colleague said, so work with them. Another colleague immediately and viscerally said "I hate glass" and did not want to hear anything further about the project. Most people responded to the seductive quality of glass, with imaginative and personal resonances from childhood arising in a favourable light. We found ourselves, while working with the glass prototypes, wanting to touch or stroke them. Our glass maker warned, but too late, that one piece had sharp edges: one of us cut a finger and the dried blood stayed on the piece for some time. This array of unexpected cultural and personal affective resonances around glass almost derailed our process. In particular, *Google Glass* became a counterpoint for us – meaning it is an opposite use of AR, both experientially and in the consumer market – provoking the ironic reference to our work as *AffeXity:Glass*, a working title that somehow stuck.

The push of cultural resonances and the pull of affect impacted the design process. The vocabulary used to describe stages of the process and reactions to what came out reflects a range of phenomenological reactions: yearning, allure, seduction, repulsion, desire to touch, hold, handle, wanting to feel the temperature and how it would fit in one's hand. Almost ephemeral: seeing through it, seeing into, suspension, reflection, refraction, distortion. We followed the lead of our glass designer who advised that it is more a question of being aware of which culturally coded symbols one incorporates, depending on whether these are helpful or not, for the design intentions. Two guiding forces in particular stood out, one phenomenological and one cultural: viscosity and *Google Glass*. Viscosity accounts for the pull toward the dreamlike quality glass added to the mix of images and video, evoking a play between imagination and memory, making it appropriate for dealing with archival material. *Google Glass* was an opposite configuration in terms of embodiment, media display, materials and market segment. Contradistinction became a mode of cultural critique and a force for design decisions.

5 Materiality in AR/MR Mobile Media

Already in *AffeXity: Passages & Tunnels*, Augmented Reality software for mobile phones was used. This particular class of software combines the abilities of AR (to combine real and virtual content, to provide interactive content, and to correctly register that content in a 3D space) with the mobility and ease of access and use that mobile phones provide. Another way to understand the affordances of AR/MR systems is in terms of location and image recognition. The former uses the mobile phone's ability to correctly register the device's coordinates, spatial orientation and movement. The latter uses the mobile phone's camera and computer graphics abilities to display and recognize visual elements. Generally, the goal of an AR/MR system was primarily to "draw the world" on the screen accurately and to add virtual content meant primarily for the user's eye.[6] More recently with the

[6] AR/MR systems have been primarily defined as concerned with visual virtual content, whether 2D or 3D. However, AR/MR technologies are also used to provide audio or haptic experiences (Billinghurst et al 2014).

increasing computing power, network stability and computer graphics capabilities of mobile phones, these AR/MR applications are capable not only of directing that computational gaze outward in order to display visual content on the screen, but they can also perceive and sense the world around the device. An AR/MR system can now approximate the physical properties of its surroundings: what surfaces, edges and dimensions it should take into account as it maps out its immediate context via the camera. These later developments in terms of visual sensing and perception are crucial for the purposes of this work as we view the digital dimensions of the project as involving a camera that *perceives*.

AR/MR exist in different configurations of hardware and software packages, and as described above, our project focused on the mobile phone as the device. We have tested different software packages and applications. Aurasma was used in the 2013 version of the project. The constraints of Aurasma allowed us to work within a framework that provided a set of interaction models and aesthetic possibilities. However, using this free application required loading our content onto the company's servers. In addition, Aurasma was sold to HP during our design discussions leading to the 2017 version. The decision was made to start working with an open source JavaScript framework for web-based AR/MR developed at the Augmented Environments Lab at Georgia Institute of Technology, called argon.js, which in turn functions with the Argon AR-enabled web browser for mobile phones (Speignier et al 2015). The Argon browser allows for computer vision tracking of images and objects, using the Vuforia AR software development kit (SDK) for Android and iOS. Vuforia offers image recognition and sensing, or tracking, capabilities for both flat images as well as more complex objects. In the context of flat images, the SDK detects and tracks features that are naturally found in the image itself by comparing these natural features against a target resource database that is set up by developers. It was at this stage of setting up a target resource database that could contain the 2D images used in 2013 as well as the layered three-dimensional objects that we had in mind for *AffeXity* in 2017.

5.1 Glass and image recognition software

The visual materiality of viscosity arose in the iteration of *AffeXity* in which we introduced glass. Aiming at producing a layered materiality that included the original 2D images and an object that could provide us with a three-dimensional, tactile object that could be displayed in an exhibition context. Glass and its perceptual affordances soon emerged as central: the glass objects, the digital cameras and the specific image capturing and sensing capabilities that they have, and finally, the screens themselves that constitute the visual membrane through which the user would encounter the video material being displayed.

The main aim of the design workshops integrating glass and AR was therefore to apprehend how Vuforia could sense the glass objects, alone or in combination with the previously used Aurasma tag images. In brief, we were attempting to turn glass objects into image recognition targets for augmented reality. We used the Vuforia SDK separately to test the feasibility of using the Argon app. Vuforia's 3D detection is called object targets. These are digital representations of the features and geometry of a physical object. There are a number of ways of constructing a 3D model of an object, ranging from more expensive 3D scanners using laser or other light sensing, to scanning software that use mobile phones' camera to detect the contours of an object. Initially, we used the Android application Vuforia Object Scanner,[7] to scan the objects by moving around them and recording different viewpoints. These attempts were made by placing the glass objects onto various white, black, and grey matte surfaces (primarily using textiles) and attempting to control the light so as not to create shadows and reflections. As part of this work with understanding the combination of

[7] https://library.vuforia.com/articles/Training/Vuforia-Object-Scanner-Users-Guide The Object Scanner uses a set object scanning target image upon which the object is placed. The mobile phone camera app then captures the contours and features of that object. However, and crucially, an object whose surfaces are shiny, give off reflections, or disturb the sensing process will not render a proper scan.

materials that we were working with, we handled the objects, taking regular photos to understand the difference between what we could apprehend with our vision and what the camera saw (see figure 8).

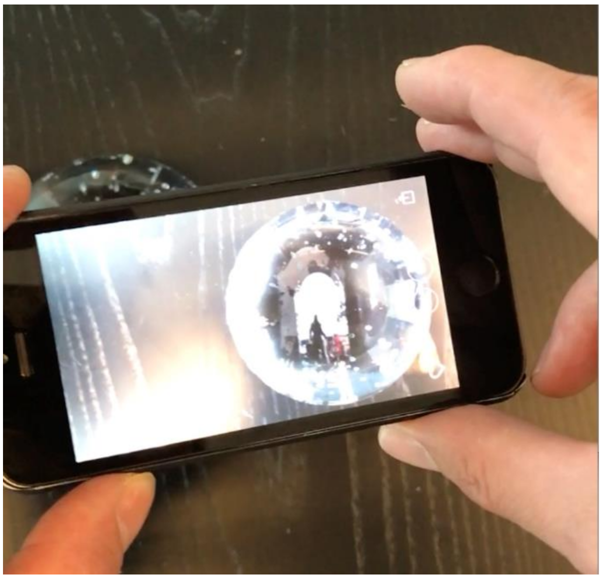

Figure 8 Scanning the shaped glass and the tracking image starts the video content with some of the glass objects. Sources: dancer: Wubkje Kuindersma, still from video: Jeannette Ginslov, and photo: the authors (from a video: https://vimeo.com/242722532)

Our initial attempts to capture our glass objects with the Vuforia Object Scanner app or with a digital camera (images that could then be recombined into a 3D model) did not work. Our assumption was that they did not register as AR tags for on one or more reasons:

- Poor lighting on the objects.
- Transparency and refraction creating false tracking points.
- The handheld scanning caused distortions in the scan.
- A combination of the above problems.

The next step in our process of sensing the glass objects as digital 3D objects was to further seek to control the environment of movement and light on the objects as well as the immediate environment by introducing various elements such as a revolving tray that would allow us to rotate the glass object evenly. This set of attempts to use the Vuforia Object Scanner app was made in a studio space with professional light setups and a lighting tent to limit reflections and refractions. The more controlled setting did allow us to scan some of the objects: particularly the ones with clear features such as opaque bubbles or surface details. These scans worked as recognition objects for Vuforia while still in the studio lighting but failed when we tried to use them in different lighting conditions. From this, we concluded that the transparency and refraction present in the glass objects would not work as a 3D target for Vuforia in a non-controlled setting. To confirm that the process would work for opaque objects we scanned an opaque object and the image recognition with a 3D digital object as the trigger worked in Vuforia under different lighting conditions.

Another phase of the prototype workshops involved placing the existing AffeXity images that were used as tags in Aurasma under the glass to create a layered object (or a viscous image). Although looking at the image and glass together with the naked eye produced aesthetic effects that intrigued us, the digital camera saw something else as the glass distorted the image differently at various angles, thus rendering the image recognition process difficult to control. This illustrates the basic phenomenological point that objects in the world, as sentient beings, also have dynamic perceptual processes.

Already at the outset, we knew from previous experience with 3D capture that glass with its refractions, dispersions and reflections would present a challenge for Vuforia's object recognition code--alone or in combination with the *AffeXity* trigger images already used in the 2013 version. However, the allure of experimenting with the layers of glass and their inherent visual and material qualities was important for the project. The contribution of the research proved at this stage to be a remateralisation of the visual in the context of AR/MR as a sort of viscosity, supported by the phenomenological perspectives of not just the users but the designers and the devices themselves.

6 Conclusion

In current critical discourse the visual has been abandoned too quickly in a turn towards materiality. All the while computer technologies, particularly mobile phones, rely on and expand what visuality means. Our lives are saturated with visual media, much of which is empowered by computational abilities and circulated through social media. This is not likely to change in the near future. This paper focused on engaging with phenomenological and computational visuality using mobile AR/MR technologies to attain a deeper understanding of how the visual can be designed as part of a complex and re-configurable materiality. The haptic and performative are not excluded from this emergent materiality, rather there is a need to understand and design for what we call a viscous materiality based on a phenomenology of visual experience.

This research challenged the current affordances of AR/MR and the current models of interaction and aesthetic of AR/MR applications. The specific case of using archival material for tags and virtual content shown in the device revealed the need to design for the affective qualities of personal and cultural memory, as well as designing for the cultural heritage locations where this material would be open for public interaction. There is, however, wider relevance to this research. Augmented and Mixed Reality applications are growing in significance to designers and the general public, as many consumer and professional products and services implement layered, networked and mobile apps into their existing business models. The general contribution of this paper points to the need for designers to expand their material and perceptual registers to include the sensory and affective qualities of viscosity, and a deeper understanding of the phenomenology of material experience.

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Textile Waste and Haptic Feedback for Wearable Robotics

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Recent textile innovations have significantly transformed both the material structures of fibers and fabrics as well as their sphere of use and applications. At the same time, new recycling concepts and methods to re-use textile waste are rapidly being developed and many new ways to make use of recycled and reclaimed fibers have already been found. In this paper, we describe how the development of a new textile, making use of recycled fibers, sparked the development of *Textile Reflexes*, a robotic textile that can change shape. This paper elaborates on the development of the new textile material, the multidisciplinary approach we take to advance it towards a robotic textile and our first endeavours to implement it in a health & wellbeing context. *Textile Reflexes* was applied in a vest that supports posture correction and training that was evaluated in a user study. In this way, the paper demonstrates a material and product design study that bridges disciplines and that links to both environmental and social change.

sustainable textile, haptic feedback, posture training, wearable robotics

1 Introduction

This research is built on three convergent technological, material and social trends: a) the increased proliferation of smart and electronics textiles in clothing and industry; b) the growing urgency to build more sustainable materials and production cycles for fashion and electronics; and c) the current interest in health and wellbeing via wearable sensors, devices and body-based training applications.

While we consider these three axes of innovation: technological; environmental; and human to be positive contributions to the design of the built and social landscape, we ascertain that a limited body of research on the intersection of these fields and their combined, and potentially contradictory impacts has been put forward. This paper aims to outline current research in the field of smart fabrics, sustainable materials and design, and health / wellbeing wearable devices. We propose a possible design solution via a case study of the Posture Awareness Vest (PAV) that integrates the *Textile Reflexes* fabric.

1.1 Textile Innovation & Sustainability in Fashion

Recent innovation in fibres and textiles have significantly transformed both their material structures as well as their sphere of use and applications in various industries from fashion, to architecture and industrial products (Braddock Clarke and O'Mahony, 1999; 2005; McQuaid, 2005; Peters, 2011; Quinn, 2010). Specifically, smart textiles and fibres are increasingly engineered with the integration of electronic circuits and sensors, which combine hybrid materials such as metals, plastics as well as chemical and biological coatings and substrates that substantially complexify the material composition of fibres and textiles. However, fashion, and apparel design is increasingly looking to innovation in textiles to differentiate its product value and uniqueness, as well as expand its functionality, life cycles, quality or costs. Notably sportswear has been developing high performance textiles to enhance performance, comfort and mobility for sports (O'Mahony and Braddock, 2002; Watkins and Dunne, 2015). In fashion, new forms of expressions stemming from the integration of electronics, 3D printing and kinetic systems is re-mapping the future of design and personal expression (Braddock Clarke and Harris, 2012; Genova and Moriwaki, 2016; Lee, 2005). Increasingly, fashion designers are looking to develop custom and unique textiles to create bespoke collections; design new consumer experiences and styles; as well as innovating with materials (Kettley, 2016; Pailes-Friedman, 2016; Schneiderman, 2016). The craft and DIY community has also been a strong proponent in teaching, supporting and facilitating the development of skills to experiment in hybrid material production that includes the integration of electronics in textiles (e-textiles) and the use of off-the-shelf electronics such as Arduino's electronic components such as Lilypad designed for e-textile crafting or desktop 3D printers for bespoke apparel and accessories (Ayala-Garcia and Rognoli, 2007; Buechley, 2013; Buechley and Perner-Wilson, 2012; Hartman, 2014).
However, current fashion production represents the second most polluting industry in the world, making sustainability an urgent concern for the industries of fashion design, apparel fabrication and textiles (Sweeny, 2015). Over the past ten years there has been a growing interest and concern in creating a more sustainable fashion industry, and as a consequence more sustainable, reusable and low-environment impact textiles. Fashion and textile design schools, private companies and designers are increasingly turning towards sustainable and recyclable materials and smaller or on-demand production chains to lower current carbon footprints related to the fashion industry and minimize its impact on the environment (Nidumolu et al., 2009). Sustainability in fashion is both a growing concern as well as a political engagement to produce better materials, products, and relationships with consumers and ameliorate the health of the planet and residents (Black, 2008; 2013; Brown, 2010; Caniato et al., 2012; Fletcher, 2008; Fletcher and Grose, 2011; Gardetti and Torres, 2013; Gwilt and Rissanen, 2011; Hethorn and Ulasewicz, 2008; Minney, 2012; Teunissen and Brand, 2013).

1.2 Pathways to Developing Sustainability in Innovative Textiles

While smart and connected textiles trace a pathway to new uses and applications for fabrics and fashion they also present new challenges for sustainability (Köhler, 2013; Köhler et al., 2013; Köhler et al., 2011). One of the key challenges in creating sustainable textiles of smart wear applications is the use of metals in textiles and the "possible end-of-life implications of textile-integrated electronic waste" (Köhler et al., 2011: 496). Not only is the separation and procession of hybrid materials complex, there is an added probability of metals and other electronic materials contaminating textiles and fibres. We know already that electronic waste (e-waste) poses an important problem and risk to the environment (Hilty, 2005; Kräuchi et al., 2005; Schluep et al., 2009; Widmer et al., 2005). Furthermore, many of the materials used to create conductivity and enhance the material function of fibres and fabrics are prone to leaching into water supplies when washed and thus polluting them with heavy metals that are difficult to filter (Köhler, 2013; Köhler et al., 2011). In light of these above points in regards to recycling an impact of use on the environment, it is worthwhile building an environmentally aware design strategy for smart fabrics and e-textiles that can effectively curb the harmful effects of the materials used, and provide conscientious methods for end-of-life use and recycling. It is these concerns that we aim to address and render transparent in the design of the *Textile Reflexes* dynamic material and the Posture Awareness Vest (PAV).

A way in which designers can act on the issue of fashion and textile waste is through their role of 'active makers' of materials (Myers, 2012; Karana et al., 2015; Rognoli et al., 2015). This paper will demonstrate a case of how the development of a new textile material sparked further innovation into a robotic textile and its implementation in a health and wellbeing context. We will first outline how the new textile material; *Textile Reflexes*, was developed. Subsequently, we will describe how electronics were integrated into this textile material and we will demonstrate a first use application of the developed robotic textile. Finally, we will discuss how this project is both an example of how multidisciplinary collaboration can further advance the development of smart and electronics textiles and of sustainable innovation touching on different societal challenges.

2 Textile Reflexes: a textile that engages with material sustainability

The *Textile reflexes* textile is made of separate squares that are stitched together along with a string across the diagonals, connecting each square to the next in the corners. This way the corner remains a flexible point and the connected squares can open and close, each responding to the movement of the other. This way the textile can grow, shrink, fold and bend. The flexibility allows it to respond to the shape of the human body allowing for some flexibility in sizing and allowing freedom for movement. The textile works best though, on a flat, horizontal surface, where gravity has no effect on it. When applied vertically, for example, in a dress, gravity pulls the textile in its opened position. This can be adjusted with elastics where it needs to be tight, for example in the waist. Figure 1 shows the moving squares textile in open and in closed position.

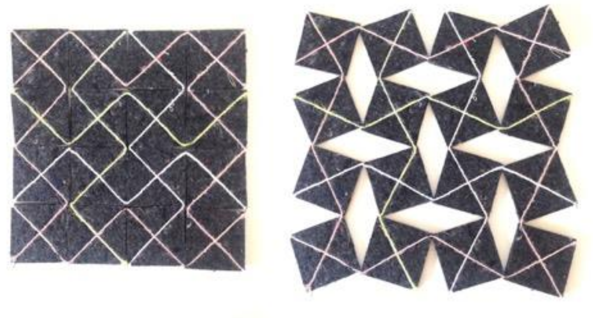

Figure 1. The moving squares material in closed (left) and open (right) position.

2.1 Development of Textile Reflexes

The development of *Textile Reflexes* started after an introduction to a recycled textile waste felt material. This material was made out of post-consumer textile waste. The felt was stiff, sturdy and had a surface that showed small patches of colour stemming from the different garments the textile waste was made out of. This interesting surface went unnoticed in earlier applications of the material. The material had so far mostly been used to isolate floors, in the automotive industry, and in other applications where it remained invisible.

Due to its stiffness, the material was not immediately suitable to make garments or fashion accessories. The development of *Textile Reflexes* started as an exploration to find a solution to that problem. How to make a stiff, sturdy textile flexible and suitable for creating wearable garments and accessories? The first and obvious thing to do was cutting it in pieces and gluing it on a base fabric with some space between the pieces. The result was a flexible material with largely the characteristics of the material it was glued on. The principle reminded too much of the well-known Prism Tote Bag by Issey Miyake. The next challenge was to find a way to make the felt flexible by its own and create an original design with it that would also make its distinct qualities more visible. In the end a similar principle of cutting the felt in pieces and putting it back together was used, but this time without a base material, just by stitching the pieces together in the corners. A string with a contrasting colour was used in the stitching to create a strong connection that also adds a playful effect that invites interaction.

The materials used in *Textile Reflexes* have a low impact on the environment. Next to not adding to the massive piles of textile waste that are already problematic, it also supports environmental consciousness by actually showing the recycled quality of the material and making people aware of the benefits of recycling textile waste.

3 Robotics innovation for textiles

Textile Reflexes is an innovative material but also a kinetic system. This unique quality of the material triggered the exploration of making *Textile Reflexes* a robotic textile. Robotic textiles as (elements of) garments could provide very different tactile experiences when compared to existing textiles. A robotic textile that changes shape could be compared to a soft muscle that can apply or release pressure. This type of interaction is what we wanted to create because it would enable us to explore new forms of feedback that can be intuitively understood and are arguably more comfortable.

3.1 Smart textiles, feedback and coaching / training

A robotic textile can change shape that allows for giving haptic feedback. It has (literally) a close impact on people. Given those opportunities, it makes sense to implement such a textile in a coaching or training context. Haptic feedback has a great potential because it provides physical input on the body and uses new channels for non-verbal communication. For applications such as posture improvement, we also expect that providing haptic feedback at the exact location of the body where a reaction (from the wearer) is needed, will require less cognitive load than, e.g. visual or auditory feedback that would require an understanding of what action needs to be taken considering the feedback provided. Moreover, haptic feedback is not only another way of perceiving information, it also includes another experiential dimension. People attribute meaning to signals they feel on their body as becomes apparent from language. We use phrases such as “a tap on the shoulder” to indicate approval, “back in the back” to indicate support and “hold me tight” to indicate a feeling of safety. See Ludden & van Rompay (2015) for a more extensive account of how touch can be experienced at different levels of experience.

In most available devices and applications that incorporate haptic feedback vibration motors are used, similar to those we find in, for example, smart phones. Their advantage is that they are cheap and easy to integrate. However, they only cover a very limited spectrum of tactile reception, even for vibration other frequencies or patterns can be sensed by humans. Pressure, which can be given through touch or as an embracement, is another dimension of haptics that can be explored. There are various experiments with inflatables creating pressure on the body (see, e.g., The, 2009; Neidlinger, 2017), but none of them seem to satisfy criteria on wearability since the compressors that are used for such application come at a considerable size and with a certain amount of sound.

As a first step towards integrating the innovative robotic textile into an actual coaching wearable, we decided to start from the most direct form of feedback, that of giving direct physical feedback as information. For this type, the feedback that is given on the body can lead to direct action starting from the actual position where the feedback is given. More specifically, we chose to integrate the robotic textile in a Posture Awareness Vest (PAV). A PAV is meant to provide support in posture correction by making people aware that they are slouching. Slouching means taking on a lazy posture that is characterized by excessive muscle relaxation and a bent head and shoulders. This could either be in a sitting, standing or moving mode. Slouching may result in headaches, pain in the back or in the jaws. A better posture is recommended to prevent these health-related issues.

3.2 Integrating electronics

To develop the electronics needed for the PAV, we had to design solutions focused on both sensing (sensing slouching) and actuating (making the *Textile Reflexes* material contract and thereby providing haptic feedback).

For sensing slouching different solutions are possible, e.g. a bend sensor below the sternum (Pfab, 2015), strain sensors on the back (Mattmann, 2007), or accelerometers, either single or multiple (see e.g., Wang, 2015). For this application we decided to use a combination of two sensor boards including both an accelerometer and a gyroscope. One reason is that we wanted to make use of an accelerometer for activity detection (for example, because we might decide not to provide feedback on slouching while a wearer is active). The decision for two accelerometers/gyroscopes was made because a single accelerometer cannot sense the relative position of the upper spine with respect to the lower spine, which we consider to be a main characteristic for posture. A single accelerometer might only detect whether the shoulders are in correct position, which still allows for many different ways of poor posture. Because of this, using only one accelerometer might result in both too many false negatives as well as false positives.

Solutions to actuate the textile are also diverse, and all come with different disadvantages. In a series of experiments, illustrated in Figure 2, we explored motors, DC (rotational) and linear ones, and air muscles (also known as McKibben artificial muscles or braided pneumatic actuators). General disadvantages of motors are that they are bulky and make noise, which makes them less useful for integration in a textile material and which might also impose problems when used in daily life.

A property of *Textile Reflexes* is that the locally actuated movement of one or more squares propagates over all other squares, i.e. moving one square results in all other squares also moving. However, when wearing the textile, friction with other garments limits this property, excluding solutions for actuation that only move single squares. A more adequate solution would therefore be to actuate a full length of squares that have to be pulled together. We found that this could be done by using the McKibben artificial muscles (see far right image in Figure 2).

The exploration of possibilities for actuation in this project is ongoing and will include other actuation mechanisms with motors, more elaborate experiments using McKibben air muscles, linear magnetic actuators, and, most promising, knitted artificial muscles (Maziz, 2017). The latter seem to fit smoothly to the required full-length actuation, can easily be integrated in a textile material because they are made of textile material themselves, and are silent.

Figure 2 actuation with a DC motor (both left), a linear motor, and a mcKibben air muscle.

4 Posture Awareness Vest (PAV) Using Textile Reflexes

In the previous section described the haptic feedback that the robotic textile could provide when applied in a garment and how it might be used in a coaching context by way of a Posture Awareness Vest. Other researchers have explored posture correction through wearable technology as well via commercially available products such as the Lumo Lift (Lumo, 2017). Drawbacks to many of these existing devices and wearables can be found in how they apply feedback (vibration) at different points of the body (often at the upper front body) than where the posture correction is actually needed (the lower back and shoulders). To explore the benefits of using a different type of feedback (pressure rather than vibration) at a more suitable location (at the direct location where action should be taken) we performed a first user evaluation study with a prototype of our PAV.

4.1 Usability and Testing Results for PAV

For our purposes, we created a first prototype of a posture vest that uses the robotic textile in the back and that will in this way be able to give direct feedback at the place where users of the vest should start correcting their posture. We aim the first user evaluation at determining the best position for tactile feedback on posture using the *Textile Reflexes* vest. Additionally, the study was aimed at obtaining a first user evaluation on the perceived quality of the tactile feedback. Quality of feedback includes comfort, noticeability, distraction, and effectiveness. Finally, we aim to understand people's willingness to wear a vest for posture feedback.

4.1.1 Stimulus and participants

For this study we have used a first prototype of the *Textile Reflexes* vest (Figure 3). This prototype did not have electronic actuators but was operated manually. For this, we integrated strings in the vest that, once pulled, contracted the vest for tactile feedback. The vest allowed for tactile feedback at three different locations in the back panel of the vest: the upper part, the middle part, and the lower part. The textile reflexes vest was designed for women. Therefore, the participants of this study were all women. We invited twenty female students, aged between 19 and 25 (mean age 21) to participate in our study.

4.1.2 Procedure

The experiment consisted of three phases: an introduction phase, a test phase, and an evaluation phase. Participants performed the evaluation individually. In the introduction phase, the participants were introduced to slouching. Through a short questionnaire, the participants were asked about their experiences on slouching and their willingness to correct their posture. The participants were then, in the test phase, asked to put on the *Textile Reflexes* vest. The participants were wearing the vest over their normal clothing but coats and vests had to be taken off. Participants were asked to sit down and type out a text on the laptop that was standing on the table in front of them. When the participants started slouching, the experimenter would pull the upper strings of the vest, for upper back feedback. The participants were afterwards asked to assess the upper back feedback on four seven-point scales to assess comfort, noticeability, distraction, and effectiveness of the feedback. General comments that participants gave were noted. This procedure was repeated for the middle back feedback and the lower back feedback. Finally, in the evaluation phase we again asked participants which of the three locations for feedback was preferred and assessed their willingness to correct their posture using the vest.

4.1.3 Results

The introduction phase of the experiment indicated that all our participants are aware of their own slouching and would like to improve their posture. 14 out of 20 participants indicated that they experienced pain in their bodies that could be the result of slouching. Of all participants, 8 indicated to be willing to use a technological aid to improve their posture. On a seven-point scale, the willingness to use a technological aid was rated 3,75 average.

Figure 3. First prototype of PAV (top) and location of strings used in user evaluation test (bottom).

Table 1 shows the results of the test phase. It illustrates how participants rated the types of feedback given on three different locations of the back on the scales that measured the quality of the feedback.

Table 1: participants' appreciation of three types of feedback

	Upper back	Middle back	Lower back
Comfortable	5,58	5,21	5,11
Noticeable	4,55	5,30	5,45
Distracting	4,45	4,40	4,30
Effective	3,20	4,35	4,60

From Table 1, we can see that the feedback at all locations was perceived as rather comfortable (scores range from 5,11 to 5,58) and noticeable (scores range from 4,55 to 5,45). Moreover, the three types of feedback were almost equally rated as moderately distracting. In terms of how much the feedback invited participants to sit straight, (i.e., the effectiveness of the feedback), the feedback given at the lower parts of the body seemed to work better than the feedback given at a higher position (scores range from 3,20 for upper back feedback to 4,60 for lower back feedback).

Finally, the evaluation phase of the experiment illustrated that 1 out of 20 participants preferred upper back feedback, 10 out of 20 appreciated best the middle back feedback and 9 out of 20 valued most the lower back feedback. Further, whereas in the introduction phase only 8 participants out of 20 indicated to be willing to use a technology for posture improvement, now 15 out of 20 participants said to be willing to use the *Textile Reflexes* vest for the improvement of their posture. Ratings about willingness to use wearable technology for posture correction were as well slightly higher after participants had experienced the tactile feedback of the vest than before (3,75 before and 4,35 after). Comments that participants gave, indicated that they would prefer to use the vest at home and that the behaviour of the vest should be controlled so that it will not be annoying ("The vest should not correct me every time I am slouching").

4.1.4 Conclusions

As participants perceived slouching as a problem, they were willing to improve their posture. A minority of participants was willing to use a technological solution to improve their posture before the experiment. After the introduction of the *Textile Reflexes* vest, the majority of participants were willing to use the vest for posture improvement. The *Textile Reflexes* vest was appreciated for its intuitive feedback and its nice and inviting aesthetics.

First, the participants of the experiment mentioned that the feedback at the place where users should start correcting their posture, felt intuitive ("It just makes me sit straight"). Being stimulated in the bending parts of the back, made users automatically correct their posture. Especially stimulation at the lower parts of the back felt most intuitive. The intuitive feedback felt more effective than a non-intuitive feedback. Moreover, the participants appreciated the feedback for feeling subtle.

Second, participants' improved willingness to use a technology for posture correction after the experiment had to do with the design of the *Textile Reflexes* vest. Participants indicated to be willing to use the vest because of its aesthetics ("The piece of clothing looks nice"). Participants' conditions on use refer to price ("If I could afford it, I would love to use it"). As well, it should be mentioned that some of the participants would not like to wear a posture correcting technology that is visible to others (“When it was more an undershirt I would like it more”, “I would use it when it is invisible under my clothes”).

Participants finally indicated that they believed that their response to feedback on posture would change when becoming habituated to it. Participants on the one hand believed that becoming habituated to the vest´s feedback would make them unconsciously improve their posture directly. On the other hand, participants indicated that becoming habituated to the feedback would make it ineffective. This should become clear in future studies.

As a conclusion, a *Textile Reflexes* vest could contribute positively to users’ posture. Feedback right on the bending spot, at the lower part of the back, creates an intuitive type of feedback that feels comfortable, yet is noticeable. It is creating a right amount of distraction to stimulate posture improvement. The textile squares make the *Textile Reflexes* vest look nice. This invites more for use than unpleasant looking technologies. Yet, some of the participants prefer to keep invisible to others their use of a technology for posture improvement.

5 Discussion

In this paper, we have brought together three convergent trends that emerge from larger societal challenges: technological, material, and social innovation with sustainability. From this convergence of trends, and emergent challenges, we have introduced the development of a PAV using the *Textile Reflexes* material. By doing so, this project serves as an example (albeit on a modest scale) of how material innovations can lead to innovations that contribute to better materials and methods for the benefit of society. Though our design and impetus emerges from structural concerns of material sustainability and physical well-being, we are also interested in how such a holistic approach to design might propose “emotional” durability in design (Chapman, 2003; Chapman, 2005; Flores and Roldo, 2012; Stead et al., 2004).

5.1 Considerations on multidisciplinary

We believe that current concerns in the environment, health and wellbeing, and technological advancement are interconnected and interdependent. It is for this reason that we approach our design inquiry and prototypes to reflex convergent interests and concerns. A multidisciplinary approach, such as we propose with the Textile Reflexes-base PAV provides a starting point to tangibly test the viability of a sustainable technology. We believe that the future of textiles and material innovation will become increasingly complex and hybrid; and for this reason, we wish to lay out pathways to pre-emptively interconnecting issues (environment; posture) that are not often considered in an equally weighted fashion.

The development of the PAV was a joint effort of designers and researchers from different disciplines; fashion and textile design, (interaction) design and computer science. The combination of disciplines was essential to drive the innovation put forward and could only work because the while all researchers had a specific background, there was also considerable overlap in expertise which allowed mutual understanding (for example, both the interaction designer and the computer scientist had worked on wearable technology before and had a maker attitude, while the textile and fashion designer had a clear interest in research on smart textiles). To further advance research and development in smart and electronics textiles as well as to further explore how material innovations can spark sustainable innovation, working multidisciplinary while being open to learning is essential.

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Change Matters: theories of postdigital textiles and material design

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This paper identifies examples of postdigital practice in textile and material design and uses the theories of New Materialism and the concept of the New Aesthetic to understand contemporary practice methods and outcomes. In the context of Zygmunt Bauman's *Liquid Modernity* it seeks to develop a theoretical context for designing textiles and materials that may be crafted algorithmically, that are alive with agency and pervasive in our subjectivity. Using key examples of contemporary designers, this paper identifies the deepening relationship between textiles and material design practice in the postdigital era. It begins to trace a legacy that asserts a continuity from textiles and material design practice in more traditional conventional formats to future and emerging design that engages and elicits both the physical and digital aspects of our culture in fluid times.

Keywords; postdigital, textile design, design theory, materials

1 Introduction

It's never not going to be like this.

Everything feels new and exciting for once.

I think in texture, shape, colour, big swathes of fabric flowing and almost having a liquidus texture to them. Molecules that are burstable, kind of mutate and turn into their own chemical reaction…and then I go on the computer and I make them.

The words above, from designer Lucy Hardcastle (Mandelup 2016) describe a new type of practice in the field of textile and material design. The clamour of industry approval for Hardcastle's stunning sensual storytelling, meant that she began working with international brands whilst still studying her Masters in Information Design. Originally trained in textile design, Hardcastle's practice typifies the post-digital approach to design. She is a maker. Making in materials and making in code.

Hardcastle uses glass blowing techniques, 3D printing, flocking, hand dyed fabrics, 3D rendering, digital animation, photography and sound effortlessly to create *"real and imagined touch, visual illusions and sensual aesthetics"* (Hardcastle 2017).

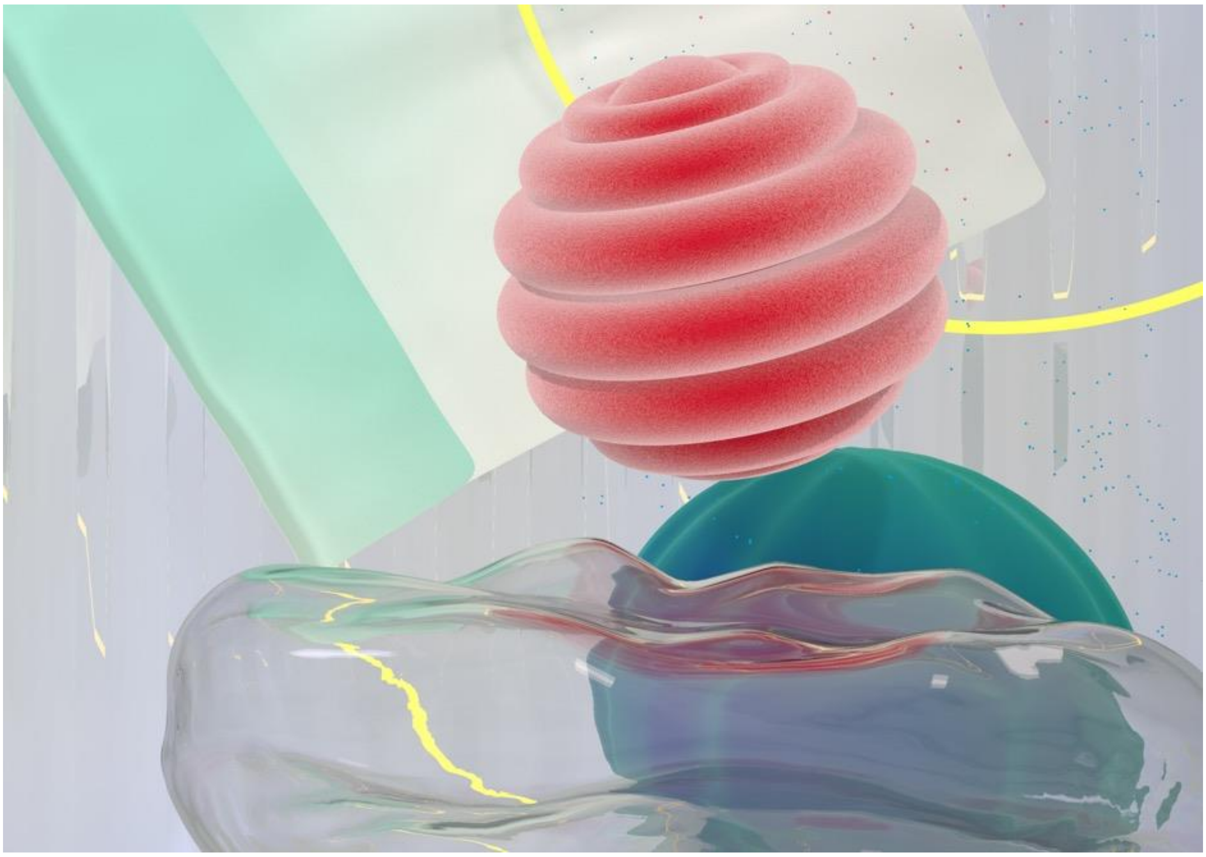

Figure 1 Conflate: A Celebration of Craft and Process for Blacks Visuals (2017) by Lucy Hardcastle Studio. Source: Lucy Hardcastle

Zeitguised are another design studio specialising in the creation of 'exquisite realities'. Zeitguised describe their work in the film GEIST.XYZ from 2016 as having a 'synthetic, ecstatic aesthetic' created through "handcrafted algorithmic textiles and procedural surfaces" (Zeitgeised 2001 – 2017). The work of Hardcastle and Zeitguised exists in two collaborating modes of understanding; the physical and the digital. In their work the two are inextricably blended in the product of what some are calling '*phygital'* design.

Nimkulrat, Kane and Walton (2016) present a publication that begins to explore what it means to be *'Crafting Textiles in the Digital Age'.* They note that textile practice is currently in a transitional phase, not only in regards to the aesthetics of crafting with or in the digital but also with due concern for the economic, social and environmental implications of that practice (Nimkulrat et al 2016, pg3). We know that design sits in a nexus (Kimbell 2012), and does not only have implications for but exists in a complex and tense relationship with the social, economic, environmental and the personal. The changes we see in design, in designing textile and materials, is itself a manifestation of changes in social, economic and environmental changes.
At The Design Research Society's Experiential Knowledge Special Interest Group conference in June 2017 entitled 'ALIVE. ACTIVE. ADAPTABLE' the premise was to discuss the collaboration between the physical and the digital in the design of materials. The organisers recognise that as materials acquire more possibilities for interaction, algorithmically, biologically or chemically, and gain increased digital or organic connectivity that we must begin to understand a design practice that deals with these agential materials (Karana et al 2017).

Figure 2 Still from Geist.XYZ: An exploration of handcrafted algorithmic textiles and surfaces (2016). Film available at http://www.zeitguised.com/things/geist-xyz *Source: Zeitguised*

This paper seeks to begin to develop a theoretical context for designing textiles and materials that may be crafted algorithmically and alive with agency. I ask how, in an age when 'its never going to not be like this', can we understand the deepening relationship between of textiles and material design practice? How might we trace a legacy that asserts a continuity from textiles and material design practice in more traditional conventional formats to future and emerging design that engages and elicits both the physical and digital aspects of our culture?

2 Postdigital materiality

> *At its broadest,* (nonetheless), *new materialism can be said to concern a series of questions and potentialities that revolve round the idea of active, agential and morphogenetic; self-differing and affective-affected matter.* (Parikka & Tiainen 2010)

Explorations into material agency (Karana et al 2017) and the expansion into interactivity and that of 'the smart' within the field of textiles align with the non-human turn of the concept of New Materialism. Its basis is in the rejection of the dualism of people and things and acknowledges an ontological hybridity in our reality (Gries 2015). In *Postdigital Artisans* (2015, p5) Jonathan Openshaw describes how we are "…reformulated by the digital moment, and where a digital mind-set is inextricably entangled with our existence…" The concept of New Materialism (Parikka & Tiainen 2010, Cole & Frost 2010, Gries 2015) draws on a broad range of schools of cultural theory, and has in some ways given birth the concept of the postdigital. Openshaw believes that we now often experience a frustration with conventional material forms. We know that the material world is alive with possibility, the digital world has taught us to expect this, yet outside of the screen we can feel let down by materiality. The artisanal work that Openshaw showcases in his publication collaborates the digital and physical; this is the essence of postdigitality. Our past heroism of the digital, and indeed the handcrafted, are cast aside to explore and debate new working methods and outcomes of design.

The space between the haptic and the computational; the glitchy, awkward space between analogue and digital formats is the realm of the 'New Aesthetic'. This is a term that goes hand in hand with the postdigital and has been attributed to James Bridle, who in 2011 began collating imagery on his blog new-aesthetic.tumblr.com

> *Whether a frame from an online video, or a screen capture of an online map (remember, digital maps are animations on pause), or fragments of code or spam; all of these are snippets, they are only momentary representations of ongoing processes – as indeed the New Aesthetic is intended to be. Each image is a link, hardcoded or imaginative, to other aspects of a far greater system, just as every web page and every essay, and every line of text written or quoted therein, is a link to other words, thoughts and ideas. Again, in this the New Aesthetic reproduces the structure and disposition of the network itself, as a form of critique. (Bridle 2013)*

The 'New Aesthetic' was coined with little thought or understanding of the theory of aesthetics or to the significance the term would go on to garner. Bridle's explanation simply describes an experience, visual but perhaps moving or virtual, of that which is digitally networked. The New Aesthetic, although developed to describe a type of visual imagery, has some use for us in describing new forms of materiality and textility that are networked or seek to represent and critique it as it happens. In recent decades, the proliferation of smart textiles and materials bound up in our networked world show us that an internet of *soft* things is already in existence ('The Internet of Soft Things' is a project by Kettley et al 2016).

3 The tension of oscillation; the uncertainty of liquefaction

Recognising the ever-fluctuating position of design in and between the nexus of the social, economic, environmental and the culturally subjective/objective is a trait of postdigital designers. The notion of a version of modernity that is in flux was developed by sociologist Zygmunt Bauman in his theory of '*Liquid Modernity'* (2000). He questions the postmodern era, criticises the speed at which it was named and posits that society moved from a 'solid' modernity to a 'liquid' modernity rather than into a postmodern state. He argues that contemporary ideas and ideologies are unlikely to be given enough time to solidify, and cannot serve as frames of reference for human actions. (*Bauman* 2007, pg 1)

In the use of metaphoric material terms to describe ways of being, Bauman's texts can be given a certain reading by those working in the field of textiles and materials. In the foreword to '*Liquid Modernity'*, entitled *'On Being Light and Liquid'* Bauman explains the development of his theories from the phrase famously used in The Communist Manifesto *'melting the solids'*. The solidity of the pre-modern state was to be dissolved and reconstituted to make way for a new and improved solid, one that would last, be reliable, predictable and manageable (Bauman 2000, pg 3) in a truly Modern age.

Bauman outlines how we have come to a second modernity, a modernity that has turned back on itself, not another melting or reconstitution but a liquefaction of our previous state, principally moving from 'system' to 'society' and from 'politics' to 'life-policies' resulting in an individualised, privatised version of modernity. He highlights patterns of dependency and interaction as a key area for liquefaction in this epoch. Old concepts still exist in a type of zombie-like limbo, neither dead or alive, but in our fluid state, it remains to be decided whether these concepts continue to exist, reincarnated or whether they must be laid to rest.

Bauman reminds us of the relationship between time and state of matter. Solids, with clear dimensions, holding their shape and resist time, while for liquids, it is time that counts. Fluids do not keep any shape for long, they are prone to change; in shape and flow, holding a shape but for a moment. Fluids are mobile, able to splash or ooze, drip or spray. When solids and liquids meet, liquids move around them or infiltrate them, while solids become drenched or moistened, requiring a lengthy process of renaturing. *"Descriptions of fluids are all snapshots, and they need a date at the bottom of the picture."* (Bauman 2000, pg 2) This line from Bauman feeds the justification of the post-digital and the New Aesthetic.

The cultural theory of the meta-modern is an explanation of contemporary society and culture as reflexive, uncertain and oscillating. Vermeulen & van den Akker developed the theory in 2010 as notions of the postdigital era also began to be concretised. Vermeulen (2012) has described the metamodern as an 'open source document' not a philosophy but an attempt at a vernacular. Indeed, metamodernism has developed through an online prescence with multiple contributors posting examples and critiques of art, fashion, literature and music that represent that vernacular relevant to contemporary culture which postmodernism is inadequate for. Metamodernism describes a culture between and beyond, a position which is in a constant, yet unbalanced state of change. It is clear that postdigital design practice aligns with the fundamental concepts of metamodernism.

I have posited the notion of *'textasis'* (Igoe 2013) as a text-ile in tension, recognizing the etymological and metaphorical connection between text and textile, thinking, speaking, writing and making. It represents the definition of textile thinking in its interconnection of the material and immaterial in *tasis*. Textasis suggests a movement between *stasis/enstasis*, that which is unmoving, immobilised, subordinated, standing firmly within oneself, to *ex stasis*/*ekstasis,* flow, excess, ecstasy, joy, insubordination, to be outside of oneself, the transgression of boundaries. In *textasis*, textiles (as a disciplinary area) is in a tension between its material form and how it performs and what it represents beyond the tactile. How is textasis manifested through the New Aesthetic and New Materialism of the postdigital?

The postdigital defines a time in which the novelty of the digital has been overcome and its value is becoming fully integrated, embedded, into our lives. But what actually defines the digital? Etymologically, the digital merely denotes something divided into discrete units; digits; fingers. A digital system can be basic or highly complex, but it is systematic and traceable. The shared reference points and language of the digital and the textile have been stated clearly before (Plant 1997) but it is worth reiterating and unpicking this in the postdigital era.

Cramer (Berry & Dieter 2015, pgs 17-18) reminds us that the digital need not be electronic and the analogue can indeed perform computationally. He gives the example of the meme of 'the hipster and the mechanical typewriter' as an artefact-in-use which could be considered postdigital; a digital system in its predetermined set of letters, punctuation marks and numbers, yet simultaneously and colloquially, analogue, performing as if flaunting its 'wireless' technology. The information the typewriter creates varies on a continuum; the quality of mark made dependent on how much use the ink tape has had or how many times the keys have been struck. Cramer's example hints at the notion that the perception of an artefact as digital or analogue can be dependent on how we interact with it. Unused on a desk, the typewriter remains elementally digital in an analogue context. Well used, on a park bench in 2013, it performs a commentary on the digital while romanticising the analogue.

Textiles, in their typical form, can be understood as digital at the time of their production; numbers of counted warp strands, a predetermined number of stitches. What makes them analogue is our relationship with them, the way we interact with them, wear them out, imbue ourselves into them. Yet, once out of use they can be unravelled, each strand or row once again can be counted. Cramer (2014, p18) points out that *"The structure of an analogue signal is determined entirely by its correspondence (analogy) with the original physical phenomenon which it mimics."* As is understood, textiles and cloth were often historically created to mimic natural surfaces such as hair, fur and skin, not only for their function but for their sensorial qualities. And so, (elementally) digital textiles ape the analogue qualities of the body. This analogy then evolves ambiently to becomes a sort of meta-analogue surface. Textile designers of the New Aesthetic are taking these postdigital, meta-analogue surfaces into a new realm of (post)digitality. Their work, situated in and embracing a glitchy, oscillating era exposes and manifests this process of becoming in the context of fluid modernity.

Lucy Hardcastle and Zeitguised's work extends this oscillating process dimensionally. Real surfaces, materials and fabrics are created, photographed, enhanced, digitally rendered and animated. Hardcastle works in the analogue as she dyes and drapes them, makes them digital by modelling them, we make them analogue by our experience of them (albeit currently a dissonant one via screen). At that point, her experiential knowledge as a designer and ours align on a varying continuum in our longing for the seeming simplicity (yet indescribable sensorialism) of the analogue in the disorientating complexity (yet algorithmically traceable nature) of the digital. In their uncanny nature, the hyper-realness of her work reveals the unfamiliar hidden within the known.

In 2016, textile designer Nadine Goepfert collaborated with Zeitguised in the development of 'Distort & Transform'; a project aiming to integrate digital research and the exploration of experimental textiles in 'real' haptic objects. The outcome was a rug which explored imagery from the Zeitguised film from 2016 'GEIST.XYZ'. The outcome of this collaboration is an abstract rug, hand knotted, sculptural in shape with varying texture, sumptuously colourful, textured and well crafted. It sits, inviting an experience but struggles for attention in comparison to the hyper-real, multimodal lusciousness of the digital work itself. The tangible, haptic object is arguably less enticing, less stimulating and too real.

Figure 3 Geist.XYZ rug by Nadine Goepfert (2016) Source: Zeitguised

> *The ways in which the New Aesthetic mediates rely on a complex framework of human and non-human 'actants' that are socially networked, act upon natural resources and the social fabric, and create new variations of semiotic construction (in the sense of agency that produces meaning.)* (Paul and Levy 2014, p41)

Paul and Levy refer to the New Aesthetic's socio-ontological foundations in Latour's Actor Network Theory (2005) which rejects the hierarchy of human existence over that of objects and delegates agency to the non-human, linking the natural, social and semiotic. Textiles and materials operating in the postdigital area have the prescence/agency imbued by the cultural history of the surface as a (designed) object with the significance of the networked representation. The interface of the screen, currently provides a dissonance between the activity and depth of our online experience and the physical sedentary of sitting at a computer. Screens will become materials in a co-poeisis of design, set in tense relationship, questioning where or if there are any boundaries, becoming more ambient as well as more unreal, awe-inspiring and dis-orientating. This questioning of the boundaries between nature and culture, between subject and object underpins theories of 'New Materialism' (Gries 2015).

4 Changing state

Notions of transitions and transgressions between textiles and material design and the jolting oscillation or powerful flow of the liquid state of our era fosters instability. Postdigital practitioners explore and critique this instability. However, just as things move together, they can also move apart. Openshaw (2015 pg 9) comments that society does not want the gap between the digital and the physical to be closed completely; just as our hunger for the digital experience has grown we have also seen a desire to rediscover some of the most tactile and analogue forms of human culture. Benjamin's concept of the lost aura in the age of mechanical reproduction can be applied to defend this dissonance.

Bridle (2013) recognises the power of the aura of the object and insinuates that the New Aesthetic is concerned with representing the nature of the aura through agency, stating that,

> *…the New Aesthetic is concerned with everything that is not visible in these images and quotes, but that is inseparable from them, and without which they would not exist.*

This statement flows the digital and analogue back towards each other one again. The politics of the networked aesthetic of the New Aesthetic relates to real, human experience. Auras include traces, that of the way something is made and used. Robbins, Giaccardi & Karana (2016) discuss the socio-ecological context of material traces; the convergence and reciprocity of people, practices and materials and advise that designers must engage with the critical value of traces as we design in more layers of digital capabilities.

Nonetheless we experience a significant proportion of postdigital culture via screens. These interfaces are reformulating our view and experience of our worlds and our ability act on it and within it (Openshaw 2015 Pg 9). Our screens are now mostly hard, flat glass. Our tactile relationship with them is limited but yet the glass absorbs and transforms us; like it absorbs heats and refracts light. This screen has power at and on its (currently) unmalleable surface.

> *The postdigital, as an aesthetic, gestures towards a relation produced by digital surfaces in a bewildering number of different places and contexts. This interface-centricity is not necessarily screenic, however and represents the current emerging asterism that is formed around notions of art, computation and design. In this conception, the postdigital is not purely a digital formation or artefact – it can also be the concepts, networks and frameworks of digitality that are represented…* (Berry 2014 pg 44)

Figure 4 Composite image from Assimilation (2016) by Molly Smisko. 'Assimilation' is a mixed reality design work. The image in the top left shows the arms and hands of a user who is wearing a virtual reality headset in the physical environment. The main image shows what that user is correspondingly experiencing in the digital, virtual environment. Video available at https://vimeo.com/176478169 Source: Molly Smisko

Postdigital design in textiles and materials is often centrally concerned with this very relationship and expresses a form of the 'New Aesthetic'. From the hyper-sensuality of Hardcastle's untouchable imagery to Amy Winters' work in the field of HCI where she develops responsive surfaces, organic user interfaces and transitive materials to soften our relationship with the computational (Winters 2016); and further still to the work of Molly Smisko a textile designer working in mixed realities. In works like 'Assimilation' (2016) Smisko immerses us in the interface using a combination of 'passive, haptic' materials and virtual worlds to deepen sensory experiences and at other times create a glitch-like disconnect that prompts us to question what we are experiencing.

All of these works force us to question where the interface begins and ends; On the screen? On our eyes? On our fingertips or skin? Inside our heads? Through the postdigital's 'interface-centricity' we must confront the notion of the subjective-objective boundary. I use Ettinger's matrixial theory to support the inherent relationality of textiles thinking and the complex relationship we have with textilic materials, both when designing and interacting with them (Igoe 2013). Ettinger's theories were developed in the context of feminist film theory but establish the gaze as a trans-subjective encounter which extends into other sensory realms. Ettinger emphasises the co-poiesis at play within the encounter which serves as transgressional and yet productive as it forges new linking;

> *…a process of interpsychic communication and transformation that transgresses the borders of the individual subject and takes place between several entities. Ettinger (2006 pgs 181-182)*

> *Through this process the limits, borderlines, and thresholds conceived are continually transgressed or dissolved, thus allowing the creation of new ones. Ettinger (1992) cited in Pollock (2009 pg 3)*

Ettinger's extension of the Lacanian gaze into a matrixial, (networked) subjective encounter encompasses the politics of the New Aesthetic of the postdigital age as well as New Materialsm's questions surrounding morphogenesis in the context of our Liquid Modernity.

5 Thin Machinery

Berry's text, *The Postdigital Constellation,* (Berry & Dieter 2014, pgs 44-45) provides an exploration of the surface as performative, calling them *"thin machinery, containing not just the possibility of a hermeneutic encounter but also an agency drawn from computation itself."* In the postdigital, the New Aesthetic work exposes and at times roughs up the grain of computation into an analogue form. Postdigital textiles and materials can provide this in reverse, providing a hermeneutic experience through its analogous agency with the potential for a digital encounter which may enhance and/or make uncanny the experience altogether.

So what of textiles and materials in this epoch of 'The New' – materialism and aesthetic? Hardcastle in calling one of her projects '*Intangible Matter'* and Zeitguised with their use of the 'phygital' are both trying to capture something which transgresses current boundaries of thought. Work which exists in two modes of understanding, but yet is also a snapshot, its meaning is transient. They are trying to express the nature of something which has two states at the same time. By its nature, this practice is diverse and difficult to label (for very long).

Other emerging designers working at the interstice of design, craft, science and computing include Lauren Bowker, founder of The Unseen. She is a textile design scientist developing colour changing dyes. Bowker is a self-styled witch, channelling 'magick' in order to visualise the data that surrounds us and that we create with our own bodies. Bowker hides the science behind the spectacle. She labels her work not as design, nor chemistry but alchemy. Anna Neklesa, having practised interior design and textiles creates 'molecular tailoring' and she too calls herself a 'haute couture alchemist'. Neklesa works with scientists to develop her 'living cotton' materials which rely on time as an essential dimension to the outcome. Neklesa's work represents textiles in *textasis* in our liquid times. Aligning with Vallgårda's notion of 'computational composites' (Karana et al 2017 pg 8) the familiarity of cotton cloth is made uncanny and given a different, unnerving performativity through its voluntary movements. It is indeed alive.

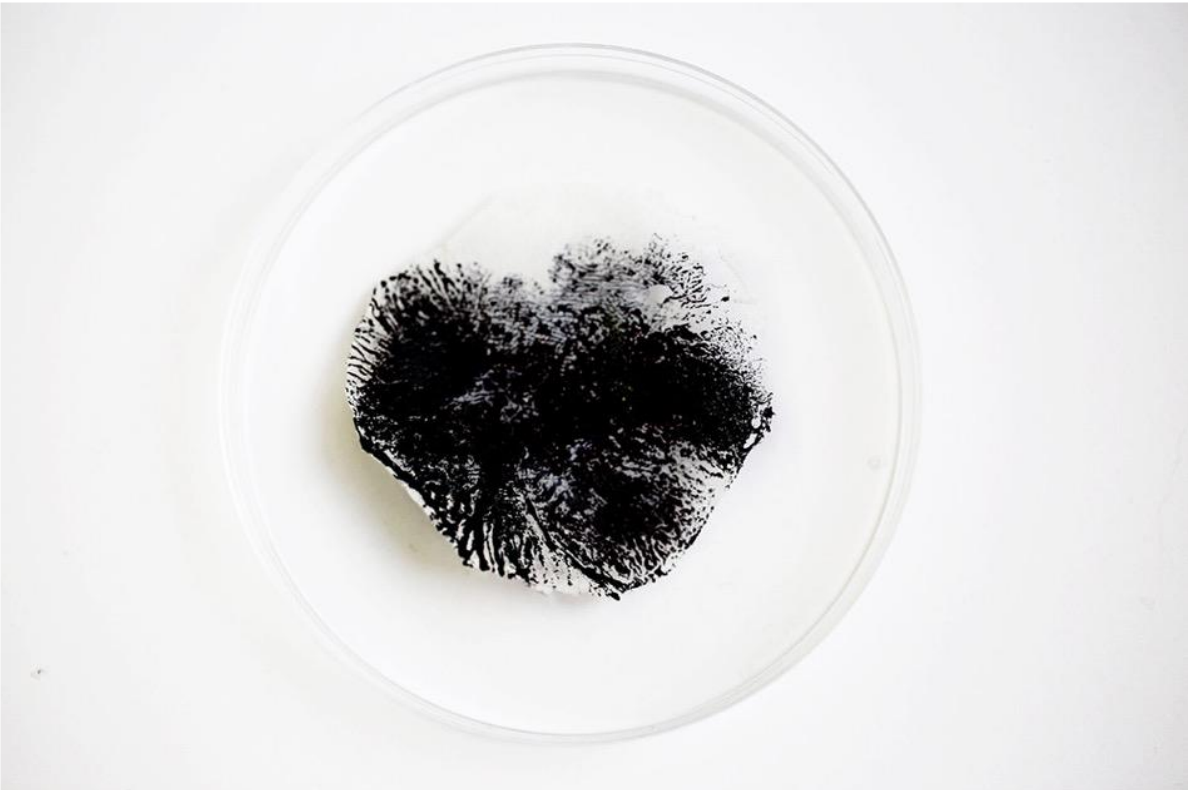

Figure 5 Living Cotton (2017) by Anna Neklesa. Video available at https://vimeo.com/222661585 *Source: Anna Neklesa*

Caroline Bassett (Berry & Dieter 2015 pg 146) sets out a critique of the postdigital in feminist terms and calls for a technophile feminism, but one that does not operate in quasi-mystical terms, such as does Bowker and Neklesa with their alchemist monikers that hold on to zombified ideas of how their practice can be understood. Bassett calls for a feminist approach that,

> *…deals in new materialities and that seeks genuinely new subjectivities… and …new intersections between different forms of thinking about the relationship between weird matter and the fantastic forms of objects and bodies under capitalism.*

Pioneering postdigital practice for almost two decades, Carole Collet has been a key figure in exemplifying practice which performs in the way Bassett describes above. Her 2012 *BioLace* speculative design project exists between synthetic biology and textile design but does not adopt a 'Mother Nature' persona. Photographs of hydroponically grown black strawberry plants whose roots have grown into a formal and recognisable lacy structure prompt us to question what we are looking at and how do we understand it and how can we take it and use it?

Figure 6 Strawberry Noir (2012) part of the Biolace series. Source: Carole Collet

Miriam Azaria works through design activism to synthesise material science and textile design to develop new models of design for circularity. Her 2014 DeNAture project envisages fibres encoded 'like tree rings' for the purposes of future cyclability. In the space she has manifested between fibre and computational code, she used a short film to communicate her ideas.

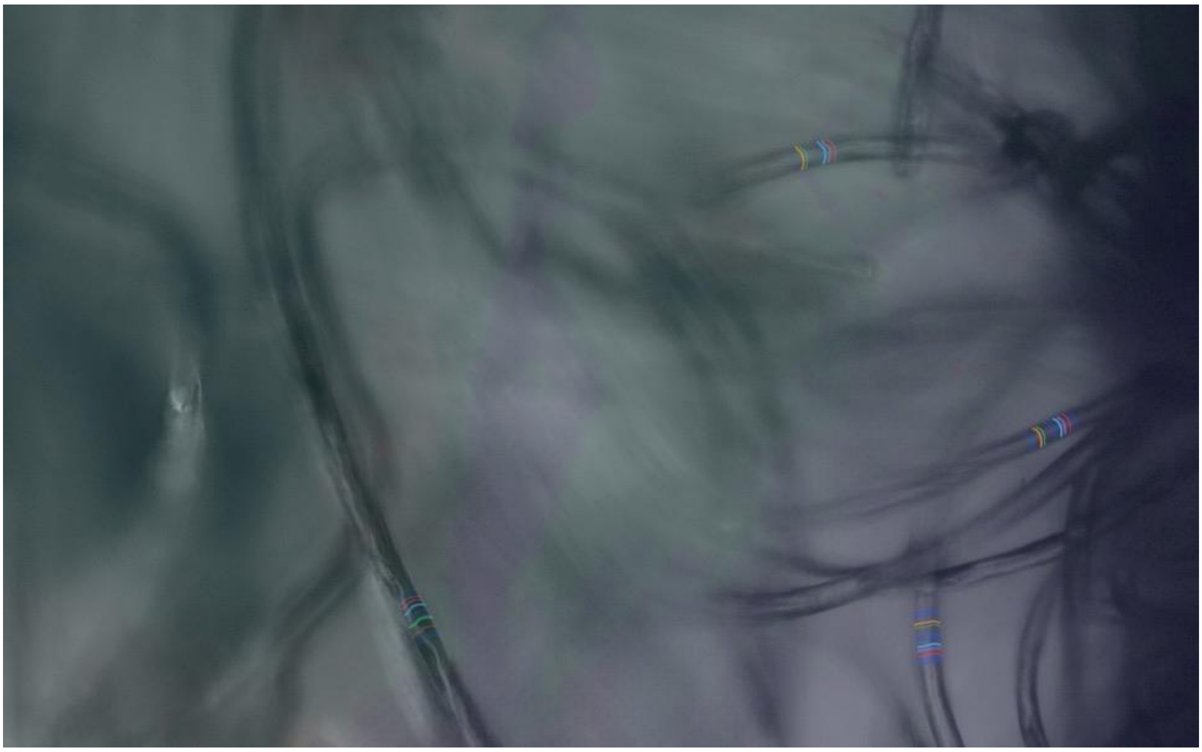

Figure 7 Still from DeNAture by Miriam Azaria (2014). A visualisation of encoded fibres. Source: Miriam Azaria

I have intentionally made no categorisation between the types of works of textile and material design that I discuss in this paper. They exist along a continuum of postdigital practice under labels which do not helpfully describe their purpose or action. They all sit at the interstice of digitality and materiality, exemplifying textasis in their oscillation between the objective, subjective and aesthetic. The corroboration of aspects of the New Aesthetic with the gravitas of the developing canon of New Materialism is interesting and useful when examining postdigital textile and material design. This work exists in a merging blur between the two. The New Aesthetic dealing with the politics of image and New Materialism with the politics and subjectivity of matter. The point of convergence is the space of debate and creative opportunity; a 'swell in the flow' of our liquid times. Nimkulrat et al (2016, pg 9) suggest that textiles cannot exist without material outcomes and can never exist solely in digital space. With this understanding that design and the act of designing is occurring in a social epoch of state change, we must accept that our current concept of what textile and material design are today is a zombified thought, we must decide whether it will flow in the liquidity or be flooded out. My aim here is to encourage a liquefaction of the notions of 'textile' and 'material' in this slippy-dippy state we find ourselves in.

The notion of the 'textile' is in particular danger of solidifying. The last two decades have seen an exponential diversification of practice in the field of textile design fed by new technologies, addressing changes in interactions between humans and with our environments. Practitioners educated in the field of textile design are working within material innovation design, and certainly are beginning to prefer to use the label of 'material designer' when describing their working practices. They, as designers, along with their work are in positive liminality. Which way to turn in this postdigital liquid modernity?

Textiles? Too decorative, too quick, too familiar, too often ignored.

Materials? Too impersonal, too slow, too plain, too performance oriented.

Postdigital design practitioners in textiles and materials work in a way which critiques the status quo and exposes the anomalies, riding the waves of our liquidus state. It is the job of the theoreticians of postdigital textile and material design to interrogate and expose our networked state and keep an eye on the horizon for the next surge.

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Responsive Knit: the evolution of a programmable material system

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Programmable knitting presents a new class of behaving textiles, responsive to environmental stimuli and programmed to change in shape as humidity levels in the environment increase. It is a hierarchical system that exploits the inherent functionality of textile fibres, yarns and fabrics to integrate shape change behaviour into the intrinsic structure of the material. The research applies a biomimicry methodology, with insight derived from the structural organisation of plant materials; specifically, the control of hygromorphic actuation for seed dispersal. This biological model has produced transferable principles for application to responsive textiles and it has been critical to the success of the research. But how can this research advance thinking on the design potential of programmable materials? This paper explores how the complex hierarchies that exist within textiles can be used to engineer a unique class of programmable systems. This challenges conventional smart interfaces that rely on mediated responses via electronic control. Instead this paper demonstrates how an alternative approach informed by biomimicry can generate a new class of smart-natural materials.

programmable materials, knitting, biomimicry, the responsive environment

1 Introduction

Digital fabrication tools have transformed the way designers are thinking about materials. The ability to manufacture directly from computational models using 3D print technologies and robotics have presented a challenge to reconsider the potential of the underlying materials themselves (Tibbits, 2017:14). New classes of materials are emerging that have been designed with the ability to sense and respond to a range of stimuli, producing intelligent responses to changes in heat, light, moisture or pollution levels in the environment. By directly connecting with environmental stimuli, these materials have the ability to act as physical sensing systems, reducing the need for mediated systems using electronic control. Whilst many of these active, programmable materials are composed of smart and synthetic materials, there is class of these materials that utilise the inherent properties of conventional materials like wood, metals and textiles.

This research positions knitted fabric as a unique programmable material system with which to engage with the responsive environment. The research question asks how programmable knitting can advance the field of programmable materials for the responsive environment. The aim of the research paper is to analyse knit production processes from a hierarchical perspective, highlighting how this can be used to develop programmable materials. In addition, the paper identifies the significance of a textiles logic and identifies how it differs from other advanced manufacturing production.

Whilst smart textiles conventionally utilise either smart synthetic materials or additional electronic components to generate shape change functionality in fabrics, this research discusses how the application of a biomimicry methodology has informed fabric development. Through mapping the hierarchies that exists in plant materials against those fundamental to knitted fabrics, the ability to engineer shape change functionality directly into the fabric during production has been established (Scott, 2015). By positioning the environmental stimuli at the centre of the research, constituent materials engage directly with the stimulus. In so doing this research uses knitted fabrics, composed of 100% natural materials as a shape-changing interface to reflect and respond to the dynamic nature of the responsive environment (Scott, 2015).

The significance of the research is how the underlying principles of knit design and technology have been exploited to produce a unique behaving textile. Whilst other programmable materials utilise 3D print technologies or CNC tooling, this system originates from an understanding of textile fibres, yarns and fabric structures, and exploits the complex hierarchies inherent to knitted fabric as a foundation for the programmable material system. The application of hierarchy in the design of programmable knitting sets an important precedent with implications for the design of alternative programmable material systems.

2 Context

Interior and exterior space can be digitally mapped according to parameters including heat, light and moisture in order to understand the underlying patterns of energy flow. The interior environment is subject to the same physical elements as those which create weather systems outdoors. In a contained space hot air rises and cool air sinks. Water evaporates into the air, and condenses back against cold surfaces. Evidence of these patterns of energy transfer are all around us, for example the heat radiating from electrical devices, or a liquid transforming to gas when boiling a kettle. Despite the ability to digitally monitor these energy patterns, the aim of conventional heating and ventilation systems is to mitigate localised changes in energy behaviour and to generate a standardised environment at the scale of a building (Addington and Schodek, 2005:64). Sensing and response systems are conventionally utilised to fully automate control of heating and ventilation, so that the interior climate can be maintained regardless of the weather outdoors. Maintaining ambient temperatures is energy intensive process that requires an input of heat during cold weather and the use of mechanised cooling systems during hot weather.

2.1 The Responsive Environment

An alternative approach is to engage directly with the responsive environment and use the pattern of energy flow as a design tool for interior or exterior spaces. Working with modelling systems such as thermal mapping, designers have produced new methods to re-imagine architectural space using the interior microclimate as the primary driver (Rahm 2006:118). In order to realise material systems that operate within this active and responsive design space new materials are required with the ability to sense and respond to environmental change. Here smart and programmable materials offer the potential to provide a dynamic interface between themselves and their surroundings:

> Whereas standard building materials are static in that they are intended to withstand building forces, smart materials are dynamic in that they behave in response to energy fields. (Addington & Schodek, 2005:4)

The introduction of these materials provides the ability to generate localised interventions in response to the natural pattern of energy flow. This presents the opportunity to redefine an interior space from the perspective of discrete stimuli that change and adapt over time.

2.2 Programmed Behaviour using Passive Responsive Materials

Materials that respond intuitively to environmental stimuli enable designers to produce climate sensitive architectures that react in real time to environmental change. Passive responsive materials change their shape directly as a result of environmental stimuli. The stimulus could be chemical, thermal, or mechanical; however, these materials act directly with the stimulus, they do not require any electrical power. Two examples are thermobimetals and wood veneer. Thermobimetals are a composite of two different metals laminated together, which have different thermal expansion properties. When heat is applied the passive component expands at a lower coefficient of thermal expansion, and the active component resists expansion up to a higher coefficient of thermal expansion. As the two materials react differently the outcome is that the metal sheet bends (Ritter, 2007:53). A recent installation, Bloom exploits this shape change functionality at an architectural scale (Sung, in eds. Ng & Patel, 2013:95). This piece, composed of 14,000 different tiles was designed to manage the thermal impact of solar energy; each tile would open and close in response to temperature changes generated by direct sunlight. The system operated autonomously in response to the changing weather conditions.

Whilst thermobimetal curls in one specific direction, it is possible to engineer natural materials to curl in different ways. Wood veneer curls when exposed to water. This is because wood is an anisotropic material and it swells and shrinks by different amounts in different directions. (Tsoumis, 1991:145). The way that it curls can be manipulated through the direction of cutting in relation to the direction of the grain. It is therefore possible to programme the material through the direction of cut. Wood veneer cut as a strip along the grain will bend top to bottom, cut against the grain will bend from the sides, whereas a diagonal cut across the grain will twist when exposed to water (Scott, 2015).

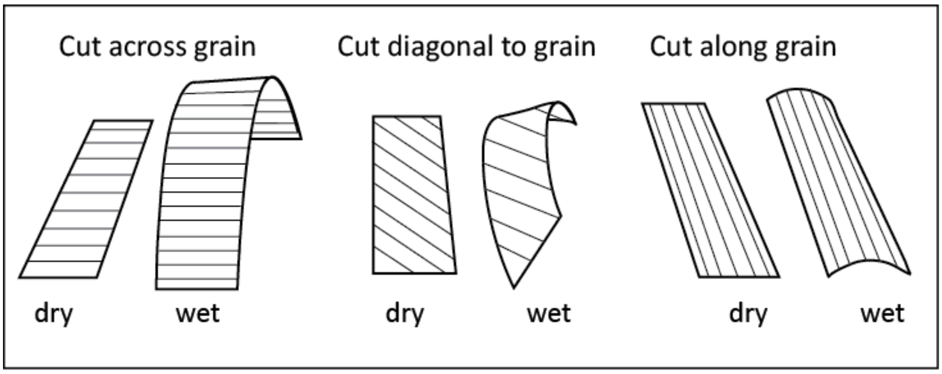


Figure 1 Illustration describing bending achieved when different cuts of veneer are exposed to water. Source: Scott.

The potential for veneer to produce environmental responsive architectures has produced a range of innovative outcomes. Techno-Naturology combines wood veneer with SMP to actuate a laser cut surface, producing heat activated shape change (Yan Ling, 2011:137), whereas Responsive Expansion (Maisonet and Smith, 2013:25-32) and Responsive Surface Structure II (Menges and Reichert, 2012:58) both utilise the moisture active properties of wood veneer in order to produce environmentally sensitive actuation. Wood veneer can be engineered to curl in specific ways by carefully controlling the way it is cut; the key consideration is the relationship between the structure of the material (the grain of wood, and direction of growth), and the geometries of cutting (the shape of the piece, and the angle of cut in relation to the structure of the material). This is significant as it demonstrates how a 100% natural material can be used to generate not only one, but a series of different shape change behaviours.

3 Methodology

Whilst innovation developing programmed behaviour using passive responsive materials has increased with progress in materials science and digital technologies, advances in biology research across a variety of scales from nano to macro has also provided a catalyst for the development of programmable material systems (Tibbits, 2017). In fact, nature presents an excellent model to inform research within this sector. The ability to sense and respond to changes in the environment is an essential characteristic of all living organisms. Plants are sensitive to a variety of changes in the environment and tropisms (directional movements) can be stimulated by light (phototropism), sunlight (heliotropism), water (hydrotropism) and chemicals (chemotropism) (Scott, P, 2008:161). As a design methodology biomimicry provides a systematic method to translate functional models from the natural world into effective, sustainable design solutions (Vincent, 2008:3140, Pawlyn, 2011:2, Bennyus, 1997:4).

3.1 Biomimicry

Biomimicry presents an opportunity to transform specific functions from nature into design. This paper focuses on analysis of sense and response systems in plants, in particular tissue structured to generate specific passive actuation in response to environmental changes. In order to apply the functionalities observed in natural materials in the design of programmable knitted fabrics, a method to formally abstract and translate the models is required. This methodology applies a direct model of biomimicry, using a problem based approach which begins with the questions of how to engineer shape change into the structure of a textile. The methodology (figure 2) is adapted from Knippers and Speck (2012).

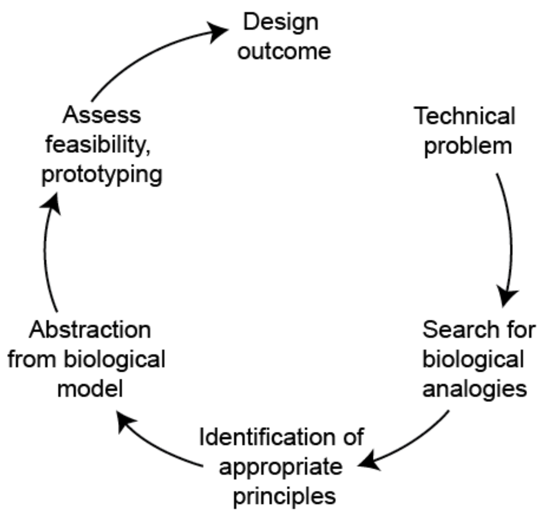


Figure 2 Biomimicry methodology using a problem based approach (adapted from Knippers and Speck, 2012:6, Figure 5). source: Scott.

In order to apply the methodology specific biological models are required to act as design principles to abstract into research, experimentation and prototyping. In this paper passive actuation systems in plants provide the biological analogies for application in textile design research.

3.2 Actuation systems in plants

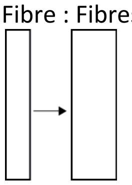
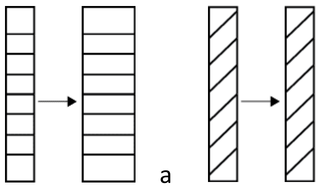
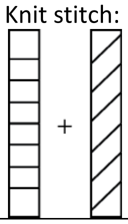
As we have seen in the example of wood veneer, some plant materials have the ability to change in shape even when the material is no longer living. For example, pine cone scales are able to open and close repeatedly. The scales open in dry weather, revealing the seeds inside, and close in wet weather (Dawson et al, 1997:668). This action can be observed even after the pine cone has fallen from the tree, suggesting that the mechanism to control the shape change is inherent to the structure of the material itself.

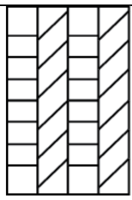
This kind of passive actuation in plants is generated as a result of the composition of the material. It occurs where the structure of the material is composed in such a way that it is programmed to bend or coil when triggered by an external stimuli such as moisture or touch. Many passive movements are caused by the differential swelling and shrinking or specific parts of the plant tissues. This hygroscopic movement is used to control seed dispersal (Abraham and Elbaum, 2013:584). The movement is controlled by the differential structure of the plant cell wall. The plant cell is composed of stiff cellulose microfibrils embedded into a flexible matrix of hemicellulose and lignin. The contrasting mechanical properties produce a bilayer effect, controlled by the orientation of the cellulose microfibrils in the cell wall (Burgert and Fratzl, 2009: 1546).

To generate shape change, water is absorbed into the cell wall causing the tissue to expand. The flexible matrix swells with the influx of water and shrinks as it dries out; however the stiff cellulose fibrils do not swell and shrink to the same extent. As the two tissues are attached to one another, the way each material behaves is effected by the other material. The expansion is therefore anisotropic and causes a bending movement in the plant tissue.

These effects are generated across different scales within a pine cone scale; by mapping the impact of scales from nano to macro against those of a knitted fabric that the opportunity emerges to engineer shape change into the structure of a knitted fabric. Table 1 illustrates the key hierarchies and their role in the passive responsive system of the pine cone hygromorph as well as the opportunity that this presents for shape change in knitted fabric.

Table 1 Table Illustrates hierarchies observed in plant materials and pine cone hygromorph, and how this translates into requirements for shape change in textiles (Developed from Gibson, 2012 1-8, and Dawson et al, 1997:668).

Hierarchy	Application to Pine cone Model	Requirement for moisture activated shape change
Biochemical **Cellulose**	Dimensional changes occur in pine cone scale as water is absorbed. This is regulated by different cell and tissue structures.	Fibre : Fibres change dimension when water is absorbed. 
Ultra-structural **Cell Wall**	Variation in winding angle relative to the long axis of the cell. High winding angle allows fibres to expand and contract (a). Low winding angle prevents this (b).	Yarn: Winding angle alters dimensional changes.  a b
Microscopic **Cells**	The pine cone scale is composed of two types of cell: sclerids and sclerenchyma fibres.	Knit stitch: Multiple unit (stitch) types required. 
Macroscopic **Tissue**	Arrangement of sclerids and sclerenchyma fibres allows scale to open and close. As the sclerids expand the scale is forced to bend due to resistance from sclerenchyma fibres.	Fabric structure. Arrangement of different units form a continuous material.

4 Materials and Processes

The hierarchical approach outlined above highlights specific opportunities to develop shape change behaviours. This section evaluates the components of knitted fabrics in order to identify how these principles can be implemented within knitted fabric design. The four hierarchies of biochemical, ultrastructural, microscopic and macroscopic translate into a knit fabric as fibres, yarns, knit stitch and fabric structure. Each section highlights how responsive behaviour can be engineered into the resultant fabric at the particular stage of construction. It is critical to note that whilst dimensional change in response to moisture can be observed at a fibre level, in order to control and manipulate the dimensional change into an overall shape change behaviour, careful control of the parameters of yarn, fabric and form are also required (Scott, 2015).

Yarns for knitting are composed of a mass of individual textile fibres twisted together. All fibres are long, fine and flexible; however their specific properties vary considerably depending on their chemical composition and physical structure (Wynne, 1997:1). All natural fibres have dynamic moisture absorption properties; fibres swell and increase in volume and density in the presence of moisture. These dimensional changes impact the yarns and fabrics made from them; changes in size, shape, stiffness, and permeability occur. This has a direct impact on their mechanical properties (Morton & Hearle, 1986:159). As the fibres swell polymer chains are moved apart as the water molecules are absorbed. The swelling of fibres in water occurs at different rates in different directions. Swelling can be considered in terms of an increase in length (axial swelling), or an increase in diameter (transverse swelling) however fibres swell more across their diameter than along their length.

> *All the moisture absorbing fibres show a large transverse swelling, but in the axial direction swelling is very small, so that the swelling anisotropy is high (Morton & Hearle, 1986:227).*

The difference in the amount of swelling across the diameter of a fibre in comparison to along the length is critical. In the biomimetic model of the pine cone hygromorph, the transverse swelling of individual fibres causes the scale to open because of the arrangement of fibres within the scale (Fratzl & Barth, 2009), and it is this principle can be transferred to knitted fabric design. However, it is critical to manipulate this anisotropic swelling in order to achieve shape change behaviours at the macro scale of the knitted fabric. To control of the dimensional swelling properties of fibres, it is necessary to consider the impact of both spinning processes in the construction of yarns as well as fabric structures and the overall fabric forms.

Whilst the orientation of fibres in a pine cone scale is determined through the growth of the material, fibre orientation in yarns is regulated during the spinning process. Here fibres are aligned and twisted together providing strength and flexibility to the resultant yarn. The yarns used for programmable knitting combine singles and folded yarns, which give contrasting balance within their structures. Singles yarns are naturally unbalanced because the twist in the yarn is always introduced in one direction only (referred to as s or z) (Wynne, 1997:59).

The amount of twist in a yarn also varies during yarn production, this is recoded as the turns per metre (tpm) for a given yarn depends on the fibre, count (a measure of the thickness of a yarn determined by the ratio of length to weight) and final application of the yarn. High twist yarns (also known as over-twist and crepe) have more twist inserted than standard twist yarns. Programmable knitting combines high twist and standard twist yarns; varying from 430tpm to 1180tpm. These yarns, predominately designed for weaving often snarl and untwist themselves, trying to achieve a more balanced state. These yarns are also prone to shrinkage because the fibres are compacted within the yarn (Taylor, 1999:172).

In order to develop programmable knitted fabrics, the configuration of knit stitches needs to be engineered to create the potential for 2D to 3D shape change. Knitted fabrics are composed of loops of yarn, and many of the characteristics of the fabric derive from the loop construction process. It is well known that knitted structures are highly extensible; in addition, knitted fabric have excellent deformation and recovery compared to other textiles (Spencer, 2001: 45).

Knitted fabric can be produced as flat-shaped pieces or as three-dimensional forms. Fabric shape can be altered by increasing or decreasing the number of stitches knitted in any course by transferring the individual knitted loops. Increasing the number of stitches at different points along a horizontal course changes the geometries of the fabric considerably. 2D, 3D and hyperbolic forms can be generated through varying both the number of needles knitting and the transfer points across a knitted course.

Figure 3 classes of weft knit fabric; plain knit, links/ links and partial knit. source: Scott.

The knitting process generates particular behaviours that are consistent across any knitted fabric. For example, a plain knit fabric will always demonstrate the same curling behaviours (figure 3), because individual knitted loops are intermeshed in the same direction. For programmable knitting this directional behaviour is exploited in order to generate shape change behaviours. By manipulating the way that the plain fabric curls by changing the orientation of stitches using stitch transfer both complex geometries and programmed shape change can be engineered directly into the knitting structure (Scott, 2015). The manipulation of the curl of knit fabric is a fundamental principle for programmable knitting.

In addition to this the knitting process can be described as additive; fabric is generated on a stitch by stitch basis, providing the opportunity to combine multiple structures and geometries within one fabric. The flexibility of knitting also allows the fundamental properties of loop length, yarn type to be altered during knitting which makes the production of a knitted fabric extremely versatile. Through analysis of the properties of natural fibres, yarns, fabric structure and form outlined above, a design system has been developed which produces shape-changing actuation using only natural materials and conventional knit technologies.

5 Design Application: Programmable Knitting

To analyse the success of the biomimicry methodology an interior installation piece, Skew (Scott, 2014) is evaluated. Designed and manufactured using Shima Seiki CNC knit technologies, *Skew*, is a

1m x 2m interior panel combining structural patterning at different scales across the full dimensions of the piece.

Figure 4 Skew: Montage of images illustrating the process of shape change behaviour. source: Scott.

Figure 5 Skew: Before Actuation source: Scott.

Figure 6 Skew: After Actuation source: Scott.

Figure 7 Skew: detail of 3D profile showing shape change at edges and different scales of patterning. source: Scott.

5.1 Fabric Construction Process

The work was programmed using the SDS1Apex system, and manufactured on a Shima Seiki NSSG 5gg knitting machine. A major advantage of programming materials using the knit production processes is that they are constructed using yarns with standard properties required for knitting (good flexibility, strength and elastic recovery (Spencer,2001:4)), so the fabrics can be manufactured using a range of knitting technologies. This piece is composed of 1/24nm s twist linen. The capabilities of the Shima Seiki programming system allow unlimited stitch transfer sequences across the full dimensions of the fabric which would be difficult and time consuming to achieve on hand operated equipment. Fabric width is determined by the width of the needle bed; and control is provided through computerised takedown and tensioning systems. This provides a mechanism to regulate fabric production and minimise faults during knitting.

5.2 Analysis

Skew is composed of a complex configuration of knit stitches organised into links/links patterns across a variety of scales. The smallest scale is five wales and five courses of face stitches opposing five wales and five courses of reverse stitches in a links/links configuration (5x5). Across the fabric the scale increases: 10x10, 25x25 and 50x50. The intention of the fabric design was to explore what happens when scales interact and whether the pace of shape change could vary dependant on the size of the repeats. It was anticipated that smaller repeats (5x5) would produce a rippling effect across the fabric on actuation whereas larger repeats would emerge as 2D to 3D forms across the fabric length.

The fabric was tested as a hanging panel, actuated using a cold water spray. In machine state the fabric hangs flat. Whilst it is possible to identify front bed and back bed stitches on the fabric, the repeats appear as a pattern of squares and there is minimal disruption to the smooth surface (figure 5). On actuation spiral peaks of different sizes form all over the fabric. The spiral peaks vary in height from 1cm (10x10) to 7cm (50x50). This causes an overall change in dimensions; the fabric lifts up from the bottom and shrinks in at the sides (figure 6). The edges of the fabric also change; in machine state the fabric is rectangular, however on actuation the edges shear to produce zigzags (figure 7).

On application of moisture the fabric instantly actuates as water is absorbed. There is a significant difference in the speed of actuation for areas with smaller repeats (10x10), transforming from 2D to 3D in three seconds whereas larger areas (50x50) transform in ten seconds. This produces a rippling effect and a sense of motion across the whole piece in addition to the overall change in form and dimensions.

When the fabric is hanging, shape change is most dramatic in the bottom half of the fabric (figure 6). This is visible as an overall effect as the fabric distorts and appears to lift up. There are two reasons for this; firstly the top of the fabric is secured in position (for exhibition a Perspex rod was used to hang the fabric) preventing movement at the top of the fabric. Secondly as moisture is absorbed, the linen becomes heavier. It is therefore harder for the shape change to occur at the top of the fabric as it is weighed down by the bottom (figure 6). Despite this, the overall change in dimensions is significant; the fabric measures 65cm x 220cm in a dry state, and 30cm x 190cm on actuation (Width measurement 20cm from bottom). Spiral peaks form all over the fabric. These vary in height from 1cm to 7cm. Shape change is also reversible. As the fabric dries it returns to a flat state and can be re-actuated with water.

Of particular interest within this piece are the edges which distort to form a zigzag up the fabric, and the sections where different scales of patterning interact (figure 7). In some places the disruption in the pattern counteracts the 3D transformation and the fabric does not change shape, however in other areas new 3D shapes are generated.

This piece was first exhibited in March 2015, as part of RTD2015 *Research Through Design,* at the Microsoft Research Centre in Cambridge. This event combined a conference and exhibition. During discussions of the work during a testing session the conversation discussed potential applications for the technology as a sensing system within the environment. Delegates commented on the potential for the material system, illustrated through Skew, to define an alternative rhythm or timeframe for architectural space (Author,2015), The suggestion is that shape change could be representative of the changing environmental conditions within the interior environment. This would provide a direct connection to microclimates that emerge within an interior space as a result of both the natural energy patterns in a space and human interventions. Examples discussed included utilising programmable knitting to monitor moisture in bathrooms and kitchens where levels vary considerably during the day and night.

6 Conclusions

The context of the responsive environment is critical to this design research; it provides an active design space which demands a material system that can directly engage with changing environmental conditions over time. In this research the design space is explored in relation to humidity and moisture levels, using textile fibres with the ability to swell, changing in dimensions when exposed to high levels of moisture. Other moisture responsive are identified including responsive wood architectures (Reichert and Menges, 2015) and superabsorbent polymer composites (Tibbits, 2014), however what is unique about programmable knitting the way that the dimensional changes at the level of the fibre are translated into an actuation motion at the level of the fabric.

The application of a textile logic in the development of programmable materials adds significant opportunity for materials development. The textile system introduces three or four levels of complexity in relation to the hierarchical system. Here shape change is determined through the relationship of fibre, yarn, fabric structure and fabric form, and changes at any level of hierarchy will produce different results in the actuated form. Each of these textile components provide the opportunity to engineer the dimensional change in an individual fibre into a macro scale shape change. Directionality introduced when yarns are spun offers the potential to translate the individual dimensional changes at the level of the fibre into an actuation motion at the level of the fabric. The infinite variety of configurations of knitted stitches provides a huge variation in the resulting shape change achievable. Programmable knitting offers not only a variety of shape change responses articulated through 2D to 3D transformations in fabrics, but a variety of speeds of responses; each fabric articulates an alternative timeframe for the responsive environment dependant on the constituent materials and configurations of knitted stitches.

In conclusion this work offers a series of examples which could be used for further research into programmable materials. Firstly, the work demonstrates that additional functionality can be designed into materials using conventional manufacturing processes such as knitting. This presents an interesting question for research that has been traditionally led through advances in materials science and technology. Instead this work provides a precedent for re-evaluating the potential of current technologies from a new perspective.

Secondly, advanced manufacturing systems for the design of programmable materials, (such as 3D print) use additive manufacturing process which, like knitting design materials from the bottom up. This presents huge opportunities to reflect the way that natural materials grow, embedding complexity into the structure of the material itself. The model of structural hierarchy derived from plant materials is significant as an example of how to analyse behaviour at individual scales across multiple hierarchies, and analysis of materials at the microscale of an individual fibre provides insight into how a material could behave at the macroscale of a fabric.

Finally, the application of biomimicry motivates inherently sustainable design choices. In this research material selection is exclusively 100% biodegradable natural fibres and by programming shape change into the fabric itself there are no additional components required for shape change to occur. Smart synthetics and electronic control have become redundant within this programmed textile system. This is the ultimate challenge working within the context of the responsive environment; the development of sustainable tools to maintain and support interactions with the environment at a material scale.

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Jane Scott is a UK based designer and academic working at the intersection of biomimicry, programmable materials, textile design and technology. As a knit specialist her research challenges the established understanding of smart materials; applying principles derived from plant biology to the development of programmable and environmentally responsive textiles. Her work has been presented internationally at conferences and exhibitions including Massachusetts Institute of Technology, Make/Shift (Craft Council), the Microsoft Research Centre, and The London Design Festival. In 2016 she received the 2016 Autodesk ACADIA Emerging Research Award (projects category) for her work Programmable Knitting.

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