Kristi Kuusk, Ana Tajadura-Jiménez & Aleksander Väljamäe (2020) A transdisciplinary collaborative journey leading to sensorial clothing, CoDesign, 16:4, 311-327

DOI: [10.1080/15710882.2020.1833934](https://doi.org/10.1080/15710882.2020.1833934)

A transdisciplinary collaborative journey leading to sensorial clothing

Kristi Kuusk[a]*, Ana Tajadura-Jiménez[b] and Aleksander Väljamäe[c]

[a]*Design Department, Estonian Academy of Arts, Tallinn, Estonia;* [b]*DEI Interactive Systems Group, Department of Computer Science and Engineering, Universidad Carlos III de Madrid, Madrid, Spain;* [c]*School of Digital Technologies, Tallinn University, Tallinn, Estonia.*

A transdisciplinary collaborative journey leading to sensorial clothing

Recent science funding initiatives have enabled participants from a diverse array of disciplines to engage in common spaces for developing solutions for new wearables. These initiatives include collaborations between the arts and sciences, fields which have traditionally contributed very different forms of knowledge, methodology, and results. However, many such collaborations often turn out as science communication and dissemination activities that make no concrete contribution to technological innovation. *Magic Lining*, a transdisciplinary collaborative project involving artistic and scientific partners working in the fields of e-textile design, cognitive neuroscience and human-computer interaction, creates a shared experiential knowledge space. This article focuses on the research question of how a transdisciplinary collaborative design processinvolving material explorations, prototyping, first-person-perspective and user studies, can lead to the creation of a garment that invites various perceptual and emotional responses in its wearer. The article reflects on the design journey, highlighting the transdisciplinary team's research through design experience and shared language for knowledge exchange. This process has revealed new research paths for an emerging field of 'sensorial clothing', combining the various team members' fields of expertise and resulting in a wearable prototype.

Keywords: **art-science; transdisciplinary; collaboration; e-textiles; body-perception; multisensory; haptics.**

1 Introduction

1.1 Towards transdisciplinary collaboration

Transdisciplinary art-and-science engagement in research is essential for overcoming the challenges posed by current profound socio-ecological changes (Root-Bernstein *et al.*, 2011). The effective practices and combined methodologies for such collaborations are still developing.

In this article we use the term 'design' interchangeably with the term 'art', as both fields are closely related in the described collaboration. Moreover, we do not see that the differences between the art and design fields have had a significant influence on the course of the collaboration. Peralta and Moultrie (2010), building on collaborative work between product designers and scientists, provide a good overview of the differences and similarities between scientists and designers, design research and scientific research. They point out that the role of designers in scientific research is 1) to unlock 'tacit' knowledge; 2) to connect scientists with non-scientists; and 3) to help disseminate scientific knowledge to the wider population. Furthermore, Peralta and colleagues propose a four-level model of designers collaborating in research, where designers act as 1) design suppliers; 2) research group members; 3) members of a team led by the scientist; and 4) team-members whose role is valued equally with the scientist. Verhoeven *et al* (2014) combines the model of Peralta and Moultrie (2010) with D'Amour *et al* (2005) in a classification of terms 'multidisciplinary', 'interdisciplinary', 'transdisciplinary' such that "Multidisciplinary: Designers as 'design suppliers' and research group members; Interdisciplinary: Designers' activity related to research questions; Transdisciplinary: Designers and researchers team up." On this basis, we classify our project as transdisciplinary.

Our project stems from the residencies programme of the EU Horizon 2020 initiative STARTS, Vertigo project, which stimulated the collaboration between arts and sciences by funding 45 artistic residencies in technology projects over three years (Henchoz *et al.,* 2019). The *Magic Lining* project (Figure 1) proposed by the three authors of this paper focuses on the sensorial experience of garments, and this article looks into it from the research perspective of how transdisciplinary collaboration between human-computer interaction (HCI), neuroscience and smart textile design can be used to discover new ways of changing one's body-perception from within a garment—i.e. a form of stimulation that is both invisible and entirely intimate to the user.

To learn more about above mentioned research question through experience, we entered into a hands-on process. *Magic Lining* project aimed to create a new type of *sensorial clothing* that focuses on making people feel good about their bodies. One can see *sensorial clothing* concept as a "boundary object" (Leigh Star, 2010) that was used to merge the three fields in order to ground e-textile development in recent work in the fields of cognitive neuroscience and HCI. This article gathers our motivations and experience gained from our experimental project. We see the potential of such transdisciplinary collaboration and acknowledge the contributions into our respective disciplines.

1.2 Haptic e-textile applications for people's wellbeing

E-textiles, as materials connecting textile softness with electronic properties (Hertenberger *et al.,* 2014), are a promising material for haptic clothing. They allow technology to become almost imperceptible in close contact with the body, and to weave or knit electronic components into the textile structure itself. In this way, clothing can begin to play a role in supporting the body in ways that are beyond the current fashion trends focusing on the visual. For example, the knitted cardigan *Vibe-ing* (ten Bhömer, Jeon, Kuusk, 2013), created in a design research context, has opened discussion of the potential for enabling vibration therapy for Osteoporosis treatment through integrating vibrating elements in a garment's pockets, which are constructed using a standard knitting machine. *Tactile Dialogues* (Schelle, Gomez Naranjo, ten Bhömer, Tomico, Wensveen, 2015) is a product that invites a dialogue between persons with severe dementia and their family members, spouse, or other caregivers through tactile patterns activated under the textile surface of a pillow. Further, the neuro-rehabilitation concept *Mollii* (2019), a close-fitting suit that is already successfully on the market, provides rehabilitation electrotherapy programmed for the particular needs of the individual. The suit reduces unwanted reflexive movements and muscular stiffness in people with spasticity or other forms of motor disability, thereby enabling the wearer to improve their posture and enhancing their range of motion and functional ability. Fitness wearables (Harrison et al., 2014; Mauriello et al., 2014, 2018;) and monitoring devices (Kersten-van Dijk et al., 2017) are also increasingly becoming an integral part of our everyday clothing.

Figure 1. *Magic Lining* concept photos representing sensory-feedback integrated in the inner layer of the garment, altering the wearer's perception of their own bodily 'material'. Photography: Iris Kivisalu. Model: Loore Martma.

While audio-visual cues have tended to dominate feedback and communication strategies, tactile or haptic cues represent a good complimentary channel and in some cases provide a necessary alternative (for example, in space and underwater environments): 'Tactons', or 'tactile icons', are structured, abstract messages that can be used to communicate non-visually (Brewster and Brown, 2004); and new forms of interface that exploit ultra-haptics have opened up the development of tactile surfaces by offering mid-air haptic feedback development (Shakeri *et al*., 2018; Ultrahaptics, 2018; Obrist *et al*., 2015). Tactile sensations can be delivered by electric stimulation, which has already been used in the rehabilitation of movement disabilities (Inerventions, 2019). *Teslasuit* (2018), is a bodysuit that utilises fine-tuned location-specific electric stimulation of the skin to deliver haptic feedback directly to the entire body. *Hardlight VR suit* (2017) follows the same whole-body concept, but instead using a force feedback approach. *Versatile Extra-Sensory Transducer* (Eagleman *et al*., 2017) can take in diverse types of real-time data—from sound waves to help the deaf, to flight status, even stock market trends—and translate these data into dynamic patterns of vibration in its motors (Keller, 2018).

These and similar technologies have already begun to enter the market, but the potential of the experiences they deliver is still largely unexplored, especially, from the perspective of the psychological effects these tactile sensations bring to the wearer.

1.3 Neuroscience and the use of sensory feedback to alter body-perception

Neuroscientific research has shown that the way people perceive their body appearance or their body physical capabilities is not something fixed. These body-perceptions change continuously in response to sensory signals relating to one's body (Botvinick *et al*., 1998). Research has shown that these body-perceptions impact on the way people interact with their environment, as each individual must continually keep track of the configuration, size and shape of their various body parts when performing actions (Maravita and Iriki, 2004). Moreover, body-perceptions are essential in forming our self-identity (Longo *et al*., 2008) and are tightly linked to self-esteem (Carney *et al*. 2010) and social interaction.

Recent studies have shown the potential of using bodily, sensory feedback (or manipulating body signals) to alter body-perception (Azañón *et al*., 2016; Botvinick *et al*., 1998; Maister *et al*., 2015; Tajadura-Jiménez *et al*. 2012, 2015a, 2017 and 2018; Tsakiris, 2010). For example, presenting discrepant visual and tactile cues, or visual and proprioceptive cues about the body can lead to a change in one's body-perception, such as the perception that one's arm is longer than it actually is and corresponding errors in physical coordination (Kilteni *et al*., 2012; de Vignemont *et al*., 2005). More recently, research has also shown that auditory feedback can be used to alter body-perception (Tajadura-Jiménez *et al*., 2012, 2015a, 2015b, 2016, 2017 and 2018). For example, one may also get the perception of having a longer or a stronger arm, merely by altering the sound corresponding to their hand tapping actions; and this will also influence one's subsequent arm movements and even one's emotional state (Tajadura-Jiménez *et al*., 2012, 2015b and 2016).

Beyond these effects on body-perception, other works have shown that similar sensory feedback alterations can be used to alter the perceived material substance of one's body. If, for example, when an object hits one's hand it sounds like it is hitting marble rather than flesh, one's hand may feel stiff and heavy as if made from that material (Senna *et al*., 2014). Other studies have shown that shifting the frequency spectrum of the sounds made when rubbing one's hands together may make one's skin feel smoother or dryer (Jousmäki and Hari, 1998). Another study suggested that one's body may feel as if 'robotized' or made of mechanic components, if, when moving one's limbs one receives vibrotactile feedback and sound from recordings of real robot articulations (Kurihara *et al*., 2013). Our project was inspired by these findings.

Our goal with the *Magic Lining* project is to create a garment that addresses the generally overlooked biosocial element of clothing (von Busch, 2018) by focusing on making people feel good about their bodies for themselves instead of having their bodies look good for others. We can feel good from the immediate physical sensations we get through the senses (e.g. affective touch experiences elicited by slow strokes McGlone et al. 2014), but also by the associated concepts triggered by these sensorial effects (e.g. we link a slow expanding tactile pattern to something light or fluid like water, air or a cloud, which may link to feelings of relaxation and not relate to self-esteem). At other times these sensations may indeed, in turn, impact on self-esteem, as the concepts elicited may link to different stereotypes or body ideals. For instance, the female stereotype of being light, the masculine stereotype of being strong, which may correspond with a sportsperson's desire for a body that is strong and hard.

1.4 Connecting e-textiles, HCI, and neuroscience

Some previous works have connected e-textiles, HCI and neuroscience. *Bisensorial*, a neuroadaptive vibroacoustic device uses music and vibrotactile stimuli on the user's back to invite desired mental states (Maranan, 2017). *Environment Dress* measures the aggressiveness of the environment: variations in noise, temperature, atmospheric pressure, ultraviolet radiation, or the amount of carbon monoxide present in our daily lives, to analyze how it affects people's mood and behavior (Castellanos *et al*., 2016). Many projects also deal with visualizing emotional data on clothing. However, our interest is to discover new ways of changing one's body-perception from within a garment via transdisciplinary collaboration.

2 Methodology: Creating a common space for sharing experiential knowledge

Our team of three brings together expertise from each of our respective fields: e-textile design, cognitive neuroscience and HCI. This meant facing not only the challenge of learning about our respective fields, but also coming to terms with our different ways of working, acquiring and sharing knowledge. We now introduce each actor of the study and their involvement in the project.

Team member 1 (Author 1) is an e-textile designer who has the role of *artist* and maker in our project. Her creative research work addresses alternative future scenarios for clothing enhanced by technology. Her goal is to apply theoretical and scientific content in a new way, combining this with her passion for developing alternative sustainable futures for textile and fashion. She proposed to design a garment that would provide its wearer with a variety of sensations.

Team member 2 (Author 2) is a multidisciplinary researcher in the fields of HCI and Cognitive neuroscience, who has the role of *neuroscientist* in our project. Her research focuses on the use of sensory feedback for altering body-perception and its applications for health. Her goal is to inform the design of novel body-centred and wearable technologies to support people's emotional and physical health needs and to effect behavioural change.

Team member 3 (Author 3) is an *HCI researcher* contributed with expertise in physiological computing and multisensory perception. Among his research interests are somatic practices and soma-based design in relation to the work of actors and dancers. Specifically, creating a closed bio- and neurofeedback loops between body and mind for health and well-being, whereby vibrations provide information about the cognitive and emotional states of the user.

In addition to the core team of researchers, two collaborators helped build the prototype: one with an extensive experience in electronics and prototyping with Arduino, and another being a senior software engineer.

Having extensive individual prior experiences in multi-disciplinary collaborations allowed the team members to carry knowledge between different disciplines and helped to guide the process. Our collaboration roughly follows Research through Design methodology (Frayling, 1993) using prototypes as the carriers of knowledge. We alternated between discussing and testing the sensations via prototypes throughout the collaboration to keep up a transparent and forward-thinking conversation between the parties. On the one hand, we would keep track of our meetings (many in the form of videoconferences), project development, activities, and prototyping by entering log entries with date in a shared online document; all of us could input logs into this document and follow the ongoing activities. This elaborate diary-like documentation was a critical data repository for analysing the collaborative process for this article. In addition, we would continue building prototypes that we could all experience at various stages during the project. We started from low-fidelity mock-ups and technical tests, and gradually moved towards fully-functioning experienceable items. One of the mediation instruments of art-science collaboration provided by the START Residencies project was a requirement to keep a blog about the project status and activities. This gave us the opportunity to reflect on the progress and plan for future steps on eight specific occasions over the course of the project: on each occasion a significant workshop or residency took place (Figure 2).

Apart from experimenting on ourselves, we organized three studies involving users: 1) 10 people gave us feedback based on a questionnaire trying out the first prototype; 2) 19 participants reflected about their sensations based on a questionnaire trying the second prototype; 3) an open-ended interview with a dancer wearing the clothing, conveying how the dress prototype was experienced.

10.11.2017	World Usability Day presentations	All 3 Authors
11-12.11.2017	WUD "Magic" workshop	All 3 Authors and other experts, participants
13.11.2017	Visiting Artist studio	Authors 1 and 2 and STARTS representative
12-23.12.2017	Residency I at Carlos III Madrid	Authors 1 and 2 and users
04.02.2018	Planning meeting in Madrid	Authors 1 and 2
09.02-20.03.2018	Residency II at TLU and Artist studio	Authors 1 and 3 and electronics expert
11.05.2018	Video making at Artist studio	Author 1 and videographer
16-29.05.2018	Residency III at Carlos III Madrid	Authors 1 and 2
04.06.2018	Technical consultancy with electronics expert	Author 1 and electronics expert
15.06.2018	Presentation at STARTS Day at Pompidou, Paris	Author 1 and external collaborator
28-30.06.2018	Presenting demo paper "Magic lining: an exploration of smart textiles altering people's self-perception" at MOCO conference in Genoa	Authors 1 and 2 and users
16.07-02.10.2018	Working at the Artist studio	Author 1 and sometimes the dancer

Figure 2. Table showing the most significant interpersonal activities throughout the project.

3 Process: Developing *Magic Lining*

Our team developed a garment aimed at changing the wearer's perception of their own body. We followed an iterative design process (Figure 2), producing three prototypes and conducted two user studies on the effects of various textile vibration patterns on body-perception (spatial haptic metaphors). Insights from the hands-on making and analysis of user studies led to the production of a fully-functioning prototype garment (Figure 3).

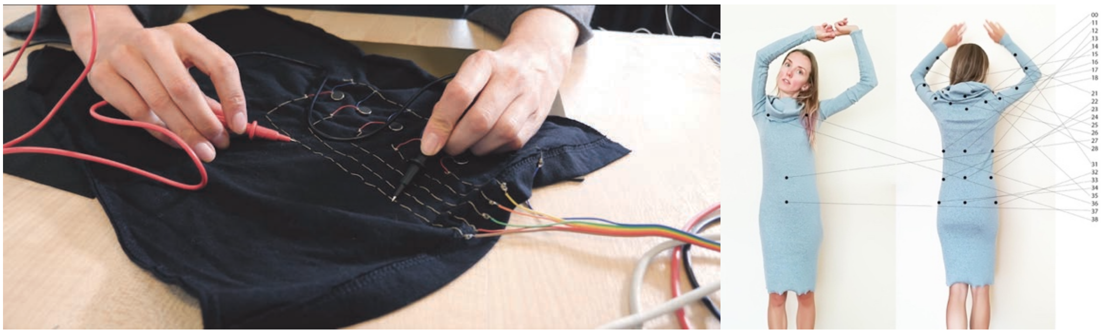

Figure 3. Left: first prototype of *Magic Lining*, allowing the user to experience a series of vibration motors delivering sensation patterns to the body through textile. Right: The vibration motor positioning on the final prototype. A video describing the project and process: https://vimeo.com/289294125. Photography: Kristi Kuusk. Model: Loore Martma.

The team members were based in Estonia and Spain, so we actively communicated mainly via e-mail and videoconferencing. At the beginning of the project we met in person for a 2-day workshop in Tallinn University, Estonia, and then again during two 2-week residencies in Carlos III University of Madrid, Spain. Additionally, two international events brought us together over the course of the project to share the results with our communities.

To kick-off the *Magic Lining* project, each team member presented their research at the World Usability Day event organized in Tallinn University. The scientists also visited the artist's studio to get a better understanding of her work as an e-textile designer. During that meeting, the lead scientist explained her work in neuroscience and proposed several keywords to provide focus for the project: 'self-esteem', 'body appearance', 'physical strength', 'body flexibility' and 'body agility'. This meeting coincided with a two-day workshop organized by the team members, which brought together around 20 people of multidisciplinary backgrounds with a common interest in the project area. The group engaged in an ideation process, to discuss the keywords and the ways in which they might guide the process of technological design. This sparked the first proposals for beginning the practical collaborative work.

Five weeks later, the first two-week residency at Carlos III University of Madrid took place. During this residency the team brainstormed ideas for a first wearable prototype. We decided to place small vibrating motors in the inner part of a sleeve. These motors would connect to an Arduino microcontroller board, enabling them to be programmed with various patterns to stimulate the wearer's skin. We discussed the possible mappings of vibrating patterns to sensations: Which pattern could help convey the sensation of being stronger, or more flexible, or build self-esteem? How would these sensations be varied by the integration of the motors into different kinds of fabrics? Could a smoother fabric help the wearer to feel sensations and emotions associated with a soft embrace? Could a harsh, coarse surface trigger sensations associated with aggression, which would in turn make one feel more powerful or strong? A large part of this residency period was dedicated to addressing ideas related to questions like above, and to introducing relevant work from each other's respective disciplines. Through these discussions, new ideas and practical considerations came into play, shaping a common space for sharing experiential knowledge.

The first vibrotactile prototype consisted of five vibration motors placed in a line (Figure 3, left) and allowed us to explore the basic idea and possible sensations by vibrating movement. Aiming at sophisticated patterns of vibration, we then proceeded by developing a sleeve that could transmit the vibrations across larger areas, creating sensations around the arm or on the back. To achieve the pattern of vibrations moving gradually about the body, our next step was to create a 3 x 7 matrix of vibrotactile material.

Figure 4: The second prototype of Magic Lining allows the user to sense vibration movements end-to-end, inside-out and outside-in, on the back and around the arm. The photo shows one of the authors trying on the prototype. Photography: Kristi Kuusk. Model: Ana Tajadura-Jiménez.

After solving several technical issues in programming the second prototype (Figure 4) and connecting the electronics, we began looking deeper into vibration patterns and behaviours. We studied previous neuroscience research to understand sensitivity to tactile stimuli differs across various body parts (e.g. Nolan, 1982), how vibrations have already been used on the body (e.g. Amemiya *et al.*, 2013 and 2016), and what kind of vibration patterns have been used (e.g. Deroy *et al.*, 2016; Harris, *et al*. 2017). We also looked at the spacing between each motor and the duration of vibrations. The insights derived from such experimentation are summarized in an article by the team members. For example: “vibration patterns influenced emotional arousal, and bodily sensations related to weight, hardness, strength and size. Importantly, the material samples alone also influenced the perceived body strength and significantly interacted with vibration patterns in building sensations of hardness and strength” (Tajadura-Jiménez, Väljamäe and Kuusk, 2020).

Having each experienced the second prototype for ourselves, our team then began preparing a user study to test systematically the effects of the different vibration movements and locations on 10 people's body-perceptions. According to the initial tests on ourselves, the conditions with the greatest potential were: a wave moving from the fingers to the upper arm; a wave from the upper arm to the fingers; a wave moving vertically from the centre of the back towards the upper and lower back; a wave moving vertically from the upper and lower back towards the centre of the back; a wave moving horizontally from the centre of the back towards the sides of the back; and a wave moving horizontally from the sides of the back towards the centre of the back.

For the user study, we changed the look and feel of the initial prototype to something more robust and comfortable, and with the vibration motors hidden from view. In order to quantify user responses, we developed a questionnaire based on previous cognitive neuroscience and psychology articles and on HCI articles (e.g. Longo *et al.*, 2018; Stroyer *et al.*, 2007; Tajadura-Jiménez *et al.*, 2015a). The questionnaire asked participants to report the bodily sensations they experience immediately before the test session and then the experience of each vibration pattern on their body. It also asked whether they felt quicker/slower, heavier/lighter, stiffer/more flexible, harder/softer than usual, and so on. In this way, we got initial insights whether the vibrations could affect the way people feel about their environment or their own body composition (e.g. wood, water, rocks etc.). When ideating and developing the patterns for such sensations we created mind maps that helped us to categorize the sensations.

To allow us to programme a wider range of patterns and with more detail, our third prototype resembled a spider's web (Figure 5), with 38 vibration motors placed in lines that cross at the centre.

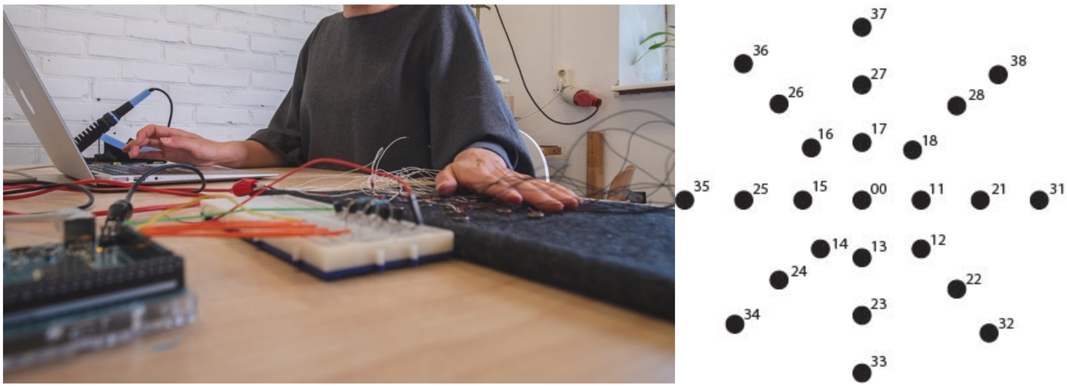

Figure 5: The third prototype of *Magic Lining* allows the co-author to sense more elaborate vibration movements with her hand. Photography: Tarmo Tammeoks. Model: Kristi Kuusk.

During the second artistic residency, the *Magic Lining* team explored further ideas about sensations, movement, vibration and textile materials. Once the spider's web of electronic circuitry was set up, we created patterns that allowed us to check all the motors individually and in batches. We then started to experiment with patterns that moved with different strengths, speeds and directions.

To create the patterns, our external software collaborator developed a pattern generator— a software programme that allowed to set the sequence and duration of each individual vibration motor, thereby generating code for the Arduino controller faster. This allowed to freely explore various patterns and different intensities.

After experiencing various patterns and analysing the results from the previous user tests, we decided to focus on simulating the sensation of three very different materials. We started experimenting with a series of vibration patterns, intensities and different textile surfaces that would simulate as closely as possible the haptic metaphor of a cloud, water or rocks (see Figure 7). We started by characterisation of these three materials generating a list of keywords that would define these distinct sensations. For example, 'cloud' made us think of keywords like air, calm, fluffy, etc. as shown in Figure 6 displaying a mind map. Based on the results from the user test of Prototype 2, we created similar mind maps for two other feelings – ‘water’ and ‘rocks’. The associations related to the materiality helped us to build up the next prototype.

Figure 6: The mind map extending the ‘cloud’ metaphor.

Parallel to this process, we sought the most appropriate textile surfaces in which to embed the vibration motors. We looked at around 40 sample materials of varying characteristics and evaluated their influence on the sensations produced by the vibration movements. We tested each material sample, this time with each of the three patterns, and selected the two samples that seemed the most extreme in relation to each other. Material sample 1 was a soft, fluffy, white nonwoven polyester of the type normally found inside warm jackets, and material sample 2 was a black, structured, woven waffle polyester that could be used for light jackets, skirts or trousers.

To enable the user to experience all three different vibration patterns on the new prototype, we added three, soft-touch, user selection/interface surfaces.

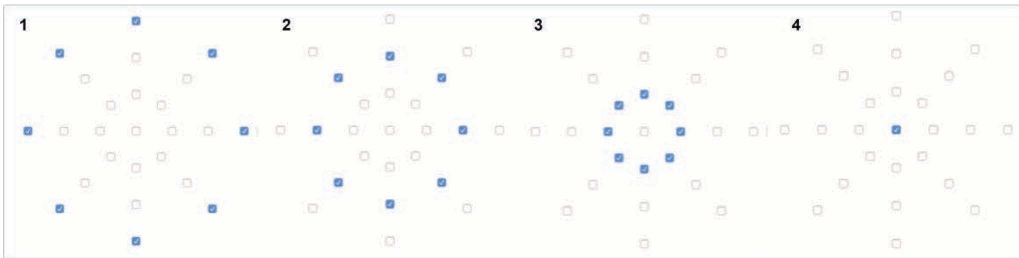

Figure 7. Vibration patterns used to simulate the feeling of ‘rocks’.

Having got the prototype to a reliable functioning state, we started to experiment with adding sound and movement to enhance the vibration patterns. We paired patterns with suitable sound files, which could be triggered by the wearer’s hand touching different surfaces. We looked at whether sound enhances the experience of touch, again relating this to each of the various vibration patterns and fabrics.

We produced a second, duplicate prototype, so that the prototypes with the two different material samples could be displayed at the same time and to enable as many visitors as possible to try both sensorial textiles. We asked 19 participants to complete a short questionnaire about their experiences. The visitors were able to try all three vibration patterns with two different surface materials. Results indicated that the different combinations of vibration patterns and surface materials could influence emotional arousal, and bodily sensations related to weight, hardness, strength and size, as described in (Tajadura-Jiménez *et al*., 2020). The feedback from these try-outs alongside our own bodily experiences informed our decisions about the final prototype.

4 *Magic Lining:* altering body-perception through haptic e-textiles

Our final wearable prototype is a tubular dress with 38 integrated vibration motors. The motors are distributed along the body and guided via an Arduino controller. The placement of the vibration motors follows the spider’s web structure of the third prototype and the logic that it would be possible to experience movements over both arms as well as around the body (Figure 7 right). Since the vibration is placed on the outer side of the arms, it can give the sensation of embracing the wearer and move around her.

The cut and material of the dress was selected based on the following criteria. For the vibrations to be felt as intended, the garment needs to be tight and close to the body. At the same time, the dress has to be flexible to allow the wearer to move freely. Jersey tubular dress with tight sleeves allows both.

This prototype invites the wearer to experience three very different materials: strong, fast, rhythmic vibration resembles a cold, rough surface, such as rocks; smooth, moving, medium vibration reminds the wearer of a flowing stream of water; and soft, distributed, slow vibration allows the user to forget him/herself in a soothing sensation of air or cloud.

Figure 8: The inside layer of the final prototype of *Magic Lining* allows the user to feel as if she/he is made of three different materials: air, water, rocks. A professional dancer

is experiencing the prototype in these photographs. Photography: Kristi Kuusk. Model: Loore Martma.

We invited a professional dancer to experience the sensations the dress evoked in her (Figure 8) as a body-conscious person who is used to reflect on her body experiences. She expressed clear sensations of feeling calmer or more nervous when the vibration patterns were switched. This also reflected in her way of speaking, the tonality of her voice, speed of movement and body language. We chose to have a detailed open-ended interview with the dancer in order to allow her experience to expand our knowledge. In fact, she described mental images of composers and pieces of music that specific vibration patterns brought to mind—thoughts that we had not previously imagined could be inspired by the garment.

Our collaborative work showed that the use of vibrotactile patterns could induce various haptic metaphors in the wearer. In other words, e-textiles enable one to 'wear' different sensations. However, it is important to stress that as the experience of vibrations via textile is still relatively novel to many, there is a 'surprise' factor at play. Wearers may eventually become habituated toward the experience—a phenomenon that is common with tactile actuators (both mechanical and electrical). The effects of long-term usage of this wearable technology need to be further studied. Nonetheless, given the specificity of somatosensory stimuli and their role in fight-flight type reflexes, the use of haptic metaphors as tactile icons or 'tactons' could be very effective.

We continue to develop our collaborative work as team members of a new project, Magic outFIT, and to explore this idea in new directions including: the use of multisensory stimulation (where vibrotactile feedback is paired with other sensory feedback such as sound, light or smell); a closed-loop bio- or neuro- feedback system; and social interaction settings. We would now like to provide some insight into our experience of this transdisciplinary shared project, and to discuss its possible implications for future collaborations of this kind.

5 Discussion

This paper details the first steps of our continuing collaboration that has been so far as fulfilling as it has been challenging. All the team members have given their time and attention to ensure our successful collaboration through working together, supporting and guiding each other. This experience has enhanced the professional skills of every one of us, while we remain experts in our specific domains. The experience has showed us the profound and fascinating new research angles that can be only achieved through transdisciplinary collaboration.

Over the course of the project we have been able to step outside of our usual routines. The e-textile designer had the opportunity to conduct formal user studies, while the neuroscientist could reflect upon the tactility of various materials. From an HCI perspective, usability of tactile 2D arrays as a powerful sensory feedback channel could be tested. We shared the tasks of sewing, soldering and programming.

As an artistic expression, the initial goal of the project was to create through a garment a sensation of air, water, or some other perceived substance, flowing through the wearer’s body. After long discussions, knowledge exchange and examples of prior work in the fields, the project gravitated towards experimenting with a person’s own body-perception. From a number of possible stimulation sites our choices often were guided by intuition and then subsequently tested in small user studies. During the whole duration of the project, through the process of moving back and forth between intuitive ideas and scientific theories and existing research, various possible directions emerged. For example, beside vibrotactile stimuli we also began to look at sound as a possible modality to combine with vibrations to create multisensory-driven bodily experiences.

Different potential user groups emerged, ranging from clinical applications to performing arts.

As a scientific endeavour, the goal of the project was to open up a space for designing multisensory wearable interfaces that utilize bodily sensations and emotional experiences. This was done by experimental prototyping and reflection on existing knowledge, in order to find alternative directions, concepts and methods for further research. Importantly, the artist brought a new, alternative approach to the scientific work, and three new lines of future research unfolded during the collaboration: 1) a new way of thinking about materials (e.g. a cloud, rocks) as sensations—haptic metaphors—relating to the definition of body-perceptions (e.g. being light or heavy); 2) the potential for the interaction between vibrotactile patterns and textile surface to induce various bodily sensations; and 3) new ways of changing one's body-perception from within a garment—i.e. a form of stimulation that is both invisible and entirely intimate to the user. Apart from these new ways of inducing bodily sensations and changing body-perception, the project opened a new application field—clothing and fashion—for the work of the scientific team members. This concept of 'sensorial clothing', which is opposed to traditional clothing fashion by shaping body-perception from the 'inside' instead of external visual appearance, fits well with current scientific frameworks that focus on changing body-perception through sensory feedback, but raised them to a practical level. It did so by highlighting the potential of engineering intimate and invisible body-changing experiences with the aim of shaping the self-identity and social functioning in the everyday life of the wearer through clothing. The task of understanding how to engineer these changes and of the emotional and social consequences for the wearer calls for new research and development work.

The project produced a series of prototypes as knowledge carriers that enabled the users to experience bodily sensations that suggest the material substance of a cloud, of water, or of rocks, thereby affecting the wearer's perception of their own body. For the transdisciplinary team those prototypes served as 'boundary objects' allowing the new knowledge to be adapted to each respective field. We believe that having such hands-on experience of prototyping, intertwined with detailed discussions, had a strong impact on the positive outcome of the collaboration.

As discussed by Verhoeven *at al.* (2014), one of the largest barriers in transdisciplinary designer-scientist collaboration was found to be an unstable team membership. We believe that STARTS funding of the artistic party of our team helped to maintain the necessary stability and the framework for the project to move forward successfully. During the publication process of our results at some conferences and journals we were often criticized for attempting to combine in a single manuscript the findings from each field and, moreover, embedding the description of the collaboration process, which was an important part of the methodology, as reflected in this article. Criticisms included that we lacked a prior hypotheses or were not aligned with the traditional structure of an empirical research paper. The progress of multi- and transdisciplinary research would benefit greatly if the sceptical and undermining character of such "disciplinary ethnocentrism" (Klein, 2005) were weakened.

6 Conclusion

Insights and ways of exchanging ideas and co-creating emerged from our experience of developing *Magic Lining* as a transdisciplinary team. We experienced a shift in perspectives, 'thinking out of the box', and cross-pollination between our areas of expertise. Following the approaches and methods of scientific practice gave structure to the artistic practice and, conversely, the artistic approach enabled moments of ‘creative chaos’ to inspire research. The team appreciated the common co-creative space and have also seen its benefits for each participants’ own work. We had to allow a generous period for getting to know one another, to gain a mutual understanding and find a common language. We achieved this through taking the time to present our ideas to one another, through creative drawing sessions, and by exploring textiles. We kept a daily log of activities, including notes and photographs, and periodically wrote blog entries with updates on the project, which helped us to maintain our focus and continue to progress.

The project required that we all stepped away from the comfort of our own discipline and accepted the challenge of viewing a task from each other’s disciplinary perspective. In this way, we each valued and took full advantage of a unique opportunity to experience with fresh eyes the work and concepts that had already been central to our own work for some years. As Sennett (2008, p. 220) has emphasised:

> “*Though much can be lost in moving from one language to another, meanings can also be found in translation.”*

Acknowledgments

This work was partially supported by the VERTIGO project as part of the STARTS program of the European Commission, based on technological elements from the project Magic Shoes (grant PSI2016-79004-R, Ministerio de Economía, Industria y Competitividad of Spain, AEI/FEDER). The work was also supported by the project Magic outFIT, funded by the Spanish Agencia Estatal de Investigación (PID2019-105579RB-I00 / AEI / 10.13039/501100011033). Aleksander Väljamäe’s work was *supported by the Estonian Research Council grant PUT1518; and Ana Tajadura-Jiménez's work was supported by RYC-2014–15421 grant, Ministerio de Economía, Industria y Competitividad of Spain.*

References

Amemiya, T., Hirota, K., & Ikei, Y. (2013). Perceived forward velocity increases with tactile flow on seat pan. In *2013 IEEE Virtual Reality (VR)* (pp. 141–142). http://doi.org/10.1109/VR.2013.6549402.

Amemiya, T., Hirota, K., & Ikei, Y. (2016). Tactile Apparent Motion on the Torso Modulates Perceived Forward Self-Motion Velocity. *IEEE Transactions on Haptics*, *9*(4), 474–482. http://doi.org/10.1109/TOH.2016.2598332.

Azañón, E., Tamè, L., Maravita, A., Linkenauger, S.A., Ferrè, E.R., Tajadura-Jiménez, A., Longo, M.R. (2016). Multimodal Contributions to Body Representation. *Multisensory Research* 29, 6–7: 635–661. https://doi.org/10.1163/22134808-00002531.

Botvinick, M., Cohen, J. (1998). Rubber hands "feel" touch that eyes see. *Nature* 391, 6669: 756. https://doi.org/10.1038/35784.

Brewster, S., Brown, L.M. (2004). Tactons: structured tactile messages for non-visual information display. In Proceedings of the fifth conference on Australasian user interface-Volume 28 (pp. 15-23). Australian Computer Society, Inc.

Carney, D.R., Cuddy, A.J.C., Yap, A.J. (2010). Power Posing: Brief Nonverbal Displays Affect Neuroendocrine Levels and Risk Tolerance. *Psychological Science* 21, 10: 1363–1368. https://doi.org/10.1177/0956797610383437.

Castellanos, M., Valverde, A. (2016). Environment Dress. STARTS Prize nomination. https://starts-prize.aec.at/en/environment-dress/ (Accessed 15 Aug. 2020).

D'Amour, D., Ferrada-Videla, M., San Martin Rodriguez, L., and Beaulieu, M. D. (2005). The conceptual basis for interprofessional collaboration: core concepts and theoretical frameworks. Journal of interprofessional care 19(S1), pp. 116-131.

de Vignemont, F., Ehrsson, H.H., Haggard. P. (2005). Bodily illusions modulate tactile perception. *Current Biology* 15, 14: 1286–1290. https://doi.org/10.1016/j.cub.2005.06.067.

Deroy, O., Fasiello, I., & Hayward, V. (2016). Differentiated Audio-Tactile Correspondences in Sighted and Blind Individuals, *42*(8), 1204–1214.

Eagleman *et al.* (2017). Providing information to a user through somatosensory feedback. Patent no: US 9,626,845 B2.

Feingold, A., Good-Looking People Are Not What We Think: Conceptualization and 770 Measurement of Attractiveness. *Psychol. Bull.* **Ill**, 304–341 (1992).

Frayling, C. (1993). Research in Art and Design. Royal College of Art Research Papers, 1. Retrieved from http://researchonline.rca.ac.uk/384/3/frayling_research_in_art_and_design_1993.pdf

Harrison, D., Marshall, P., Berthouze, N., Bird, J. (2014). Tracking physical activity: problems related to running longitudinal studies with commercial devices. In Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication (UbiComp '14 Adjunct). Association for Computing Machinery, NY, USA, 699–702. https://doi.org/10.1145/2638728.2641320.

HardLight VR. (2017). Hardlight Suit. http://www.hardlightvr.com/ (Accessed 21 Sept. 2018).

Harris, L. R., Sakurai, K., & Beaudot, W. H. A. (2017). Tactile Flow Overrides Other Cues To Self Motion. *Scientific Reports*, *2017*(Apr), 1–8. http://doi.org/10.1038/s41598-017-01111-w.

Henchoz, N., Puissant, P., Solange Leal, A., Moreira, T., Vinet, H. (2019). Artist residencies for innovation: development of a global framework. In ACM SIGGRAPH 2019 Art Gallery (SIGGRAPH '19). Association for Computing Machinery, New York, NY, USA, Article 10, 1–5. https://doi.org/10.1145/3306211.3320140.

Hertenberger, A., Scholz, B., Contrechoc, B., Stewart, B., Kurbak, E., Perner-Wilson, H., *et al*. (2014). 2013 e-textile swatchbook exchange: the importance of sharing physical work (pp. 77–81). Presented at the International Symposium on Wearable Computers, New York: ACM. http://doi.org/10.1145/2641248.2641276.

Höök, K., Jonsson, M.P., Ståhl, A., & Mercurio, J. (2016). Somaesthetic appreciation design. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (pp. 3131-3142). ACM.

Inerventions AB. (2019). Mollii a life in motion. https://inerventions.se/en/ (Accessed 14 Jan. 2019).

Jousmäki, V.,Hari, R. (1998). Parchment-skin illusion: sound-biased touch. *Current biology* 8, 6: R190. https://doi.org/10.1016/S0960-9822(98)70120-4.

Kawamura, Y. (2004). Fashion-ology. New York: Berg. http://doi.org/10.2752/9781847888730.

Keller. (2018). Could This Futuristic Vest Give Us a Sixth Sense? https://www.smithsonianmag.com/innovation/could-this-futuristic-vest-give-us-sixth-sense-180968852/ (Accessed 8 Aug. 2018).

Kersten-van Dijk, E. T., Westerink, J. H.D.M., Beute, F., IJsselsteijn, W. A. (2017) Personal Informatics, Self-Insight, and Behavior Change: A Critical Review of Current Literature. *Human–Computer Interaction*. 32:5-6, 268-296, http://doi.org/10.1080/07370024.2016.1276456.

Kilteni, K., Normand, J-M., Sanchez-Vives, M.V., Slater, M. (2012). Extending Body Space in Immersive Virtual Reality: A Very Long Arm Illusion. *PLOS ONE* 7, 7: e40867. Retrieved from https://doi.org/10.1371/journal.pone.0040867.

Kurihara, Y., Hachisu, T., Kuchenbecker, K.J., Kajimoto, H. (2013). Virtual Robotization of the Human Body via Data-Driven Vibrotactile Feedback. In *Proceeding ACE 2013 Entertainment - Volume 8253* (ACE 2013), 109–122. https://doi.org/10.1007/978-3-319-03161-3_8.

Kuusk, K. (2016). Crafting sustainable smart textile services. Eindhoven University of Technology. The Netherlands.

Kuusk, K., Tajadura-Jiménez, A., Väljamäe, A. (2018). Magic lining: an exploration of smart textiles altering people's self-perception. In Proceedings of the 5th International Conference on Movement Computing. Genoa. https://doi.org/10.1145/3212721.3212893.

Klein, J. T. (2005). Interdisciplinary teamwork: The dynamics of collaboration and integration. In S. J. Derry, C. D. Schunn, & M. A. Gernsbacher (Eds.), Interdisciplinary collaboration: An emerging cognitive science (pp. 23–50). Mahwah, NJ: Erlbaum.

Leigh Star, S. (2010). This is Not a Boundary Object: Reflections on the Origin of a Concept. *Science, Technology, & Human Values,* 35(5), 601–617. https://doi.org/10.1177/0162243910377624.

Longo, M.R., Schüür, F., Kammers, M.P.M., Tsakiris, M., Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition* 107, 3: 978–998. https://doi.org/10.1016/j.cognition.2007.12.004.

Maister, L., Slater, M., Sanchez-Vives, M.V., Tsakiris, M. (2015). Changing bodies changes minds: Owning another body affects social cognition. *Trends in Cognitive Sciences 19*. https://doi.org/10.1016/j.tics.2014.11.001.

Maranan, D. S. (2017). *Haplós: Towards Technologies for and Applications of Somaesthetics*. University of Plymouth.

Maravita, A., Iriki, A. (2004). Tools for the body (schema). *Trends in Cognitive Sciences* 8, 2: 79–86. https://doi.org/https://doi.org/10.1016/j.tics.2003.12.008.

Mauriello, M., Gubbels, M., & Froehlich, J. E. (2014). Social fabric fitness (pp. 2833–2842). Presented at the the 32nd annual ACM conference, New York, New York, USA: ACM Press. http://doi.org/10.1145/2556288.2557299.

McGlone, F., Wessberg, J., & Olausson, H. (2014). Discriminative and affective touch: sensing and feeling. Neuron, 82(4), 737-755.

Nolan, M. F (1982). Two-Point Discrimination Assessment in the Upper Limb in Young Adult Men and Women, 965–969.

Obrist, M., Subramanian, S., Gatti, E., Long, B., Carter, T. (2015). Emotions Mediated Through Mid-Air Haptics. In *Proceedings CHI'15*, 2053–2062. https://doi.org/10.1145/2702123.2702361.

Peralta, C., Moultrie, J. (2010). Collaboration between designers and scientists in the context of scientific research: a literature review. Proceedings of DESIGN 2010, the 11th International Design Conference, Dubrovnik, Croatia, pp. 1643-1652.

Radziun, D., Ehrsson, H.H. (2018). Auditory cues influence the rubber-hand illusion. *Journal of Experimental Psychology: Human Perception and Performance 44*, 1012–1021. https://doi.org/10.1037/xhp0000508.

Root-Bernstein, R., Siler, T., Brown, A., Snelson, K. (2011). ArtScience: Integrative Collaboration to Create a Sustainable Future. Leonardo. 44. 192-192. 10.1162/LEON_e_00161.

Satomi, M., Perner-Wilson, H. 2007. Massage me. http://www.massage-me.at (Accessed 21 Sept. 2018).

Schelle, K. J., Gomez Naranjo, C., ten Bhömer, M., Tomico, O. & Wensveen, S. A. G. (2015). *Tactile dialogues: Personalization of vibrotactile behavior to trigger interpersonal communication.* In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15), Stanford, CA, USA (pp. 637-642). New York, NY, USA: ACM.

Senna, I., Maravita, A., Bolognini, N., Parise, C.V. (2014). The marble-hand illusion. *PLoS ONE* 9, 3: 1–6. https://doi.org/10.1371/journal.pone.0091688.

Sennett, R. (2008). *The Craftsman*. New Haven, London: Yale University Press.

Shakeri, G., Williamson, J. H., Brewster, S. 2018. May the Force Be with You: Ultrasound Haptic Feedback for Mid-Air Gesture Interaction in Cars.

Shusterman, R. (2008). *Body consciousness: A philosophy of mindfulness and somaesthetics.* Cambridge University Press.

Strøyer, J., Jensen, L. D., Avlund, K., Essendrop, M., Warming, S., & Schibye, B. (2007). Validity and Reliability of Self-Assessed Physical Fitness Using Visual Analogue Scales. Perceptual and Motor Skills, 104(2), 519–533. https://doi.org/10.2466/pms.104.2.519-533.

Tajadura-Jiménez, A., Basia, M., Deroy, O., Fairhurst, M., Marquardt, N., & Bianchi-Berthouze, N. (2015a). As Light As Your Footsteps: Altering Walking Sounds to Change Perceived Body Weight, Emotional State and Gait. In Proceedings of the

33rd Annual ACM Conference on Human Factors in Computing Systems (pp. 2943–2952). New York, NY, USA: ACM. https://doi.org/10.1145/2702123.2702374

Tajadura-Jimenez, A., Bianchi-Berthouze, N., Furfaro, E., & Bevilacqua, F. (2015b). Sonification of surface tapping changes behavior, surface perception, and emotion. IEEE Multimedia, 22(1). https://doi.org/10.1109/MMUL.2015.14

Tajadura-Jiménez, A., Deroy, O., Marquardt, T., Bianchi-Berthouze, N., Asai, T., Kimura, T., & Kitagawa, N. (2018). Audio-tactile cues from an object's fall change estimates of one's body height. PLOS ONE, 13(6), e0199354. Retrieved from https://doi.org/10.1371/journal.pone.0199354

Tajadura-Jiménez, A., Marquardt, T., Swapp, D., Kitagawa, N., & Bianchi-Berthouze, N. (2016). Action sounds modulate arm reaching movements. Frontiers in Psychology, 7(SEP). https://doi.org/10.3389/fpsyg.2016.01391

Tajadura-Jiménez, A., Vakali, M., Fairhurst, M. T., Mandrigin, A., Bianchi-Berthouze, N., & Deroy, O. (2017). Contingent sounds change the mental representation of one's finger length. Scientific Reports, 7(1). https://doi.org/10.1038/s41598-017-05870-4

Tajadura-Jiménez, A., Väljamäe, A., Kuusk, K. (2020). *Altering One's Body-perception Through E-Textiles and Haptic Metaphors*. Frontiers in Robotics and Ai. doi.org/10.3389/frobt.2020.00007.

Tajadura-Jiménez, A., Väljamäe, A., Toshima, I., Kimura, T., Tsakiris, M., & Kitagawa, N. (2012). Action sounds recalibrate perceived tactile distance. Current Biology, 22(13), R516–R517. https://doi.org/10.1016/j.cub.2012.04.028

ten Bhömer, M., Jeon, E., Kuusk, K. (2013). Vibe-ing: Designing a Smart Textile Care Tool for the Treatment of Osteoporosis. In Proceedings of the 8th international conference on design and semantics of form and movement, Wuxi, China, 2013, pp. 192-195.

Teslasuit (2018). New generation of smart clothing. https://teslasuit.io/teslasuit (Accessed 8 Aug. 2018).

Tsakiris, M. (2010). My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia* 48, 3: 703–712. https://doi.org/10.1016/j.neuropsychologia.2009.09.034.

Ultrahaptics (2018). Touch Development kit. https://www.ultrahaptics.com/products-programs/touch-development-kit/ (Accessed 8 Aug. 2018).

Verhoeven, F., Roumen, M., Brinksma, A., van der Lugt, R. (2015). Transdisciplinary designer scientist collaboration in child oncology. In 4th Participatory Innovation Conference 2015 (p. 262).

von Busch, O. (2018) Ways to make fashion work for us. https://www.ow-ourworld.nl/ways-to-make-fashion-work-for-us/ (Accessed 8 Aug. 2018).

Zoll. (2017). Life vest. https://lifevest.zoll.com (Accessed 21 Sept. 2018).