The Breathing Garment

Exploring Breathing-Based Interactions through Deep Touch Pressure

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Master's Thesis

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Abstract

Deep touch pressure is used to treat sensory processing difficulties by applying a firm touch to the body to stimulate the nervous system and soothe anxiety. I conducted a long-term exploration of deep touch pressure from a first-person perspective, using shape-changing pneumatic actuators, breathing and ECG sensors to investigate whether deep touch pressure can guide users to engage in semi-autonomous interactions with their breathing and encourage greater introspection and body awareness. Based on an initial collaborative material exploration, I designed the breathing garment - a wearable vest used to guide the wearer through deep breathing techniques.

The breathing garment presents a new use case of deep touch pressure as a modality for haptic breathing feedback, which showed potential in supporting interoceptive awareness and relaxation. It allowed me to engage in a dialogue with my body, serving as a constant reminder to turn inwards and attend to my somatic experience. By pushing my torso forward, the actuators were able to engage my entire body while responding to my breath, creating a sense of intimacy, of being safe and taken care of.

This work addresses a gap in HCI research around deep touch pressure and biosensing technology concerning the subjective experience of their emotional and cognitive impact. The long-term, felt engagement with different breathing techniques opened up a rich design space around pressure-based actuation in the context of breathing. This rendered a number of experiential qualities and affordances of the shape-changing pneumatic actuators, such as: applying subtle, slowly changing pressure to draw attention to specific body parts, but also disrupting the habitual way of breathing with asynchronous and asymmetric actuation patterns; taking on a leading or following role in the interaction, at times both simultaneously; and acting as a comforting companion or as a communication channel between two people as well as between one person and their soma.

Keywords

Deep Touch Pressure, Soma Design, Breathing Awareness, Wearables, Haptics, Mental Wellbeing, Shape-Changing Interfaces

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List of acronyms and abbreviations

DTP	Deep Touch Pressure
ECG	Electrocardiography
EDA	Electrodermal Activity
EMG	Electromyography
HCI	Human-Computer Interaction
HF	High Frequency
HR	Heart Rate
HRV	Heart Rate Variability
LF	Low Frequency
OSC	Open Sound Control
PZT	Piezoelectric
RIP	Respiratory Inductance Plethysmography

1 Introduction

Worldwide, common affective health problems such as anxiety, depression and stress are one of the leading causes of disease [1], with up to 1 in 3 people projected to experience it at some point in their lives [2]. Mental and physical health are tightly interconnected and mediated by other factors such as social interactions and other lifestyle choices [3]. Thus, affective health problems such as chronic stress, even comparatively low levels someone might face in their regular workplace or family life, can not only have a long-term negative impact on physical and mental health [4], [5], but also influence our cognitive functions, how we perceive and interact with others and how we perceive our own body [6].

In human-computer interaction (HCI), designing for mental health and wellbeing has become more and more common, with a wide range of systems being developed to support affective wellbeing [7]. Some clinical approaches, particularly in the context of stress management, aim to support introspection through concepts like body awareness and mindfulness. These can be cultivated through practices like meditation, yoga, breathing exercises or body scans, an exercise during which one carefully attends to different body parts one by one to take note of any present sensations [8]. As breathing awareness is an essential aspect of these practices, there is a large body of HCI systems which uses breathing data to encourage self-awareness [9]. Breathing can both be an automatic bodily function as well as controlled consciously; thus, such systems tap into semi-autonomous interactions with breathing to guide and sustain users' attention to their inner self, supporting self-discovery and curiosity. Furthermore, practicing slow and regular breathing techniques can soothe anxiety and provide relaxation [10], ultimately promoting mental wellbeing.

In this thesis, different interactions with breathing are explored as a way of guiding attention towards bodily sensations, aiming to support deeper self-awareness and relaxation. Most breathing-based systems in the HCI literature provide feedback through visual and auditory modalities, e.g. via responsive virtual reality simulations [11], [12] or lights coupled with audio [13], [14]. Wongsuphasawat et al [15] suggested that auditory feedback might be more effective for calming breathing techniques than visual feedback since it allows users to close their eyes and ignore visual distractions. As breathing itself is experienced more aurally than visually, it might be more easily matched to auditory than to visual feedback.

However, few such systems have explored haptic breathing feedback. As indicated by the results by Wongsuphasawat et al [15], haptic feedback might be a suitable modality for breathing guidance since breathing is experienced physically with the rise and fall of the stomach or chest. Furthermore, haptic feedback inherently needs to be close to the body, which might help people to focus on their physical experience while breathing and block out external stimuli. Frey et al [14] investigated vibration feedback to guide breathing, but found that it was experienced as disruptive and thus much less effective than alternative feedback modalities. Other designs provide breathing guidance through tactile, shape-changing interfaces which users can hold in their hands [16], [17], but are also potentially problematic since they direct users' attention towards an external object outside of their own bodies.

1.1 Research Question

The lack of designs exploring immediate haptic breathing feedback raises the questions whether alternative forms of haptic feedback, such as pressure, could be more suitable than vibrations to support bodily awareness while engaging with breathing-based interactions. In particular, the work presented here was inspired by deep touch pressure (DTP), a method used in sensory integration therapy. This is an alternative approach in psychotherapy which has been successfully used to treat anxiety and provide relief in stressful situations [18]. It uses tools such as weighted blankets, pressure garments, swaddling, or firm hugs to apply a firm touch to the body, stimulating the nervous system and modulating the physiological stress response.

DTP has not received much attention in HCI, with only a few studies investigating wearable haptic pressure vests using inflatable pneumatic chambers [19] or shape memory alloy springs that constrict when heated [20]. However, this approach has shown potential as a coping mechanism for anxiety and stress [18], [21] and could help users to direct their attention to their bodily sensations, enhancing the breathing guidance and facilitating a desired state of relaxation. This led me to pursue the following research question: Can a deep touch pressure garment support the wearer in engaging with semi-autonomous interactions with their breathing to encourage greater introspection and body awareness?

1.2 My Work and Aim

To explore this question, I designed a wearable garment with integrated inflatable pneumatic pads to provide pressure, as well as biosensors for measuring respiration and heart rate. My design process was based on a first-person material exploration [22], [23] of the biosensors and inflatable pads, focusing on how different properties of the pads, such as their placement on the body and inflation pattern, can influence how the resulting pressure is experienced. Throughout this process, I engaged with soma design, a methodology that is grounded in sensuous and aesthetic first-person experiences of sociodigital materials [24]. Soma design emphasizes the need to engage fully with the interaction as it is created, making the designer act simultaneously as researcher and end user to gain deep, subjective knowledge of the material affordances as well as their own soma - the unity of physical and emotional experiences. In this way, the designer's lived body, their emotions, values, meaning-making, and movement-based exploration become another resource in the design process [25].

My methods were based on previous work on combining biosensing and embodied exploration of actuation to explore material properties [26], [27]. Such interactions support introspection by displaying bodily reactions as they unfold in real time [28], allowing users to react accordingly and thus become more aware of their physical and emotional selves. As previous soma design explorations [25], [27] have found, this process can promote empathy and understanding of oneself and others, which contributes to mental and emotional wellbeing. Building on this previous work, my aim was to explore interesting qualities in biodata and couple them with actuation to turn them into a felt experience, helping users to connect with their body while developing a deeper understanding of the connections between breathing and bodily experiences.

Based on results from a preliminary material exploration, I conducted a series of soma design workshops to explore couplings of respiration and heart rate data with inflatable pads. Afterwards, I designed a wearable garment using inflatable pads and biosensor data to provide pressure-based haptic feedback and breathing guidance. The garment's reactions to changes in breathing and heart rate can make the wearer more aware of their physical response, which might stay unnoticed otherwise, and thus more connected to their soma.

1.3 Contributions

This work makes two contributions. First, the current research in HCI on DTP prototypes focuses mainly on the construction and the design process [20], [29], but lacks exploration of the subjective bodily experiences such pressure garments can provide. Thus, I followed an embodied approach from a first-person perspective to engage with the subjective experience of DTP in a novel way, connecting haptic pressure with breathing practice to support interoceptive awareness and relaxation. Since previous studies involving haptic feedback have mainly used soft vibrations, pressure could present an alternative for interactions in which haptic feedback is desired, but users experience vibration as disruptive or distracting [14].

Second, I have conducted a guided exploration of the shape-changing inflatable pads as a design material. While shape-changing elements are not a novel design material in HCI [30], [31], my first-person embodied exploration of the pads over a period of six months contributes to further opening up the design space around shape-changing pneumatic pads in the context of breathing. Based on my subjective use experience, I characterize material and experiential qualities of inflatable pads, including how they can be placed on different body parts to elicit different emotions and how a collaborative exploration of the arising somaesthetic experiences can enable new ways for two people to connect physically and emotionally. My results show that the inflatable pads can afford a wider array of interactions than the breathing guidance constituting the primary focus of this thesis, and thus can inform and encourage other researchers to further investigate the design space around pressure-based actuation.

1.4 Structure of the Thesis

Section 2 presents a brief overview on deep touch pressure and breathing as well as existing work in HCI in these areas and introduces design methods to engage with biosignals as design material from a first-person, somaesthetic perspective. Section 3 and 4 describe the design process including interviews with psychologists, first-person material exploration, and a series of soma design workshops, and how the intermediate learnings informed the design of a pneumatic garment for breathing guidance, which is presented in section 5. This breathing garment was used to explore a variety of breathing techniques in different contexts. Lastly, sections 6 and 7 present results and discuss the effectiveness of pressure-based haptic breathing feedback for supporting body awareness and relaxation. To further situate this work within soma design, the breathing garment is characterized as an exemplar a somaesthetic appreciation design [32]. The material exploration rendered a number of material and experiential qualities of inflatable shape-changing pads, which suggest two distinct use cases for the garment and opportunities for future work.

2 Background

2.1 Deep Touch Pressure

Deep touch pressure (DTP) is a method used in sensory integration therapy, an approach aimed at treating sensory processing difficulties which are experienced by, among others, people with anxiety disorders or people on the autism spectrum [18], [21], [33]. Patients are provided with specific patterns of targeted sensory stimuli in a carefully defined dosage, a so-called sensory diet, in order to improve the nervous system's ability to process these stimuli. For this purpose, DTP therapy uses tools such as weighted garments and blankets to provide a comforting pressure sensation. Its calming effect can be attributed to increased activity of the parasympathetic nervous system, which plays a significant role in anxiety management [18]. In practice, DTP has been applied to increase attention [34], reduce disruptive behavior [35] and reduce anxiety symptoms [21] in patients with bipolar disorder, developmental disorders and patients on the autism spectrum, particularly in children and students. While it has shown promising results, many DTP studies suffer from questionable research methodology and thus have been found to have limited efficacy and empirical evidence [36], [37].

DTP-related work in HCI mainly focuses on the development of different compression garments, but rarely explores subjective user experiences or interactive designs based on DTP. Vaucelle et al [19] designed a pressure vest containing pneumatic chambers along with three other haptic devices based on other methods of sensory integration therapy. Such vests are the most common form of designs for deep touch pressure. They are inflated using manual pumps, and have also been applied to simulate hugs in long-distance interactions between parents and children [29]. Another type of compression garments for DTP is made with shape memory alloys (SMA) which contract when heated, exerting pressure on the wearer's body [20]. They are less obtrusive and noticeable than inflatable vests, which can be bulky and noisy, but are uncomfortable when not sufficiently insulated and require an external power source. Foo et al [38] investigated the user experience of SMA-based vests and found that users perceived compression stimuli as more or less intense or comfortable depending on the location on the body, associating the compression with calming, secure and restricted sensations. SMA-based vests have been used to assist during meditation practices by supporting focused attention via rhythmic haptic stimulation [39].

In addition to the DTP prototypes that have been developed in HCI research, there have also been commercial prototypes of inflatable vests. While the Vayu vest [40] and Squease vest [41] require an external hand pump to be inflated, the Tjacket [42] is controlled via an automatic pump that can be operated with an app. Only the Vayu vest has been tested in a published study. Reynolds et al [43] concluded it to be effective in reducing arousal after a stress test; however, they did not distinguish between healthy participants and those in treatment for affective disorders. Furthermore, the Tjacket is the only one of either the commercial or research prototypes that contains integrated physiological sensors, although their website does not make clear which type of sensors are used. As occupational therapists have suggested that physiological sensors could be useful to monitor the vest's effectiveness and allow for more personalized, context-aware treatment [44], this presents an opportunity for future work.

The design work presented in this thesis uses shape-changing pneumatic pads to provide DTP. Their degree of inflation can be controlled quickly and easily, thus allowing for a wide variety of actuation patterns. Unlike shape memory-alloys, pneumatic pads do not heat up and can be worn comfortably on the body for a longer amount of time [45]. In HCI, shape-changing interfaces have been used for different functional and hedonic purposes including communicating information and possibilities for action, providing haptic feedback, and embodying emotion through life-like movements [31]. Due to their dynamic characteristics, designers and users alike often use metaphors to describe their behavior and perceive shape-changing artifacts as displaying certain personality traits or other life-like qualities [30], [46]. However, the subjective experience of interacting with shape-changing materials, as well as their inherent communication qualities, have so far rarely been investigated [31].

2.2 Breathing

Controlled breathing techniques are used in affective health therapy [47] as well as in bodily practices such as Feldenkrais or yoga. They modulate autonomic and central nervous system activities which can lead to improved relaxation and alertness [10]. In clinical applications, yogic breathing has been found to reduce stress, anxiety, and depression in both healthy people [48] and diagnosed patients [49], with other breathing exercises such as diaphragmatic breathing showing similar results [50]. It has been suggested that each person has a unique optimal breathing rate, called the resonance frequency, which ranges between 4.5 and 7.0 breaths/min and seems to be most effective for regulating HRV, decreasing stress and improving mood [51].

A growing number of works in HCI are focused on designing interactive systems to extend breathing awareness. Prpa et al [9] provide an overview of the underlying theoretical frameworks and design strategies used in breath-based interactions. While some aim to regulate physiological indicators of stress by slowing the breathing rate [12], [52], [53], others use breathing exercises as gentle guidance to help users develop sustained attention towards their bodily sensations [54]–[56]. Many of these systems provide feedback to make breathing more accessible to users. In this way, they can make users more aware of their bodily sensations and reactions, allowing them to experience their internal state from a more embodied perspective. By helping them to deliberately direct attention towards their body and understand the connection between their physical and emotional states, such systems support interoceptive awareness which can be beneficial for emotion regulation and developing a higher sense of trust in one’s body [57].

A wide variety of stimuli have been used to provide breathing feedback, targeting audio, visual, or kinesthetic modalities. Some designs make the users’ real environment react dynamically to their breathing pattern [58], [59] or incorporate feedback into a VR environment by letting users control the scene with their breathing [60], [11]. Such games have also been developed for smartphones, for example the games Chill-Out [53] and Dodging Stress [61] which train players to take slow, deep breaths by increasing the game difficulty when their breathing rate deviates from the target rate of 5-6 breaths per minute. Other systems consist of small tangible interfaces, such as fidget spinners with added visual feedback [62], shape-changing airbags [17] or stuffed animals [16], to mirror the user’s breathing or instruct them when to breathe in and out.

Several studies have compared how audio, visual, or kinesthetic feedback modalities are perceived by users and which is more effective for breathing guidance and relaxation. Frey et al [14] designed a wearable pendant which provides visual, audio and haptic vibration biofeedback, and found that most participants preferred visual and audio feedback over vibration since they experienced it as easier to follow and less interruptive. Wongsuphasawat et al [15] developed an app which gives users instructions to breathe at 6.4 cycles per minute via audio or visual feedback. In their study, audio feedback was experienced as more calming, possibly because it allowed people to close their eyes and ignore all visual distractions. However, Zhu et al [13] found that audio feedback should be simple and changed very gradually to avoid distracting from the breath. Furthermore, natural sounds such as ocean sounds were experienced as more relaxing since they are often associated with relaxation and provide a constant rhythm. Dijk & Weffers [63] created a multimodal experience mimicking an ocean shore to test different types of breathing guidance. They used ocean wave sounds as well as a haptic touch blanket which uses small vibration motors to provide the sensation of a haptic wave travelling up and down the body. Their findings suggest that guided breathing at a steadily decreasing rate is experienced as more relaxing than using a fixed rate or simply mirroring back the user's own breathing rate without any guidance. However, Macik et al [64] found that a very low breathing rate can cause frustration and discomfort if users are unable to breathe along, and thus might counteract any relaxing effects.

2.3 Engaging with Materials from a First-Person Perspective

2.3.1 Material Exploration

Both digital and physical materials play a huge role in defining the fundamental properties and affordances of interactive systems [22]. New platforms, sensors, and other smart materials are constantly being developed in response to rapid technological advancements. Designers need to familiarize themselves with these emerging materials to understand the design space and be able to use them in their projects. By making sure to explore the material properties early on in the design process, designers can not only acquire a deeper understanding of what they are working with, but also open up unexpected design possibilities and sources of creative inspiration [65].

Marking this shift towards materiality in HCI [22], several methodologies and guidelines for material exploration and material-centered design have been developed. Karana et al [66] propose the Material Driven Design (MDD) method to gain an understanding of how novel materials can be used to create meaningful experiences. They emphasize the importance of first characterizing the technical and experiential properties of the material by exploring how it is experienced, what kind of interactions it can afford and which emotions it can elicit, before proceeding further in the design process. While they mainly suggest conducting user studies to gather information, the field of HCI has produced a much wider array of exploration methods. Wiberg [67] proposes a multi-dimensional framework to guide a systematic application of these methods in material-driven design research, working back and forth between details and wholeness, texture and materials.

A number of recent works in HCI have explored data as a material for design [68]. Particularly relevant are the studies which couple biosensor data to actuation, thereby giving physical signals a material form and making them available for design [27], [28]. For instance, Aslan et al [16] presented two designs of tangible artifacts which allow users to feel their own heartbeat and breathing patterns. But rather than simply reflecting these biosignals back to users, their designs adopt an embodied, somaesthetic perspective which aims to make internal processes visible, thereby enabling shared exploration of bodily reactions and critical reflection.

2.3.2 Somaesthetic and First-Person Design

Somaesthetic design is a design approach that puts sensory experiences and emotions at the center of the design process to incorporate the body in a holistic manner and build a subjective understanding and deeper meaning [25]. It is based on the work by Richard Shusterman [69], who combined the two words *soma*, i.e. the united, interconnected whole of our body and mind, and *aesthetics*, the ability to appreciate our experiences that can be trained through active engagement with our senses. The somaesthetic design field offers a variety of strong concepts such as somaesthetic appreciation designs [32], experiential qualities such as estrangement [70], and design methods such as embodied sketching [71].

Somaesthetic design methods focus on gaining awareness of physical experiences, exploring materials through touch and interaction, and testing out possible sensations first-hand. This is done from a first-person, autobiographical perspective [72] which puts the researcher themselves, their movements and subjective experiences at the center of the design work. By engaging with the materials at hand and taking a slow, conscious approach to their exploration, researchers simultaneously act as designers and end users which allows them to build a deep subjective understanding of the design space and how their body relates to it. They repeatedly touch and probe the materials they are designing with to make full use of their affordances.

To be able to fully attend to their sensations and engage with their soma, designers need to continuously cultivate their somaesthetic sensibilities [25]. This is done through first-person, active engagement with different body practices and material exploration, for example yoga, meditation, or Feldenkrais. In a Feldenkrais practice, an experienced practitioner guides the design team in exploring the nuances of different movements by disrupting the habitual ways in which they are performed, slowing down movements or shifting their focus between different body parts. Through such a slow, thoughtful reflection, one can develop the ability to differentiate between barely noticeable changes in the body. As designers learn to articulate their subjective experiences, they also learn to appreciate the aesthetics of their own somas, which allows them to share their experiences with others and build a common language and understanding. Essentially, the designer's lived body, their subjective experiences, feelings, meaning-making and movement-based exploration become a resource in the design process.

Soma design methods often rely on estrangement [73], i.e. disrupting usual habits and movements by performing them in an unfamiliar way or slowing them down significantly. This provides a way of deconstructing familiar movements, experiencing them more consciously and questioning inherent assumptions. Familiar contexts contain many cultural, political and personal associations that are easily overlooked. Defamiliarization creates space for active critical reflection rather than passively propagating the existing ideals [74], thus opening up new perspectives and ideas for design. There is a large diversity of embodied design methods connected to the process of estrangement, eight of which were presented by Wilde et al [70]. They identified four main strategies for estrangement: Re-contextualization, enactment of specific movements, changing bodily sensations through artefacts, and altering the material. The latter two make use of materials to provoke disruptions in the design process, drawing on material-centered theories of design.

Several works have taken a somaesthetic, first-person based design approach towards couplings of biodata and actuation. Umair et al [28] used thermochromic materials and different types of haptic actuators to create wristbands which react to a rise in skin conductance, thereby prompting the wearer to reflect on their emotional response to their environment. Alfaras et al [27] presented three different sensor-actuator couplings: EMG signals collected during a balancing act and soundscapes, electrodermal activity (EDA) and temperature, and accelerometers coupled with synchronous and asynchronous movements. They emphasized how making these physiological signals more accessible for design allowed them to share their own experiences with others and directly engage with other people's unique understanding of their bodies. To facilitate such collaborative exploration processes, Windlin et al [75] constructed the Soma Bits, a prototyping toolkit consisting of various sensors, actuators and soft shapes which allows researchers to explore their material affordances and develop new design concepts based on embodied interaction.

3 Methods

I followed a research through design approach [76], [77] to guide the exploration of physiological sensors and actuators, centered around deep touch pressure and breathing awareness. This was done from a first-person perspective [22], [23], inspired and guided by somaesthetic and embodied concepts and methods [25], [73]. While I had prior experience with breathing exercises in the context of yoga and Feldenkrais practice both at home and in guided group lessons, I have not studied any breathing practices or deep touch pressure therapy in depth. Throughout the design exploration, I took new learnings into account to continuously reframe my problem, which eventually led me to shift from only focusing on deep touch pressure therapy for anxiety and stress relief towards a broader goal of supporting body awareness and relaxation by combining deep touch pressure and breathing techniques. An open, playful research process like this is well-suited for exploring the affordances of a particular technology or material and allows for discovering new opportunities, design inspirations and unanticipated effects.

The design process was roughly divided in two main phases. The initial phase was focused on familiarizing myself with the available materials, consisting of physiological sensors and shape-changing inflatable actuators, and learning about affective disorders, existing treatments, and the research work done on affective health within the HCI community. For this purpose, I first conducted semi-structured interviews with three psychologists, followed by a preliminary exploration of the materials. Afterwards, I iteratively created new interaction sequences for the inflatable actuators, respiration and ECG sensors, which I first tested by myself. The more interesting sequences were incorporated in four soma design sessions, which took place over the course of three weeks and consisted of collaborative embodied explorations of the chosen materials and actuation sequences.

The second design phase was informed by preliminary results concerning the most evocative qualities of the inflatable pads. I decided to focus on using them as guidance for a variety of breathing patterns, some of which were based on breathing feedback. After two initial design sessions during which I tested several breathing techniques used in therapy and yoga practice, I selected the five most evocative and interesting patterns for further exploration. In parallel, I created a wearable vest with two inside pockets to hold the inflatable pads. This garment was used along with the previous set-up during the final investigation of the five chosen breathing techniques. For three weeks, I conducted daily evaluation sessions to explore the impact of each breathing pattern in different contexts over a longer period of time. However, I worked exclusively by myself during this phase since collaborative explorations were no longer possible as a result of restrictions imposed due to the COVID-19 pandemic.

In the following chapter, I will further describe the methodology used during the interviews, the first-person exploration of the materials, the collaborative soma design sessions, and the initial investigation of different breathing techniques.

3.1 Interviews

During the first phase of the design process, I conducted semi-structured interviews with three psychologists to learn more about affective health and available therapies from a clinical perspective and to potentially take inspiration for the subsequent design process. One interview was done in person, while the other two took place on Skype due to geographical constraints.

The three interviewees had working experience in clinical psychology and psychotherapy, focused on affective health. Before the interviews, I prepared a list of questions regarding their educational and professional background, what kind of patients they had worked with and which therapy techniques and tools they had used. I was also interested in learning whether they were using treatment methods to specifically address physical symptoms or elicit certain physical experiences, such as deep touch pressure. These questions were used to guide the interviews, which were conducted as open conversations and documented by taking notes. Each interview lasted between 35 and 60 minutes.

3.2 Initial First-Person Material Exploration

3.2.1 Materials

Throughout the entire design process, I engaged in a first-person material exploration [22], [23] to learn about the characteristics and affordances of the available materials, which consisted of different biosensors, actuators and additional fabrics and technology.

3.2.1.1 Sensors

The sensors I used were part of the BITalino toolkit provided by Plux[1], a Portuguese company which develops biosignal acquisition systems. The basic BITalino (r)evolution kit contains a small board which can be connected to up to eight different sensors and communicates via Bluetooth. It was developed specifically for collecting biosignal data and includes a software and visualization framework as well as several programming APIs. Alternatively, the smaller R-IoT device can be connected to up to two additional sensors and sends data via Open Sound Control (OSC) messages.

Plux offers a large variety of sensors, including electromyography (EMG), electroencephalography (EEG), electrocardiography (ECG), electrodermal activity (EDA), a piezoelectric respiration sensor (PZT) and an inductive respiration sensor (RIP). The PZT sensor only measures localized movements caused by inhaling and exhaling, while the RIP sensor measures the overall displacement of the chest or stomach and is therefore more robust to noise. Both are worn on a strap around the torso, as shown in Figure 3-1a).

During my initial exploration, I used both (r)evolution (see Figure 3-1b) and R-IoT BITalino (see Figure 3-1c) devices to test a variety of sensors including EMG, ECG, EDA, PZT and RIP sensors.

Figure 3-1: **Sensors used during material exploration: a) RIP sensor worn around the stomach, b) BITalino (r)evolution kit, c) BITalino R-IoT**

[1] https://plux.info

3.2.1.2 Actuators

To explore different kinds of actuation, I used heat pads and shape-changing actuators in the form of inflatable pads which are shown in Figure 3-2a. The inflation is controlled by an Arduino MKR WiFi 1010 which can receive instructions via OSC messages over Wi-Fi. Depending on the transmitted value, the pads inflate or deflate with the indicated speed or stay at a constant level of inflation. The air flow is regulated by an Arduino MKR Motor Carrier, an air pump motor and a valve, which produces a rhythmic noise when inflating or deflating. Additionally, the Arduino is connected to a pressure sensor which transmits the current internal pressure of the inflatable pad in regular intervals via OSC. A Processing script was used to manage the delivery of the OSC messages.

To combine the sensors with the actuation, I created a Python script which receives data from all components via OSC, processes the sensor data, and sends instructions corresponding to the desired actuation sequence to the Arduino controlling the inflatable pads. I used the ServerBit[2] platform, which was developed at Plux to let BITalino devices communicate with external applications and devices, to make the R-IoT data available in Python. Then, the raw sensor data was analyzed using the biosignals API provided by Plux as well as self-written code. For the RIP sensor data, the average duration of an inhalation, an exhalation and the ratio of inhalation to exhalation were calculated and used to create different actuation sequences for the inflatable pads. The ECG data was used to calculate the average heart rate and standard deviation as well as heart rate variability features based on the R-to-R peaks, which have been shown to change significantly when experiencing stress or anxiety [78], [79].

The calculated features include the root mean square of successive R-R differences (RMSSD), the high and low frequency components of the signal (HF and LF) and the ratio of LF to HF signals. They were computed every 0.5 seconds based on the last 2000 data samples. Since the R-IoT device had a sampling rate of 200 samples per second and the (r)evolution device a rate of 100 samples per

Figure 3-2: **Materials used during exploration and soma design sessions: a) Two heat pads and one shape-changing actuator with inflatable pads in different sizes and shapes, b) Wearing an exercise belt to hold the large round shape in place**

[2] https://github.com/BITalinoWorld/revolution-python-serverbit

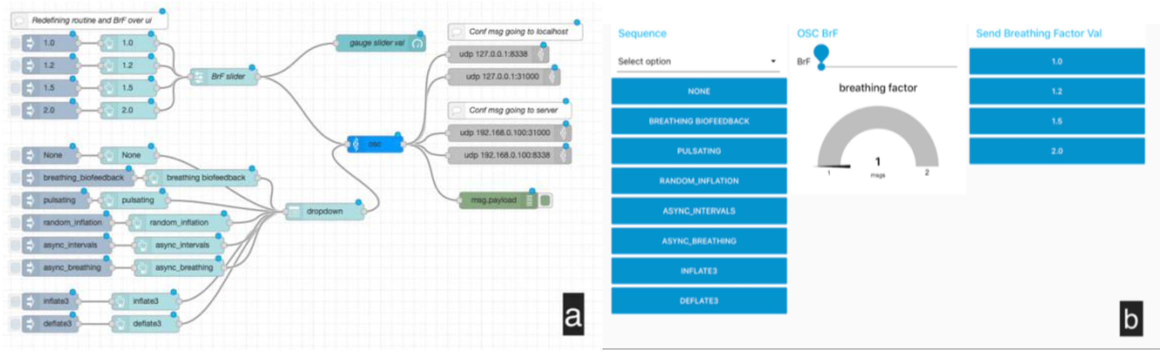

Figure 3-3: Node-RED interface used during the first design phase: a) Interaction flow, b) User interface

second, this corresponds to the last 10 or 20 seconds of data. The actuation was started after 30 seconds to allow the devices to gather initial data. At first, the actuation sequences were controlled through a Jupyter Notebook script, but later on we built a basic interface on Node-RED[3] (see Figure 3-3) to switch between different sequences more easily. Node-RED is a flow-based programming tool which allows users to connect multiple systems and applications. Using the node-red-dashboard module[4], I created an interface to control the actuation sequences and certain parameters, which are then communicated to the Python script via OSC. The entire workflow, including the R-IoT data, interface, Python script, Processing script, and actuators is shown in Figure 3-4.

3.2.2 Procedure

To explore the materials described above, I used an embodied, autobiographical approach [72] which allowed me to tinker with the materials and learn more about their affordances. I alternated between creating new elements, i.e. adding a new sensor, developing new actuation sequences or making inflatable pads in new shapes or sizes, and testing them out on my body. For this, I placed the pads on my body to feel what kind of sensory experiences they could evoke and how they impacted the way I experienced my body. I explored different shapes and sizes of pads, using different materials to attach them to my body such as a scarf, a non-elastic polyester belt and an abdominal sweat belt which is intended to be wrapped around the body during exercise to increase sweating (see Figure 3-2b). I constantly iterated my process based on my experiences, evaluating what worked, what didn't work and what would be worth exploring further in the soma design workshops. I documented my exploration by taking pictures, videos and notes of my observations.

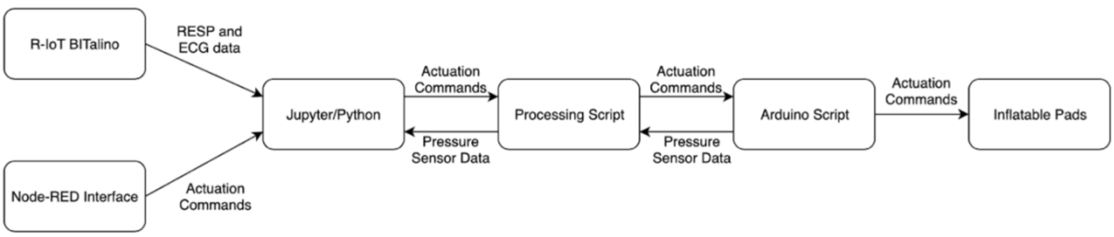

Figure 3-4: The workflow used to control the pneumatic actuators. Arrows indicate transmission via OSC

[3] https://nodered.org
[4] https://github.com/node-red/node-red-dashboard

3.3 Soma Design Workshops

About halfway through the material exploration phase, I started planning more focused soma design sessions in collaboration with my thesis supervisor Miquel Alfaras and two other researchers at Plux. We conducted a total of four such sessions over the course of three weeks in parallel to the previously described first-person exploration. Since they were spread out throughout the design process, they served as reminders to let the design be guided by the somaesthetic experiences provided by the sensors and actuators. Bodily experiences are easily forgotten without doing them over and over. Thus, repeating these soma sessions over several weeks allowed us to hone our somaesthetic sensitivities by carefully attending to our bodies while exploring various sensations [24].

3.3.1 Materials

During the design sessions, we used inflatable pads in different shapes and sizes as well as a RIP sensor to monitor breathing. We decided to focus on breathing data rather than ECG because one generally has more intentional control over their breathing rate, whereas the heart rate is almost impossible to manipulate. Thus, the breathing data gave us more room for deliberate exploration of different actuation sequences. While we noted small inaccuracies in the actuation early on, for example that the pads were often inflating and deflating a little too quickly to accurately reflect the user's breathing pattern, this did not prevent us from exploring the sensorial experiences they could provide [80]. In this sense, the pads should be thought of as experiential artifacts [81] rather than functioning prototypes. They were not intended to represent a final design idea, but simply served as tools to present new and interesting experiences and discover their affordances through playful, embodied interaction. As described by Sundström et al [81], we used the pads to stimulate conversations and discussions between the workshop participants. Each person was included in the exploration, either as an active participant or as an observer, and contributed their own subjective interpretation of the experience colored by their personal perspective.

To facilitate an open exploration of the design space, the pads themselves had to be able to support different experiences and interpretations. While we attempted to give the inflation and deflation patterns meaning by connecting them to the user's breathing pattern, we also used actuation sequences without any relation to breathing. Thus, the pads added an element of ambiguity, pushing users to make sense of the inflation sequences based on their own background, expectations and experiences. Such ambiguous materials can serve as probes to explore the design space around new materials and technologies, and eventually generate new practices and design ideas [26].

3.3.2 Procedure

We began each session with a Feldenkrais exercise to become attuned to our body and direct our attention inwards, towards our physical sensations. This allowed us to sensitize ourselves and place the somaesthetic experience of the following interactions in the foreground of the session [23], [24]. Since we did not have access to a Feldenkrais practitioner at our location, we followed along to pre-recorded sessions.

Before and after the Feldenkrais exercise, we each filled out a body sheet to document our subjective experiences and share them with each other [25]. These sheets depict an empty outline of a human body onto which one can draw and write how they are experiencing different parts of their body, as shown in Figure 3-5. A list of evocative adjectives, which may or may not be used, is also provided to suggest how subjective feelings could be articulated.

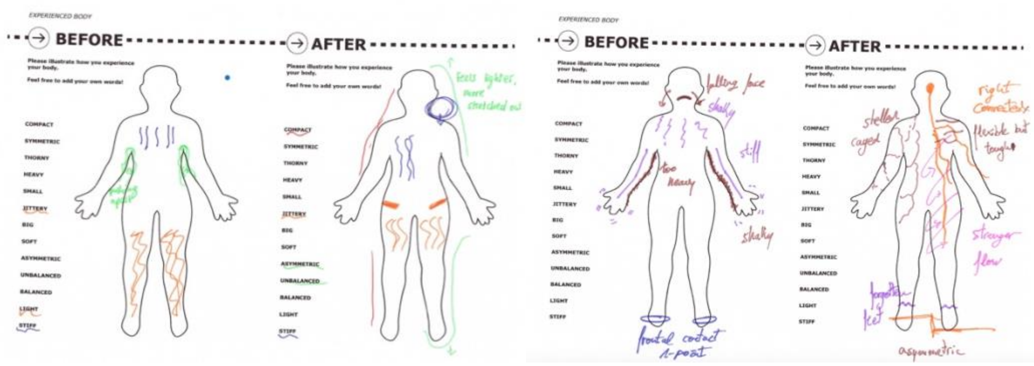

Figure 3-5: Two examples of body sheets, which we filled out at several times during each soma design session

After shortly discussing the body sheets, we moved on to our material exploration of the inflatable pads and the breathing sensor. Our approach was based on several works documented in the literature [23], [25], [70], [73], [82]. We each took turns during the exploration to allow every participant to experience the actuation for themselves. While one person was wearing the breathing sensor around their torso and placing the inflatable pads on different parts of their body, the others were directing and observing the exploration as well as managing the actuation sequences and taking notes on the comments made by the other participants. However, this meant that it was not possible to let one person explore the same actuation pattern for an extended amount of time.

After the exploration, we filled out another body sheet to reflect on potential changes in our bodily experiences. Lastly, we had a final discussion about what resonated with us during the design session, what surprised us, what felt uncomfortable, what was missing during the exploration and what needed to be developed or changed for the next session.

3.3.3 Evolution of the Design Process

The interaction with the pads was based on an approach developed by Anna Vallgårda [70], called Props for Embodying Temporal Form. It aims to open up the design space around specific actuators by exploring them in relation to the body. This enables researchers to discover the affordances of these technologies and allows for new forms of interaction to emerge. As proposed by this method, we placed the inflatable pads on different parts of the body and investigated how different "temporal forms", i.e. different actuation sequences and patterns, are experienced. Furthermore, we also positioned the pads between our bodies and another surface, such as the floor, the wall, a chair or another person, or strapped them to our body with a scarf or a belt (see Figure 3-6).

Over the course of the sessions, we expanded our repertoire of shapes, actuation sequences and additional materials. During the first session, we only used a single actuator with inflation patterns based on breathing. Starting from the second session, we included a second actuator as well as actuation sequences which were not linked to the sensor data. In the third session, we were joined by another PhD student who provided a unique experience as a product designer unfamiliar with soma design or HCI. During this session, we used a smaller inflatable pad and asynchronous actuation patterns for the first time. We built three more pads for the last session, two smaller ones and one large round pad, and used an exercise belt to strap them to our body, which was the closest we came to an actual wearable garment. This was also the only session in which we incorporated noise-cancelling headphones and short pauses in the breathing-based actuation sequences to suggest breath holding.

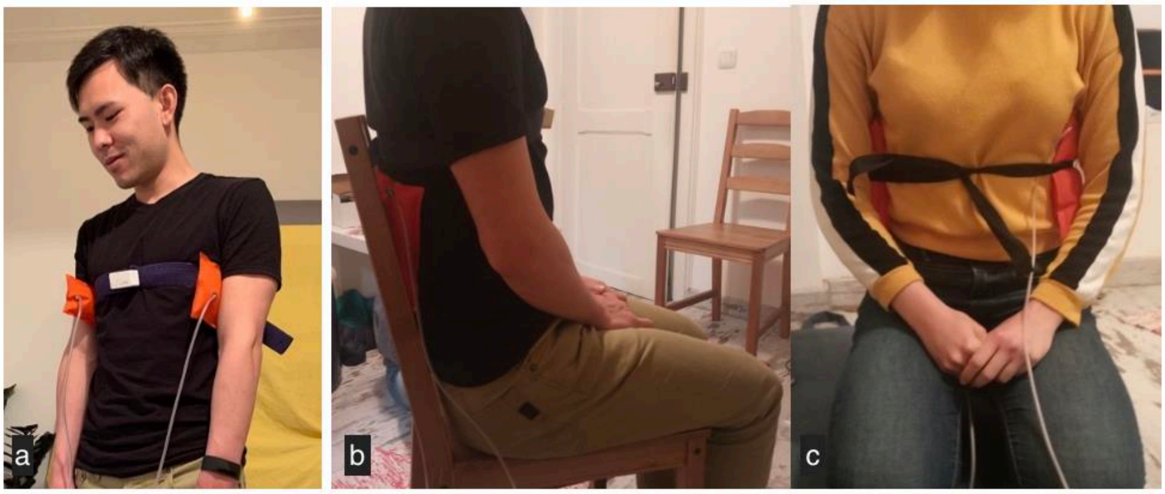

Figure 3-6: Different placements of the inflatable pads: a) under the arms, b) between back and chair, c) on both sides of the stomach secured by a strap

3.3.4 Data Collection and Analysis

In addition to filling out body sheets at several points during each session, we also documented our process by taking pictures and videos. During the exploration, at least one person was always tasked with documenting the structure of the session and interesting observations. Furthermore, we each took notes during the final discussion and compiled them in a single document after the end of the session.

To analyze the collected data, I used both top-down and bottom-up approaches. First, I classified each observation into one of eight categories: New learnings, exploration, material limitations, missing information, potential use case, challenging what is given, improvements compared to the previous sessions, and future work. Then, I compared the insights over the course of the four soma design sessions to identify any recurring themes and common threads throughout our exploration.

As a second step in the analysis, I created an affinity diagram [83]. I wrote each observation on a separate note and iteratively sorted all of them into small groups according to similar issues and themes, taking care to put aside the previously identified categories to let new themes emerge. Each group was given a title to define their common theme and further classified into higher-order groups. In total, I identified seven main themes: observations related to our design procedure, unexpected experiences, distractions from the bodily experience, material and embodied influences, negative or uncomfortable experiences, different modalities of perceiving the inflatable pads, and potential applications for future designs.

3.4 Initial Exploration of Breathing Techniques

During the soma design workshops, interesting interactions between the pressure and breathing emerged. This led me to turn towards connecting the shape-changing pads more directly with specific techniques for breath regulation, consisting of controlling the duration of inhalations and exhalations or alternating between diaphragmatic and thoracic breathing. For this purpose, I conducted two more design sessions by myself in a similar manner to the previous soma design sessions. They were focused on exploring the short-term impact of different breathing techniques from psychotherapy literature [84], [85] and yoga practice [86], guided by the pads.

At the beginning of each session, I followed a 20-minute gentle yoga practice to sensitize myself to my bodily responses and breathing. After filling out a body sheet, I explored different actuation patterns, pad positions and body positions for about an hour each time, before filling out another body sheet at the end. During the exploration, I used the two medium-sized inflatable pads as well as the exercise belt from previous sessions to hold them close to my body. Underneath this belt, I wore a RIP breathing sensor which was connected to a R-IoT device. Furthermore, I put on noise-cancelling headphones to listen to white noise throughout the entire session which allowed me to focus on my body and the sensation of the pressure applied by the pads rather than the auditory feedback caused by the actuator pumps.

3.4.1 First Session

For the first session, I created three new breathing techniques to explore different durations of inhalation and exhalations (see Figure 3-7, first three techniques). Each had two versions, with the pads either inflating synchronously, i.e. at the same time, or asynchronously, i.e. in the opposite rhythm. In the synchronous versions, inflation corresponded to inhalation and vice versa. The first pattern was based on a breathing rate of 5.5 breaths per minute with equal duration of inhale and exhale which has been associated with increased heart rate variability and relaxation [85]. Another technique that has been suggested to reduce anxiety and improve sleep is the 4-7-8 technique [84] which calls for inhaling for a count of 4, holding the breath for a count of 7, and exhaling for a count of 8. I implemented this as well, choosing a duration of 4s, 7s and 8s for the respective intervals as is frequently recommended. Third, I selected a simpler 3-3-2 pattern, i.e. inhaling for 3s, exhaling for 3s and holding the breath for 2s. I found these shorter intervals to be closer to my regular breathing rate. Lastly, I also included the breathing feedback pattern which I had already used during the soma design sessions. It reflected my own breathing intervals while multiplying them by 1.5. This factor was chosen since it was able to slowly and noticeably increase the duration of a single breathing cycle over time without making the difference between two successive intervals too large. To explore each of these techniques, I put the pads on different places on my stomach and chest and followed them for several minutes while lying on a yoga mat, sitting on a chair or leaning against the wall.

3.4.2 Second Session

During the first session, I found the pads to be effective in directing my breathing when placed on my upper or lower back. This led me to look into diaphragmatic and thoracic breathing exercises, specifically those used in yoga practice. Diaphragmatic breathing is used in therapy to manage anxiety and stress [87] and has been shown to provide cognitive and mental health benefits for healthy individuals as well [88]. Furthermore, it is part of several yogic breathing techniques, such as the three-part breath [86] which is often used at the beginning of a practice to transition from daily life, focusing one's attention on the present moment and the sensations of one's physical body. During this technique, yoga students are encouraged to first take about five deep stomach breaths and then five deep chest breaths. Lastly, both are combined by first filling the stomach with air and then letting it expand into the rib cage and chest. During the exhalation, the air is first released from the chest, followed by the rib cage and lastly the stomach.

I used this technique as inspiration to create two new actuation patterns, intended to be used with one pad placed on the lower back and one placed on the upper back. These patterns were designed to combine several aspects of previous patterns which have been shown to provide a relaxing effect, namely prolonged breathing intervals and a focus on diaphragmatic breathing. I was intrigued by the switch between diaphragmatic and thoracic breathing since it requires a certain amount of awareness and control of one's breathing movements and body. Thus, the first pattern was intended to encourage this change between stomach and chest breathing. It consists of inflating and deflating one pad for a certain amount of breaths at a speed of 6 breaths per minute, and then switching to the other pad for the same duration. This allowed me to practice switching between diaphragmatic and thoracic breathing and explore their different effects. The second pattern mimics the last phase of the three-part breath technique as described above. The pad placed on the lower back is inflated first, followed by the pad on the upper back. Then, the latter is deflated again, and finally the pad on the lower back. Each inflation and deflation interval has a duration of 3 seconds. Including the 2 second pause in between breaths, this results in a breathing rate of about 4.3 breaths per minute (see Figure 3-7, last technique). In the following chapters, I will refer to this technique as the three-part-breath pattern.

3.4.3 Data Collection and Analysis

During the two sessions, I spent about 5-10 minutes exploring each breathing technique. Before moving on to the next, I took a few minutes to reflect on my experience while following the pattern, particularly regarding any potential differences between different techniques, body positions or placements of the pads on my body.

In addition to the body sheets which I filled out before and after each session, I documented my observations by keeping a diary of the different effects on my breathing and bodily experience. To analyze the collected data, I conducted a brief thematic analysis and evaluated the suitability of each breathing technique for supporting relaxation and body awareness.

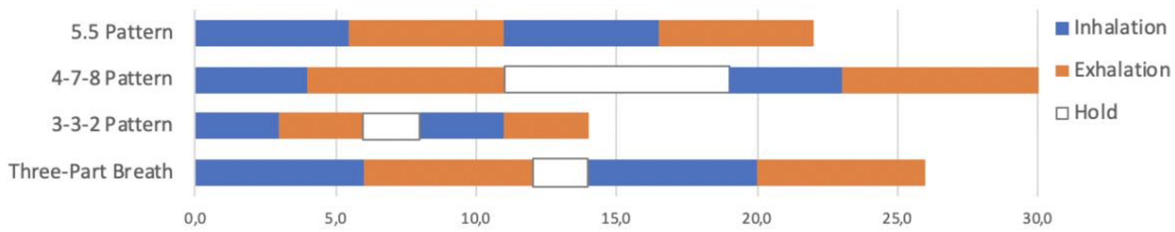

Figure 3-7: Interval lengths in seconds for two breathing cycles of each new breathing technique with fixed intervals

4 Design Exploration

This chapter presents the results of my initial exploration of the materials and breathing techniques. I will first summarize what I learned from the interviews with the three psychologists, followed by the results of my initial material exploration, the soma design sessions and lastly the exploration of different breathing techniques.

4.1 Interviews

Two of the psychologists I interviewed are currently working or have in the past worked with clinical patients, one with children and the other with adults suffering from common disorders, i.e. depression and anxiety. They mainly use transdiagnostic treatments and cognitive-behavioral therapy which teaches patients to challenge and restructure their harmful thought patterns. As part of the treatment, they often incorporate breathing exercises to help patients relax, for example breathing together, instructing them to take deep breaths or to squeeze certain muscles in a specific order. In sessions with children, one interviewee also uses easy cognitive exercises such as puzzles to distract patients and help them to calm down.

All of the psychologists emphasized that physical reactions are a very important component of common affective disorders, and thus should also be addressed in therapy. While none of them had heard of deep touch pressure therapy before, one stated that she had instinctively used similar techniques before to calm very upset children, by "just grab[bing] them and hold[ing] them until they calm down". She had also noticed that children on the autistic spectrum like to hug themselves when they are overwhelmed, which made her think that DTP garments could be helpful for these patients. However, in her opinion, it would be more helpful to create something that can guide people to breathe in and out for a specific amount of time. Regarding the placement on the body, she favored the upper body, especially the upper arms. She would not consider placing something around the shoulders or neck because people with an anxiety disorder often feel like they cannot breathe. Therefore, a garment which extends to these areas might exacerbate rather than soothe their symptoms.

4.2 Initial Material Exploration

At first, I explored the EMG, ECG, EDA, PZT and RIP sensors by themselves using the BITalino visualization software OpenSignals. I attached the sensors to my body and tried to manipulate the signals by taking exaggerated breaths, holding my breath or moving around. Furthermore, I took long-term recordings (>20 min) and inspected the changes over time by visualizing them in graphs and calculating various features such as the mean value and standard deviation. This allowed me to learn about the affordances of each sensor and decide which of them would be appropriate for a wearable garment designed to support body awareness and relaxation.

It became clear that some signals were easy to manipulate, such as the respiration and EMG signals which reacted immediately even to small movements or changes in breath. On the other hand, EDA and ECG were much harder to influence, and it was not always evident why some actions led to changes in the sensor data while others did not. In particular, the EDA changes were very gradual and barely noticeable. These tests led me to extract several requirements on the sensors. Since I intended to couple the sensor data with DTP to draw attention to bodily sensations, the sensors should be suitable to provide real-time feedback which can reflect reactions to DTP in the moment rather than long-term trends. Furthermore, they should be linked to relaxation as one of my goals was to create a relaxing and calming experience. Based on these requirements, I decided to focus my further exploration on the ECG sensor to monitor heart rate and heart rate variability, as well as the RIP sensor to measure breathing. I chose the RIP sensor rather than the PZT sensor since it can provide more reliable data due to its lower sensitivity to the wearer's movements and the placement on the body. Both ECG and respiration sensor feedback have shown potential to manage stress and anxiety and promote relaxation [11], [89], [90].

I also considered measuring breathing with the pressure sensor that is part of the air circuit in the actuators. After strapping the inflatable pads tightly to my chest and stomach area, I plotted the pressure readings in a graph. In some respects, this worked even better than the RIP sensor. The RIP sensor contains a wire coil which is stretched during inhalation and relaxed when the wearer exhales or holds their breath. This makes it hard to distinguish between slow, shallow breaths and holding the breath, whereas the difference was much clearer in the pressure sensor readings. However, I decided not to use it going forward since its values strongly depend on the level of inflation: the more inflated the pad, the higher the pressure. The pads are not completely airtight which causes the pressure to slowly decrease over time, making the sensor readings less reliable.

In the next step, I combined the RIP sensor with the inflatable pads and explored different actuation sequences, including inflating and deflating the pads for the same amount of time as my average inhalation and exhalation, extending these intervals by a certain factor, using predefined actuation intervals, and soft pulsating. When using two pads at the same time, I experimented with inflating and deflating both in parallel, in opposite patterns, or with one being delayed by a few seconds. The sequences which simulated the user's breathing pattern were adapted to changes in real time to reflect their current breathing rate. The breathing data proved to be a good match for the inflatable pads, since their inflation and deflation were easily associated with the chest and stomach expansion caused by breathing.

However, I struggled to create a meaningful actuation sequence based on the HR and HRV features extracted from the ECG data. I found myself biased by my earlier exploration of the breathing sensors, which led me to try to fit the ECG features to a breathing pattern. This of course did not work since they are two very different biosignals. The inflation speed of the pads also turned out to be too slow to reflect the user's heartbeats. Eventually, I created a simple threshold algorithm to make the pads pulsate gently when the heart rate is low, and increase the speed and intensity of the pulsation if the heart rate exceeds a certain threshold.

During my exploration, I placed the inflatable pads on different body parts such as the arm, shoulder, or stomach. They seemed to react immediately to small changes in my breathing which made them appear very responsive and sensitive. If I stopped focusing on taking regular, deep breaths, the inflation and deflation intervals instantly became noticeably shorter. At first, the actuation intervals also seemed shorter than my natural breathing rhythm. This was likely due to a lack of feedback during the warmup, which meant that I often did not remember to take deep breaths during the first 30 seconds. To make the interval length feel more comfortable, I extended it by a factor of 1.2-2.0. As an added benefit, this caused the intervals to gradually become longer and longer, thus guiding me to slow down my breath. Progressively lowering the respiration rate has previously been shown to have a calming effect [63].

To be able to feel the pressure, the pads had to be placed underneath the body or strapped to the body with a fairly rigid material. It was not enough to hold the pad in place with my hands since I felt the pressure predominantly in my hands, distracting me from the body part on which the pad was placed. Elastic bands were also not a good option since they stretched to compensate for the expansion of the pad, thus failing to transfer the pressure to my body.

This first-person exploration allowed me to rapidly learn about the materials without first creating a working prototype. I had to physically try out the interactions on my own body, not just imagine them, to understand their impact on how I perceived my body [25]. For this reason, this method was ideal for a quick, initial exploration of the design space and the material affordances.

4.3 Soma Design Workshops

Based on my individual exploration of the BITalino sensors, I conducted four soma design workshops with three other researchers to explore couplings between the RIP sensor and the inflatable pads in more depth. The actuation sequences were the same as those I had used during my individual exploration, for example imitating the participant's breathing pattern or inflating and deflating for a specified amount of time. When using two actuators at once, they were sometimes inflated synchronously and sometimes asynchronously, performing the exact opposite or completely unrelated patterns. While the person experiencing the actuation was usually the one wearing the breathing sensor, we also experimented with one person feeling actuation patterns based on another person's breathing rhythm, as shown in Figure 4-1. We incorporated additional tactics used in embodied design [70] such as playing around with our senses by closing our eyes or wearing noise-cancelling headphones to block out any external stimuli.

Using these methods, we tried to disrupt the usual way of breathing to deconstruct the breathing experience and explore how it could be used in design. The pressure provided by the pads allowed us to direct our attention inwards and focus more intently on individual body. This led to a number of discoveries which I will describe below.

4.3.1 All elements work together to shape the experience

During our exploration, we identified a number of components which contributed significantly to shaping the overall experience, including the shape of the pads, their position on the body, the additional auditory feedback caused by the actuators, our body position and the Feldenkrais practice. The inflatable pads turned out to be very versatile: smaller shapes were able to apply more intense and localized pressure, while the bigger shapes distributed the pressure over a larger area of the body. However, they all required some form of support pressing them against the body in order to be effective. This led us to discover three different modalities of interaction: Using the body weight by sitting, leaning or lying on the pad; strapping them to the body with some kind of rigid, inflexible material; or consciously holding the pad in the hands, between the knees or under the armpits. The former was more passive, while the latter required us to actively hold the pad in place.

The position of the pads on the body also changed how we perceived the pressure. It felt more comfortable and engaging when applied to the upper body and the torso compared to the lower body. One participant stated that they expected to feel breathing actuation on their torso or upper body. Therefore, putting the pads between the knees or under the thighs felt "weird, like it's not supposed to be there". Generally, putting two pads simultaneously on different body parts made it hard to decide where to direct our attention which created an ill-fitting, incongruous experience. However, placing them on only one body part or symmetrically on either side of the body allowed us to become more aware of how we experienced that specific body part. The physical sensations were felt more intensely, which often persisted even after the workshop was over.

Another element contributing to our exploration was the rhythmic noise caused by the air pumps in the actuators. While some participants perceived them as relaxing, others found them annoying or distracting since they ended up focusing more on the sound than on the pressure, diverting their attention away from their bodies. During the last design session, we introduced noise-cancelling headphones which helped us to stay focused on the pressure applied by the pads and on our breathing instead of the actuator sound.

In addition to the technological materials, we also found that the shape and position of our bodies influenced our experience. Sitting or lying down allowed us to place the pads underneath our bodies which made it easier to feel the actuation and gave us more options to explore. This also applied to explorations with two people who placed one pad in between their bodies to experience the

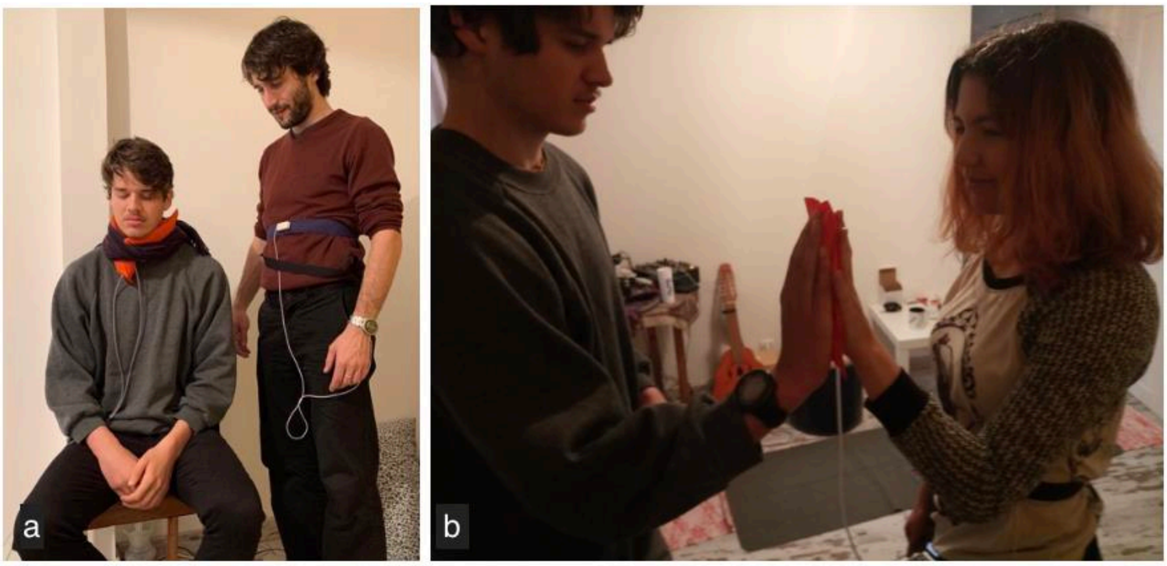

Figure 4-1: Pairing up to experience another person's breathing: a) Putting two pads on the neck, secured by a scarf, b) Holding the pad between our hands

actuation patterns at the same time. While this proved to be difficult when standing up due to differences in height, it was much more comfortable when sitting back-to-back or when pressing the soles of our feet against each other.

The Feldenkrais practice at the beginning of each session was essential for allowing us to turn our attention inwards and listen to our physical signals. It made us feel more centered and grounded in our bodies which also directly influenced the following exploration. Several Feldenkrais recordings were only working with one side of the body which created an imbalance in our bodies, as if one side was longer or heavier than the other. In those workshops, we then went on to explore one-sided and asynchronous actuation patterns by placing the pads on only one side of the body, inflating and deflating them in opposite rhythms, or executing two completely unrelated actuation patterns at the same time. Another example of this occurred when we put the pads under our feet using an asynchronous actuation pattern which caused our feet to move up and down in a manner similar to walking movements. Just like the Feldenkrais practice titled "Learning to walk again" which we had completed before, it slowed down and disrupted the habitual way of walking.

4.3.2 From relaxing to anxiety-inducing

We found that the pads were able to evoke a wide variety of emotional reactions depending on the actuation pattern, which body part they were situated on, and how they were held. This opens up the design space for many different applications.

On the shoulders and back, the pressure felt very comfortable and soothing and was often compared to a massage or to "someone putting a comforting hand on your shoulder". One participant associated asynchronous actuation patterns on the shoulders and back with a "kneading cat", an activity which cats only perform on soft surfaces when they are happy and at ease. Furthermore, placing the pads near the lower back or waist area when sitting on a chair or lying down provided a sense of support and stability, which made us feel secure and comforted. The pressure was also experienced positively on the stomach area, but much less engaging compared to the shoulders and back. It was barely noticeable when sitting; instead, we had to lie down on our stomach on top of the pad.

By contrast, the pads were also able to induce anxiety when placed on more sensitive body parts. Putting them anywhere close to the neck or face created an invasive, uncomfortable experience. While they did not obstruct our breathing physically, they created an impression of not being able to breathe properly which might be similar to what an anxiety or panic attack feels like. Several participants compared the experience to the feeling of "having a snake wrapped around your throat".

Other explorations provoked neither a strong negative nor positive reaction. As mentioned before, placing the pads on the lower body felt rather uncomfortable and unnatural since the participants could not relate those body parts to their breath. Furthermore, the pressure also had little effect if two pads were used simultaneously with very distinct actuation sequences. This sometimes led one or both pads to inflate during an exhalation or deflate during an inhalation which was experienced as hindering and annoying rather than supportive. Thus, when using two different actuation sequences at the same time, it is important to make sure that they do not actively work against each other in order to create a cohesive experience.

4.3.3 Pads take different roles in the interaction

During our exploration, we found that the pads were able to take on different roles in the interactions. In some cases, they were perceived as giving breathing instructions even though we did not provide any rules or advice to adapt the breathing to the inflation. Nevertheless, one participant seemingly felt like they were doing something wrong if they were not able to match their breathing to the actuation. The lack of pressure during the shift from deflation to inflation caused them to feel "lost till [they] realized [they] should have been inhaling already". This shows that the pads were perceived as guiding or even steering the breath. They also influenced our physical form by moving body parts up and down or by prompting us to sit up straight.

On the other hand, the pads also took a more passive role in the interaction. At times, we were deliberately breathing in a different rhythm in an attempt to control or influence the pads to inflate more slowly or quickly. This was quite difficult and required us to focus on our breath, diverting our attention away from the haptic feedback and how it was impacting our bodies. The interaction became centered on the inflatable pads themselves as a separate participant. These two modalities created an interesting contrast between breathing "with" the pads when following along to the actuation pattern and breathing "against" the pads when trying to change the pattern. However, it was not always clear whether the pad was adapting to the breathing or vice versa, which introduced a sense of ambiguity in the interaction.

The pads were seen as active partners in other contexts as well. We often talked about them as if they were another living being that "needed to be held" or that was actively "supporting as well as pushing the body". Sometimes, we were neither trying to follow nor influence the pad, but simply breathing in our own rhythm alongside the actuation. In such situations, the pads became like a companion, providing a soothing sense of presence while allowing us to experience our own breathing and the pressure simultaneously. The actuation pattern was not distracting, but rather seemed to complement our individual breathing rhythm.

Lastly, the pads also served as a communication channel to share our breathing with another person. We explored this in different positions. In some cases, one person was wearing the breathing sensor while the other placed the pads on their own body. In others, two people were experiencing the actuation at the same time, making indirect contact through the pads by standing side-by-side, back-to-back or pressing their hands or feet against the pads from either side. One participant remarked that it felt "less invasive than direct [physical] contact", which suggests that this could be helpful in a potentially sensitive situation in which direct physical contact would be uncomfortable. For example, the pads could be used in therapy to let patients share their experience with a therapist or to let the therapist guide the patient's breathing.

4.3.4 Emphasis on embodied experiences

Throughout the soma design sessions, we found that performing a Feldenkrais practice at the beginning was essential to sensitize ourselves to how we experienced our bodies, shaping the following exploration and making it easier to reflect on its effects on our somatic sensations. Some Feldenkrais practices were centered around a single side or area of the body, for example the shoulders. As a result, our exploration of the inflatable pads and actuation patterns was also focused on those same body parts, trying to create a similar feeling of asynchronicity and imbalance.

There are other parallels to be drawn between the Feldenkrais practices and our exploration. Some of the Feldenkrais recordings instructed us to perform very small movements with one body part which changed the way we experienced and moved our entire body. For example, executing small foot and shoulder movements during a practice titled "Learning to walk" completely changed how we carried ourselves when walking through the room. Similarly, we found that placing the pads on one body part sometimes affected our entire body. For example, putting them on the neck or lower back made us sit up straighter. We also tried an asymmetric actuation pattern which caused one pad to inflate and deflate twice as fast as the other. Placing the pads on either side of the stomach made the entire body sway and twist from side to side.

Additionally, these exaggerated movements sometimes helped us to experience our breathing more intensely. While sitting down, we placed the large round pad between our back and the chair. Its inflation and deflation pushed the entire upper body back and forth in a way that mimicked the chest expansion and contraction during breathing. Placing one pad underneath each armpit also turned out to be effective for guiding sustained breathing. The inflation pushed our arms a little away from the body, which seemed to direct the natural chest expansion of the breath. It created a sensation of equal pressure on both sides of the torso, which we related to a pressure vest.

Overall, the pads were able to support our breathing and guide us to attend to different body parts. At the end of each session, we were left feeling much more in touch with our bodies, calmer and more centered in ourselves. One session in particular stands out, at the start of which I felt very anxious and worried. I was preoccupied with other thoughts which made me unable to focus on my body and notice my physical sensations. However, exploring the inflatable pads with an exercise belt tightly wrapped around my entire torso succeeded after a while to bring my attention back to my physical self. I ended the session in a much more relaxed and calm state, feeling more connected to my body and somewhat comforted. To me, this powerful experience demonstrated the potential of combining haptic pressure actuation and gentle breathing guidance to ground ourselves within our bodies and provide a relaxing yet stimulating experience.

4.3.5 Learning from Failures

During our explorations, we did not always succeed in creating interesting experiences. In the first workshop, we realized that we could not just hold the pads with our hands since the feeling of pressure became too dominant on the hands and could barely be felt on the targeted body part. Instead, we needed to strap the pads to our body with an inflexible material. This turned out to be quite difficult, especially on areas like the shoulders or the stomach. We also had to design the actuation patterns carefully to allow them to guide the breath. During one of the workshops, we placed one pad on the stomach and one on the chest and let them inflate in an alternating rhythm. Our idea was to use the pads to help us focus on either diaphragmatic or thoracic breathing. However, being on two different body parts, the pads interfered too much with each other and were never quite able to guide our breathing.

At the beginning, we found the actuation sequences which were based on breathing sensor data to be inaccurate. There was a small delay between the actual breathing and the actuation, and the intervals were often perceived as too short. Additionally, we were missing a hold phase during the first three workshops. This meant that the pads were always either inflating or deflating, while a natural breathing pattern contains a short pause before each inhale and exhale. At first, we incorporated both the duration of the participants' inhale and exhale in the actuation. However, they were quite uneven which led the pads to be either close to bursting or not inflated enough to exert noticeable pressure. While these problems were not so distracting as to severely impact our exploration, we were quickly able to solve them by making changes in the code on the fly. Other obstacles even provided ideas for our exploration. We frequently used two medium-sized pads, one of which was slightly larger than the other and thus needed more time to inflate. This caused the pressure to be slightly uneven which inspired us to explore asymmetrical actuation sequences.

Some participants found the sound of the actuators to be immensely distracting. The air pumps were quite loud, which made it possible to adapt our breathing to the sound instead of the pressure applied by the pads. At times, the sound was much more prevalent than the pressure, which could barely be felt when the pads were deflated, making us uncertain of how to breathe. Interestingly, other participants perceived the actuator noise as soothing and relaxing. We were able to mitigate this problem by wearing noise-cancelling headphones playing white noise during the last workshop.

4.4 Towards A Final Use Case: Yogic Breathing

4.4.1 Evocative material qualities of inflatable pads and open questions

Following the initial exploration of the biosensors and pneumatic actuators, I turned to further investigate their most evocative qualities in the second phase of my design process. While my original goal had been to design a DTP garment for anxiety and stress management, the exploration of the pads had led me to turn towards using them to cultivate body awareness and well-being through breathing exercises. Thus, going forward I focused on those material elements which had shown potential to support breathing and relaxation during the soma design sessions.

During my previous explorations, I had successfully used the inflatable pads for breathing guidance by providing breathing feedback or simple predefined breathing intervals. From my interviews with psychologists, I had learned that exercises such as breathing together with the patient or instructing them to take deep breaths are used in therapy to help patients to calm down. Breathing also plays an essential role in bodily practices like Feldenkrais or yoga which can improve body awareness and well-being [91], [92]. Therefore, I decided to explore the impact of different breathing techniques used in therapy and meditation practice, guided by the pads.

The initial exploration and interviews revealed the torso to be the most effective area to place the pads. I discarded the neck and shoulders since this position was experienced as too invasive, as well as the lower body where the pressure was difficult to relate to the breath. However, it remained unclear whether the stomach, chest, upper or lower back areas were equally suitable for breathing guidance.

Going forward, I decided to use two medium-size pads since they can provide more localized pressure which is more noticeable than the distributed pressure caused by large pads. Additionally, they are small enough to be placed side-by-side or on opposite sides of the body simultaneously, which increases the available options for different actuation patterns.

The last open question was concerned with the targeted use cases. Should the pads be used while lying down and meditating, while sitting, while standing? During the previous exploration, I had decided to focus on single-person actuation. However, both sitting and lying down had been able to provide interesting experiences, and thus lent themselves to be investigated further.

4.4.2 Session 1

During the first session, I tested three new breathing techniques - the 5.5 pattern, the 4-7-8 pattern and the 3-3-2 pattern - as well as a standard breathing feedback pattern. Overall, I found that each pattern allowed me to focus on my breathing and become more aware of my body. Even hours after the session, I was still breathing more consciously and deeply and felt more relaxed. However, it is difficult to compare the effect of different breathing patterns since I used them all in direct succession.

Due to the shorter intervals, the 3-3-2 pattern turned out to be the easiest to sustain for several minutes without requiring much focus. On the other hand, I could only follow along to the 4-7-8 pattern for a few breathing cycles that required all of my concentration. At least for a beginner who is not used to taking such deep breaths, this technique does not seem suitable for prolonged use. The constant 5.5 breathing rate fell somewhere in the middle between these two patterns. It was easier to sustain and required less attention since all actuation intervals had the same length. After a while, I began to subconsciously predict when the pads would begin to inflate or deflate which allowed me to shift my focus to other aspects of the experience. Since the longer intervals encourage the user to breathe more deeply, this might give the 5.5 pattern an added benefit compared to the 3-3-2 pattern. Lastly, the breathing feedback seemed a little inaccurate during the exploration. The intervals were quite short and varied considerably from breath to breath, which prompted me to adjust the sensor data processing after the session. I combined intervals with a duration of less than 1 second with the previous interval since they were likely to be faulty and added a variable hold interval in between breaths which could be adjusted easily during the exploration.

The pressure was less effective when the pads were placed on the stomach. Since they were pressing down on my body, they were hindering my ability to breathe deeply. Breathing in an opposite rhythm, i.e. inhaling when the pads were deflating and vice versa, felt more comfortable, but required much more concentration. With this technique, the inflating pads seemed to push the air out of my stomach and thus support my exhalation. However, this pattern was very unfamiliar at first because it combined inflation with exhalation, unlike every other pattern I had tried so far. During the exploration, the pads gave the impression of a small extra pair of lungs, providing additional visual feedback and reinforcing my breath. While they restricted my breathing when placed on the stomach, putting them on my back instead caused them to push my body forward, engaging me to breathe more deeply. Compared to the stomach, the pressure was more noticeable on the back and felt more comfortable when sitting or lying down. Furthermore, I found that putting the pads on the lower back when lying down encouraged me to breathe more with my stomach, while placing them on my upper back made me breathe more with my chest. The inflation and deflation of the pads seemed to direct the natural expansion and contraction of the stomach and chest during the breathing cycle.

Lying on my back also made it easier to take deep breaths, compared to lying on my stomach or sitting. However, both lying down and sitting seemed to be useful for different purposes. Focusing on my breathing while lying on my back was akin to a meditation practice. Thus, this could be integrated into a regular practice or support small breaks in between other activities. On the other hand, putting the pads near the lower back or waist area when sitting on a chair provided a sense of support and stability. Furthermore, this position allowed me to do other tasks simultaneously which suggests that the pads could be used to provide gentle reminders to breathe deeply during work tasks such as writing or reading. It is easy to switch between sitting and lying down, which allows the wearer to choose whatever position they feel can bring the most benefit in the current moment.

4.4.3 Session 2

During the first session, I found that placing the pads on my upper and lower back was effective to guide me to predominantly use my chest or stomach while breathing. To explore this further in the second session, I created two new breathing patterns based on diaphragmatic and thoracic breathing exercises used in yoga practice. These patterns were intended to be used with one pad placed on the lower and the other placed on the upper back. The first pattern only activated one pad at a time, guiding me to alternate between diaphragmatic and thoracic breathing for a certain number of breaths. The second pattern corresponded to the three-part breath technique originating from yoga practice. Both turned out to be effective for guiding me to use my stomach or chest while breathing. However, I could only follow the actuation for a few minutes at a time since both patterns provided a fairly slow breathing rate of respectively 6 and 5 breaths per minute. This can be expected since I do not practice deep breathing exercises regularly. Beginners are usually recommended to start slowly and work their way up to a longer practice to become used to taking deep breaths.

When switching between diaphragmatic and thoracic breathing, I found the former to be more relaxing and comfortable. This is supported by research showing that regular diaphragmatic breathing practice can reduce anxiety levels [50]. Due to the guidance provided by the pads, the change required little effort or conscious thought. I was able to focus on my breathing and how I experienced my body; however, the switch from one pad to the other was very surprising and took me out of the experience each time. Therefore, this actuation pattern seemed to be ill-suited for an extended practice. It could be useful as a first step to teach beginners to become more aware of the difference between diaphragmatic and thoracic breathing or to sensitize oneself at the beginning of a deep breathing practice.

While the three-part breath pattern was a little more complex than other breathing techniques I had tried before, the pressure against my lower and upper back was very effective in guiding my breathing from my stomach to my chest and back. I did not have to think about how I was supposed to breathe and was able to focus on relaxing my body and distancing myself from any worries or conscious thoughts. Compared to lying on my back, the pattern was less effective when sitting since I could not feel the pressure comfortably on both my upper and lower back in this position. However, this was easier when sitting with a straight back, suggesting that the pads could also be used to support a good posture when sitting for longer periods of time.

In addition to these two patterns, I also experimented with an asynchronous pattern which inflates one pad while deflating the other and vice versa. However, this was very unpleasant and made me feel a little dizzy. This suggests that the actuation should always be focused either on the upper or lower back, but not both at the same time to avoid motion sickness.

5 The Breathing Garment

5.1 The Final Design

During the majority of my design process, I used an exercise belt (see Figure 3-2b) to keep the inflatable pads in place. While this worked fine, it was a little difficult to put the pads on the right place on my back by myself. Thus, to make handling the inflatable pads easier, I created a garment in the shape of a vest (see Figure 5-1a). On the inside of the back part of the jacket, two pockets are attached to hold the pads, one on the lower and one on the upper back (see Figure 5-1b and c). The bottom pocket is big enough to fit two medium-sized pads side-by-side, while the top pocket can fit one medium-sized pad.

The garment had to fit tightly around my upper body, but still leave enough room to allow the pads to inflate without making it difficult to breathe. Therefore, I tailored the vest according to my body measurements to make sure that it was tight but not uncomfortable. Unfortunately, this means that the vest is only usable by people with a similar body type to mine and cannot be created as a unisex or one-size garment. It is made out of a firm and resistant material so that it does not expand when the pads inflate, but rather holds its shape to transfer the pressure. It can be closed in the front with a hook and loop fastener. On one side, two loop strips are attached side-by-side to allow the wearer to slightly adjust the tightness of the vest if required.

The two air tubes which are used to inflate the pads can be pulled through a small hole in the middle of the bottom seam of the lower pocket. After the pads are attached, they can be positioned in the pockets. The three-part breath actuation pattern is intended to be used with one pad placed in each pocket so that one puts pressure on the upper back, while the other presses against the lower back. All other actuation patterns are used with both pads placed side by side in the bottom pocket.

The vest leaves enough space to wear the chest strap required for the respiration sensor (see figure 5-2a) underneath. The RIoT Bitalino, which is connected to the respiration and ECG sensors, can either fit underneath the vest or stay outside and rest on the floor or on a desk next to the user. After positioning the sensors, the user can put on the vest and close it tightly with the hook and loop fastener, as shown in figure 5-2b. The pads are hidden underneath the vest and inflate inwards, which makes the actuation invisible from the outside.

Figure 5-1: The vest prototype: a) closed, b) both pads in the bottom pocket, c) one pad in each pocket

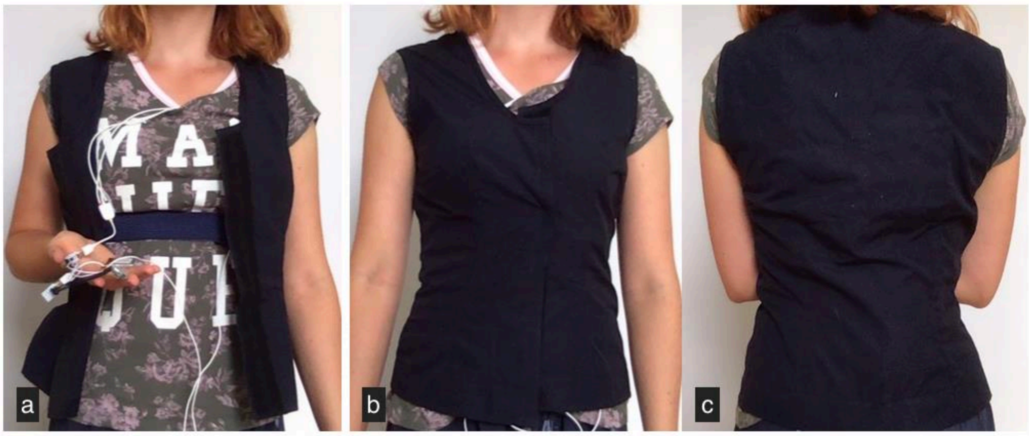

Figure 5-2: Wearing the vest: a) the chest strap for the RIP sensor and the electrodes for the ECG sensor are worn underneath the vest, b) the sensors are hidden when the vest is closed, c) the inflated pads are not visible from the back

5.2 Use Case: Breathing Guidance

My exploration of different breathing techniques led me to identify five patterns which I found to be the most interesting and impactful. However, I only tested each of them for a few minutes at a time during the design sessions. While this allowed me to investigate the pads' effectiveness to guide different manners of breathing and their short-term impact on my bodily experience, it left the question as to what kind of effect the pads could have when used over a longer period of time. Thus, I decided to explore the five most evocative actuation patterns for a longer duration as a final evaluation of the concept. I chose the following patterns:

1. 5.5 pattern: Providing a constant rate of 5.5 inflate/deflate cycles, i.e. breaths, per minute
2. Three-part breath pattern: as described in chapter 3.4.2, with inflation/deflation intervals of 2 seconds for each pad and a 1 second pause in between breaths
3. Standardized breathing feedback based on RIP sensor data with a 2 second pause in between breaths. It mirrors the user's breathing intervals, multiplied by 1.7 to gradually increase the duration of one breath.
4. Adaptive breathing feedback with an actuation change triggered by rapid breathing. At baseline, the inflation speed is set to 50% of the maximum, which makes the pads less noticeable. If the calculated inhale or exhale duration is considered too fast, i.e. shorter than 2 seconds, the inflation speed is increased to 100% until the intervals become longer again.
5. HRV feedback based on ECG sensor data: The ECG data recorded during the first 30 seconds is used as a baseline to calculate the LF/HF ratio, which is an HRV feature often used as an indicator for stress [93]. When it is close to or below the baseline, the pads are inactive. Once it increases by more than 50%, indicating significantly elevated stress levels, the 5.5 breathing pattern as described in 1 is activated until the LF/HF ratio decreases again.

To explore these five patterns, I finalized the set-up for the inflatable pads and biosensors. Since I created the garment in parallel, I could only use it during the second half of this final evaluation. Before it was ready, I used the exercise belt to keep the two medium-sized inflatable pads in place. Below, I wore a RIP and an ECG sensor which were connected to an R-IoT device. Additionally, I used noise-cancelling headphones which played white noise to block out the sound of the actuator pumps and force me to rely exclusively on the pressure to guide the breathing techniques.

Figure 5-3: Node-RED interface used during the second design phase: a) Interaction flow, b) User interface

As during the previous soma design sessions, the actuation was controlled through a simple Node-RED interface (see Figure 5-3) which allowed me to easily switch between patterns and adjust certain parameters on the spot. I added new actuation patterns for each breathing technique to the previous interface (see Figure 3-3), as well as an option to quickly adjust the hold interval of the standardized breathing feedback. Furthermore, I created the options to inflate or deflate the pads for a certain number of seconds, as well as to adjust the actuation speed between 0 and 100% of the maximum. Being able to quickly change those parameters was useful to find the appropriate starting level of inflation and actuation speed for each pattern at the beginning of the session.

5.3 Evaluation Procedure and Data Collection

I explored each of the five breathing techniques during 2-3 sessions with a duration of 30-60 minutes each. I conducted one to two evaluation sessions every day over a span of three weeks to examine the impact of the breathing practice over a prolonged period of time. During these sessions, I turned back to my overarching research question: Can a deep touch pressure garment support the wearer in engaging with semi-autonomous interactions with their breathing to encourage greater interoception and body awareness? My investigation of this aim was particularly focused on how the pads influenced my breathing, on the comfortableness of the set-up, and on any potential differences or similarities between the experiences caused by different breathing techniques.

Additionally, I questioned whether the breathing exercises could be integrated into daily tasks outside of a dedicated practice. If they could provide similar benefits in this context, it would allow users to easily make such a breathing practice part of their daily routine. Thus, I explored the pads in different contexts and positions, including when lying on my back or sitting on a chair, while working, writing, reading, or watching a movie. Furthermore, I frequently changed the parameters of each actuation pattern, such as the inflation speed or breath hold interval, to investigate which combination would be more suitable for the respective breathing technique and position.

I began each exploration session with a short body scan to attune myself to my emotions and bodily sensations. Afterwards, I put on the chest strap for the RIP sensor, as well as the ECG electrodes when using the HRV feedback pattern. On top of the sensors, I wore either the exercise band to keep the inflatable pads in place, or the vest as shown in figure 5-2b. Each session was focused on a maximum of two different actuation patterns or two different use contexts. I explored each combination for at least 20 minutes before moving on to the next to make sure that I was experiencing more long-term effects.

While following the breathing guidance, I took notes on my observations, taking care to interrupt other activities as little as possible. After each session, I spent a few minutes reflecting on the impact of the breathing exercises and the pressure feedback on my physical and mental state. I documented my experiences by taking pictures and notes of my observations and by keeping a diary of my physical and emotional experiences as well as notable changes in the RIP and ECG sensor data. As before, after the soma design sessions, I created an affinity diagram to analyze the collected data.

6 Results

The experiential impact of the different breathing techniques was shaped by several factors including the breathing rate, the inflation level and speed of the pads, the position of the pads, and the focus required in the respective use context. This chapter presents my experience of using different breathing patterns in different use contexts and body positions.

6.1 Impact of Different Breathing Techniques

6.1.1 5.5 and Three-part Breath Pattern: No Feedback, no Pressure

The 5.5 and the three-part breath pattern both keep a consistent pace and rhythm with a respective breathing rate of 11 seconds and 9 seconds per breathing cycle. Unlike the two breathing feedback patterns which adapt to and slowly extend the user's breathing rhythm, the 5.5 and the three-part breath patterns guide them to intentionally control their breathing to adopt a certain interval length or focus their breathing in a certain body part.

The two patterns were not influenced by my own breathing and thus provided no feedback, which was both positive and negative. On one hand, it was reassuring to know that the pattern would not be affected by my breathing rate. I did not feel evaluated or pressured to stick to the pattern, but rather free to follow the pads as much as I found beneficial in the current situation. This made me more comfortable to take small breaks from breathing deeply. For example, since the 5.5 second intervals were slightly too long to follow comfortably, I often took slightly shorter breaths to add a pause in between breathing cycles while still roughly following the guidance. On the other hand, I would have liked to receive feedback on whether I was breathing "in the right way" or becoming calmer. I could only rely on my own experiences and feelings to evaluate whether the breathing guidance provided by the pads had any effect, such as whether I was feeling calmer or more relaxed. There was no external, seemingly objective source to answer these questions, which left me no choice but to turn my attention inwards and reflect on my bodily signals. This helped me to sensitize myself towards subtle physical and emotional reactions to the actuation.

The three-part breath pattern presented an unfamiliar way of breathing and thus required a little more attention and practice until I was able to follow along without having to consciously control my breath. This was facilitated considerably by the pads which exaggerated my breathing movements by alternately pushing my chest and stomach forward. I experienced my breathing like a gentle wave flowing through my body, engaging my entire torso. In this way, the breathing practice turned into a holistic, full-body experience. This effect was more profound when I was lying down since the uniform contact to the floor allowed me to feel the pressure equally against my stomach and chest. Therefore, such a position seems to be the most suitable for the three-part breath technique.

However, I could not maintain the 5.5 pattern for more than a few minutes without becoming fatigued since the intervals were slightly too long to follow comfortably. It was easier to breathe along when lying on my back with closed eyes, but I still took frequent small breaks. It felt frustrating to not be able to follow the pattern exactly, which caused it to be less relaxing than the three-part breath pattern. In a few instances, I began to inhale or exhale before the pads were inflating or deflating, which created the impression that they were following me instead of the other way around. Nevertheless, even when losing track of the patterns, they still encouraged me to take deeper breaths compared to my normal breathing rhythm of 3-4 seconds per breathing cycle.

6.1.2 Standardized Breathing Feedback

The standardized breathing feedback pattern mimicked my natural breathing pattern without providing any instructions or evaluation of my breathing, which made the guidance more subtle and less intrusive than the others. Instead of pushing me to achieve a certain breathing rate, the pads served as a reminder to breathe regularly and evenly. They created the impression that I was following another person's breath, which is a technique used in therapy to help patients relax. Even when I was not following the actuation pattern, for example when taking a break to hold my breath, the pads seemed to be breathing for me. Since the breathing intervals were closer to my normal breathing rate, they allowed me to direct more attention towards breathing and maintain the breathing practice for a longer time without becoming fatigued.

The pads made my own breathing intervals more tangible and apparent and guided me to gradually slow down my breathing. This allowed me to intentionally adjust the length of my breaths without feeling pressure to adapt to a certain rhythm all at once. At times, it was hard to tell whether my breathing was adjusting to the pattern or vice versa, thus creating the impression that I was engaging in a dialogue with my body. The pads seemed to be a representation of my physical self rather than an external influence. They gave me space to observe my breathing and physical sensations while nudging me towards a state of deeper relaxation and calmness, which helped me to become more conscious of my breathing and feel connected to my body.

6.1.3 Adaptive Breathing Feedback

The adaptive breathing feedback pattern was set to a higher actuation speed when the duration of an inhalation or exhalation fell below a threshold of two seconds. While this small change was intended as positive feedback, it ended up impacting my experience negatively. I was constantly aware of the pads and the pressure, trying to identify the current actuation speed and keep my breathing intervals above the threshold. This required considerably more focus in the first few minutes after starting the actuation because I was less sensitized to the pressure.

When the intervals were becoming longer, I felt like I was doing something right; when they were getting shorter, I felt guilty and frustrated for not being able to breathe as deeply. As a result, I was mainly focused on monitoring the actuation speed instead of my breathing or other bodily experiences, and thus was unable to extend my breathing as much as when using the standardized breathing feedback. Instead of guiding me to attend to my bodily experiences and calm down, it drew my attention towards the pads as external elements. This effect was amplified when combining the breathing practice with another task. When inflating with maximum speed, the pads seemed to demand me to stop the other task and instead focus on breathing deeply. I felt like I was constantly being monitored which disrupted my concentration, causing stress instead of reducing it. It was a relief to take off the garment because I no longer felt pressured to actively control my breathing.

6.1.4 HRV Feedback Pattern

Unlike the other four actuation patterns, the HRV feedback was based on ECG data instead of respiration data. The actuation was activated when the LF/HF ratio, used as an HRV indicator to reflect stress levels [93], crossed a threshold determined by baseline measurements taken during the first 30 seconds of the recording. Since the measurements could not be mapped directly to inflation and deflation intervals, it was difficult to connect the actuation pattern with my bodily experience. In contrast to my breathing, I was unable to perceive changes in my HRV or influence it directly. This was frustrating because I did not understand why the actuation was sometimes activated and sometimes idle even though I did not feel any more or less relaxed or anxious. Rather than reflecting stress, the ratio seemed to be higher when working on cognitively demanding tasks such as writing or trying to recall a certain memory.

The actuation pattern was often activated for only one or two breathing intervals, repeatedly starting and stopping. The first inflation always came as a surprise since I was unable to feel and interpret my heart activity in the same way that I could perceive my breathing. Thus, I was constantly expecting the actuation to start which occupied most of my attention and prevented me from simultaneously engaging with any other tasks. It created a constant level of anxiety and pressure to lower my LF/HF ratio again, distracting me from the calming breathing exercises. Additionally, it was difficult to extend my breathing from a normal rhythm of about 2 second intervals to 5.5 second intervals from one breath to the next. However, this pattern caused me to take deeper breaths than normal, even when the pads were not inflating.

6.1.5 Actuation Switch

Whenever I switched to a different actuation pattern or adjusted a parameter, the pads were inactive for a few seconds. During this time, I often stopped breathing since I had become used to adapting it to the pads. Thus, when there was no actuation, I subconsciously felt like I was not supposed or allowed to breathe. In some instances, I started inhaling before I could actually feel the pads inflate. Upon realizing that I was not following the pads, I also held my breath and waited for the actuation to catch up.

6.2 Impact of Different Use Contexts

6.2.1 Improving body and breathing awareness

During activities which required less attention or when the breathing intervals were closer to my normal breathing rate, it was easier to relax and focus on letting the actuation guide my breathing. For example, I was able to subconsciously adapt my breathing to the actuation while I was reading but had to make a conscious effort to do so during more involved tasks like writing or watching a movie. I was least distracted when lying down and meditating. By closing my eyes and putting on noise-cancelling headphones, I was able to remove any visual or auditory distractions and attend only to my body and breathing. The difference to other use contexts was more apparent for the 5.5 and three-part breath patterns due to their longer intervals.

Over time, it became easier to follow the actuation pattern while simultaneously focusing on another task. The improvement was most noticeable for the three-part breath pattern as I became used to directing my breathing between my stomach and chest. Being guided by haptic feedback on my back rather than auditory or visual stimuli helped me to divide my attention between the breathing practice and other tasks. I was able to focus on other tasks while keeping the breathing guidance in the back of my mind, thus progressively extending my breathing intervals without having to consciously control my breathing. This suggests that with more practice and experience, it might be possible to integrate the breathing exercises into daily tasks without compromising the attention or performance in those tasks.

In addition to my breathing, the pads also increased my focus on work. I found that putting on the sensor and actuator set-up helped me to create a space for studying. Over the course of the exploration sessions, it became a part of my routine to explore different actuation patterns while studying. Positioning the pads on my lower back was ideal for this since it allowed me to sit at a desk without limiting the mobility of my upper body, but still stay conscious of my breathing while keeping other distractions away. The actuation also encouraged me to take small breaks from time to time to take a few deep, conscious breaths before getting back to my work.

6.2.2 Causing distraction from breathing

The more attention was required by an activity, the less I was able to focus on my breathing. When trying to follow the breathing guidance while working on another demanding task, I found the pads irritating and distracting. This often caused me to lose track of the breathing pattern or hold my breath entirely. In particular, the adaptive breathing and HRV feedback patterns as well as tasks such as writing or watching a movie demanded considerable attention.

When I was focused on another task, I was not paying as much attention to the pads and thus not following the pattern closely. Due to the threshold, this caused both the adaptive breathing and HRV feedback patterns to switch back and forth between the different types of actuation which created an additional distraction. Since the HRV feedback pattern was completely inactive while my LF/HF-ratio was close to the baseline, the contrast was even more pronounced. I was constantly expecting the actuation to start which occupied most of my attention. The threshold-based actuation made it nearly impossible to focus on another task for more than a few minutes while also engaging with my breathing, which was not the case for the other patterns.

It was most difficult to focus on breathing when watching a movie. Since I was distracted by the video, I barely noticed the actuation changes. It was hard to take more than a few deep breaths in a row, which made the breathing practice less relaxing and soothing than during other contexts. Instead, I experienced it as irritating or interrupting. There was a mismatch between my actual breathing intervals and the way I experienced them. Sometimes, the breathing feedback indicated that my breaths were becoming longer, but I did not feel like I was actually following the actuation. At other times, I thought I was relaxed and breathing slowly, but the adaptive breathing feedback pattern showed that my breathing intervals were hovering around the 2 second threshold.

Practicing deep breathing exercises while doing other tasks was mentally quite tiring. At the end of most exploration sessions, I felt sleepy and fatigued, in a similar way to how one feels after a long day of work. This lack of energy was partly due to taking deeper breaths than I was used to, but also due to simultaneously focusing on several tasks for an extended period of time. Following the adaptive breathing feedback pattern was particularly tiring because it required a lot of attention to keep my breathing intervals above the 2 second threshold. When using the 5.5 interval or the three-part breath pattern, I felt like I needed a break after 10-15 minutes. The breathing cycles were too long to follow closely for an extended amount of time without taking any breaks. I could follow the standardized breathing feedback pattern comfortably for the longest time, i.e. about 30-40 minutes. I ended each exploration session when I became too fatigued to continue, which was usually after approximately one hour. However, on days with two sessions, the second tended to be shorter than the first.

6.3 Impact of Different Body Positions

My body position and posture affected how I experienced the pads and which inflation speed felt the most comfortable. When using the three-part breath pattern, lying down rather than sitting made it easier to control whether I was breathing into my chest or my stomach. The pads also encouraged me to keep my back straight while sitting on a chair, supporting a good posture. In this position, I was more sensitive to the inflation and deflation of the pads, particularly the one placed on the upper back, and able to take deeper breaths.

Depending on my body position and the length of the breathing intervals, I experimented with different inflation speeds. I used the maximum speed as default at first; however, this turned out to be too fast since the pads became uncomfortably big. They pushed my chest forward to such an extent that it created the impression of taking an excessively deep breath completely filling my lungs with air, even if this was not actually the case. The ideal inflation speed was the one which allowed me to feel the guidance clearly without causing physical discomfort, which ranged between 60 and 85 percent of the maximum value. When sitting, I could feel the pressure more intensely and thus preferred a slower inflation speed. When lying down however, I preferred the speed to be closer to the upper bound, likely due to my added body weight pushing the air out of the pads.

7 Discussion

My first-person exploration of a wearable garment with integrated biosensors and inflatable pads spurred a number of experiential qualities of pneumatic pads in the context of deep touch pressure and breathing, utilizing deep pressure as a previously underused modality for respiration and HRV feedback.

In this chapter, I will first discuss the garment's impact on body awareness and relaxation, depending on each breathing technique, and relate my results with previous breathing-based systems and DTP garments in HCI. Furthermore, I will discuss the experiential qualities and affordances of the pneumatic pads which emerged throughout the design exploration. To further situate my work within soma design, I will then frame the breathing garment as an example of a somaesthetic appreciation design as defined by four key qualities described by Höök et al [32]. Lastly, I will reflect on the effect of reductionist uses of biosignals in my design process compared to previous studies and outline potential use cases of my pneumatic garment as well as opportunities for future work.

7.1 The Breathing Garment

The inflatable pads proved to be suitable to guide different breathing techniques and direct my attention towards different body parts. I became more aware not only of my chest or back, but also the sensations in my entire body during rest as well as during movements. The pads gently pushed me to engage my whole body during the breathing practice. Their constant presence on my lower back served as a reminder to turn inwards and listen to my body and its needs: Was I feeling anxious? Tired? Restless? Stiff? Breathing was no longer just a matter of necessity, but rather became an intentional choice. In combination with the deep pressure, it helped me to focus on my body and put unrelated thoughts on hold. As with previous experiences from yoga or Feldenkrais practice, I started noticing sensations in my body that I had not been aware of before. This concerned my stomach, back and chest in particular, which were directly affected by the pads, but also other areas like my shoulders, thighs or head. The three-part breath pattern had the strongest impact in this regard since it was guiding me to fully utilize my stomach and chest when breathing. After each exploration session, I was breathing more deeply and deliberately than before which created a deep sense of calmness and relaxation. I developed a heightened awareness of my body, reflecting on which body parts were engaged during my breathing, which were carrying tension, which felt energized or exhausted.

That being said, while the garment was able to instill a general sense of calmness, it is difficult to assess whether it could also soothe acute feelings of anxiety or stress since I did not put myself purposefully into such a state before an exploration session. However, both I and the other researchers who participated in the soma design sessions during the first design phase often felt less anxiety and tension after using the inflatable pads, as evident from our observations and body sheets. Additionally, there was one notable soma design session at the start of which I was feeling very overwhelmed, anxious and unable to focus on my body. This session turned out to be a very powerful experience: Although I was doubtful whether the pads would have any positive effect, I was able to calm down and adopt a more objective perspective on my emotional and physical reactions after exploring different breathing patterns guided by the pads for about 30 minutes. This suggests that if one is open to engaging with the pressure and breathing guidance provided by the pads, they might be able to soothe sudden feelings of anxiety and stress.

7.1.1 Comparison of Different Breathing Techniques

Based on my exploration, the most suitable actuation patterns for guiding a calming breathing practice seemed to be the standardized breathing feedback, the three-part breath and the 5.5 breathing pattern. All three were able to create a relaxing, soothing experience and thus show high potential for further development. In particular, the standardized breathing feedback pattern had a comforting and reassuring effect, allowing me to appreciate my body and its ability to breathe steadily. However, the 5.5 and three-part breath patterns required more attention and mental energy, which makes them more appropriate for shorter, more deliberate breathing practices while lying on the back. This position can make it easier to maintain a deep concentration and turn one's attention inwards by removing external distractions and is thus commonly used during meditation. Its beneficial impact is further supported by findings which suggest that the relaxing effect of deep breathing practices is partly due to the fact that it requires practitioners to voluntarily control their breath, modulating the autonomic nervous system [10]. While all techniques had the greatest effect when I could devote my full attention to the breathing practice, the standardized breathing feedback also allowed me to follow the guidance subconsciously, suggesting that it could be integrated into daily activities as a reminder to take deep breaths. Unlike the other two patterns, it slowly increases the breathing intervals over time which could provide a gentler starting point for people who are unfamiliar with deep breathing exercises and often struggle at first with more extreme breathing rates of 5-6 breaths per minute.

The two threshold-based patterns were less suitable for a calming breathing practice to increase body awareness. While using them I felt pressured to calm down and reduce my breathing rate, which made it difficult to actually do so. In this context, the long breathing intervals could have been counterproductive for relaxation. Wongsuphasawat et al [15] suggested that overexertion during slow breathing may prevent the usual calming effect of deep breathing techniques. Furthermore, they found that participants did not necessarily feel calmer after reducing their breathing rate. The benefits of slow breathing exercises are not solely due to reducing the breathing rate; rather, they are created by turning our attention towards our bodies, discarding intrusive thoughts and focusing on our awareness of the present moment [9]. Therefore, a gentler approach like the standardized breathing feedback pattern seems like a much better option to support relaxation and interoception since it avoids pulling the attention towards the actuators.

Throughout the exploration, I found myself constantly adjusting the parameters of the breathing patterns, such as the inflation speed or the length of the breath hold interval. This shows that there is no single value which fits all breathing patterns, use contexts, or positions. For example, longer breathing intervals cause the pads to inflate much more and thus require a lower inflation speed. The involved parameters need to be adapted to the interval lengths and body position in order to make the actuation clearly noticeable yet comfortable for the user. Since users might have varying preferences and abilities to take slow breaths, for example due to prior experience with deep breathing techniques, they need to be able to easily modify these parameters on the spot without having to change the underlying code. During my exploration, this was possible through the Node-RED interface. If the garment were to be adopted for wider use in the future, a more convenient option might be to integrate such adjustments into the breathing garment in the form of tactile interactive elements, eliminating the need for a computer interface.

7.1.2 Establishing a Routine

Over the three-week exploration, I formed a habit of completing the exploration sessions every day at around the same time. The simple act of getting ready for the breathing practice already made me feel calmer. Taking the time to focus on my breathing and my physical sensations felt like part of a self-care routine, similar to a regular meditation or yoga practice. The standardized breathing feedback and three-part breath patterns were particularly helpful by encouraging me to focus on the pressure caused by the pads and on my breathing, and not think about anything else. They guided my attention towards my experience of the present moment, calmly observing my body and breathing.

The daily practice had lasting effects even beyond the individual sessions, suggesting that the pads could be suitable for encouraging a routine practice to support relaxation and body awareness over a longer term rather than during a specific situation. I felt calmer and more balanced throughout the entire day, and I experienced my breathing more intensely, leading me to take deeper breaths than usual. After exploring the three-part breath pattern, I found myself using my stomach and chest more deliberately and distinctly while breathing. The sessions also changed the way I physically experienced my body. I often carry a lot of tension in my back, but after using the pads, my entire body felt limber and relaxed, similar to how I feel after a yoga practice or a massage. Even though I was a little sleepy and tired after most sessions, it felt comfortable and satisfying, similar to how one feels after a long workout. My thoughts and movements became slower and more deliberate, making me feel calmer and more centered. However, it was difficult to continue immediately with other tasks, and I needed to take a short break after each session to re-energize myself. Similar experiences have been reported by Höök et al [32, p. 3133], who felt “more grounded in ourselves, more reflective, and a bit slower in our movements and reactions” after engaging in regular Feldenkrais practice as part of their soma design process.

7.1.3 Comparison to Previous Work

A small number of previous HCI studies have focused on the development and use of weighted vests and compression garments for DTP. However, there seems to be a gap in exploring the subjective experience of wearing such a vest. Some studies were unable to evaluate this since the developed prototype was not yet ready for user tests [19], [20]. Others only investigated whether the intended effect of the garment was achieved, such as Fertel-Daly et al [34] who found that wearing a weighted vest can help preschool children with developmental disorders to improve their attention to tasks and reduce distractions. This is on par with the use of biosensing technology in HCI, whose emotional and cognitive impact on users has been similarly underexplored. Research on personal health and fitness often incorporates sensory biofeedback to improve user engagement and learning, but rarely explores its effects on users’ perception of their body and its capabilities [94].

My work contributes to filling this research gap by evaluating the experience of using pneumatic wearables with varying sizes and inflation patterns on different parts of the body. Since DTP has been shown to be more effective when repeatedly increasing and decreasing the pressure [21], it is important to compare different inflation patterns. Previously, Foo et al [38] evaluated the user experience of compression garments based on shape memory alloys by applying both constant and pulsing pressure to different body parts. They found that while individual preferences varied, pressure on the torso was overall experienced as more comfortable than on the shoulders or arms. Users reacted more sensitively towards pressure on the upper back than on the lower back and felt that lower back compression supported their posture. The compression garments created a calming and warm effect, making participants feel secure and comforted. These findings mirror my experiences and those of my co-researchers during the first design exploration, which suggests that pneumatic garments can provide a similar user experience as compression vests using shape memory alloys.

While DTP garments have not yet been used to support a deep breathing practice, Zhu et al [13] developed an interactive device resembling a small table lamp to facilitate relaxed breathing and reduce stress. It uses vapor, light and sound to guide users through mindful breathing exercises. The participants explored the device in their own home during different activities, such as during work or meditation practice. Their experiences were similar to my own exploration of the five different actuation patterns: Users found that following the breathing guidance distracted them from other tasks; however, afterwards they felt calm, peaceful and were able to focus more efficiently. While the preferred settings and perceived stress reduction varied between participants, several reported that they felt sleepy after using the device. This could be explained as an effect of mindful meditation which traditionally incorporates calming as well as arousing elements to achieve the desired state of alert wakefulness. However, novice meditators lack the experience to stay awake and engaged throughout the meditation practice, and commonly feel tired during the early stages of a meditation practice [95]. This might explain why I, as a beginner in deep breathing and meditation, often felt sleepy during my exploration. While this experience seems to indicate that the breathing garment could be able to support mindful meditation, the fatigue is likely temporary and will diminish as I become more experienced with the breathing exercises.

7.2 Experiential Qualities of Shape-Changing, Pneumatic Pads

Previous studies on shape-changing interfaces mainly focus on their technical components, but rarely evaluate how users experience these interfaces [31]. Since this only allows for limited insights on the kind of tasks they are suited for and the impact of the context on user experience, further investigations in these areas are needed to improve the understanding of the design space around shape-changing interfaces and inform their further technical development. My design exploration led me to identify a number of experiential qualities of shape-changing, pneumatic actuators, which I will discuss in this section.

7.2.1 Suitability for Breathing Guidance

Throughout my design process, I used the inflatable pads to provide breathing feedback and guidance for different breathing techniques. Haptic pressure has been explored little in this context, with most studies utilizing visual or auditory stimuli [11], [13], [15]. However, the inflatable pads seem to be a viable alternative. The haptic instructions were easy to understand and follow, guiding me to turn my attention inwards and away from external distractions.

There are several factors which make pressure a suitable modality for breathing guidance. First, breathing is inherently experienced most strongly via the tactile sense, i.e. by feeling the movement of air and the expansion of the chest and stomach. Thus, many Feldenkrais and yoga practices incorporate different ways of feeling one's breathing and steering it to different body parts. When placed on the back, the inflatable pads push the torso forward to encourage inhalation, and gently lower it during exhalation. In this way, the actuation mimics natural breathing movements which reduces the cognitive load required of users to match a visual or auditory stimulus to their respiratory behavior [15]. This makes inflatables an effective tool for providing breathing guidance and feedback, but less so for ECG and other sensor data.

Second, by integrating the inflatable pads in a garment, the wearer can feel the feedback directly on their body. This allows them to notice pressure changes without having to devote their full attention to the pads. Unlike visual and auditory stimuli, which are perceived at a distance from the body, the physical closeness of the inflatable pads makes them feel more like an extension of the body rather than an external object. During my exploration, this experience was crucial to help me feel more aware of and connected to my soma.

When designing for body awareness and relaxation, providing guidance via external stimuli can be problematic as shown by a number of tactile prototypes developed for breathing guidance [16], [17]. Users interact with these artifacts by putting their hand on them to feel the inflation. But while the tactile guidance allowed them to perform the breathing exercises more effortlessly than visual or auditory cues, it also pulled their attention away from their own bodies and towards an external artifact. Instead, subtle haptic pressure might be more suitable for designs which aim to support users in listening inward and reflecting on their somatic experience. Since the pressure is perceived directly on the body, it can provide a focus point that is directly connected to one's physical experience and breathing.

Lastly, the pressure sensation itself might have a relaxing effect on the body. Pneumatic elements are used in deep touch pressure therapy to calm down patients by stimulating their parasympathetic nervous system [18]. The inflatable pads provide a constant, slowly changing pressure on the upper and lower back. In combination with the deep breathing practice, this creates an overall calming and relaxing experience.

However, these arguments do not hold for all types of haptic feedback. Frey et al [14] designed a wearable pendant which uses vibrations to provide breathing biofeedback. Their participants experienced the vibrations as less relaxing and more dominant than visual and auditory feedback, associating them with phone notifications. This suggests that vibration feedback might be too disruptive and attention-grabbing to be suitable for a calming breathing practice, which seems to benefit from more subtle stimuli.

7.2.2 Subtleness

When the pads are in contact with the body, the pressure changes caused by inflation and deflation can gently guide the body to perform certain movements or direct attention to certain body parts. However, the pressure can also be surprising or uncomfortable if it is too strong, too sudden or located at a sensitive body part such as the neck. By contrast, a moderate inflation speed causes the pressure to intensify and disappear gradually, creating a more subtle, comfortable experience. This potential for subtlety is significantly enhanced by the constant presence of the pads. Ideally, they should always be inflated to a certain degree, albeit at varying levels, and inflate and deflate slowly to avoid surprising the user with a sudden change in pressure.

Such an element of subtleness is important for breathing guidance intended to support body awareness and relaxation. The pressure should not draw attention to the stimulus itself, but rather to the body and the breath. In particular, gentle actuation patterns such as the standardized breathing feedback and three-part breath are well-suited for supporting body awareness and interoception while minimizing distraction. The standardized breathing feedback gradually increases the breathing intervals which allows the user's natural breathing pattern to slowly adapt over time, making the guidance more subtle and effective. Furthermore, a slower actuation speed makes the guidance appear less like a firm command and more like a gentle suggestion to follow a certain pattern. It allows the user to become more open to the experience and surrender control over their breathing and thoughts. However, more aggressive patterns with longer intervals or abrupt changes like the HRV feedback pattern kept me acutely aware of the pads and thus unable to attend to my somatic experience.

7.2.3 Multisensory Feedback

In addition to the pressure, the pads also provide auditory feedback via the air pumps. When inflating or deflating the pads, they create a rhythmic noise which becomes louder as the actuation speed becomes faster. Inflation sounds noticeably different from deflation, which makes it possible to use the sound for breathing guidance in addition to or instead of the pressure. Before disguising the actuator noise with noise-cancelling headphones, this auditory feedback easily caught my attention, distracting me from the pressure. However, after incorporating the headphones, it became clear that the pressure was just as easy and comfortable to follow. Thus, both modalities seem to be suitable for breathing guidance. But while the auditory cues are more salient and overshadow the pressure, the haptic cues are more subtle and draw attention not only to the breathing, but to the body as a whole.

Depending on the situation, the sound produced by the air pumps can have a calming or a distracting effect. When I was only focusing on my breathing, the additional guidance provided by the constant, rhythmic sounds felt soothing and comfortable, especially when using an actuation pattern with longer breathing intervals such as the 5.5 pattern. However, the sound disrupted my concentration when combining the breathing practice with another task like reading or writing. I also found that the pressure and sound could have considerably different effects even when using the same actuation pattern. This contrast was most evident when using the three-part breath pattern, which inflates and deflates each pad for 2 seconds and contains a 1 second pause between each breath. Thus, it creates an audible switch every 1-2 seconds, which made me feel hurried and slightly anxious. However, I could not hear the switch anymore when wearing headphones, which allowed me to focus on the soothing and relaxing effect of the pressure.

7.2.4 Different Interaction Roles

Many different ways of perceiving the inflatable pads emerged throughout the exploration. They took on a variety of roles in the interaction, including giving breathing instructions, adapting to the user's breathing, and acting as a companion or partner. These roles were shaped by the inflation pattern and the use context. For example, the 5.5 breathing pattern was more likely to be perceived as strict breathing instructions aiming to influence the user, while the feedback patterns presented the pads as something to be influenced by the user. At times, they took on multiple roles simultaneously, for example giving breathing instructions while also offering a gentle and reassuring presence.

Furthermore, the pads also acted as a communication channel both between two people as well as between one person and their soma. During collaborative explorations, they allowed two people to connect physically and emotionally by sharing their breathing with each other. However, the pads can also enhance a person's awareness of their own body and breathing, enabling them to connect to their body in a whole new manner. While breathing is usually a subconscious, automatic process, the haptic breathing feedback and guidance can make it more perceptually available to the attention. In this way, the pads encourage users to become more conscious of how their breathing impacts different body parts, such as the chest or the stomach.

The pads are able to evoke very different emotional reactions depending on the inflation pattern and the body part on which the pressure is experienced. An asynchronous pattern on the neck was perceived as unsettling and anxiety-inducing, while a soft rhythmic pressure on the lower back felt reassuring and relaxing. As described above in section 7.2.3, using the three-part breath pattern with or without noise-cancelling headphones created a similar emotional contrast. Whereas the auditory feedback caused by the inflation changes made me feel anxious, the pressure guidance allowed me to surrender my conscious thoughts and connect deeper with my physical self, creating a calming and introspective experience. This dual nature characterizes inflatable pads as a versatile design material which could contribute interesting qualities in many different contexts.

7.2.5 Enabling and Facilitating Communication

When using the standardized breathing feedback pattern, I was able to communicate with my body through the pads. As the pads were mirroring my breathing intervals while pushing me to gradually extend my breath, I was trying to match my breathing to the actuation, feeling the changes reflected by the pads. They allowed me to perceive my breathing changes and bodily reactions more directly, guiding me to attend to the physical and emotional sensations evoked by the breathing practice. In this way, I was establishing a dialogue with my body, using the pads as a communication channel.

This communication was bilateral, in the sense that I was able to influence the pads by manipulating my breathing while they also guided me to extend my breath. While I experimented with breathing contrary to the guidance by holding my breath or taking intentionally short breaths, I was only able to maintain this for a short amount of time before feeling uncomfortable. Not following the pads seemed wrong since I was not engaging in the dialogue but closing myself off to my body.

Unlike other biosignals like EDA or HRV, breathing can easily be influenced in a variety of ways. While it is impossible to stop breathing completely, one can hold the breath, make the inhalations and exhalations longer or shorter, deeper or shallower, and practice diaphragmatic or thoracic breathing. The pads were very responsive to such changes, causing the impression that they were listening to me. This often felt comfortable and intimate, like the pads were taking care of me, but could also feel invasive or threatening when the pads were placed close to sensitive body parts like the neck or face. Thus, the contact point of the communication was essential for setting the tone of the interaction. In the context of breathing guidance, less sensitive body parts such as the back and stomach proved to be more suitable.

During the first exploration phase, I also used the pads to communicate with other people by taking turns to feel each other's breathing. While this was not explored further, we noted that imitating another person's breathing through the pads can create a sense of connectedness while being less invasive than direct physical contact. In a situation where physical contact feels uncomfortable, the pads could still allow people to establish a sense of intimacy. Several studies have explored breathing synchronization to promote shared experiences, trust and empathy in social interactions, although many focus on supporting communication in situations where direct physical contact is impossible [9].

7.2.6 Evoking Metaphorical Imagery

Throughout the exploration, we often used metaphors to explain how we experienced the pads. They were compared to living things such as animals, to an interactive balloon, or, most commonly, to a pair of lungs. Placing the pads close to the neck was likened to a snake coiling around the throat, while putting them on the back evoked associations with a kneading cat. Other metaphors were related to nature, such as describing the three-part breath technique as a “slow wave going through the body”.

Nature and animal metaphors are often used to describe sensations caused by tactile interfaces [96], [97]. Users seem to compare shape-changing interfaces to wild animals most frequently when their behavior is unexpected or difficult to understand [46]. To classify how movements of shape-changing interfaces are perceived by users, Rasmussen et al [31] devised two types of expressive parameters, adjectives and associations. Most interfaces were found to trigger associations with living beings such as humans, animals or nature. A possible explanation for this phenomenon is that people assign sensory and emotional words, such as personality traits, to non-living objects because it helps them to make sense of their experience and communicate it to others [98]. Therefore, they often describe the sensations caused by tactile interfaces with familiar metaphors, related to animals like cats or snakes [99] or to similar movements like breathing [97].

Metaphors are not only commonly used by users to describe their perception of shape-changing interfaces, but also by designers to communicate certain qualities and affordances to users. For example, Bucci et al [97] created small robots which expand and contract rhythmically, imitating breathing movements to communicate different emotional states. Hemmert et al [96] designed mobile phones which react to the user’s approaching hand by imitating animal-like postures of affection and avoidance, thus signaling their availability to users. When sketching shape-changing interfaces, designers commonly use metaphors due to the dynamic characteristics of the prototype [30]. Such metaphors can connect abstract concepts, for example happiness vs sadness, to concrete images, such as smiling vs sobbing, thereby giving these concepts a physical form that can be integrated into a physical design. This allows designers to draw on users' preliminary knowledge and make the interaction more intuitive and familiar, corresponding to the concept of "metaphoric mapping" [100]. It enables users to understand abstract concepts with minimal conscious effort, giving the interaction a quality of immediacy.

There have been several attempts at defining a language for tactile interfaces [101]–[103], mainly focusing on describing vibration and material textures. Furthermore, many tactile prototypes, such as the CuddleBits [97] and the animated mobile phones developed by Hemmert et al [96], are designed to be seen and carried by users, creating opportunities for visual feedback. However, my exploration of pneumatic pads showed that pressure is able to provoke associations with animals and other living things by itself, without additional visual indications. This suggests that the work on tactile language can be extended to haptic pressure as well, although more work is needed to compare the language used to describe different types of tactile interfaces.

7.2.7 Causing Misalignment and Disruption

During the first phase of my design process, I experimented with asynchronous actuation by using two pads with conflicting or complementing patterns at the same time. While they proved to be a powerful tool to disrupt the habitual and familiar ways of breathing, they need to be crafted carefully in order to complement natural breathing patterns. If the pads contradict each other or the natural flow of air, following their guidance feels like working against the body instead of engaging with the body. For example, when switching the two pads during the three-part breath pattern, they were guiding me to first breathe in with my chest and then with my stomach. This way of breathing made me feel like I was not getting enough air, thus appearing forced and unnatural.

However, when all aspects complemented each other, the asynchronicity was able to provoke interesting and unexpected experiences. Most actuation patterns were based on the pads-as-breathing-lungs metaphor, inflating to signal inhalation and deflating to suggest exhalation. But the pads were also able to direct my breathing in the opposite way: during inflation, the pads put pressure on my stomach and chest, thus pushing air out of my body and guiding me to exhale. Conversely, deflation made room for my stomach and chest to expand and thus prompted me to inhale. This inverted pattern was possible when the pads were placed on my stomach or when wearing the breathing garment which distributed the pressure more evenly around my torso.

Turning the familiar breathing pattern upside down disrupted my habitual way of breathing and forced me to re-evaluate the pads' connection to my breath. But while this was effective at drawing my attention to the mechanics of breathing, it took a lot of mental effort. Since this way of breathing was less familiar, it required me to slow down and breathe very deliberately and thoughtfully. I had to consciously think about every single breath, which kept my mind occupied and prevented me from noticing any other sensations in my body.

In HCI, misalignment between different sensorial stimuli has mainly been explored in the context of augmented and virtual reality. Marshall et al [104] examined misalignment caused by conflicting multisensory stimuli, affecting vision, hearing, touch, kinesthesia, smell and taste. They position sensory alignment as a spectrum ranging from full alignment over imperceptible misalignment up to extreme conflict between senses. When using the pads for breathing guidance, I found that more extreme forms of misalignment required a lot of focus and mental effort, distracting my attention from my body. While it could be interesting to explore this sense of defiance in other design contexts, but I found it to be unsuitable when designing for body awareness and gentle breathing guidance. However, experimenting with misalignment proved to be useful at the beginning of my design process to explore the material affordances of the inflatable pads.

When designing for a certain bodily experience, in this case breathing, designers first need to understand what it entails before they are able to create interesting disruptive experiences. My exploration of different kinds of misalignment allowed me to gain a fuller understanding of the properties and affordances of the inflatable pads, particularly in the context of breathing. Soma design proved to be well suited for exploring misalignment between different stimuli due to its practice of estrangement and disrupting habitual bodily experiences. Such methods encourage deeper examination and understanding, thus unpacking their experiential qualities and opening up the design space. Tennent et al [105] suggested extending the possible range of such disruptive strategies beyond geometrical misalignment, i.e. creating contradicting effects. In addition, they propose deliberately adding noise or removing a certain sense, for example with blindfolds or noise-cancelling headphones.

Wilde et al [70] presented a range of embodied design methods that utilize estrangement to enable reflection on the body. To better understand and communicate the felt experience of an embodied design ideation process, they applied a framework to these methods consisting of four questions: What is done to disrupt the usual way of doing a certain action? Which norms or structures are destabilized by this disruption? Which novel aspects emerge? What is embodied by this process? Applying this framework to my design process, I used the inflatable pads to guide different breathing techniques via pressure on the torso, thus disrupting the user's physical experience. This destabilized the habitual way of breathing. As a result, a deeper awareness of one's breathing, related body movements and a new form of interaction with one's body emerge. By making the breathing more directly perceivable and guiding users to focus on their body, this method embodies body awareness and interception.

7.3 The Breathing Garment as a Somaesthetic Appreciation Design Exemplar

In recent years, interactive systems that utilize breathing guidance to support self-awareness have garnered more attention in HCI, with several being grounded in somaesthetic theories [9]. Examples include the breathing light designed by Ståhl et al [56] as well as a tactile prototype which mirrors the user's breathing [16]. Such designs often utilize breathing as a gentle stimulus to support and guide people in attending to their bodily sensations. The goal hereby is to achieve an intimate correspondence between the designed system and the body, allowing it to become an extension of the body instead of pulling users' attention away from their body [32].

During my design process, I adopted a number of soma methods and concepts [23], [25], [70], [73] to explore the inflatable pads and actuation sequences from an embodied first-person perspective, carefully attending to the emerging experiences. To further situate my work within soma design, I will frame the breathing garment as an instance of a somaesthetic appreciation design, a strong concept defined by Höök et al [32]. I will demonstrate how it fulfills the four key qualities which set somaesthetic appreciation designs apart from other strong concepts: They exhibit subtleness in guiding attention towards the body, make space for reflection, create an intimate correspondence between movement and interaction, and help users to articulate their bodily experiences to increase somatic awareness.

7.3.1 Subtle Guidance

The first quality of a somaesthetic appreciation relies on using subtle interactions to guide a person's attention. Stimuli that are too prominent could shift the focus towards external stimuli, distracting from the desired internal reflection and appreciation of the body. Therefore, the design should provide subtle guidance that is able to support both slowly shifting attention between different body parts as well as sustaining the focus on a single area or movement.

As described in section 7.2.2, the inflatable pads were able to slowly and subtly guide breathing through gentle pressure. The haptic feedback intensifies and fades away gradually while providing a steady level of pressure, taking care to avoid any surprising or sudden changes. It allows users to close their eyes and ignore any external distractions. In this way, the pressure serves as a constant reminder to keep the attention on the breath, pulling the user back towards their physical experience if their mind starts to wander.

I explored several breathing techniques which were able to sustain the user's attention on their breathing while supporting the shift between inhalation and exhalation through changes in pressure. The standardized breathing feedback pattern gently encouraged observation and reflection without judgment while at the same time nudging users to take deeper breaths. Furthermore, the three-part breath pattern encourages users to engage their entire torso by guiding them to let their breathing flow between their stomach and chest. This turns the breathing practice into a full body experience, allowing users to perceive their breathing in a more nuanced and holistic way.

7.3.2 Making Space for Reflection

The second quality of somaesthetic appreciation designs relates to 'making space' which is defined in two different ways by Höök et al [32, p. 3135]: "on the one hand it concerns slowing down the pace of life and actively disrupting everyday habitual routines. On the other hand, it [...] became important to build a secluded space, forming a certain atmosphere or feeling safe, enclosed, taken care of."

In my design work, I used the inflatable pads to slow down and disrupt the habitual way of breathing. They guide users to take deep, conscious breaths and actively steer their breathing towards their stomach or chest. Many people are unfamiliar with such breathing methods and simply consider breathing to be an automatic bodily function. By encouraging users to focus on different body parts or take deeper breaths than they normally do, the pads can turn this subconscious process into active engagement with the body. They suggest how one can use their breathing to become more connected to the body, more attentive to arising emotions and physical sensations, and hence more reflective and centered within themselves. Over time, users can form a more conscious and deliberate way of being in the world and gain a different perspective of their breathing, which might lead them to develop a new appreciation for their body.

The second aspect of 'making space' also manifested in my exploration of the breathing garment. While it did not create a literal space with physical barriers towards the outside world, positioning the pads on either side of my lower back when lying down seemed to form a small indent in the floor to enclose my body, causing a comfortable and safe feeling. I felt unsteady without the pads, like the lack of support could cause me to roll to the left or right side at any moment. The pads supported my lower back and made me feel more connected to the floor, more grounded in myself and my environment. The intimate and caring quality of the experience was further enhanced by the pressure guidance. Unlike visual or auditory stimuli which are perceived over a distance, haptic feedback inherently requires close physical contact to the user. Since it cannot be perceived by other people who are present, it creates distance between the user and their environment, making them feel like they are in their own world. By addressing the tactile sense, the pads establish a personal space in which the user's experience is solely their own [52].

The simple act of putting on the garment every day made me feel calmer and more centered, even before activating the actuation. Taking this conscious time for myself allowed me to notice and reflect on my physical and mental wellbeing. The noise-cancelling headphones created a metaphorical barrier to the outside world which eliminated auditory distractions, enabling me to turn my attention inwards and attend to the sensations which arose during the exploration. In this way, the design allowed me to slowly establish a routine deep breathing practice.

7.3.3 Intimate Correspondence

The third important quality of a somaesthetic appreciation design is a tight interconnection between the user's movements and the system's response and interactions. This requires an intimate correspondence, using immediate feedback loops which are synchronized to the user's felt body experience. The system should follow the rhythm of the body in such a way that it is perceived like an extension of the body rather than a separate unit. Thus, it should not engage users in an active dialogue that requires them to reply and could redirect their attention to the external world.

In my design, this quality was best supported by the standardized breathing feedback pattern. It adheres to the user's natural breathing rhythm while extending the actuation intervals slightly, gently guiding the user to gradually take deeper breaths. The pads do not dictate a specific pattern, but rather respond to the user's breathing which gives the guidance a more personalized and intimate quality. This creates an implicit interaction which subtly reinforces and extends the user's breathing without requiring any deliberate participation from their side. The pressure-based feedback further enhances the impression that the pads are actively guiding the breath. By physically pushing the body forward, they seem to take control of the breathing which elicits a sense of intimacy, of being safe and taken care of. Since the focus is not on the pads themselves, but on the gentle pressure they provide to guide the breath, they are perceived more like an extension of the body rather than an external system.

A failure to incorporate this quality could explain why the HRV feedback pattern did not allow me to connect to my body in the same way as the other actuation patterns. It only activates the actuation if the LF/HF ratio is above a certain threshold. Thus, the interaction is not implicit, but rather demanding constant attention from the user to monitor the actuation and take it as a cue to take deeper breaths. During my exploration, the pads did not seem to be responding to my actual bodily experiences which made me feel disconnected from the interaction and prevented me from making sense of the feedback in a personally meaningful way.

7.3.4 Articulating Experience

Lastly, a somaesthetic appreciation design encourages active reflection on the felt bodily experience. It supports users in making sense of their emotional and physical sensations as they occur, as well as in visualizing or verbalizing their experience after the session. Articulation is an essential part of the interaction since it allows users to share their experience with others, thus enabling them to discover similarities and differences between their experiences which further promotes body awareness.

During my design process, I found that the inflatable pads were able to direct my attention to aspects of my breathing that I had not experienced before, such as feeling my breathing flow from my stomach to my chest, which encouraged me to reflect on how my breathing affected different parts of my body. This introspection was best supported by the standardized breathing feedback pattern which made me more aware of my own breathing intervals and pushed me to try to make sense of their changes over the course of the breathing practice. For example, when I was struggling to extend my breathing intervals, it made me wonder whether I was more stressed or anxious on those days. Thus, the inflatable pads guided me to reach a new understanding and knowledge of my body and the interconnections between my breath, my emotions, and my physical sensations.

During the collaborative soma design sessions in the early exploration phase, all participants documented their bodily experiences throughout the session with soma body sheets. This allowed us to visualize our sensations which was often easier than articulating them verbally. Comparing each person's perception of the interaction with the pads encouraged me to reflect more deeply on why the pads had a certain impact on me, but not on the other participants. I was forced to explain my sensations in more detail to allow the others to understand, which helped me to articulate my experiences more clearly and comprehensively.

Unfortunately, such co-exploration sessions were no longer possible later on due to the COVID-19 pandemic. When doing design work by myself, the body sheets stopped being helpful because they no longer served as a starting point to explain my experiences to someone else. Instead, I took quick notes on my initial impression during the sessions and later reflected more deeply on my experiences based on these notes. This often allowed me to identify recurring themes and explanations for my reactions and thus gain new insights about the interaction. For example, it helped me to understand that I experienced the inflatable pads as comfortable and soothing because I let myself surrender my control over my breathing to them, which I had not consciously realized during the interaction.

7.4 Possible Use Cases

During my exploration, I found that the position of the inflatable pads on the body, the actuation pattern and the use context strongly impacted my emotional experience of the interaction. It ranged from anxiety-inducing when the pads were placed on the neck, to calming when practicing slow breathing techniques. This suggests that the pads could create interesting interactions both by emulating physical symptoms of anxiety or by helping users to calm down and find a deeper awareness and connection to their body. This points to two potential user groups: people who seek to understand the felt experience of anxiety, and people who want to practice deep breathing to manage their mental health and stress levels.

7.4.1 Breathing Guidance for Relaxation and Body Awareness

The first potential application of the inflatable pads I would like to highlight relates to guiding a calming and introspective breathing practice. They can provide instructions and feedback via a comforting and soothing pressure sensation, thus creating a relaxing experience that helps users to focus on their body. Previously, Azevedo et al [106] presented a haptic device to reduce anxiety in certain situations, such as in anticipation of public speech. In comparison, I found that a daily breathing practice guided by the inflatable pads allowed me to feel calmer throughout the entire day, not only during the session. Thus, it seems that the pads are more suited for encouraging a routine practice to support mental health and stress reduction over a longer term rather than during a specific situation.

Haptic breathing instructions might be particularly helpful for beginners. I found that because I allowed the pads to control my breathing, I was free to turn my attention towards my physical sensations and distance myself from any worries or conscious thoughts. Breathing feedback via haptic stimuli has not been explored much in HCI; however, rhythmic pulsing compression applied on the torso which was not intended to mimic or guide the user's breathing has shown potential to improve focused attention on breathing and help users to adopt a slow breathing rhythm. Thus, haptic pressure feedback could be able to provide a focus that is closely connected to users' bodily experience and breathing, thus supporting introspection instead of pulling the attention towards an external stimulus.

Prior research supports that regular conscious breathing practice can be beneficial for mental health. Mindfulness-based clinical interventions [8], which commonly incorporate breathing exercises, and yogic breathing exercises have been shown to alleviate symptoms of depression and anxiety and improve overall mental wellness, both for healthy people [48] and people diagnosed with an affective disorder [107]. Furthermore, many studies confirm a link between slow breathing exercises and a reduction in subjective anxiety [10], [13], [52], [85]. To guide such exercises, the inflatable pads might have an additional advantage compared to audio, visual or even other types of haptic stimuli since they simultaneously provide deep touch pressure. DTP strategies have been used in therapy to reduce anxiety and sensory overload [108]. A pressure vest, such as the breathing garment with integrated inflatable pads, can be used by patients at home to supplement therapy treatments. It can be used at any time for any desired duration and allows users to control the intensity of the pressure via the inflation level and speed, which is an essential quality of DTP therapy [108].

However, such a garment should be able to adapt to users' personal preferences regarding the targeted locations on the body, the intensity of the pressure stimulus and the temporal pattern. Foo et al [38] found that male and female users of a compression vest had distinct preferences for the intensity and the location of the pressure stimulus. About half of the participants preferred a constant compression while the others favored a pulsing sensation. Such differences also exist in the context of breathing guidance. Bumatay & Seo [52] investigated two different breathing techniques for stress management, using manually set or biofeedback-based intervals. They found that the biofeedback was preferred by users who appreciated being able to give up their control and focus on their breath, while other users were uncomfortable with giving the system control over their breathing and preferred to choose the intervals themselves. Due to such individual differences, any wearable for haptic breathing guidance should allow users to customize the actuation as well as provide predefined actuation patterns.

7.4.2 Communicating the Felt Experience of Anxiety

The second potential use case for the inflatable pads targets people who do not have any personal experience with anxiety disorders and want to gain a better understanding of what this can feel like. Beuthel and Wilde [109] developed a method to design wearables which can communicate the felt experience of physical discomfort to the wearer. This allows the designer to articulate an experience that is difficult to put into words. Such wearables can support empathic engagement with another person's physical discomfort and create a sense of community for people with similar personal experiences.

While Beuthel and Wilde developed two designs two communicate their experience with tinnitus and knee problems, the inflatable pads could be used to create a similar prototype that demonstrates the felt experience of an anxiety disorder. During the early collaborative exploration sessions, we noted that inflating the pads in an asynchronous pattern close to the neck can restrict breathing. Such a feeling of not being able to breathe properly is common during anxiety attacks [110] and can further intensify the anxiety. Additionally, people often breathe much faster and shallower than normal when experiencing anxiety [111], which could be reflected by rapidly inflating and deflating the pads. Combining the inflatable pads with breathing sensors could allow users to measure their breathing intervals during a moment of intense anxiety and later share it with another person, for example a therapist, to communicate their felt experience.

7.5 Reflection on Designing with Biosignals

My design work was based on an embodied exploration of ECG and respiration sensor data combined with haptic pressure actuation to investigate the material properties of pneumatic shape-changing pads. As discussed previously, an important quality of the inflatable pads is that by employing subtle actuation patterns, they are able to direct the user's attention inwards to help them become more aware of their breathing and arising somatic experiences. However, I found that the actuation sequences which monitored my biosignals and reacted to certain thresholds did not allow me to attend to my internal state. Instead, I felt compelled to explicitly watch out for actuation changes and keep a tight control of my breathing so that my biosignals did not cross the respective threshold. This often made me feel more stressed than before, whereas the gentler actuation patterns created a calming experience, allowing me to reflect on my bodily sensations.

HCI systems which are based on biosignals commonly use biosensors to collect quantifiable and measurable data. They follow approaches such as the quantified self which treat the body as a functional, quantifiable object that can be monitored, understood and shaped towards a certain outcome by means of technology [112]. Some examples are smartphone games which aim to teach players deep breathing skills by monitoring their breathing rate and providing in-game feedback, such as increasing the difficulty or reducing the game score if the player's breathing rate deviates from the target rate [61] [53]. The games' effectiveness in managing stress levels is evaluated based on the players' physiological signals, equating lowered stress levels with an increased heart rate variability and a reduced breathing rate and electrodermal activity.

However, the problem with such a dualistic approach is that it cannot capture the immeasurable qualities of the players' subjective and emotional experience [112]. Focusing too much on numeric representations of biosignals can easily lead users to disregard the relation between the interaction and their somatic selves. A system that promotes a mechanical regulation of biosignals without considering the users' subjective, first-person experience can cause the information to become disembodied, disconnecting users from their body and environment. The experiential qualities of a slow breathing practice, such as a heightened awareness of thoughts and emotions as a result of attending to the body and breath, significantly account for its calming effect [9]. Therefore, any design which forces users to attend to an external stimulus or representation of data, such as a handheld device [16] [64], is of limited value for an introspective breathing practice since it pulls users' attention away from their bodies.

In fact, a predominant focus on quantifying users' emotional experiences can be counterproductive to supporting mental wellbeing and stress reduction. Physiological indicators of low stress, such as a slow breathing rate, do not necessarily correspond to a subjective decrease in stress [15] and can even increase stress under certain circumstances. Macik et al [64] developed a handheld device which guides users to gradually slow down their breathing to 6 breaths per minute. While participants were able to make their breaths significantly longer, they reported feeling more stressed when using the device, likely because they were not able to meet the target breathing rate. This caused frustration and prevented the breathing technique from having a relaxing effect.

Instead, a more beneficial approach towards designing with biosignals would be to use technology to support users in turning and sustaining their attention inwards, allowing them to explore their inner self. This approach has recently garnered more attention in HCI, particularly in the context of designing for mindfulness and mental wellbeing [9]. Instead of simply monitoring the user's performance via physiological indicators, technology can make imperceptible processes such as the heart rate variability or electrodermal activity directly accessible. In this way, it can direct users' attention towards their somatic experiences and support their internal exploration. By expanding our possibilities for self-reflection and learning, technology can help us to gradually develop a more responsive and perceptive body [112]. However, personal agency is key: If users feel that technology is overanalyzing or controlling their practice, this can create an adverse effect and disturb the introspective experience [113].

7.6 Contributions and Future Work

My work contributes to several open research questions related to designing with biosensing technologies, shape-changing interfaces, breath-based systems and designing for mental wellbeing. In the area of affective health, Sanches et al [7] called for more work aimed at altering the somatic perception of users through tangible interfaces, as well as more exploration of alternative therapeutic methods. Furthermore, the majority of breath-based systems evaluate the physiological effects of breathing techniques guided by visual or auditory stimuli, neglecting their attentional, somatic and emotional impact [9], [94]. These subjective aspects of the user experience have also been little investigated for shape-changing interfaces, as well as their communication qualities and suitability for different use contexts [31].

These research gaps were addressed in my work by using deep touch pressure as a modality for breathing feedback and guidance of various breathing techniques, demonstrating the effectiveness of haptic pressure feedback for interoception and breathing awareness. I explored the subjective experience of a wearable DTP garment with integrated shape-changing pneumatic pads and biosensors from a first-person perspective, which led to insights about the experiential impact of shape-changing and biosensing technology in the context of a deep breathing practice, as well as the experiential qualities and affordances of the pneumatic pads.

The results of my exploration open up room for further investigation, particularly in the following three areas: Developing a more sophisticated breathing garment to support a regular breathing practice, exploring the impact of individual user differences on the resulting experience, and investigating the affordances of the inflatable pads in more depth, particularly with regards to misalignment and breath sharing.

There are two aspects of the breathing garment which offer room for improvement. The current set-up includes two cables connecting the inflatable pads to the air pumps, as well as noise-cancelling headphones to muffle the noise caused by the air pumps. While this is not uncomfortable per se, it restricts the wearer's movement to a small area around the actuators and requires them to be careful when changing their body position. Therefore, finding an alternative to the air pumps could grant the wearer more freedom of movement and make it possible to test the garment in different environments. Previous research presents robotic textiles as a viable option, for example pneumatic artificial muscles which expand and contract with air pressure [114] or shape-changing textiles which are operated by an electronic actuator and have been used to create a wearable breathing trainer [115]. The ideal actuation parameters, such as the inflation speed or the length of the breath hold interval, depend on the current breathing pattern, use context and body position, and should be adaptable to the users' personal preferences in order to make the actuation clearly noticeable yet comfortable. For example, longer breathing intervals cause the pads to inflate much more and thus require a lower inflation speed. Thus, robotic textiles could replace the current browser-based interface with a more seamless interaction that does not direct the user's attention away from their physical experience, thus allowing them to stay immersed in their practice.

Secondly, the pluralism of users' experience of the breathing garment offers room for further investigation. People perceive the effects of misalignment differently depending on many factors such as their body height and size, their sensitivity towards sensory stimuli, their emotions, attitudes and level of skill in the investigated practice [105]. Therefore, testing the breathing garment with a larger, diverse group of people is crucial to obtain deeper insights into the impact of the different actuation patterns as well as the experience caused by wearing the garment itself. A collaborative exploration and discussion of each person's subjective experiences can allow participants to reflect on their differences and similarities and develop a richer somatic understanding of themselves. Thus, it is essential to keep such pluralist accounts in mind in order to design systems which can accommodate and take advantage of interindividual differences.

Thirdly, I identified several promising affordances of the inflatable pads which should be explored in more detail, namely misalignment and breath sharing. Since my work focused on designing for single-person breathing techniques to promote body awareness and relaxation, I did not continue to investigate the pads' potential in these areas. Intentionally creating different kinds of misalignment, for example by adding noise or removing a certain sense, can help to further unpack the experiential qualities of the inflatable pads, as described by Tennent et al [105]. While visual and kinesthetic misalignment has been heavily studied in HCI, there is much room to explore misalignment based on other modalities like touch or audio [104]. Furthermore, the inflatable pads can provide an interface to share one's individual breathing rhythm with others. Research has shown that synchronizing breathing can foster feelings of connectedness and mutual understanding in social connections by making such private, usually hidden information available to others [9]. The inflatable pads can make breath sharing less intimate by creating an additional layer in the interaction, thus possibly helping users to establish social relationships that require trust and empathy, for example in psychotherapy.

8 Conclusion

Throughout my design process, I pursued the question of how a deep touch pressure garment can be used for breathing guidance to support body awareness and relaxation. For this purpose, I conducted a first-person material exploration of inflatable shape-changing pads coupled with respiration and ECG sensors. The initial results led me to develop a wearable vest which situates the pads on the upper and lower back to guide various breathing techniques. Using this vest, I explored deep touch pressure as an alternative modality to visual and auditory stimuli for breathing guidance and feedback.

The haptic pressure proved to be an effective modality for breathing feedback and guidance. The garment was able to guide different breathing techniques while engaging my whole body, serving as a constant reminder to turn inwards and attend to my experience. Unlike auditory or visual stimuli, the pressure provides a focus point that is directly connected to users' physical experience and breathing, allowing them to stay attentive to arising sensations and hence more reflective and centered within themselves. It creates a calming and introspective environment in which the user feels more balanced and connected to their body, having lasting effects beyond a single session. Thus, the inflatable pads seem to be suitable for encouraging and guiding a routine breathing practice to support relaxation and interoceptive awareness over a longer term.

My work contributes to previous research in HCI on interactive systems which utilize breathing data to foster self-awareness [9]. Throughout my design process, I incorporated the soma design practice of making strange and disrupting the habitual [73] which encouraged me to examine my somatic experiences more consciously. In doing so, I addressed a gap in the research around DTP and biosensing technology concerning the subjective experience of their emotional and cognitive impact. My aim was not to measure biosignals as a way of diagnosing or monitoring users, as is often done, but to design for evocative balance [26], empowering users to connect more deeply with their body by making internal processes visible and enabling critical reflection on their experiences. Such a use of biosignals steers away from the quantification and datafication of our physical experiences, focusing on the mind and body as an interconnected whole and allowing users to form their own interpretation of their physiological signals.

This practice of misalignment and making the habitual strange presents soma design as a particularly promising approach for material exploration. It allows researchers to disrupt bodily experiences which facilitates a deeper examination and understanding, thus unpacking their experiential qualities and opening up the design space. My soma-design based exploration of the inflatable pads showed that they can support a wider array of interactions than those presented in this work. Thus, I want to inform and encourage others to further investigate the design space around pressure-based actuation, in particular regarding their potential for misalignment and breath sharing. Going forward, more work is needed to evaluate how the pressure vest and the breathing techniques might affect different users, addressing pluralist accounts of their somatic experience.

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