Design Science

Affective Matter: designing human-material interactions to enhance health and wellbeing

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Abstract

Our emotions do not always surface into our awareness, making it difficult to manage them and communicate them to others. Even when emotions do not reach our awareness, they still express themselves as physiological changes, often unperceived by ourselves and others. To aid in emotion self-regulation and increase the bandwidth of emotion communication, I designed a programmable affective sleeve that translates physiological aspects of emotions into material haptic action. The affective sleeve has been developed as a case study for Affective Matter. Affective Matter suggests a method for human-material interaction that enhances health and wellbeing.

I first discuss the three foundations of Affective Matter underlying the design of the affective sleeve: Embodiment, Entrainment, and Material Intelligence. I then proceed to the methods and results of an exploratory study I developed and conducted that tests the psychophysiological impact of the sleeve on 36 participants. The study results suggest that the pace of the affective sleeve's haptic action can be programmed to regulate the wearer's breathing pace to either have a calming or a stimulating impact on the wearer. The results also show varied affective responses to distinct haptic stimuli. Discussion of the results suggests future research directions and therapeutic applications for the benefit of individuals with mental health and neurodevelopmental disorders.

Keywords: programmable materials, health and wellbeing, emotion self-regulation, embodiment, entrainment, material intelligence, wearable environments, affective computing, haptic feedback, emotion communication, therapeutic garments

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1. Introduction

Since ancient times, humans have been regulating their emotional and physical health through their environments: through walks in nature, heliotherapy or hydrotherapy (Gianfaldoni *et al.* 2017; Aldahan *et al.* 2016). Despite the discourse on design and emotions (Desmet & Hekkert 2007, 2009; Karana *et al.* 2014), experience of space (Zumthor 2010; Pallasma 1996, 2011; Bachelard 1957/2014), and healthcare architecture (Ulrich *et al.* 2008; Simonsen *et al.* 2022), research on how designed environments impact our mood and our health is limited (Dannenberg & Burpee 2018; Evans 2003). I have developed Affective Matter as a research area to investigate how material environments can enhance our health

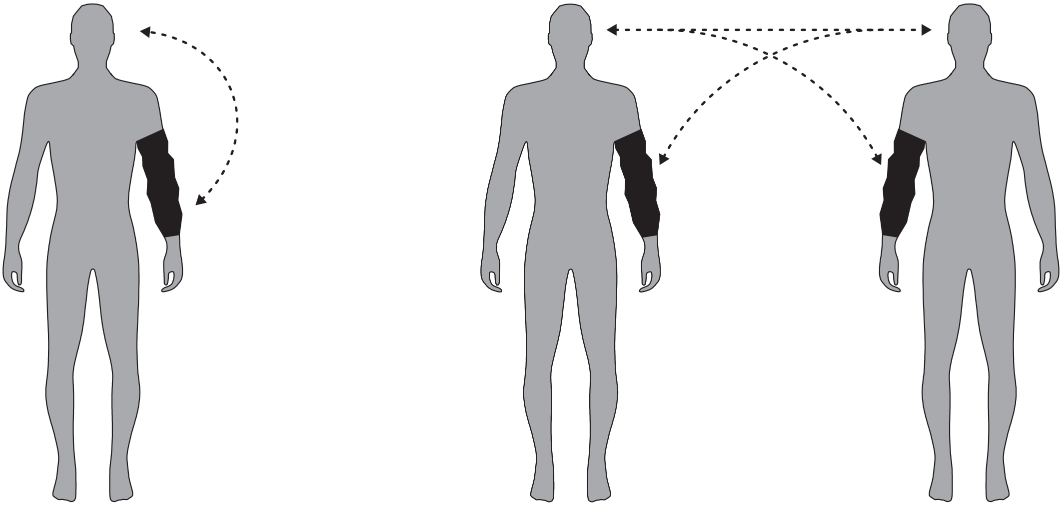

Figure 1. Conceptual diagram showing the sleeve as a medium for emotion self-regulation and communication.

and wellbeing through the design of human-material interactions (Papadopoulou *et al.* 2019; Papadopoulou 2022).

In this paper, I define and discuss the foundations of Affective Matter, and the methods and results of an exploratory study testing a programmable affective sleeve I developed as a case study for Affective Matter. The aim of designing the affective sleeve was to allow for material-mediated emotion self-regulation and communication. Emotions can have physiological expression in one's body, without surfacing into one's awareness (MacLean 1988; Van Der Kolk 2015). This body–mind miscommunication makes it difficult to both self-manage and communicate emotions. I designed and conducted a study to test the impact of the programmable affective sleeve on regulating the wearer's breathing for the purpose of material-mediated emotion self-regulation, and to explore the affective impact of various sensory properties of the sleeve that could be used in material-mediated emotion communication (Figure 1).

I designed the affective sleeve following the three foundations of Affective Matter: Embodiment, Entrainment, and Material Intelligence. Based on Embodiment, the sleeve was designed to impact the wearer's affective state through somatosensory stimulation: the sleeve allows physiological aspects of the wearer's affective state to translate into haptic action consisting of sensations of warmth and pressure. Based on Entrainment, the sleeve was designed to promote entrainment of the wearer's bodily rhythms to the rhythms of the haptic action it provides: The sleeve was programmed to provide haptic action according to the wearers' individual breathing rate aiming at the synchronization between bodily and material rhythms. Based on Material Intelligence, the sleeve was designed to provide haptic action through programmable material behavior: I developed a novel material mechanism that utilizes pneumatic control to provide warmth and pressure through material transformation.

2. Foundations of Affective Matter

2.1. Embodiment

Nearly all theories about emotion have suggested that the body plays a role in emotional reactions. However, the body was traditionally regarded as separate from the mind, and bodily emotional reactions as the result of mental processes (Barrett & Lindquist 2008). It wasn't until William James (1884), who argued that emotions are the feelings of physiological reactions, that the traditional mind/body dichotomy was challenged. Many recent embodied approaches to emotion discuss the important role of the body in emotion processing (Damasio 2000; Barrett 2018; Niedenthal 2007; Winkielman *et al.* 2008; Nummenmaa *et al.* 2014). Embodiment is "generally understood as the sum of bodily preconditions of cognition, emotion, and behavior" (Lux *et al.* 2021). Embodiment theories posit that higher-level processes are grounded in our sensory and motor bodily interactions (Winkielman *et al.* 2015; Clark 1999; Wilson 2002).

Interoception is defined as "the sense of the physiological condition of the body" (Craig 2002). Disrupted interoceptive processes have been associated with mental health disorders (Paulus & Stein 2010; Khalsa & Lapidus 2016). Interoceptive awareness involves the process of being conscious of internal sensations, like heart and breathing rates, and the ability to identify and respond to such sensations (Price & Hooven 2018; Cameron 2001; Craig 2015). Interoceptive awareness plays a key role in bodily awareness (Tsakiris 2017; Seth 2013; Damasio 2000). Bodily awareness can be understood as the general representation and experience of one's own physical body (De Vignemont 2020) and relies greatly on somatic sensory processing (Kearney & Lanius 2022). Traumatic experiences can cause somatic sensory processing dysfunction resulting in emotional and bodily detachment (Gottfredson & Becker 2023; Lanius *et al.* 2010; Van Der Kolk 2015).

A variety of sensory-based interventions are being used for the healing of trauma, anxiety, depression, and other mental health disorders. These involve breathwork, somatosensory stimulation, or attention to the body (McGreevy and Boland 2020; Ogden *et al.* 2006; Payne *et al.* 2015; Mehling *et al.* 2011; Canbeyli 2013). It has been shown that deep touch activates the parasympathetic system, decreases sympathetic arousal, and promotes calmness (Reynolds *et al.* 2015; Chen *et al.* 2013; Afif *et al.* 2022). In addition, respiratory patterns are influenced by emotions and influence emotions (Jerath & Beveridge 2020). Slow breathing activates the parasympathetic nervous system and reduces anxiety (Jerath *et al.* 2015; Russo *et al.* 2017; Zaccaro *et al.* 2018), while fast breathing activates the sympathetic nervous system (Komori 2018).

I designed an affective sleeve that provides haptic action (pressure and/or warmth) in pace related to breathing to aid in emotion self-regulation, and potentially emotion communication. Emotion regulation "refers to the processes by which we influence which emotions we have, when we have them, and how we experience and express them" (Gross 1998). Based on Gross' (1998) process model for emotion regulation, the affective sleeve operates primarily at the last stage of emotion generation, which concerns the modulation of experiential, behavioral, or physiological responses. Keltner & Gross (1999) define emotions "as episodic, relatively short-term, biologically based patterns of perception, experience, physiology, action, and communication that occur in response to specific physical and social challenges and opportunities."

The extent to which emotions are considered biologically defined or culturally constructed varies across emotion science literature, as do other aspects of emotion processing (Barrett 2018). This paper describes the process and results of an exploratory study with university members (students and staff), testing the psychophysiological impact of the affective sleeve I developed through physiological measurements and self-reports. The study does not address all aspects of emotions (cultural, social, cognitive, etc.), the complexity of individual experiences, or the depth required in therapeutic processes.

2.2. Entrainment

As humans, we have the tendency to synchronize our rhythms with each other and with our environments (Large & Jones 1999; Repp and Su 2013; Clayton *et al.* 2005). We synchronize our biological rhythms with the cycles of the day and night (Schmal *et al.* 2020; Duffy & Wright 2005), and our dancing rhythms with the beat of the music (Bachrach *et al.* 2015; Trost *et al.* 2017). The phenomenon of synchronization of rhythmic systems is broadly defined as entrainment (Clayton *et al.* 2005). Entrainment between physiological systems can occur when one's cardiac activity is synchronized with one's breathing activity (Yasuma & Hayano 2004), or when the heart rate of a newborn is synchronized to that of the newborn's mother (Feldman *et al.* 2011). Interpersonal physiological synchrony has also been demonstrated when one is empathizing with another, including synchrony in cardiac activity (Helm *et al.* 2012; Kodama *et al.* 2018), skin conductance (Coutinho *et al.* 2019), respiratory activity (Helm *et al.* 2012), and neuronal brain activity (Djalovski *et al.* 2021).

Although empathy is today understood as the mental projection of a person to another person (Riess 2017), initially empathy was introduced to the English-speaking world as the translation of the word Einfühlung (Ganczarek *et al.* 2018). Einfühlung was a central concept in German aesthetics (Vischer 1873; Lipps 1903, 1906) and had the meaning of projecting oneself into a person, object, space, or landscape (Ganczarek *et al.* 2018; Lanzoni 2018). Empathy as Einfühlung involved the mental fusion of the perceiver with the object of contemplation, and often the physiological resonance between the perceiver and the object (Lanzoni 2018; Lee & Anstruther-Thomson, 1912). The idea of merging with the artwork can also be found elsewhere in arts and design: design has been described as an active dialog with an artifact (Schön 1984), and as a process of fusing and embedding meaning (Stiny 2006, 2022) that in some ways can be extended to all material objects (Knight & Stiny 2015).

The idea of emotion self-regulation via entrainment to touch-related stimuli has been successfully demonstrated in prior studies. Two of the first studies in the field were those conducted by Costa et al. (2016) and Azevedo et al. (2017) using vibration stimuli. Costa et al. (2016) used the concept of false (interoceptive) feedback, showing that participants wearing a wristband device with rhythmic vibration lower than their heart rate had lower anxiety during an anxiety-inducing task compared to the control group due to their belief that the vibration represented their actual heartbeat. Azevedo et al. (2017) utilized a similar vibration wristband to show that exposure to slow (in relation to relaxed heart rate) rhythmic vibration, as opposed to no exposure, led to decreased anxiety during the anticipation of public speech.

Other studies have targeted entrainment to breathing instead of heart rate and have used stimuli other than tactile ones, such as light and sound (Ghandeharioun & Picard 2017). Studies by the author and others (Papadopoulou *et al.* 2019; Papadopoulou 2022; Choi *et al.* 2021; Haynes *et al.* 2022) have targeted entrainment to breathing via haptic stimulation. By designing the pneumatic affective sleeve, my aim has been to develop a novel method for emotion regulation via entrainment focused on breathing and deep touch (as opposed to light touch), which is known to reduce sympathetic arousal and has established therapeutic use (Ayres 1972; Eron *et al.* 2020). Also, it has been my intention to extend the notion of "wearable" from that of a localized device to that of a wearable environment and to explore affective responses to various parameters of haptic stimuli.

It should be clarified that it is not tested in this study whether the sleeve increases one's interoceptive awareness. The intention to synchronize breathing with haptic action for the purpose of emotion self-regulation was intentionally not revealed to the study participants. It should also be clarified that breathing regulation in the context of this study is understood as increasing or decreasing one's pace of breathing. It is not tested whether breathing maintains a consistent, regulated pace. Investigating this parameter could be beneficial for individuals with dysfunctional breathing (Vidotto *et al.* 2019). Such an investigation is outside the scope of this study.

2.3. Material intelligence

The social sciences took a material turn during the past decades, focusing on making, material culture, and embodied processes of meaning (Ingold 2013; Dolphijn & Van der Tuin 2012). Materiality has also been at the forefront of the design discourse: Researchers have been developing frameworks for evaluating materials, including their performative, experiential, affective, and sensorial properties (Karana *et al.* 2014; Pedgley *et al.* 2021; Desmet & Hekkert 2007, 2009), with Desmet & Hekkert (2007, 2009) particularly contributing to design and emotions. Materiality has also manifested in the design and computation discourse as an expansion of visual frameworks to incorporate material qualities, and making methods (Knight & Stiny 2015).

Advanced material properties have allowed the exploration of new shape-changing and material interaction capabilities (Pedgley *et al.* 2021). Programmable materials, often also referred to as responsive materials (Xia *et al.* 2022) or smart materials (Ritter 2007), are materials that are designed to change shape or properties in a controlled manner through an activation method, such as temperature, humidity change, or pressure change (Papadopoulou *et al.* 2017). Programmable materials are being used in a variety of research and industry domains (Tibbits 2017, 2021), interaction design (Ishii *et al.* 2012; Wiberg 2018), and biomedical applications (Bar-Cohen 2002; Ramasamy *et al.* 2007; Belforte *et al.* 2014). Shape-changing materials have also created opportunities for new modes of affective material expression in the design fields (Davis 2015; Farahi 2018).

Through Affective Matter, my aim has been to develop programmable material environments that can aid in emotion self-regulation and potentially in emotion communication. Self-regulation and communication systems have been explored since the era of cybernetics (Kline 2015), but with the machine rather than the material paradigm in mind. Ashby's famous homeostat was designed to maintain equilibrium through continuous adaptation (Ashby 1952). The homeostat was operating as a "black box," achieving equilibrium through the relation between input, output variables, and the feedback loop between its components. Another explored method for self-regulation was the actual hybridization between humans and machines. The Cyborg, initially conceived by Manfred Clynes, was envisioned as a human-machine organism that integrated artificial with physiological operations to adapt to any environment (Clynes & Kline 1960).

The machine paradigm faded away with the advancement of artificial intelligence. Within the context of artificial intelligence, the machine has become more "humane" rather than the human more "machine-like." For example, in the HCI field, research on affective computing (Picard 1997) has focused on how to equip machines with emotional intelligence to make them respond better to human needs. Research in the era of cybernetics first demonstrated possibilities for emotion self-regulation and communication through machine intelligence. Research within the context of affective computing first demonstrated possibilities for emotion self-regulation and communication through software intelligence. The goal of my research on Affective Matter has been to demonstrate possibilities for emotion self-regulation and communication through material intelligence.

In the context of this study, material intelligence is defined as the ability of matter to address the physiological aspects of the wearer's emotions in a novel, programmable manner through a design specifically developed to deliver haptic action. Aspects of intelligence not currently addressed are the ability of materials to respond to changes in affective needs on the fly and the ability of materials to accommodate personal preferences. Reflections on these aspects are provided in the conclusions, in response to participants' behaviors in the study, for consideration in future developments of the sleeve prototype.

3. Methods

3.1. The design and fabrication of the affective sleeve

An earlier design for an affective sleeve was developed by the author and collaborators (Papadopoulou *et al.* 2019). The affective sleeve was made from felt fabric with embedded shape memory alloy (nitinol) wires, which allowed the sleeve to change shape when current passed through, producing warmth and slight pressure (Figure 2). We conducted a study with 18 participants, divided into a Slow, a Fast, and a Control group. After a baseline phase requiring participants to watch a relaxing nature documentary, participants were asked to wear the sleeve while taking a spatial cognition quiz to induce stress (Figure 3). Participants in the Slow and Fast groups wore the sleeve programmed to provide haptic action at a pace equal to, and 25% faster than, their relaxed individual breathing rates, respectively. Participants in the Slow group demonstrated fewer symptoms of stress and a lower breathing rate than participants in the Fast group during testing (Papadopoulou *et al.* 2019).

Since the design of the first iteration of the affective sleeve, additional wearable prototypes for emotion self-regulation using haptic stimulation have been developed by HCI researchers. Developed wearables include, for example, a belt device

Figure 2. A prototype of an affective sleeve, used in prior study, made from felt fabric and a shape memory alloy (nitinol). When electrical current passed through the nitinol wires of a sleeve's cuff, the cuff changed shape producing slight warmth and pressure. Developed by the author and collaborators (Papadopoulou *et al.* 2019).

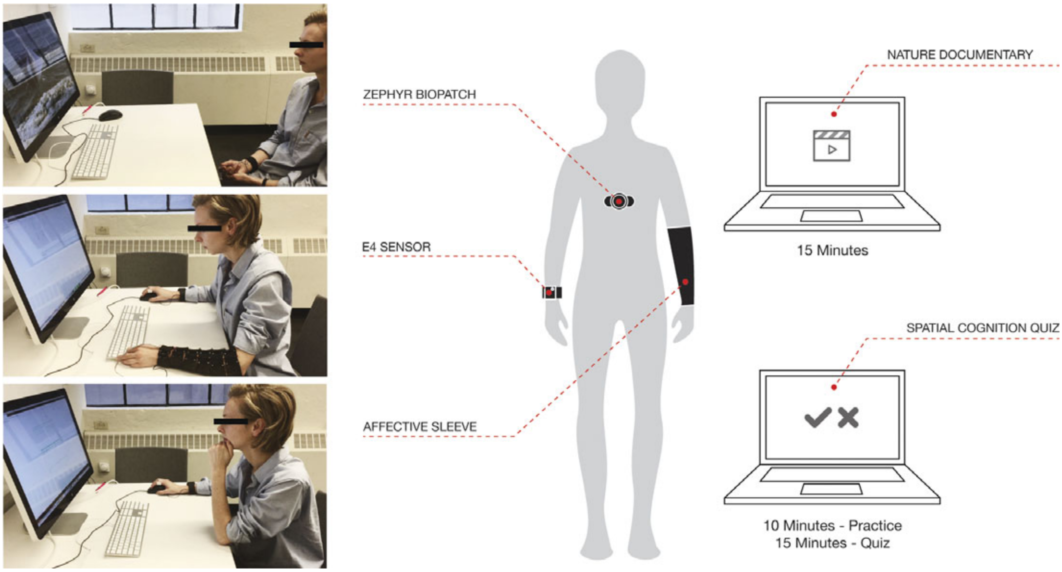

Figure 3. The procedure of the prior study testing an affective sleeve included a baseline, testing, and survey phase. Participants were distributed to the Fast, Slow, and Control groups. In the Fast and Slow groups, the haptic action was equal to 125% and 100% of individual relaxed breathing rates respectively. The study included physiology and self-report measurements (Papadopoulou *et al.* 2019).

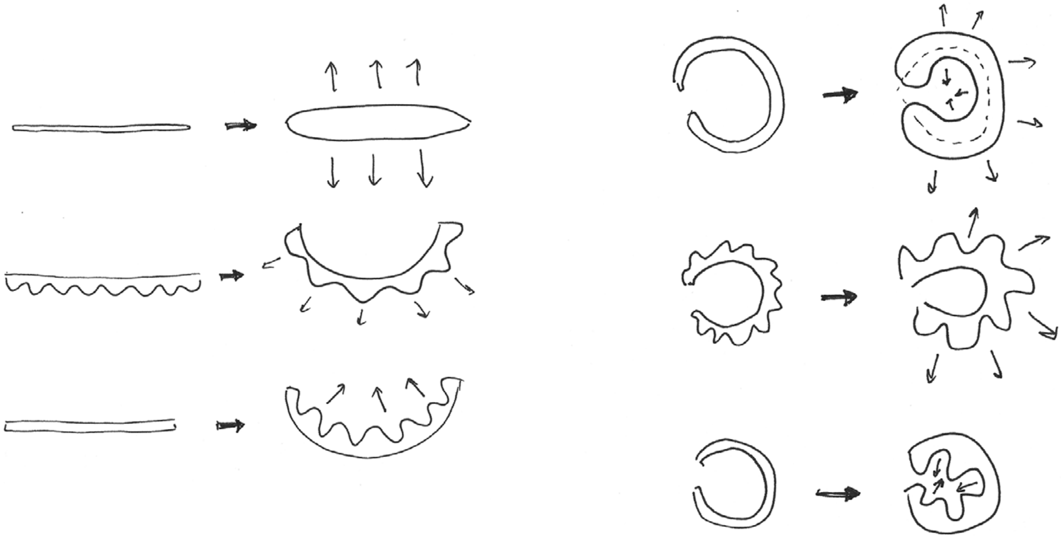

Figure 4. Sketch showing the natural behavior of a fabric bladder upon pressurization (top), the behavior of a programmable pneumatic fabric actuator based on common approaches in prior inventions and science literature (middle), and the behavior of the programmable pneumatic actuator I developed (bottom).

(Choi *et al.* 2021), a pillow (Ban *et al.* 2022), a scarf (Cochrane *et al.* 2022), and a pneumatic vest (Goncu-Berk 2021). Although some of these prototypes involve material actuation through shrinkage and expansion (Choi *et al.* 2021, 2022; Ban *et al.* 2022; Goncu-Berk 2021), they do not incorporate material programmability in the form of novel, non-obvious material behavior. In addition, research in the field often lacks studies with human subjects to evaluate the psychophysiological impact of the developed prototypes.

I made the choice to fabricate the sleeve from inflatable fabrics, to be light and reliable in its actuation and provide a good sense of felt pressure. The sleeve was designed with the aim to provide haptic action: the sleeve's inflation would produce the feeling of pressure, and embedded heat pads within the fabric layers would produce the feeling of warmth. Although there are several examples of transformable pneumatic bladders made from fabrics or elastic materials (Sparrman *et al.* 2021; Cappello *et al.* 2018; Walker *et al.* 2020; Ou *et al.* 2016), none of those examples would be appropriate for the sleeve: previously developed methods for pneumatic actuation of materials would either not allow for strong pressure sensation or become bumpy upon pressurization, resulting in a distracting ballooning effect (Figure 4).

After a series of design iterations, I developed a novel programmable wearable material solution consisting of a pleated two-level structure for increased volume. The structure was made from coated nylon fabric and was strategically constrained using heat-sealing to allow more air volume in the bottom part of the structure. Because of the difference in tension between the bottom and top levels of the pleated structure, when pressurized, the structure was forced to curve inwards, allowing a good amount of felt pressure towards the skin, eliminating any

Figure 5. The pneumatic affective sleeve was comprised of five cuffs that curved around the arm upon pressurization and also included embedded heatpads. The sleeve was designed to be modular to accommodate different body sizes (left). Preliminary prototype of the pneumatic affective sleeve showing how the novel material mechanism forces the air towards the skin increasing felt pressure and eliminating any ballooning effects (right).

Figure 6. Close-up photograph of the prototype of the pneumatic affective sleeve used in the study.

ballooning behavior and rendering the material transformation invisible to the wearer and imperceptible by others (Figure 5).

The final prototype of the pneumatic affective sleeve has a modular design consisting of five cuffs of the designed transformable pleated structure (Figures 5 & 6). A heatpad was embedded within the fabric layers of each of the five cuffs. The electronic system, including a microcontroller, relays, solenoid valves, and mini motor pumps, allowed for independent control of the pressure and temperature levels of each of the sleeve's cuffs. The electronics system was enclosed in a wooden box with added interior sound insulation to eliminate noise from the motor pumps that could cause distraction or otherwise negatively impact the experience of wearing the sleeve.

3.2. Study design and hypotheses

The first goal of the study was to test the impact of the sleeve's haptic action on the wearers' affective state. The second goal was to explore the affective impact of different conditions of haptic action. Arriving at correspondences between distinct conditions of haptic action and distinct affective states could lead to insights regarding personalized haptic action and mediated affective communication. Analytic studies with human subjects investigating the affective impact of mediated haptic communication, especially in terms of its physiological dimensions, are scarce (Smith & MacLean 2007; Salminen *et al.* 2008; Tsalamlal *et al.* 2014). Although the aspect of interpersonal communication was not directly tested in the study, it was part of the study design intentions to arrive at a repertoire of affective haptic stimuli.

The first study hypothesis, corresponding to the goal of emotion self-regulation, was: The pace of the sleeve's haptic action has a positive correlation with the wearer's breathing rate, and a negative correlation with the wearer's perception of calmness. To test this first hypothesis, I used a between-subjects experimental design: Comparisons were made between three participant groups (Slow, Regular, Fast), each wearing the sleeve with haptic action slower than, equal to, and faster than individual relaxed breathing rates, respectively. The second study hypothesis, corresponding to the goal of defining a repertoire of affective haptic stimuli, was: Distinct conditions of haptic action correspond to distinct affective states. To test the second hypothesis, I used a within-subjects experimental design: Each participant was tested on seven conditions of haptic action with distinct parameters.

I used a combination of breathing rate (BR) and electrodermal activity (EDA) measurements, self-reports, and interviews. Increases in BR, EDA levels, and EDA fluctuation are associated with the activation of the sympathetic nervous system (SNS). Decreases in BR, EDA levels, and EDA fluctuation are associated with the activation of the parasympathetic nervous system (PNS) (Balban *et al.* 2023; Jerath & Beveridge 2020; Van der Mee *et al.* 2021). SNS activation increases physiological arousal, increasing one's heart rate, blood pressure, and attention, promoting the body's "fight or flight" response. PNS activation decreases physiological arousal, promoting the body's "rest and digest" processes (Waxenbaum *et al.* 2023).

Changes in one's physiology may be due to changes in one's affective state or physical activity. For example, being stressed, excited, or angry are typically states of high arousal, whereas being depressed, calm, or bored are typically states of low arousal (Jerath & Beveridge 2020; Russell 2003). To minimize physiology changes due to physical activity, the study required participants to remain seated throughout testing. Physiology measurements alone are often not sufficient to identify one's affective state (Barrett 2018; Folz *et al.* 2022). The use of self-reports and brief interviews allowed for both the affective and sensory evaluation of the sleeve. The self-reports allowed participants to report changes in their affective state and evaluate the sensations of the sleeve's haptic action.

The study was subject to several limitations due to the hosting university's prevention measures during the pandemic. Participation in the three study groups was not equal and not as large as initially planned. Because of the unequal number of participants in the three groups, results were not tested for statistical significance. Thus, even though this is a hypothesis-driven study, it should be considered an exploratory study. The results provide important insights that can be further validated in future experimental studies.

3.3. Experimental procedure

The study was approved by the Institutional Review Board (IRB). Participants were students or staff at the Massachusetts Institute of Technology (MIT) and were recruited through email advertisements. The advertisement called participants to participate in a "45-minute study to evaluate the effects of material haptic sensations on emotional health and wellbeing," informed them about the $20 gift card compensation and about the fact that participants would be wearing a "novel wearable technology that produces the sensations of warmth and slight pressure along the forearm, and biometric sensors to collect physiology signals."

In addition to the affective sleeve, participants were asked to wear the Mindfield E-sense Skin Response sensor to measure their electrodermal activity (EDA) and the Mindfield E-sense Respiration sensor to measure their breathing rate (BR). The skin response sensor was worn on participants' index and middle fingers, on the intermediate phalanges, to allow participants to use their fingers to respond to the surveys using the mouse and keyboard. The skin response sensor was worn on the dominant hand because participants were instructed to wear the sleeve on the non-dominant hand. The respiration sensor was placed on the participant's chest using an elastic strap.

The testing procedure lasted approximately 45 minutes and included the following four phases: (1) Consent (approx. 5 minutes): Participants read and signed the consent form. (2) Baseline (approx.10 minutes): Participants wore the skin response and respiration sensors. During the Baseline phase participants were instructed to "sit and relax." (3) Testing (approx. 25 minutes): Participants wore the sleeve aided by the investigator who adjusted the sleeve for custom fit. The testing phase included a one-minute habituation session to the sleeve followed by testing of seven haptic conditions in randomized sequence including a control condition. Each haptic condition lasted one and a half minutes and was followed by a survey on a specifically developed for the study user interface. A survey also preceded the testing of the conditions. (4) Brief interview and debriefing (approx. 5 minutes) (Figure 7).

Participants wore the sensors during the baseline and testing phases and the sleeve during only the testing phase. In the baseline phase, relaxed breathing and electrodermal activity measurements were collected to allow for comparison with

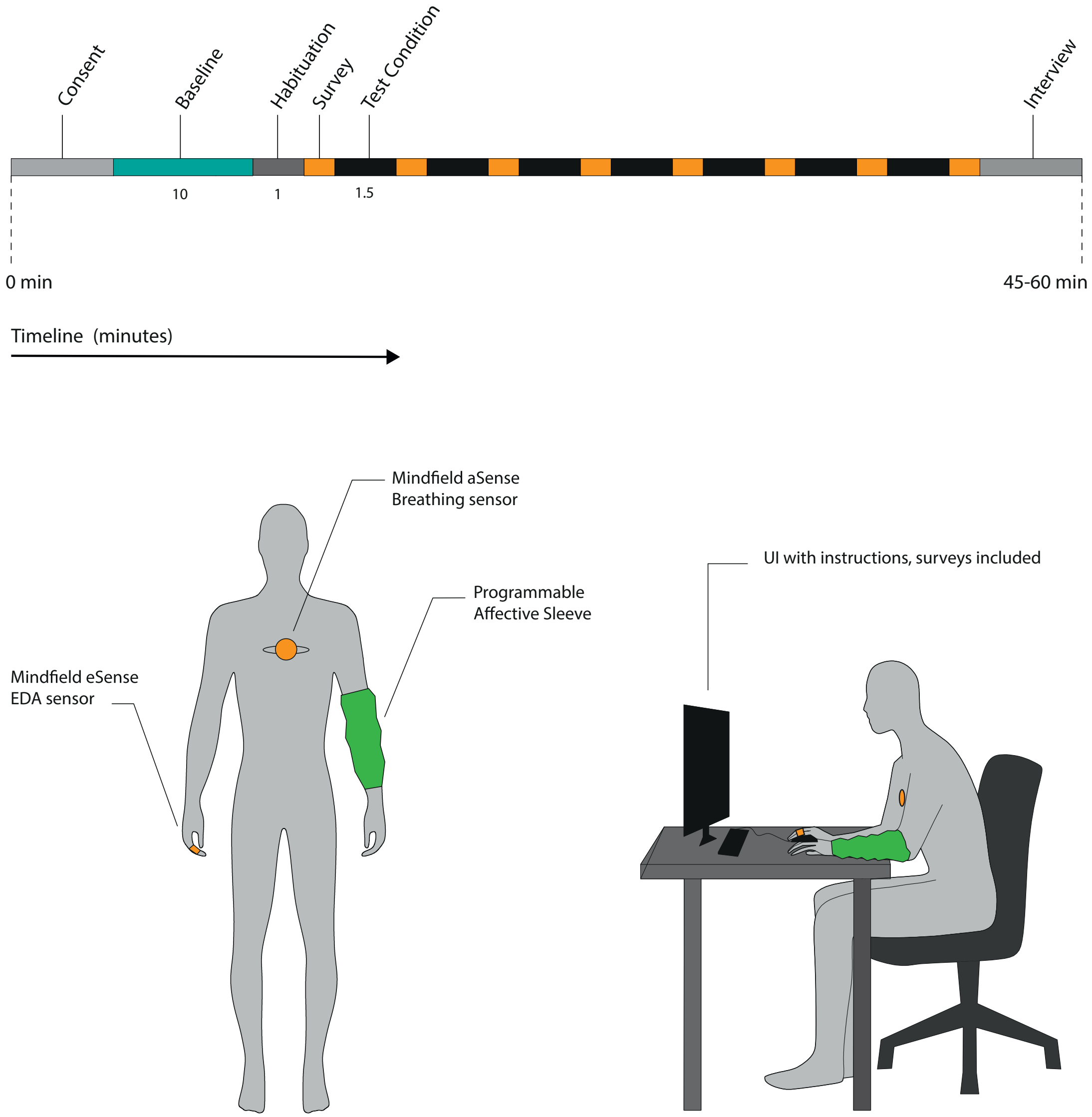

Figure 7. Experimental procedure and setup: The study lasted approximately 45 minutes (60 maximum) and comprised of four phases: Consent, Baseline, Testing, and Interview. Testing included a brief habituation session and seven testing conditions. A survey followed the habituation and each of the testing conditions. During testing participants sat at a desk, in front of a desktop computer, and wore the sleeve on their non-dominant hand, the electrodermal activity sensor on their dominant hand, and the breathing activity sensor on their chest.

the testing phase and to program the sleeve's haptic action in individualized manner. Throughout the procedure participants sat at a desk in front of a desktop computer to follow the testing instructions and fill out the surveys provided on the user interface (Figure 7). Participants were tested individually. The investigator interacted with the participants for the purpose of adjusting the sleeve and the sensors before and after the testing phase or in case of a technical issue. The study took place in a multipurpose room in the university. During the testing phase the investigator was in the room but remained seated at a distant and non-visible by the participant location.

For the testing phase, each participant was assigned to one of the following three groups: Slow group, Regular group, and Fast group. The pace of the sleeve's haptic action was programmed as follows: In the Slow group the pace of the sleeve's haptic action was 30% slower than the participant's relaxed breathing rate. In the Regular group the pace of sleeve's haptic action was equal to the participant's relaxed breathing rate. In the Fast group the pace of sleeve's haptic action was 30% faster than the participant's relaxed breathing rate. The relaxed breathing rate for each individual participant was defined as the participant's average breathing rate during the baseline phase, measured through the smartphone app of the Mindfield E-sense Respiration sensor.

The seven conditions of haptic action differed regarding the occurrence of the activation/deactivation cycle of haptic action (HAC), the sensory type of haptic action, and the rhythmic pattern of haptic action. The cycle of haptic action was

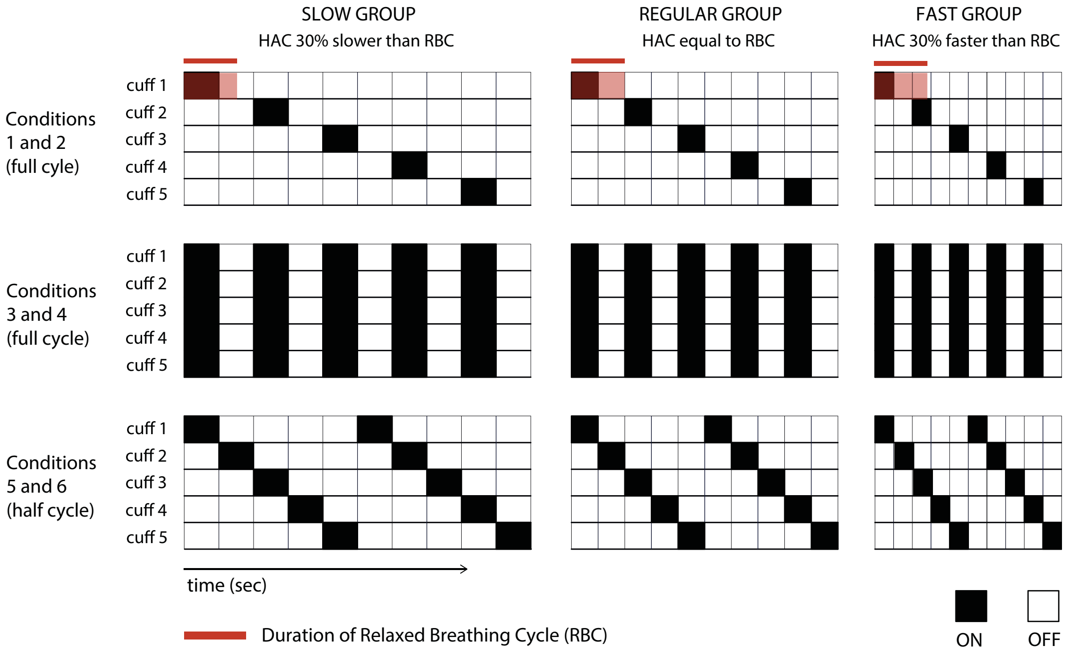

Figure 8. The affective sleeve was designed with the intention of entraining the wearer's breathing activity to the sleeve's haptic action. A cycle of haptic action (HAC) was defined as the duration of pressure/temperature activation (Cuff ON) and deactivation (Cuff OFF) of a sleeve's cuff. A relaxed breathing cycle (RBC) was defined as the duration of a participant's average relaxed breathing cycle, including inhalation and exhalation, as measured during the baseline. HAC's length was 30% slower than, equal to, or 30% faster than the length of the wearer's RBC in the Slow, Regular, and Fast groups, respectively. HAC's occurrence differed based on the conditions of haptic action: In conditions with a full HAC (conditions 1, 2, 3, 4), a cuff or series of cuffs was activated after a full HAC of any previously activated cuff. In conditions with a half HAC (conditions 5, 6), a cuff was activated after a half cycle of any previously activated cuff. The length of activation (Cuff ON) as opposed to deactivation (Cuff OFF) was always equal to 50% of a HAC.

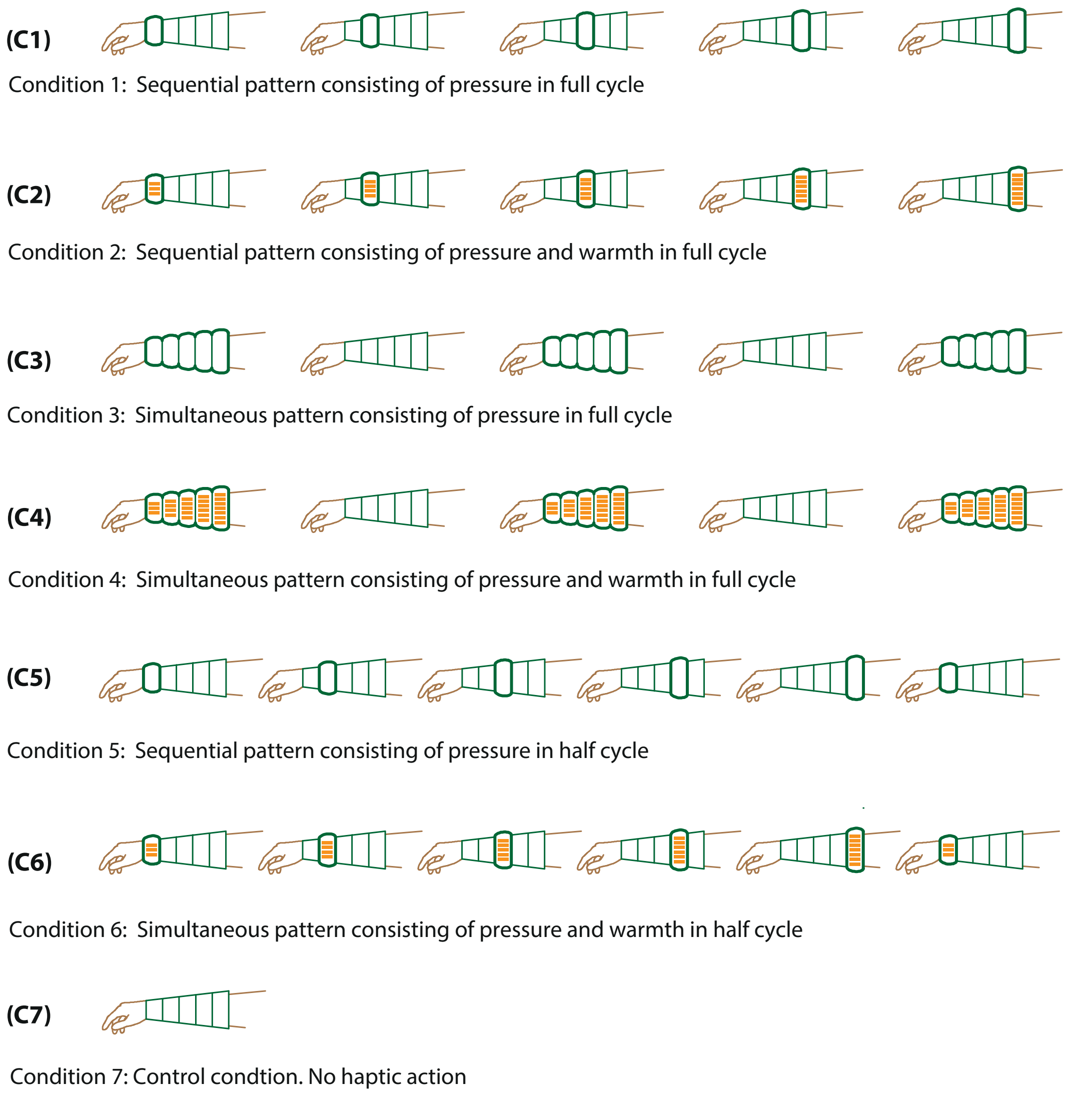

Figure 9. Participants were tested on seven conditions of haptic actions in randomized sequence: (C1) Sequential pattern consisting of pressure in full cycle; (C2) Sequential pattern consisting of pressure and warmth in full cycle; (C3) Simultaneous pattern consisting of pressure in full cycle; (C4) Simultaneous pattern consisting of pressure and warmth in full cycle; (C5) Sequential pattern consisting of pressure in half cycle; (C6) Simultaneous pattern consisting of pressure and warmth in half cycle. (C7) Control Condition.

defined as the duration of pressure/temperature activation and deactivation of a sleeve's cuff. The occurrence of the cycle differed based on the conditions of haptic action: In conditions with a full cycle (conditions 1, 2, 3, 4), a cuff or series of cuffs was activated after a full cycle of any previously activated cuff. In conditions with a half cycle (conditions 5, 6), a cuff was activated after a half cycle of any previously activated cuff. The length of activation as opposed to deactivation was always equal to 50% of a cycle. The length of the cycle was 30% longer than, equal to, and 30%

shorter than a relaxed breathing cycle (RBC), including inhalation and exhalation, for participants in the Slow, Regular, and Fast groups, respectively (Figures 8 & 9).

Regarding the type of haptic action, conditions consisted of either pressure only (conditions 1, 3, 5), or both pressure and warmth (conditions 2, 4, and 6). Regarding the pattern of haptic action, conditions consisted of either sequential or simultaneous haptic action. In sequential haptic action (conditions 1, 2, 5, 6) each of the sleeves' cuffs produced haptic action one after the other in a direction from the wrist towards the elbow. In simultaneous haptic action (conditions 3, 4) all five cuffs produced haptic action at the same time (Figures 8 & 9). The pattern of sequential haptic action was initially inspired by the body scanning meditation (Gibson 2019), and the progressive muscle relaxation techniques (Toussaint *et al.* 2021). In both techniques, the practitioner gradually shifts their focus of attention from one body location to another, in coordination with their breathing activity, to increase somatic awareness and release tension.

The condition with sequential pattern with warmth and pressure was the only one tested in the prior study by the author and collaborators (Papadopoulou *et al.* 2019). It was thus unclear in the prior study to what extent each of the sensory stimuli of warmth and pressure contributed to the psychophysiological impact of the haptic action. It was also unclear whether the specific pattern of haptic action played a role in the impact. In the present study, the distinction between conditions with pressure only and conditions with both pressure and warmth aimed at providing insights regarding the impact of the two different stimuli. Conditions including only warmth and no pressure were not implemented because without the pressure stimulus the feeling of warmth lingered beyond each cuff's actuation and extended beyond each cuff's location. The cuffs' inflation contributed to making the warmth sensation more discrete.

A simultaneous pattern of haptic action was added to the conditions' parameters to compare its effectiveness against the sequential pattern. The two kinds of cycles of haptic action were chosen because of their potential synchronization to the cycle of breathing. Based on my second hypothesis, variations in the testing parameters were essential to show distinct psychophysiological responses to distinct conditions of haptic action. A control condition with no haptic action was required to determine whether any psychophysiological impact was indeed due to the implemented haptic action. The duration of each of the haptic conditions was one and a half minutes to allow enough time to adjust to the experience of the sleeve without causing tiredness.

Based on the chosen testing parameters, each participant was tested on the following seven conditions of haptic action in randomized sequence: (C1) Sequential pattern consisting of pressure in full cycle; (C2) Sequential pattern consisting of pressure and warmth in full cycle; (C3) Simultaneous pattern consisting of pressure in full cycle; (C4) Simultaneous pattern consisting of pressure and warmth in full cycle; (C5) Sequential pattern consisting of pressure in half cycle; (C6) Simultaneous pattern consisting of pressure and warmth in half cycle. (C7) Control Condition. During the control condition the sleeve remained inactive producing neither warmth nor pressure (Figure 9).

Prior to testing, and after each of the seven haptic conditions, participants were requested to fill out a survey as part of a user interface (UI) developed especially for the study. The survey was divided in three sections. The first section addressed the affective evaluation of the sleeve, the second section addressed the sensory evaluation of the sleeve, and the third section prompted participants to add comments regarding the experience of the tested haptic condition. The affective and sensory evaluation sections included multiple choice questions and questions requiring response using a slider. Participants were prompted by the UI to continue to the next steps of the testing phase without having to interact with the investigator.

3.4. Study participation and demographics

Participants' ages ranged from 18 to 39 years old. The average age of participants was 29. The study took place at the Massachusetts Institute of Technology over the course of five weeks. Data from one participant were excluded from the study due to technical failures during testing. In total, data from 36 participants were used. The study had to stop abruptly due to COVID-19 prevention measures, thus participation in the three groups was unequal: Out of the 36 participants, 15 took part in the Regular group, 13 in the Slow group, and eight in the Fast group. The gender distribution in the three groups was: eight male, six female, and one participant of other gender in the Regular group; eight female and five male participants in the Slow group; five female and three male participants in the Fast group.

Physiology data were discarded if a sensor malfunction or other technical failure was detected that could impact the results. BR data from all conditions were discarded from one participant in the Slow group. BR data from individual conditions were discarded for two participants in the Regular group and one participant in the Fast group. EDA data from all conditions were discarded from two participants in the Regular group, one participant in the Slow group, and two participants in the Fast group. No self-reported data needed to be discarded.

4. Data analysis and study results

4.1. Self-reported data analysis

4.1.1. Survey-based sensory evaluation of the sleeve

Participants filled out the sensory evaluation upon completion of testing of each of the haptic conditions. The questions addressed the sensory stimuli of warmth and pressure separately and were the following: (1) Did you feel a pressure/warmth sensation?," requiring a yes/no response; (2) "Was the pressure/warmth sensation pleasant or unpleasant?," requiring a response using a slider on or between the markers "Very unpleasant; A bit unpleasant; Neutral; A bit pleasant; Very pleasant"; (3) "If 5 is the highest and 1 is the lowest intensity of warmth/pressure you felt during this session, what was the maximum warmth/pressure you felt in the area covered by each of the five cuffs?," requiring a response on a scale from 1.0 to 5.0 using vertical sliders. The vertical sliders were positioned above a diagrammatic image of the sleeve, in corresponding positions to each of the five cuffs.

To the questions "Did you feel a pressure/warmth sensation?" in conditions with haptic action of warmth and pressure (conditions 2, 4, 6) all participants provided an affirmative response regarding both sensations. This result suggests that the sensations were perceived as intended. In conditions with haptic action of pressure only (conditions 1, 3, 5) and in the control condition (condition 7) a small percentage of the participants reported feeling warmth (20% in condition 1, 27% in condition 3, and 17% in condition 5). In addition, 13% of the participants reported feeling pressure during the control condition (condition 7). In the responses to the questions “Was the pressure/warmth sensation pleasant or unpleasant?” all groups rated both sensations above neutral in terms of pleasantness, but the Slow and Regular groups rated the sensations slightly higher in pleasantness.

To the questions “If 5 is the highest and 1 is the lowest intensity of warmth/pressure you felt during this session, what was the maximum warmth/pressure you felt in the area covered by each of the five cuffs?” in conditions with sequential pattern of haptic action (conditions 1, 2, 5, 6) participants rated pressure and

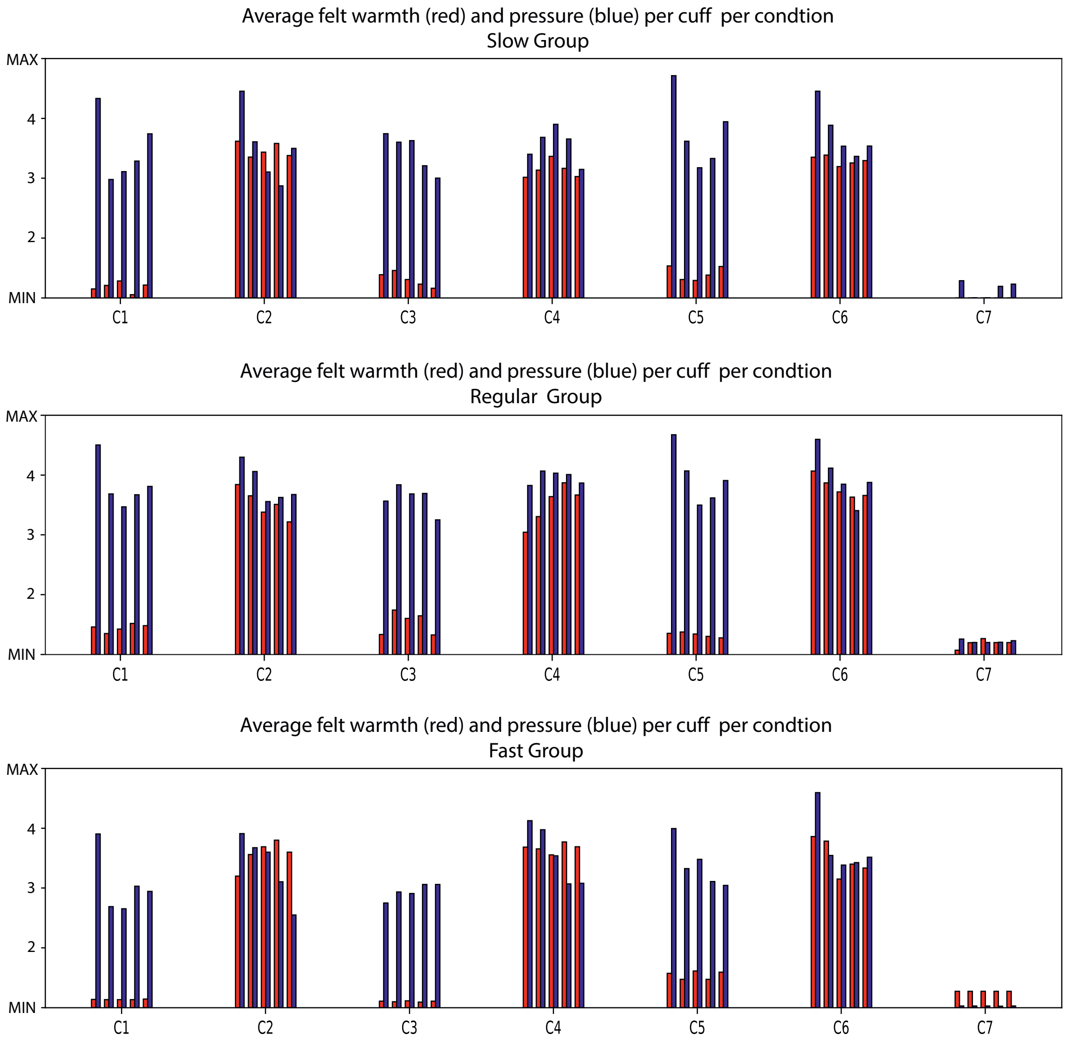

Figure 10. Graphs showing responses to the questions “If 5 is the highest and 1 is the lowest intensity of warmth/pressure you felt during this session, what was the maximum warmth/pressure you felt in the area covered by each of the five cuffs?” Bars represent intensities for warmth (red) and pressure (blue) for each of the five cuffs. In conditions with sequential pattern of haptic action (C1, C2, C5, C6), pressure and warmth felt more intense at the ends of the sleeve and lower in the middle. In conditions with simultaneous pattern of haptic action (C3, C4), warmth and pressure felt more intense in the middle of the sleeve and lower at the ends.

warmth as the highest in intensity at the first cuff (closest to the wrist) and fifth cuff (closest to the elbow) and the lowest in intensity at the middle cuffs of the sleeve (second, third, and fourth cuff). In conditions with simultaneous pattern of haptic action (conditions 3, 4) participants on average rated the middle cuffs (second, third, and fourth cuffs) as the highest in intensity, and the cuffs at the ends (first and fifth cuffs) as the lowest in intensity. The results demonstrated that, interestingly, the intensity of sensations was pattern dependent: the simultaneous pattern of haptic action had the opposite effect in felt intensity from the sequential pattern (Figure 10).

4.1.2. Survey-based affective evaluation of the sleeve

The affective evaluation section of the survey was designed based on the circumplex model of affect, which is a two-dimensional model for affective evaluation (Russell 1980, 2003). According to the circumplex model of affect, each affective state is defined by the values of arousal and valence which form the two axes of the circumplex. Values of highest and lowest arousal are located at the top and bottom end of the vertical (arousal) axis, respectively. Values of most positive valence and values of most negative valence are located at the right end and left end of the horizontal (valence) axis, respectively. Typical two-dimensional models are discussed in literature as being reductive by assuming opposite affective states as mutually exclusive (Norman *et al.* 2011). To allow for more ambiguity I enabled independent evaluation of each affective state, allowing someone to report, for example, feeling “sad” and “happy” at the same time.

The survey included eight questions with sliders, each addressing a distinct affective state. The eight states were each labeled with two similar feelings (e.g., Excited/Enthusiastic) and formed four affective dimensions of opposite states: Tired/Lethargic — Excited/Enthusiastic; Sad/Gloomy — Elated/Happy; Upset/Distressed — Serene/Contented; Tense/Jittery — Placid/Calm. The questions were formulated as follows: “Right now to what extent do you feel being at a certain affective state (e.g., tense or jittery)?” Participants were prompted to respond by placing the slider thumb anywhere on or between the marks “Not at all,” “A little,” “Moderately,” “Quite a bit,” “Extremely.”

Participants filled out the affective evaluation eight times. First, participants filled out the affective evaluation before the testing procedure. Pretesting evaluation measurements were used as a baseline for each participant. Then, participants filled out the affective evaluation upon completion of testing of each of the haptic conditions. Participant responses were mapped onto a numeric scale from 0.0 to 100. When opposite affective states were plotted side by side as the two ends of the same continuum, the values in the Regular group tended to be more symmetric than those in the Fast and Regular groups. The group comparison of the absolute change from baseline (pretesting) for each haptic condition per participant showed a noticeable decrease in the feeling of “tired/lethargic” for the Fast group, and a noticeable decrease in the feeling of “excited/enthusiastic” for the Slow group.

When values provided by each of all participants are mapped on the affective circumplex we can observe the tendencies of the collective affective map per condition, per group. The collective affective maps of the Slow group gravitate towards the bottom and the bottom-right quadrant of the circumplex where affective states of low arousal are located -- including the feeling of tiredness, which is of negative valence, and the feeling of calmness, which is of positive valence. The collective affective maps

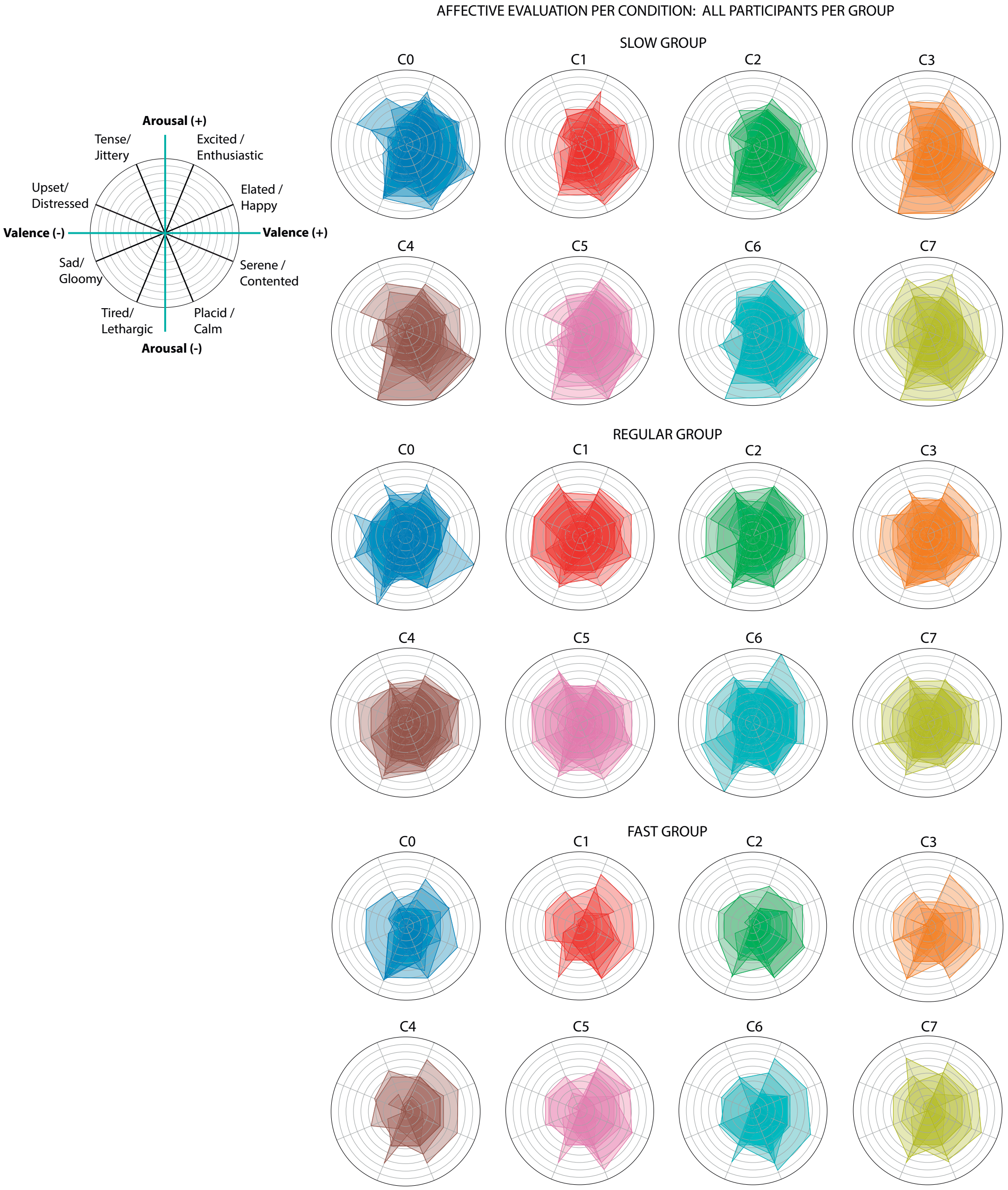

Figure 11. Radar charts showing the affective evaluation per condition for all participants per group. Individual evaluations for each condition are mapped on the affective circumplex creating a collective affective map per condition per group. The collective affective maps of the Slow group gravitate towards affective states of low arousal and slightly negative valence, like calmness and tiredness. The collective affective maps of the Regular group gravitate towards the center of the circumplex, expressing a neutral affective response. The collective affective maps of the Fast group gravitate towards affective states of high arousal and positive valence, like excitement and happiness.

of the Regular group gravitate towards the center of the circumplex, expressing a neutral affective response. The collective affective maps of the Fast group gravitate towards the upper right quadrant of the circumplex where high arousal and positive valence are located, including feelings of excitement and happiness (Figure 11).

The results are aligned with the study’s first hypothesis as they suggest a correlation between the pace of haptic action and the levels of arousal, indicating that faster pace of haptic action promotes energetic feelings and slower pace of haptic action promotes calmness.

4.1.3. Interviews and survey-based feedback

At the last section of the UI survey, participants were prompted to provide comments regarding the experience of the sleeve’s haptic action at each condition. Survey comments were analyzed together with the responses to the brief interview following the testing procedure. The questions used in the interview were:

“1) How would you describe the experience of wearing a programmable sleeve with haptic action?; 2) Do you have any comments regarding the sensations (warmth and/or pressure) produced by the sleeve?; Was there a considerable difference in felt sensations in the various conditions of haptic action you experienced?; 3) Do you have any comments regarding any emotions you felt due to the haptic action of the sleeve? Think of the different conditions of haptic action you experienced; was there a considerable difference in the way these made you feel?; 4) Do you have any comments regarding the design of the sleeve?; 5) Would you wear a programmable sleeve with haptic action if it improved your wellbeing -- for example, if it reduced your stress levels?”

Regarding the experience of the haptic patterns, 66% of the participants in the Regular group, 62% in the Fast group, and 38% in the Slow group had a strong preference for either the simultaneous or the sequential pattern of haptic action. The simultaneous pattern of haptic action (condition 3, condition 4) was the most controversial as many participants either strongly liked it or disliked it. Between the conditions of sequential pattern of haptic action (conditions 1, 2, 5, 6) there was a higher preference for those with half inflation cycle (conditions 5 and 6) compared to those with full inflation cycle (conditions 1 and 2).

Between the two conditions with simultaneous pattern of haptic action (conditions 3 and 4) participants typically expressed a preference for condition 4 which included warmth. Some of the participants who had a slightly stress-provoking experience associated the sleeve with a blood pressure cuff, especially when the condition did not include warmth (condition 3). Many of the participants who reported having a calming experience during conditions 3 and 4 made the association of the sleeve’s haptic action with the activity of breathing, noting for example that “(the sleeve) felt like sleeping alongside someone peacefully breathing,” and that “(wearing the sleeve was like) having a kitten or puppy in one’s arms”. Some of the participants remarked that the sleeve was “guiding their breathing” or that their breathing was “in sync with the sleeve.”

The soothing effect of some of the haptic conditions was sometimes associated with human touch. A participant in the Regular group noted regarding condition 4 that “the squeezing of the forearm in harmonic sequence was comforting and reminded (them) of when a family member or friend holds a person to let them know that everything will be alright.” Other participants perceived the same haptic condition as energizing or anxiety provoking while still making the association with human touch or aliveness. A participant in the Slow group noted regarding conditions 3 and 4 that they “felt almost stressful, like (someone is) grabbing (you).”

Regarding the conditions with a sequential pattern of haptic action, conditions with half cycle of haptic action (conditions 5, 6) were typically preferred over conditions with full cycle of haptic action (conditions 1, 2) and were often associated with the experience of having a massage. Although all conditions included elements that could be associated with massage, the association with massage was almost exclusively made in reference to conditions 5 and 6. Other participants perceived the sequential pattern of haptic action as slightly anxiety provoking because of creating a certain kind of anticipation. A participant from the Regular group noted regarding the sequential pattern:

“The sequence indicates something, a direction or a motion or something. Having the expectation that something will happen … The fact that there is a pattern (…) that you expect to hear again, like a ringtone, the first time is fine but then is annoying. Whereas the one with the whole sleeve (having simultaneous pattern of haptic action) felt soothing, it just kept going and did not feel like a rhythm as much, it was more like a chord rather than a rhythm.”

Some participants perceived the sleeve’s rhythm as something playful and pleasant. For example, a participant in the Slow group compared the rhythm of the sleeve to the musical rhythm of “a xylophone up and down” noting that it was a very relaxing experience. Another participant in the Slow group associated the experience of wearing the sleeve in different patterns and paces of haptic actions to that of listening to different music styles to regulate her mood. The participant noted: “It reminds me of when I listen to music, active music, when I am tired and I want to work (..) and also (relaxing music) for calming, for meditation and for falling asleep.”

Most participants (19 out of 36) expressed a preference for the haptic action that combined both pressure and warmth rather than pressure alone. Participants who enjoyed the warmth sensation remarked that they wanted “to crank up the heat,” or that it “felt peaceful” and that it made them “fall asleep.” The ones who did not enjoy the warmth noted that it felt “intense,” “strange” or “made them sweat.” One participant found warmth agitating noting that “heat in general makes (him) more aggressive, certain feelings of (his) like annoyance get amplified with heat.”

Time had an impact on the experience of the sleeve’s haptic action. Although the levels of pressure and heat remained the same throughout the duration of a condition, participants often felt that the intensity of either pressure, warmth, or both, changed. This perceived change sometimes affected how pleasant the haptic action felt. A participant in Slow group noted: “The way heat comes in gradually, then intensifies, and then decreases, I wish it stayed at the middle level all the way.” Participants’ affective experience throughout the study was also impacted by time. A participant in the Regular group noted: “When I realized the range of the produced sensations, I felt kind of relaxed.” Another participant in the Slow group noted: “Just doing it a lot, I just felt more chill.”

Participants were also asked how they would modify the conditions to achieve a greater variance of affect. Some of them responded that a pattern of haptic action with less predictability would be more anxiety provoking. Others suggested that less predictability and more variance in the sensory stimulation would promote more excitement. A participant in the Fast group gave the following suggestion: “I would design something emulating someone pressing my arm. Maybe two or three at a time and shifting around. I might feel more interested overall when engaging more sensors at the same time, in different modes."

When asked if they would be willing to wear the sleeve in their everyday lives, participants were more willing to do so if they had already been involved in other forms of wellbeing practices such as acupuncture, or other wearable solutions. Some participants argued that they would be more comfortable wearing the sleeve only at home, and others that they would be comfortable wearing it all day. One participant in the Slow group suggested a full-body variation of the sleeve, noting: "Yes - Oh yes, I would wear a suit, go to work and if I need a break I would take a full body massage."

4.2. Physiological data analysis

4.2.1. Electrodermal activity

To arrive at insights regarding changes in electrodermal activity I measured and compared average changes from baseline and increases or decreases during testing. The EDA sensor provides two types of useful measurements: Electrodermal Activity Levels (EDA - L), and Electrodermal Activity Response (EDA - R). Typically, higher EDA - L and higher EDA - R indicate high arousal states. EDA - L provides information on the average overall increase or decrease in arousal, whereas EDA - R provides information regarding arousing events in time, as it measures the fluctuations in electrodermal activity. The EDA - R values per minute, and EDA - L values were calculated by the E - Sense Mindfield smartphone application. The sensor's sampling rate was 5 measurements per minute. According to the sensor's manual, a response event was detected if the signal was greater than 0.5 microsiemens or continuously rising for 2 seconds.

I retrieved the EDA values from the sensor and calculated average values for each participant for each haptic condition tested. I then calculated the relative average EDA-L change from baseline for each haptic condition per participant using thse following formula: EDA-L relative change = EDA-L avg/baseline EDA-L avg −1. To arrive at conclusions regarding the EDA-R measurements I calculated the absolute change from baseline for each haptic condition per participant using the following formula: EDA-R absolute change = EDA-R avg - baseline EDA-R avg. Finally, I calculated the average values per condition per group for a comparative analysis between groups and between conditions (Figure 12).

The results demonstrated that in conditions with a simultaneous pattern of haptic action (conditions 3 and 4) participants had higher EDA increase from baseline than conditions with sequential pattern of haptic action (conditions 1, 2, 5, 6). Overall, in condition 4, with haptic action consisting of warmth and pressure in simultaneous pattern in full cycle, participants had the highest EDA increase from baseline. The results did not demonstrate important consistent differences between conditions including pressure and warmth (conditions 2, 4, 6) and conditions including only pressure (conditions 1, 3, 5). The comparison between the Slow, Regular, and Fast groups showed similar tendencies among the three groups regarding EDA levels (EDA – L) change. The variation in the EDA response (EDA-R) results is not surprising because the results were based on absolute and not relative change. The EDA increase in the control condition could be attributed

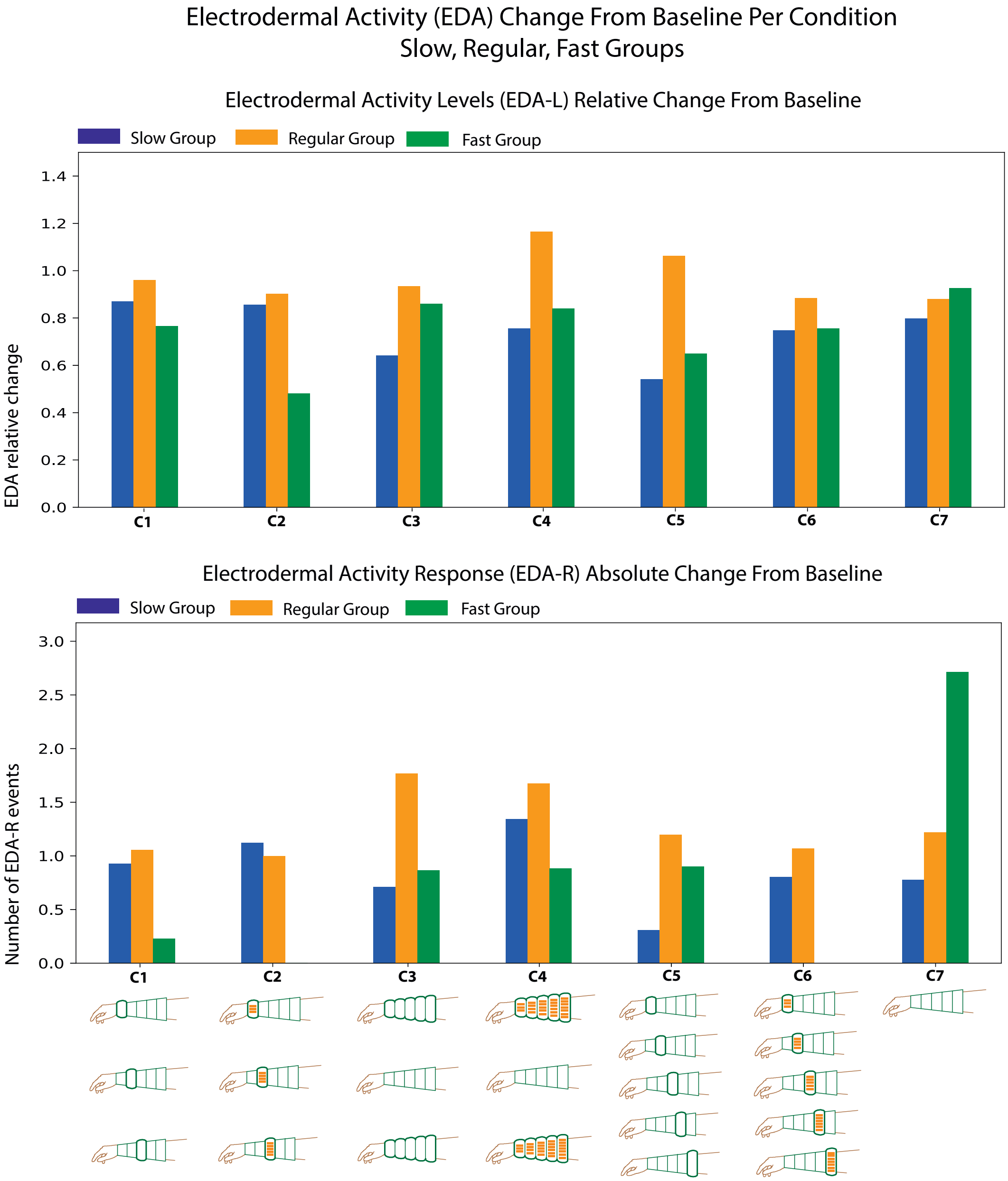

Figure 12. Graphs showing the change of electrodermal activity (EDA) from baseline per condition for each group. The relative change of EDA levels (top) and the absolute change of EDA response (bottom) demonstrate that conditions with simultaneous pattern of haptic action in full cycle (conditions 3 and 4) had on average the greatest increase in EDA. There were no important consistent differences between conditions with pressure alone and conditions with pressure and warmth.

to fidgeting behaviors, because the sleeve was inactive, or to a carryover effect of previously tested conditions (Figure 12).

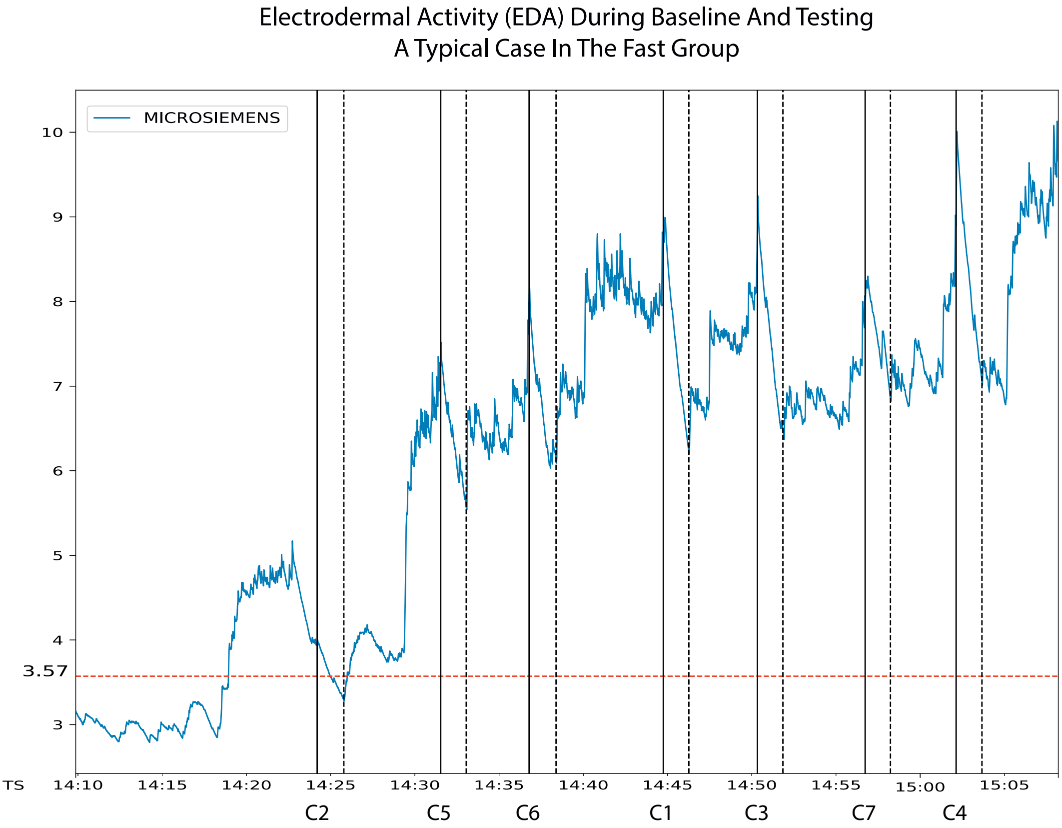

Figure 13. Plot of the electrodermal activity (EDA) of one participant of the Fast group during baseline and testing. The participant was tested in a randomized sequence of conditions (conditions 2, 5, 6, 1, 3, 7, 4) according to the study protocol. The red dotted line represents the average baseline measurement. The continuous lines represent the start of each of the conditions of haptic action. The black dotted lines represent the beginning of the UI surveys following each condition. In this typical example of EDA activity, we observe that the EDA levels drop during the conditions, while the sleeve is active, and increase during the surveys, when the sleeve is inactive.

To gain insights on how EDA levels increase or decrease within a haptic condition, I used linear regression, fitting a first-degree polynomial in the EDA data. I first calculated the first-degree polynomial for EDA-L data of each participant individually. Because of the large number of EDA measurements per second, I calculated the mean slope values for each group and multiplied the results by 100 to enhance readability of the graphs. The group comparison of the mean EDA-L change (slope) within each condition demonstrates that participants of all groups had on average a decrease in EDA levels from the start to the end of the conditions. The decrease in EDA levels within haptic conditions in the Fast group was approximately double than that of the decrease in the EDA levels in the Slow and Regular groups (Figures 13 & 14).

A comparison between EDA-L change (slope) within the testing conditions and their succeeding surveys showed that levels decreased during the conditions but increased during the surveys. In the Slow and Regular groups, the amount of decrease during the conditions was typically greater than the amount of increase during the succeeding surveys. In the Fast group, the amount of decrease during the conditions was approximately equal to the amount of increase during the succeeding surveys (Figure 14). The combined results suggest a longer and more relaxing effect of the sleeve in the Slow and Regular groups as opposed to a faster-acting and stronger impact of the sleeve in the Fast group, which possibly had an energizing impact in the short term.

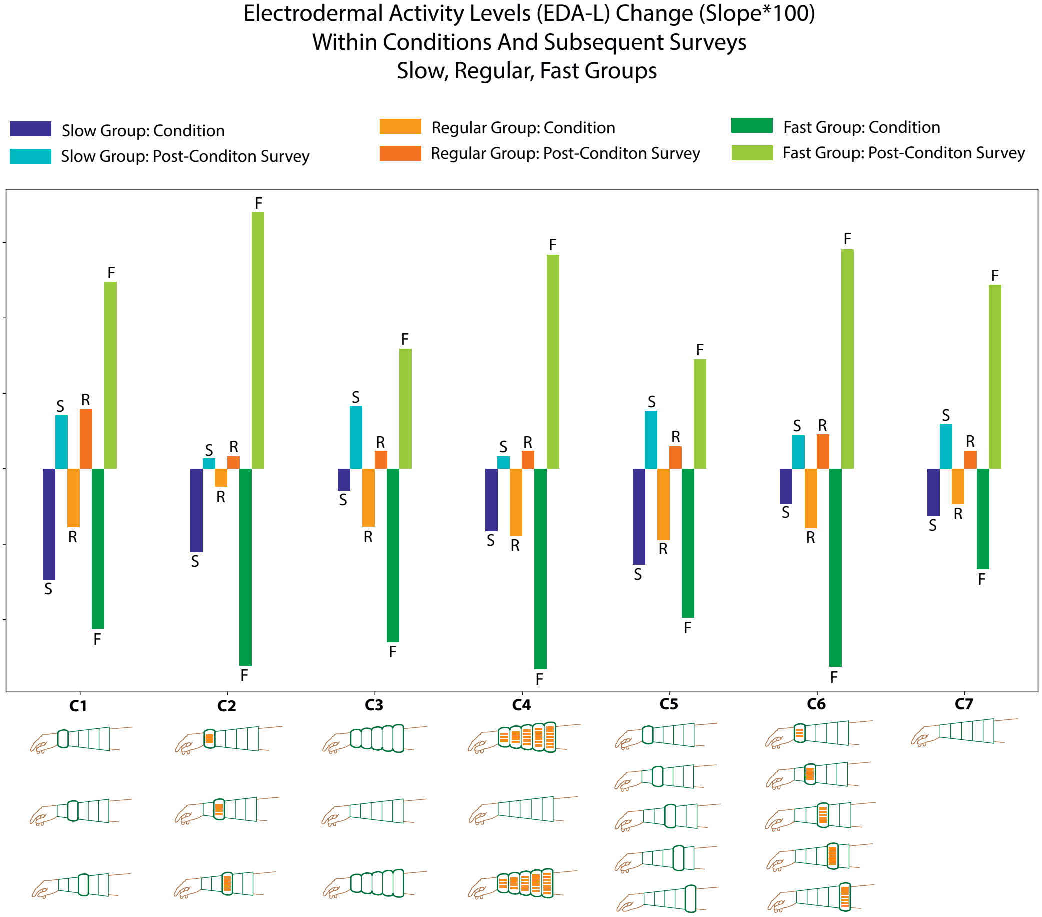

Figure 14. Graph showing the mean change (slope) of electrodermal activity levels (EDA-L) within each condition and within each subsequent survey per group. EDA levels decreased during the conditions but increased during the surveys. In the Slow and Regular groups, the amount of decrease during the conditions was typically greater than the amount of increase during the succeeding surveys. In the Fast group, the amount of decrease during the conditions was approximately equal to the amount of increase during the succeeding surveys. The combined results suggest a longer and more relaxing effect of the sleeve in the Slow and Regular groups as opposed to a faster acting and stronger impact of the sleeve in the Fast group, which possibly had an energizing impact in the short term.

4.2.2. *Breathing activity*

To arrive at insights regarding changes in breathing activity I measured the increases or decreases in average breathing rates (BR) from baseline. The Midfield Respiration sensor measures the extension and contraction of the chest to determine breathing cycles. The sensor's sampling rate is 5 values per second. To process the data, I first retrieved the breaths per minute (BPM) values from the E-Sense Midfield smartphone application. From the baseline phase I excluded the first and last minute of the recorded data to remove calibration and motion artifacts. From the remaining data I first calculated the average values for the baseline and each of the haptic conditions for each participant. I then calculated the percent relative change from baseline for each condition per participant using the following formula: BR percent relative change = (BPM avg/ baseline BPM avg – 1) *100.

I calculated the interquartile range (IQR) for each of the groups and excluded values above the third quartile and three IQR (Q3 + 3 IQR) and below the first quartile and three IQR (Q1–3 IQR). When, in a participant's measurements, the values of more than four haptic conditions lay above or below the set range, all BR values of the participant were discarded, assuming a displacement or malfunction of the sensor. BR data were discarded from two participants of the Regular group from all conditions. BR data were also discarded from five individual conditions from participants in the Slow group.

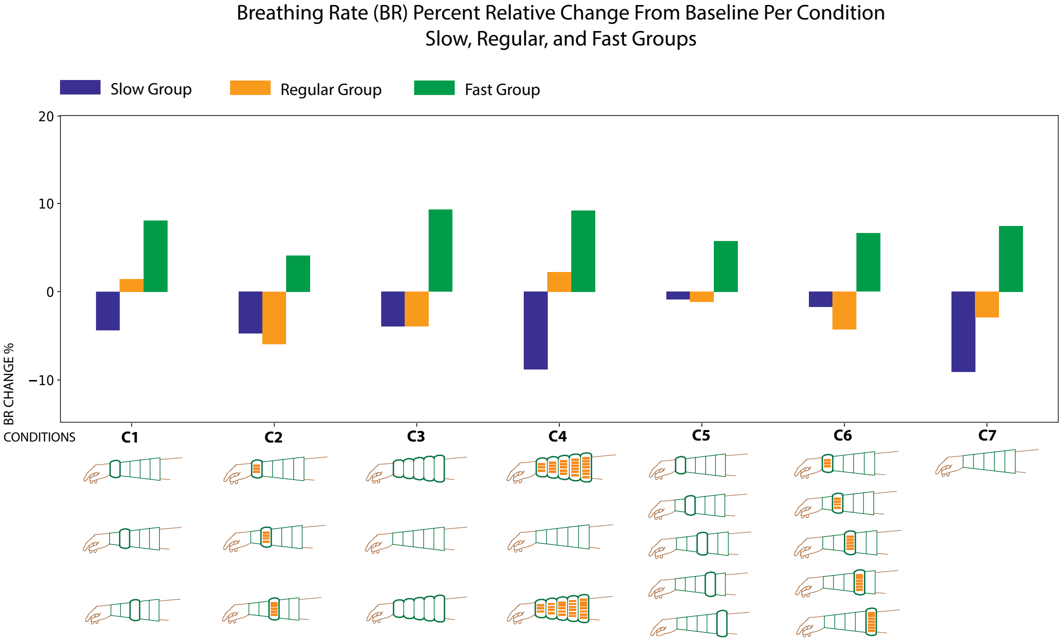

Figure 15. Graph showing the mean relative percent change of breathing rate from baseline for each group using the mean values for each participant. The results are aligned with the study's first hypothesis as they suggest a positive correlation between the wearer's breathing rate and the pace of the sleeve's haptic action. Participants in the Slow group exhibited on average 4.79% decrease in BR from baseline; Participants in the Regular group exhibited on average 2.08% decrease in BR from baseline; Participants in the Fast group exhibited on average 7.20% increase in BR from baseline.

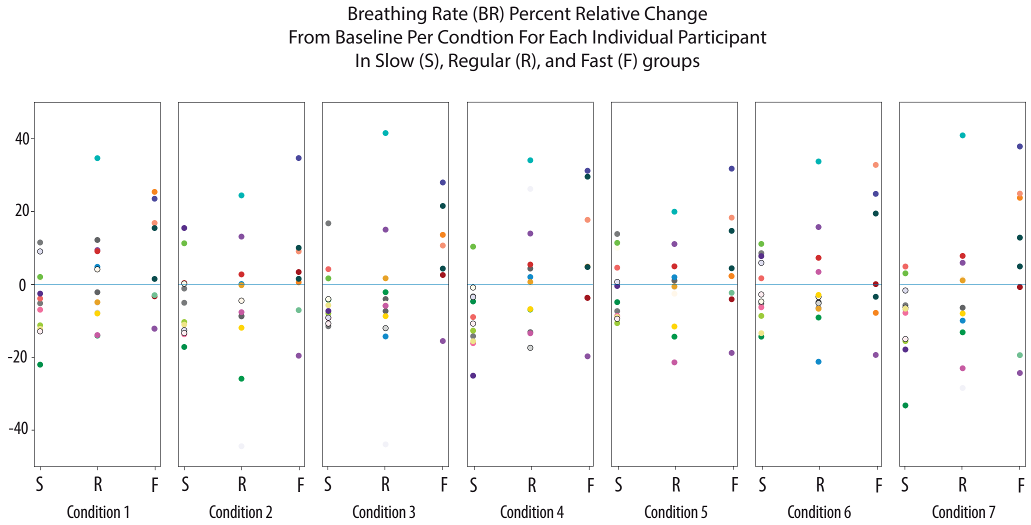

Figure 16. Scatterplots showing the mean relative percent change of breathing rate from baseline for each individual participant in Slow (S), Regular (R), and Fast (F) groups. Values of each participant are represented with distinct colored dots. More participants show a decrease in breathing rate in the Slow group than in the Regular. Values of the Fast group are concentrated above zero. The values in the Regular groups are more spread out than in the other two groups. Although the trends are aligned with the study hypothesis, more studies would be needed to arrive at a more concentrated distribution of the data, leading to statistically significant results.

To arrive at conclusions regarding the impact of the sleeve's haptic action on breathing regulation, I calculated the mean BR relative percent change from baseline for each individual participant (Figure 16), and then for each group using the mean values for each participant (Figure 15). The results are aligned with the study's first hypothesis as they suggest a positive correlation between the wearer's breathing rate and the pace of the sleeve's haptic action. Per group, the results are as follows: Participants in the Slow group exhibited on average 4.79% decrease in BR from baseline; Participants in the Regular group exhibited on average 2.08% decrease in BR from baseline; Participants in the Fast group exhibited on average 7.20% increase in BR from baseline (Figure 15).

The comparison of BR relative change per group per condition demonstrated that conditions with haptic action of warmth and pressure (conditions 2, 4, 6) were typically more effective, causing greater BR change. Regarding the pattern of haptic action, the comparison of BR relative change per group per condition demonstrated that conditions with simultaneous pattern of haptic action (conditions 3 and 4) typically caused greater BR change than conditions with sequential pattern of haptic action (conditions 1, 2, 5, 6) (Figure 15). Taken together, the BR and EDA results, suggest that conditions causing higher EDA increase from baseline had a greater impact on breathing regulation. Although the trends are aligned with the study hypothesis, more studies would be needed to arrive at a more concentrated distribution of the data, possibly leading to statistically significant results.

5. Conclusions

5.1. Summary of main study results

Limitations in the number of participants did not allow for testing the statistical significance of the results to prove or disprove the first hypothesis. Nevertheless, the results are aligned with the first study hypothesis, suggesting that the pace of the sleeve's haptic action has a positive correlation with the wearer's breathing rate and a negative correlation with the wearer's perception of calmness. The results showed on average an increase in breathing rate (BR) in participants of the Fast group and decrease in participants of the Regular and Fast groups, with the decrease being greater in the Fast group. The results also showed a much greater change of electrodermal activity (EDA) levels within conditions in the Fast group compared to the Regular and Slow groups. These results suggest that a faster pace of the sleeve has a stronger but more brief arousing impact, and a slower pace of the sleeve has a lighter but long-lasting calming impact.

Additional results aligned with the first hypothesis were provided by the analysis of the qualitative data. Analysis of the self-reports demonstrated that a fast pace of haptic action promoted feelings of high arousal but of positive valence, like feelings of excitement, rather than feelings of negative valence, like anxiety. Also, the results demonstrated that the slow pace of haptic action promoted feelings of negative arousal and positive valence, like feelings of relaxation, but also feelings of negative arousal and negative valence, like feelings of tiredness. Based on self-reports, the results of the regular pace of haptic action showed only a minimal psychophysiological impact. Further experimental studies are needed to evaluate the significance of the perceived changes.

Based on the study results, distinct conditions of haptic action did not correspond to distinct affective states. Therefore, the results are not aligned with the second hypothesis as stated. Further differentiation between the conditions would be required to potentially prove the second hypothesis. However, the results demonstrated a differentiation in the affective response to the type, cycle, and pattern of haptic action, which, if further explored could potentially lead to conditions with distinct affective response. Some of the important results are the following: Conditions with a half cycle of haptic action on average felt more natural than conditions with a full cycle of haptic action; Participants' preferences for a sequential versus a continuous pattern of haptic action were polarized; Conditions with pressure and warmth were typically perceived as more calming and pleasant compared to conditions with warmth alone; Perception of intensity of the sensation depended on the pattern of haptic action; Conditions including warmth and simultaneous pattern of haptic action had the greatest psychophysiological impact.

5.2. Discussion of study methods

The study was the first to test the impact of a programmable pneumatic sleeve producing haptic action of warmth and pressure in various patterns along the forearm for the purpose of emotion self-regulation and communication. The results were similar to some of the results of the prior study conducted by the author and collaborators using the nitinol-based sleeve (Papadopoulou *et al.* 2019). Both the prior and the present study suggested that a faster than relaxed pace of haptic action increases one's breathing rate and decreases one's perception of calmness. The present study also suggested that a pace slower than a relaxed breathing rate can lower one’s breathing rate and increase one’s perception of calmness. Finally, the results of the present study contributed to the clarification of the role of each sensory stimulus, suggesting that pressure had a greater impact when combined with warmth, and that warmth had, on average, a soothing and pleasant effect.

The study results showed that conditions that led to a greater change in BR caused a higher increase in EDA levels from baseline. This result seems to contradict the first hypothesis as a decrease in BR should promote calmness, which is a state of low arousal. As shown in the results, there was a decrease in EDA levels within the conditions suggesting that the peak of arousal at the beginning of each condition was a startling response due to the novelty and intensity of sensations. It seems that the physical stimulation of haptic action led to an increase in physiological arousal and, in the Regular and Slow groups, also led to a decrease in BR and reported calmness. Similar to receiving a massage, it seems that the sleeve’s haptic action can be physically stimulating while also having a calming effect. Measurements of change of EDA levels within the conditions were revealing regarding the haptic action’s soothing impact in the Regular and Slow groups.

One goal of the study was to test associations between distinct haptic conditions and affective states. In this regard, it is worth exploring the parameter of predictability of the pattern of haptic action. Many participants commented on the potentially anxiety-provoking or playful feeling of an unpredictable pattern of haptic action. Some participants reported feeling more anxious or excited at the beginning of testing, and calmer later when the pattern of haptic action became known. Patterns incorporating unpredictable changes in cycle, pattern, or type of haptic action will likely be stimulating, resulting in curiosity, excitement, or stress. Building a repertoire of affective haptic stimuli could allow for individualized haptic action for material-mediated emotion self-regulation and communication.

An important parameter worth exploring further is the perception of sensory intensity relative to the pattern of haptic action. Warmth and pressure were perceived as higher at the ends and lower at the middle of the sleeve in the simultaneous pattern of haptic action, but lower in the middle and higher at the ends of the sleeve in the sequential pattern of haptic action. It would be interesting to explore what kind of bodily or cognitive mechanisms cause different perception in intensity based on the sequence of produced sensory stimuli, and whether different patterns would yield a different result in felt intensity.

5.3. Reflections on Affective Matter: embodiment, entrainment, material intelligence

5.3.1. Embodiment

An important contribution of this work is that it highlighted possibilities for not only reducing but also increasing physiological arousal levels. Many products and research prototypes focus on the calming aspect of somatosensory feedback. However, individuals with developmental disorders such as autism spectrum disorder (ASD), sensory processing disorder (SPD), or disorders related to emotional health, such as post-traumatic stress disorder (PTSD) may suffer from hypostimulation instead of hyperstimulation, or may alternate from hypoaroused to hyperaroused states (Corrigan *et al.* 2011; Miller *et al.* 2009; Yi *et al.* 2022). It is worth exploring in the future how the sleeve can aid in emotion regulation of individuals with the aforementioned disorders by aiding them to calibrate their arousal levels.

Further testing would be required to assess the psychophysiological impact of the sleeve on non-neurotypical populations and evaluate the potential of possible applications. Testing could also be conducted within the context of occupational therapy practices targeted at children or adults with ASD or PTSD, with an appropriate study protocol. Reactions might differ in non-neurotypical populations from those measured in this study, and thus preliminary testing to anticipate reactions would be required. The possibilities for atypical reactions are greater in non-neurotypical individuals who may be especially sensitive to sensory stimuli. Thus, it would be important to consider customization options.

It is worth exploring the possibility of testing the impact of the affective sleeve within the context of embodied approaches to psychotherapy, such as somatic experiencing (Levine 2010; Payne *et al.* 2015) and sensorimotor psychotherapy (Ogden *et al.* 2006), which focus on somatic symptoms in trauma activation to restore body–mind connection. The affective sleeve could potentially help in emotion self-regulation when trauma-related heightened arousal responses are triggered. Another potential area for contribution is interoceptive exposure (Lee *et al.* 2006; Boettcher *et al.* 2016), a component of cognitive behavioral therapy that exposes the client to self-induced physiological states associated with a phobia or panic disorder. The affective sleeve could allow the wearer to experience or regulate certain physiological states.

The design of the sleeve aimed to have a dual somatic impact through somatosensory stimulation and entrainment to the wearer's breathing. As discussed earlier, breathwork and somatosensory stimulation have been shown through various practices and therapeutic methods to enhance bodily awareness, which has been associated with increased emotional awareness and better emotion regulation. The study suggested that the use of the sleeve could aid in emotion self-regulation, but it remains to be shown in future studies whether the long-term use of the sleeve leads to greater bodily awareness and improved emotional awareness.

5.3.2. Entrainment

A goal of the study was to use entrainment as a strategy to either increase or decrease breathing to regulate physiological arousal. The study results were aligned with this goal. It was not measured in the study whether the wearers' breathing was in synchrony with the haptic action of the sleeve. The haptic action of the sleeve consisted of pressure and/or warmth, made possible through the pressurization and internal heating of the sleeve's cuffs. Additional measurements need to be taken in the future to test whether the onset time and durations of inhalation and exhalation of a sleeve's cuff coincide with the onset times and durations of the inflation and deflation of the cuffs. A potential therapeutic aspect of the sleeve could be the regulation of dysregulated breathing, which can be caused by mental health disorders, among other causes (Vidotto *et al.* 2019; Blechert *et al.* 2007; Cohen *et al.* 2007).

As it was the goal of the study to test whether the haptic action could regulate (increase/decrease) breathing to regulate arousal levels and aid in emotion regulation, participants were not informed that the haptic action of the sleeve was based on their breathing. No measurements were used to test participants' levels of interoceptive awareness. To test this aspect, questionnaires or interviews at the end of the testing procedure could incorporate relevant questions or interoceptive awareness tasks. It would be useful to understand to what extent the arousal increase or decrease was due to heightened interoceptive awareness and whether heightened awareness of slow and fast breathing could further decrease and increase physiological arousal, respectively.

The study included the affective evaluation of various haptic conditions to explore individualized haptic action and potential contributions to material-mediated emotion communication. Given the findings on interpersonal physiological synchrony and empathy discussed earlier, it is worth exploring whether a pair of sleeves worn by two remotely connected individuals can enhance physiological synchrony and promote empathy. Additionally, as therapists and clients tend to exhibit physiological synchrony (Koole & Tschacher 2016; Tschacher & Meier 2019), it would be useful to explore how material-mediated interpersonal communication can be integrated into mental health therapy.

5.3.3. Material intelligence

The study demonstrated a good amount of variability in participants' perceptions of the different conditions of haptic action. Participants' perceptions of the cycle, pattern, and type of haptic action sometimes differed significantly. For example, although most found the warmth calming, a few found it aggravating; although most felt the pressure along the forearm as a gentle touch, a few perceived it as intense grabbing. To address the variability in human experiences, preferences, and cultural backgrounds, a digital interface paired with the sleeve could allow wearers to customize the parameters of the haptic action and evaluate these parameters in terms of their affective impact. Such an interface has been conceptually explored by the author for both material-mediated emotion self-regulation and communication (Papadopoulou 2022).

During the interviews, some study participants expressed interest in having a full-body affective garment instead of just a sleeve, or a pair of sleeves for both hands. Given that the sleeve was designed to utilize both somatosensory stimulation and breathing as strategies for emotion self-regulation, it is worth exploring in the future to what extent material intelligence depends on the location of the garment or material coverage and to what extent it relies on entrainment to material rhythms alone. Is a five-cuff sleeve more effective than a single cuff? Another important aspect to explore is whether the physiological activity should be located at the same site as the haptic action it is intended to entrain. Is material-mediated emotion self-regulation more effective if breathing is entrained to the haptic action of a vest or to that of a sleeve?

Regarding future development, implementing real-time haptic action would provide the option of an automatic dynamic response when needed. Haptic action could be activated if certain levels of breathing and/or electrodermal activity were detected. In addition, the sleeve could learn how to best respond based on the wearer's physiological reactions. In a dynamic human-material affective interaction model, it would be interesting to explore how the human and the programmable material could define the intelligence of the system through a continuous dialog. It should also be noted that a non-deterministic interaction might be challenging to be used for health or wellbeing applications, as an unpredictable haptic action might have undesirable psychophysiological impact.

In a dynamic human-material interaction model, both the material (sleeve) and the wearer could learn from the exchange of information. My intention was to create a system for emotion self-regulation that would not require the user's attention. The study results possibly suggest that the wearers self-regulate their emotions simply through rhythmic entrainment to matter. The question that then arises is whether the wearer learns through this interaction: Will the wearer, after having worn the sleeve for some period and having experienced material-mediated self-regulation, be more capable of unmediated self-regulation without the use of the sleeve?

5.4. Design futures of Affective Matter

The affective sleeve was designed as a wearable environment. Any environment or object can potentially impact our mood and emotions through its tactile, visual, acoustic qualities, and cultural characteristics. As designers, we have the skills to shape the sensory and affective qualities of places, objects, and the interactions they afford. The affective sleeve, as a case study of Affective Matter, demonstrates a way to harness physical material qualities and orchestrate them in a manner that can be beneficial for one's emotional health.

The foundations of Affective Matter —Embodiment, Entrainment, and Material Intelligence— could serve as a conceptual basis for the design of other types of affective environments, including garments and architectural enclosures, possibly extending the types of sensory interactions beyond touch, to incorporate entrainment to light or sound, and possibly extending potential therapeutic applications. Affective Matter suggests a method for designing human-material interactions to enhance health and wellbeing; it demonstrates one possible way to contribute to the quest for tools and methods for emotional wellbeing, neurodiversity, and inclusion.

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