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Using Technology to Regulate Affect: A Multidisciplinary Perspective

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USING TECHNOLOGY TO REGULATE AFFECT: A MULTIDISCIPLINARY PERSPECTIVE

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by

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Abstract

Using Technology to Regulate Affect: A Multidisciplinary Perspective

by

Pardis Miri

This dissertation is motivated by the prevalence and adverse impact of anxiety and anxiety disorders. In this dissertation, I address the following two question in the context of affect regulation:

1. What is the role of technology in supporting affect regulation? What are the ways that such technology can assist? Are some ways more easily made effective than others?

2. Paced breathing is a well-known and effective technique for reducing autonomous nervous system arousal. How can paced breathing be effectively supported by technology for affect regulation?

I give a rationale for the need of an interdisciplinary approach and provide a multidisciplinary literature review of technology that assists in regulating affect. I develop a framework that describes three distinct roles of technology for affect regulation: cueing, involvement, and feedback. Finally, I present the design and evaluation of the experience and efficacy of a high-fidelity prototype of vibrotactile breathing pacer.

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Chapter 1

Introduction

1.1 Affect Regulation using Technology in a Social Setting

Affect is defined as an umbrella term for emotion, mood, and personality. Affect as subjectively experienced in emotion, mood, and other feelings is a central aspect of mind. All mental states, including thoughts, and perceptions, are influenced with affect. Affect ranges from attitude to well-being, and informs basic processes such as memory and perception to moral judgment [87, 61].

Affect is part of the human experience and often a strong motivator, as is the experience of affect regulation. Have you ever felt so angry with someone in authority that you had to inhibit the urge to tell them what you really thought of them? If your answer is "yes," then you know first hand about affect regulation, which refers to the things we do to influence whether an affective state occurs, and if so, how it is experienced or expressed.[1]

[1] This example was first given by Gross and Barrett [62].

Regulating high arousal negative affective states (including negative emotions and moods as well as stress responses) is challenging. Being in a high arousal affective state reduces cognitive abilities [127], and cognition is often required when resolving stressful situations. In such situations, a person may choose the strategy of surface acting, in which a person pretends to be in an appropriate affective state and thus suppressing their own feelings. Or, a person may choose to modify the tone of their voice, mask their facial expressions and body movements, etc. They may attempt to distract themselves or avert their eyes to modify their feelings. Indeed, a person can invoke a combination of such strategies [164].

Adopting such strategies, however, can exert a social cost. For example, using suppression can leave a negative impression on others because of the micro-facial expressions that the person could display [152]. Such strategies can also lead to health problems; there are health-related consequences with use of suppression and surface acting, including insomnia and cardiovascular diseases [111, 25].

While affect regulation is important in all social settings, it has become increasingly recognized and studied in the context of the professional work environment. Affect regulation in a professional setting has been referred to as emotional labor. Emotional labor, like physical labor, can be effortful and fatiguing when done repeatedly all day long, and can be costly in terms of performance errors and job burnout as well [56]. With the changing nature of work towards the gig economy and the growth in the service sector, emotional labor is a growing problem, and reducing the impact of such labor is important for the economy.

Because of the growth in importance of affect regulation, there is significant interest in developing technologies that help people regulate high arousal negative affective states in everyday life [10, 28, 7, 11, 17, 37]. This period of rapid expansion, however, is not currently supported by a deeper understanding of the foundations of such technologies. Developing such understanding is complicated by the need to engage multiple disciplines: understanding the mental processes we use in accomplishing affect regulation; the settings in which such technology will be used and the implications that arise from such use cases; the kinds of technology-supported interventions that can be used and understanding their effectiveness. We found that addressing these questions required a multidisciplinary approach that we call the WEHAB approach. WEHAB comes from the first letters of the four disciplines we build upon: wearables, emotion regulation[2], haptics, and biofeedback.

This dissertation addresses two overarching questions in the context of affect regulation:

1. What is the role of technology in supporting affect regulation? For example, What are the ways that such technology can assist? Are some ways more easily made effective than others? We answer this question by developing a taxonomy of affect regulation technologies (discussed in Chapter 2). Then, based on affect regulation theory, we argue that any technology intervention is best done before the affect is fully surfaced (Chapter 6).

2. Paced breathing is a well-known and effective technique for reducing autonomous

[2]In our earlier papers, we referred to emotion regulation rather than affect regulation.

nervous system arousal. How can paced breathing be effectively supported by technology for affect regulation? We explore this question by designing a high-fidelity prototype of a vibrotactile breathing pacer and using it to evaluate the importance of the choice of vibrotactile pattern, the placement of the vibrotactile tactors, and the role of personalization of the vibrotactile patterns on the experience and efficacy of the pacer (Chapter 5).

The following is a list of the contributions that are made in this dissertation.

- A rationale for the need of an interdisciplinary approach for the design of technology that assists in regulating affect.
- A literature review of the multidisciplinary WEHAB approach for technology that assists in regulating affect.
- A framework that describes three distinct roles of technology for affect regulation: cueing, involvement, and feedback. Two projects or products that use the same roles share a set of design issues. Viewing technologies with this framework encourages designers to think about comparisons between technologies that share goals, and to explore applying techniques that are used for one to be used for another.
- The design and evaluation of a effective vibrotactile breathing pacer.

1.2 Overview of Chapters

1.2.1 Overview of Chapter 2

This chapter emphasizes the importance of a multidisciplinary approach for designing affordances that assist people in regulating their affect in everyday life. We call this "affect regulation in the wild", or "AR-in-the-wild".

Affect regulation is currently receiving growing attention from the Human Computer Interaction (HCI) community [37, 17, 72, 112]. Several startups have sought to address AR-in-the-wild by developing wearable technologies designed to support affect regulation [28, 41, 10]. However, early efforts are not appropriate for AR-in-the-wild, which is not surprising: they weren't designed to be. We argue that these designs fall short because they are not fully grounded in all four domains that are relevant to AR-in-the-wild: emotion regulation theory, biofeedback, haptics, and wearables. As we noted above, we call these four domains together WEHAB. With better knowledge of these WEHAB domains, designers can deploy appropriate tradeoffs across all four domains, as compared to optimizing for a smaller, incomplete set of these domains. We give brief overviews of the four domains of WEHAB and describe how they relate to the problem of affect regulation wearables.

The material in this chapter comes from [114].

1.2.2 Overview of Chapter 3

This chapter presents a conceptual framework for AR-in-the-wild, in the context of WEHAB, that provides a structure for exploring the use of vibortacticle-based technology for affect regulation.

AR-in-the-wild has the hallmarks of a grand challenge problem: it requires a multidisciplinary approach, technological innovation, and deeper understanding of human behavior and perception. We present a systems architecture derived by combining three models from WEHAB: an mHealth model from the domain of wearables [82, 81], the Affect Regulation Model (PM) from the domain of affect regulation[60], and the circular model from the domain of biofeedback[144]. This AR-in-the-wild system architecture is derived from a literature review of the domains of WEHAB, and is also informed by consultations with practitioners and researchers from these fields. We believe that the AR system architecture derived from WEHAB domains of knowledge presented in this paper will help guide future efforts in this important problem space.

We conclude with examples of using the WEHAB framework that illustrates the value of an interdisciplinary approach and discuss the gap between a more traditional HCI approach versus a WEHAB approach. The benefit of using the WEHAB approach is that it allows designers to think about the space of exploration in terms of all of these four relevant domains as well as to deploy tradeoffs to make significant progress rather than optimizing along a single domain.

The material in this chapter comes from [113].

1.2.3 Overview of Chapter 4

We have designed and implemented HapLand, a scalable, robust biofeedback haptic system testbed to facilitate research-based haptics-enabled wearables design for the purpose of affect regulation. In this paper, we give an overview of HapLand and our plans for using HapLand for future research.

The material in this chapter comes from [112].

1.2.4 Overview of Chapter 5

To the best of our knowledge, we were the first to build and evaluate an inconspicuous vibrotactile breathing pacer. Given the small amount of work published on the design of effective vibrotactile breathing pacers, we were drawn to a set of questions: Where should the tactors be placed on the body? Does the choice of body site placement affect the way a person breathes or feels about the device? What kind of haptic pattern is effective in paced breathing? Which patterns are more likely to positively affect the way a person breathes or feels about the device? How important is personalization of the haptic patterns for each individual?

To facilitate the description of our research, we first give some terminology about vibrotactile breathing pacers:

Pattern The vibrotactile effect that cues a user's breathing. We use *biphasic* patterns: the part of the pattern that queues inhalation (the *inhalation phase*) feels different from the part of the pattern that queues exhalation (the *exhalation* *phase*).

Shape The haptic encoding of the pacer, independent of its pace (such as breaths per minute). The biphasic property of our patterns are encoded in the shape. We consider three shapes: *horizontal*, in which the two phases differ only in their frequencies, *vertical*, in which the two phases differ only in their amplitudes, and *diagonal*, in which the two phases differ in both their frequencies and amplitudes. These somewhat arbitrary names come from the way we represent PIV's shapes in frequency - amplitude space diagrams (see Figure 5.3).

Order This arises from our patterns being biphasic, and indicates which of the two phases feels more intense. Order = *Strong inhale* means that the inhalation phase feels more intense, while order = *strong exhale* means that the exhalation phase feels more intense.

Placement Where the tactors are placed on the body (the *body sites*). We consider three body sites for placement: on the abdomen, on the chest, and on the lower back (see Figure 5.3).

Pacer experience Self-reported measures on how well participants attend to the pacer, differentiate between the two phases of the pattern, and synchronize their breathing with the pacer. We also assessed positive affect (PA) and negative affect (NA).

Pacer efficacy Physiological measures on how well the participant follows the breathing pacer and of the resulting decrease in sympathetic nervous system arousal.

Our study was about pattern, placement, and personalization for a vibrotactile breathing pacer.

To evaluate our prototype, we analyzed measures of participants' emotions, physiological data of breathing patterns as measured by breath gauges, and skin conductance measured by EDA sensors. Specifically, we measured regularity of breath duration and regularity of breath depths. Irregularities of these values measure the difficulty the participant is having in pacing their breathing. In addition, we measured how much the participant actually synchronized their breathing with the vibration patterns. As for the skin conductance, we measured the the linear slope of SC wave, as well as Skin Conductance response measures.

We describe the design and evaluation of PIV, a personalizable and inconspicuous vibrotactile breathing pacer. Given the prevalence and adverse impact of anxiety and anxiety disorders, our goal is to develop technology that helps people regulate their anxiety through paced breathing.

We examined two previously unstudied questions: what is an effective vibrotactile pattern for paced breathing, and where should the tactors be placed on the body to make the pacer most effective? We designed a series of personalized vibrotactile pacing patterns, and evaluated them on three body sites, in terms of self-reported and psychophysiological measures including skin conductance (SC) and breath wave parameters.

The results show that personalization plays an important role in PIV's pattern and placement design choices. We concluded that the choice of frequency based, strong-exhale-phased patterns and abdomen placement are appropriate for future studies.

The material in this chapter comes from a paper that is under second review for the journal *ACM Transactions on Computer-Human Interaction* (ToCHI).

Chapter 2

Background

2.1 WEHAB Solution Space

While affect regulation behaviors are widespread and largely intuitive, in their day-to-day life, people occasionally fail to implement them effectively. Over the years, affect regulation research has identified several reasons for such failures, such as failing to detect rising negative affect and not selecting an appropriate affect regulation strategy [151]. These in turn suggest simple interventions that can correct the maladaptive course of affect regulation. For example, being cued as a reminder with appropriate affect regulation strategies can help the person become aware that they are overreacting and make an attempt to substitute an alternative behavioral approach [14, 110]. Such observations give rise to the question of how technology affordances can assist with affect regulation. Imagine an affordance—a vest, a wristband, etc.—that helps a person become aware of and take action to regulate rising and inappropriate emotions. We call this “affect regulation in the wild”, since engagement takes place in uncontrolled settings such as in the middle of a discussion with colleagues or interacting with the general public. Being in the wild imposes conditions on the affordance. For example, given the potential sensitivity of the situations in which such technology would be deployed, both the placement of the technology on the body and its engagement with the wearer should be as private as possible.

Indeed, designing affordances for affect regulation in the wild is very challenging, in part because it requires a multidisciplinary approach [126]. We believe that the four disciplines that need to comprise this multidisciplinary approach are wearables, emotion regulation, haptics, and biofeedback. The contribution of this chapter is to present what we call the WEHAB approach (WEHAB comes from the first letters of the four disciplines). The WEHAB approach consists of two parts: the WEHAB solution space and the WEHAB framework. The WEHAB solution space contains the portion of each of the four disciplines that are necessary for designing wearable affordances for emotion regulation in the wild (see Figure 2.1). The WEHAB framework describes a generalized design for such affordances (see Figure 3.1), and is discussed in Chapter 3.

To the best of our knowledge, no project has approached the problem at hand from the vantage point of these four disciplines. In this section, we give a brief overview of the WEHAB solution space and how it relates to the problem of affect regulation wearables. Note that when discussing each solution space (that is, the part of the discipline important to the problem at hand), we refer to the other solution spaces because of the multidisciplinarity of the approach. We start first with emotion regulation because it our ultimate goal.

The contribution of this chapter is presenting a helpful overview and integration of wearables, emotion regulation, haptics, and biofeedback, to help tackle this design challenge for affect regulation technologies. In this chapter, we review some relevant concepts from each of the four domains, and describe how they relate to the problem of affect regulation in wild.

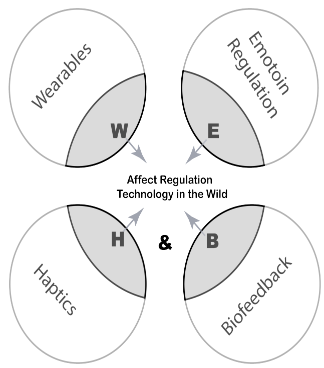

Figure 2.1: The gray portions comprise the WEHAB solution space, and the gray area of each circle is the solution space for the discipline indicated by that circle.

2.1.1 Emotion Regulation Solution Space

Emotion dysregulation is the inability, even when one's best efforts are applied, to change emotional experiences and actions under normative conditions. Symptoms of dysregulation include inappropriate affect, chronic worry, avoidance, sustained negative affect, and excessive sympathetic or parasympathetic arousal [36]. Emotion regulation refers to the processes people use to influence the type (i.e., which emotion one has), intensity, duration, and quality (i.e., how the emotion is experienced and expressed) of their emotions. The emotional states people hope to achieve when they engage in emotion regulation are referred to as emotion goals (e.g., feeling less angry). People tend to pursue emotion goals as a means to experience pleasure and avoid displeasure, obtain success, understand the world, and facilitate relationships. Emotion motives like these explain why people engage in emotion regulation [161].

Several models of emotion regulation exist [116] that generally overlap while highlighting different aspects of emotion regulation such as regulation strategies [115, 165], regulation ability [24, 57], and the temporal sequence of events [59]. Among them, we chose Gross's process model of emotion regulation (PM) [59] because it is a temporal model, and therefore amenable to identifying points for potential interventions.

According to the PM, there are four stages of the emotion regulation process: identification (i.e., evaluating whether an emotion needs to be regulated or not based on emotion goals, the situation, and the ongoing emotion), strategy selection (i.e., selecting an appropriate regulation strategy based on situational demands and regulation skills), strategy implementation (i.e., employing a specific tactic that implements the selected strategy: paced breathing, alcohol consumption, and exercise are all tactics of the response modulation strategy), and ongoing strategy implementation monitoring (i.e., determining whether the ongoing emotion regulation effort should be maintained, switched to a different strategy, or stopped).

Within this overarching model, the PM identifies five families of regulatory strategies one can deploy to change one's emotion. These include: situation selection (e.g., avoidance of the situation altogether), situation modification (e.g., changing specific aspects of a situation), attentional deployment (e.g., thinking of errands unrelated to the situation to distract oneself), cognitive change (e.g., reinterpreting the meaning of the situation), and response modulation (e.g., suppressing the bodily expressions of the emotion). These strategies are hypothesized to operate by interfering at different points in the emotion generation process. The model also suggests that strategies that intervene at earlier stages of emotion generation tend to require less effort and be more effective than strategies that intervene later. Using "$<$" to indicate the comparative ease of implementation, situation selection or modification $<$ attentional deployment $<$ cognitive change $<$ response modulation [59].

One can identify three modes for emotion regulation: intrinsic (i.e., when an individual has a goal to regulate their emotions without involving anyone else), extrinsic (i.e., when a person has the goal to regulate their emotion by involving others or has a goal to regulate someone else's emotion), and both (i.e., when intrinsic and extrinsic emotion regulation co-occur) [59]. An example of the "both" mode is when James regulates Sarah's emotions (extrinsic regulation) in order to calm himself down (intrinsic regulation).

In this thesis, we focus on the intrinsic mode, which we adopt for the WE-HAB framework (described in Chapter 3). In the context of intrinsic emotion regulation, researchers interested in enhancing emotion regulation with the use of technology have mostly focused on facilitating cognitive change and response modulation strategies through smartphone apps and, more recently, through wearables, for the most part based on wristbands. The wearables have been referred to as calming technologies [28, 31, 39, 41, 118, 136, 7, 163]. The apps are mostly natural language processing (NLP) based or crowd-sourcing based. NLP-based smartphone apps have been developed to provide personalized response modulation strategy-based recommendations (for example, going for a hike, calling a friend, etc.), pulled from an individual's social network [122]. Anonymous crowd-sourcing-based smartphone apps have been developed to improve cognitive change (i.e., present an alternative human-generated explanation for an unhelpful thought [80]).

The four stages of Gross's PM can be used to reason about how people fail in regulating their emotions. [59]. The first reason is failure at the identification stage. This failure could occur due to a lack of emotional awareness, an inability to track emotion dynamics, or an inability to correctly trade off between multiple active competing goals. Even after a person has become aware of an emotion and has activated a goal to regulate that emotion, there can remain an inability to effectively trade off between the currently active goal and other competing active goals.

Tamir et. al. [159, 160] introduced a taxonomy for emotion regulation that distinguishes between two motives: hedonic goals that are aimed at increasing short-term pleasure or decreasing short-term pain, and instrumental goals that are aimed at inducing long-term meaning. Such motives can conflict: skipping a cocktail party may reduce momentary anxiety (hedonic) but reduce the satisfaction of having a larger professional social network (instrumental). This distinction is important when designing wearables because targeting hedonic motives as compared to instrumental motives may make the device more pleasurable if not ultimately more helpful [109]. For example, if a person who is suffering from anxiety is always recommended to call a friend (a tactic for distraction in a context of extrinsic emotion regulation), they will not develop the ability to deal the anxiety on their own, say, by using self-soothing strategies.

The second point for failure arises when a person is unable to correctly select or switch to an appropriate emotion regulation strategy. For example, people generally prefer reappraisal to distraction when emotion intensity is low, but prefer distraction to reappraisal when emotion intensity is high: at high-intensity levels, reappraisal is often no longer effective. However, people can misjudge the intensity of the emotion they are experiencing. A technology monitoring psychophysiological indicators of emotional intensity such as the electrothermal activity may therefore be designed to suggest optimal regulatory choices to a person.

Third, a person may be unable to effectively implement a selected emotion regulation strategy. For example, a person may decide to implement the tactic of paced breathing (i.e. attempting to make a specific number of breaths per minute), but reap only limited gain due to lack of skill. The person could fail to ensure that they are following paced breathing, to determine how effective they are in implementing the tactic, and to decide when to stop using this tactic. If they were cued with their physiology measurements as a biofeedback, they could be notified when their breathing is indeed properly paced, and when their arousal level has been reduced enough to stop paced breathing.

Fourth, failure at emotion regulation monitoring can contribute to failures at emotion regulation selection and implementation stages. For example, if one's arousal level is high, then the strategy of reappraisal is not suitable—it would be difficult for the person to find an alternate way of thinking about the situation. Instead, distraction may be more an appropriate strategy until one's arousal is sufficiently low. In many situations, the intensity of emotions gradually decreases, suggesting that an optimal decision strategy would be to switch from distraction to reappraisal. However, people are known to exhibit inertia in emotion regulation decisions, which suggests that they may benefit from technological prompts to facilitate appropriate strategy switches [155].

Importantly, people seem to differ systematically in ways that bear directly on how they go about regulating their emotions. For example, people exhibiting incremental beliefs about emotion (i.e., seeing emotions as the kinds of things that can be changed) compared to entity belief (i.e., seeing emotions as relatively immutable) seem to be generally more effective at regulating their emotions. Major dimensions of individual differences include regulation frequency (how often a particular form of emotion regulation is used), emotion regulation self-efficacy (how capable a person believes himself or herself to be in using a particular regulation strategy), and emotion regulation ability (how successful a person actually is in using a particular form of emotion regulation). Such factors play an important role in the success of emotion regulation and should be considered in the development of emotion regulation devices. For example, a machine-learning based tool could be trained on collecting useful information to account for such differences.

Anett Gyurak et al. suggested that, given the high demand for moment-to-moment emotion regulation in everyday life, for well-being purposes it is often critical that emotion regulation processes be relatively implicit (that is, automatic) [65]. Thus, it is important to design emotion regulation wearables as a technology that influences behavior in a subtle manner. Such technology has been referred to as mindless computing [12]. At the beginning, adopting new and more helpful ways of emotion regulations requires effort. Eventually, however, the transition from explicit (often called effortful) to implicit forms of emotion regulation are formed for the newly adopted ways of emotion regulation, and they become habitual and implicit. This is factor that is important in the design of wearables for emotion regulation.

2.1.2 Biofeedback Solution Space

The next solution space we consider is biofeedback. Biofeedback is a process that enables an individual to learn how to change his or her physiology through real-time physiological feedback. Simplifying, the circular model of biofeedback consists of three steps: (1) monitoring: measuring a physiological process of interest; (2) feedback: presenting what is monitored as meaningful information to the user; (3) implementation: user behavior aimed at changing the physiology and developing mastery so that this behavior occurs automatically [144].

The most common processes that are monitored in biofeedback include electrical correlates of muscle contraction (electromyography or EMG), skin conductance (electrodermal activity, EDA), cardiopulmonary processes such as heart rate variability (HRV), and photoplethysmography (PPG), temperature, and brain activity (electroencephalography, EEG). Challenges encountered at the monitoring step include the lack of universal response norms (e.g., for peripheral vasoconstriction, skin conductance, and muscle contraction), variability between devices, and the negative impact of conditions such as room temperature and humidity.

The feedback stage involves presenting the signals measured in the monitoring stage in some perceptual modality. The choice of feedback modality depends both on the people using the feedback and the requirements of the problem to which people are applying the biofeedback (e.g., improving asthma via HRV biofeedback). Researchers have suggested that feedback solutions should strive to be simple, unambiguous, gentle (e.g., the use of smartphone assistants like Siri or Cortana), automatic, personalizable (i.e., the ability to let the user have control over their wearable haptic device), customizable (e.g., allows for thresholds to adjust over time as training goals change), responsive (e.g., users not having to go to an "app" to get an intervention), standalone (i.e., users do not need to stop what they are doing with their device for the intervention to occur), and minimally distracting [45, 144]. Following these desirable conditions for feedback has nudged biofeedback researchers and practitioners into settling on a very limited number of practical feedback modes and avoiding further exploration. In addition, most biofeedback sessions are conducted in a dedicated setting, for which auditory and visual feedback is adequate—there is no need to use a haptic approach for biofeedback. This may explain in part why the choice of haptics to implement biofeedback has not been thoroughly studied.

The implementation step in biofeedback involves the teaching of various behaviors that lead to desirable changes in the physiological state of the user. These include autogenic relaxation (repetitions of a set of visualizations that induce a state of relaxation including autogenic imagery), progressive muscle relaxation (consecutive two-step or three-step process of muscle tension followed by muscle relaxation), passive muscle relaxation (process of imagining muscles in a relaxed state that involves no muscle tension), and slow paced breathing aided by counting methods, one hand on the chest and the other on the stomach, and imagery techniques (e.g., cool air going in and warmer air coming out of the nostrils, balloon expansion while inhaling/contraction while exhaling, etc.). [18]

The circular model of biofeedback can be thought of as an externalization of the monitoring stage of Gross's PM of emotion regulation. According to the PM, emotion regulation often involves several iterations of identification, selection and implementation. Imagine a person has identified a need to regulate the emotion of anger. This is the first stage of PM. They select the strategy of rumination and begin to implement it. Periodically, the person will monitor how well rumination is working, via interoceptive input (i.e., internal stimuli) to the brain. Based on this, they will make one of three choices: to continue with the rumination strategy, to abandon rumination and adopt a more contextually appropriate strategy (for example, reappraisal), or to stop because either they have reached their desired emotional state or have decided to quit altogether. From this perspective, using biofeedback to assist in emotion regulation can be thought of as partial externalization of the monitoring stage of PM. With biofeedback, the changes in the undesired emotion (e.g., its intensity, duration, type, etc.) induced by strategy implementation are perceived through changes in the person's physiology and communicated through sensory modalities (visual, haptics, audio) rather than using the path of interoceptive input to the brain.

We are particularly interested in haptic feedback because of the need for confidentiality of emotion regulation in the wild: vibrotactile-based devices can be designed that are noticeable only by the wearer, wearable tactile actuators are small and can be easily be obscured beneath clothing. This is consistent with much of wearable research, which has concentrated on haptic feedback.

As mentioned above, biofeedback research has concentrated on visual and auditory modes of feedback. Some research results on visual and auditory modes feedback most likely apply to haptic feedback as well. What wearable research supports doesn't necessarily agree with what biofeedback research supports or favors, however. We speculate that this is because the two communities are often pursuing different regulatory motives: wearable researchers are more interested in hedonic goals and biofeedback researcher are more interested in instrumental goals. For example, wearable research has argued that truthful heart-rate-mimicked biofeedback is not as effective as slow manipulated heart-rate-mimicked biofeedback for nervous populations [37, 102]. Reducing a person's immediate level of nervousness is a hedonic goal. On the other hand, in the context of physiology measures deviating from an acceptable range, biofeedback research supports using physiology-mimicking representations such as perception of heartbeat or breathing sound over non-physiology-mimicked representations such as perception of sinusoid waves or square waves; truthful over manipulated or partial truthful representations; and real-time over reflective forms of interventions [144]. For example, biofeedback research suggests that it is helpful to give access to the heart rate, whenever the user wishes it, but it is even more important to help users with interpreting the heart rate signal in a positive way. Based on a user's history and on how the information is presented to the user, he or she may interpret a fast real-time heart rate as something fearful ("I am losing control"). It would be better to help the user frame it as something positive to advocate courage in dealing with the current situation ("I am strong and ready") [148]. These reflect long term changes in behavior, and thus are instrumental goals.

Personalization (the ability to let the user have control over their wearable haptic device) has been suggested by biofeedback experts to be a powerful method to enhance the learning process and user experience. For instance, one person may learn best with continuous exposure to the feedback signal, while another person may learn best while using imagery with minimal feedback. Understanding and applying the biofeedback information to influence a change in physiology is certainly more complicated than swallowing a pill, but it constitutes the essence of the treatment, and needs to be accommodated in the research design and accepted by those who evaluate biofeedback research [150]. A drawback of using personalization is that it can introduce unwanted variability in the treatment group. However, using an active learning process that involves active participation and individualization of the biofeedback stimulus (and its body site, if applicable) to fit an individual learner, is a major ingredient of successful biofeedback training.

As an illustration of biofeedback that can have an effect on emotion regulation, we describe Heart Rate Variability Biofeedback (HRVB). HRVB teaches patients to restore autonomic balance by increasing parasympathetic activity, which in turn decreases sympathetic activity [52, 53, 54, 55]. As branches of the autonomous nervous system, sympathetic and parasympathetic activity prepare visceral organs for resources expenditure ("fight or flight") and resource replenishment ("rest and digest"), respectively. Research studies have suggested that HRVB is effective in reducing psychological and physical symptoms of anxiety, depression, chronic pain, asthma, hot flashes, migraine, epileptic seizure, etc [76, 144]. A healthy heart is not a metronome [149] and the time intervals between successive heartbeats (IBI) greatly differ; this is called Heart Rate Variability (HRV). High HRV provides the flexibility to rapidly cope with an uncertainty and changing environment including reflecting a greater capacity for regulated emotional responses [15, 20, 83, 135], while reduced HRV is associated with vulnerability to physical and psychological stressors, and to diseases [96].

HRVB training has been show to immediately produce large-scale increases in baroreflex gain (the degree of HR change in response to an inverse change in blood pressure) [98, 145] and strengthen the vagal tone (the contribution of the parasympathetic nervous system to cardiac regulation) [96]. Research studies have identified stronger vagal tone as contributing to better executive cognitive performance, better social functioning, as well as better emotional and health regulation [149]. Sympathetic nervous system activity increases the heart rate during inhalation (i.e., inhibition of vagal activity) thus shortening the IBIs, while parasympathetic nervous system puts on the brakes and brings the heart rate down during exhalation (i.e., vagal stimulation) consequently lengthening the IBIs. This phenomenon is called respiratory sinus arrhythmia, or RSA and the stronger the vagal tone, the higher the amplitude of RSA and vice versa. RSA is mediated by the vagus nerve and is largely responsible for generating heart rate variability [93].

Resonance frequency theory, proposed by Lehrer, suggests that an efficient way to increase vagal tone is through slow paced breathing at the resonance frequency. The resonance frequency is the breathing rate at which the baroreflex causes body gas exchange and oxygen saturation to be optimized and varies from 4.5 to 6.5 breaths per minute from person to person [95, 97, 168]. Vaschillo [168] found that an individual's resonance frequency correlates with the blood volume in that individual, and so a biofeedback-based technique to determine the precise rate of breathing is required for each individual. Similarly, Lehrer suggests that taller people and men have lower resonance frequencies than women and shorter people, due to larger blood volumes. Note that once the exact resonance frequency is determined (over the course of approximately three weeks), there is no need to recalculate it again. Lehrer also observes that many stimuli at this frequency, including breathing, rhythmic muscle tension, and emotional stimulation, can activate or stimulate the cardiovascular system's resonance properties [94].

HRVB practitioners have found that breathing diaphragmatically, at the resonance frequency, with a 40:60 or 33.3:66.7 inhalation to exhalation ratio, and with pursed lips during exhalation, not only maximizes HRV but also increases respiratory efficiency [76]. One obstacle is that, unlike infants, most adults do not practice diaphragmatic breathing because of several factors. Aside from simple lack of awareness about the technique, some reasons for this are concerns of self-image (some people tend to pull in their abdomen in an attempt to look slim and attractive) and an inability to engage abdominal muscles because of lack of muscle tone due to age or injury, and so on [128]. To master whole-body effortless-paced diaphragmatic breathing, a person needs to focus on activating the lower abdominal muscle. Some practitioners find it to useful to apply pressure at key locations (i.e., the Spina Iliac Anterior Superior, or SIAS) during exhalation, and to place either respiratory strain gauges or surface EMG sensors to visually track the expansion of the abdomen while inhaling [128].

2.1.3 Haptics Solution Space

We now consider the solution space of haptics, which is important for biofeedback being done in an inconspicuous manner.

A large portion of haptics research that has explored emotion regulation has focused on extrinsic emotion regulation using vibrotacticle actuators [120, 77, 21, 107, 99, 71, 167]. In this type of emotion regulation, someone else has the goal of regulating your emotions or you reach out to someone else to get help with regulating your emotions. The choice of vibrotactile feedback has been driven by the perception that a vibration effect can serve as a low fidelity substitute for the sense of human touch [26]. Therefore, touch-emotion related studies, including findings on calming effects of touch by Coan [35] and other scholars [40, 68, 169], as well as Keltner's work that communicated six distinct emotions via touch [69, 70], play a role in shaping haptic-emotion research studies. Most studies have explored vibrotacticle effects to effectively elicit, reduce, aggravate or transform a specific emotion. For example, Lemmens et al. [99] developed tactile patterns based on "butterflies in the stomach" associated with love by sequentially firing motors in the stomach area in a circular pattern, and "a shiver down the spine" to convey fear and anxiety applied on an arm or other parts of the body; the goal of this research was to enhance the emotional experience while watching a movie. McDaniel et al. [107] described six motion patterns (e.g., wave, spiral, shoulder tap, etc) to elicit emotional responses in visually impaired individuals. He suggested that longer duration haptic effects may be used to convey sadness whereas shorter durations ones may be used to convey happiness. Benali-Khoudja et al. [21] described haptic patterns including "divergent wave", a "vertical shutter", a "horizontal line sweep", etc., inspired from hand writing and voice recognition.

Examples of tactile devices (in particular vibration) that researchers built in the context of emotion expression and emotional information communication include a mid-air haptic device by Obrist et al. [120], HaptiHug, HaptiHeart, HaptiButterfly, HaptiShiver, HaptiTemper and HaptiTickler by Tsetserukou et al. [166], a 6x4 grid of haptic motors by McDaniel et al. [107]. Furthermore, Benali-Khoudja et al.[21] made an attempt to build a vibrotactile system (the VITAL), and describe the fundamentals of a tactile "language". Rehman et al. [77] built a vibrotactile chair to enhance visually impaired individuals' experience by conveying online affective information in tactile form. Kim et al. [167] built a grid of 12 tactors and developed a mapping algorithm that directly translates the visual saliency of a video to the level of the vibration intensity of each motor in the tactile grid in real-time. In sum, most research studies in the area of haptics with respect to extrinsic emotion regulation are vibrotactile focused and use of haptics for intrinsic emotion regulation is under studied. In the context of intrinsic emotion regulation domain, researchers, interested in improving dysregulation with use of technology, have mostly focused on facilitating cognitive change and response modulation strategies through smartphone apps and more recently through wearables, for the most part based on wristbands. These have been referred to as *calming technologies* [163, 118, 28, 41, 31, 39, 136]. Machine-learning-based smartphone apps were developed to provide personalized response-modulation-strategy-based recommendations (going for a hike, calling a friend, watching a movie, etc.), pulled from each individual's social media [122]. Anonymous crowd-sourcing-based smartphone apps were developed to improve cognitive change (i.e., present an alternative human-generated explanation for the unhelpful thought) [80]. These are examples of promising directions in app development for emotion regulation. *Breathe* a focused breathing app, with visual and haptic feedback on WatchOS 3 [16], *Doppel* (a Kickstarter-funded wearable wristband with pre-built haptic effects in forms of rhythm of music, heartbeat, and breathing designed to up-regulate positive emotion and down-regulate negative emotion), and *EmotionCheck*, a biofeedback device that emulates slow heartbeat haptic signals and applies them via a haptic wrist-worn device [37], are examples of use of wearables for intrinsic emotion regulation. An example of visual biofeedback with focus on improving intrinsic emotion regulation is as follows: Gevirtz et al. built a biofeedback system that presented heart rate variability (HRV) as visual biofeedback to participants to regulate emotion. The experimental procedure consisted of participants sitting in front of a computer screen looking at a visual moving object, and monitoring their physiology data as they performed focused breathing [52, 53, 54, 55].

There are several advantages in using haptic interventions. They include (1) Haptics is provided through the largest organ of the body and is not prone to rapid decay of short-term sensory memory [33]; (2) Relative to vision and audition, the spatial resolving power of the skin is poorer than the ear's but better than the eye's [91]. One common measure indicates that people can resolve a temporal gap of 5 ms between successive taps on the skin [51]; (3) Haptic signals are simple, personal, and subtle, making them attractive for use in technological aids [51] especially when other channels including visual and auditory are overloaded or unreliable [73, 137]; (4) Stereognosis – the ability to perceive and recognize the form of an object in the absence of visual and auditory information by using tactile information – is useful for wearable technology that lack displays and digital interfaces; (5) Due to the lack decay of short-term sensory memory, haptics works well for learning.

There has been substantial research in exploring how vibrotactile attributes (such as amplitude, frequency, duration, etc.) can invoke an emotion. This line of research (e.g., [21, 71, 120]) has been followed for many years but does not align well with the understanding of those who research emotion and emotion regulation.

Some results such as those by Benali-Khoudja et al. [21] and Yoo et al. [172] have hinted that haptics, applied naively, most often have a negative impact and thus would not be suitable for emotion regulation. Benali-Khoudja suggested that about 91 percent of the tactile icons tested in their study might be inappropriate for expressing positive and relaxing emotions (e.g., serene and relaxed) [21], which indicates challenges with generating positive-valence-low-arousal tactile icons based on manipulation of attributes such as frequency, amplitude, duration, etc. Results from Mood Glove [105] also support Yoo's claim: the use of haptic sensations did not alter valence. Instead, it heightened participants' self-reported arousal values, resulting in a more intense mood perception of a film scene.

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All existing haptic-based approaches have made important contributions, but none of these have fully addressed the important characteristics of a haptic effect that may regulate an emotion. Hence, we believe that the question of whether a haptic effect can regulate emotion is still unanswered. Perhaps it will be resolved through crowd sourcing: companies developing wearable haptic devices are likely to open their wearable devices for creation and communication of more complex individual based haptic effects. Through trial and error, effective haptic effects will thrive and the rest will be discarded. That is why effect customizability (i.e., the device being programmable for creation of various haptic effects) is an important factor to consider when designing a wearable. Some examples of promising directions in facilitating haptic effect creation and customization are the tactile effect simulation tool Macaron [142], the tactile animation tool Mango [141], and the Mechanical Turk based tool for rating the affect of vibrotactile effects HapTurk [143] as well as creating and supporting search of vibrotactile lexicons [63, 119, 147].

2.1.4 Wearable Solution Space

The final solution space is wearables. For both emotion regulation and biofeedback, the vast majority of research has been in the context of lab-based experiments. In the wild, people are currently on their own to regulate their emotions by relying on the strategies and techniques that have been taught and evaluated in the lab. Can technological affordances aid those who fail to self-regulate their emotions in the wild? If so, the technology would most likely be based on wearables.

Wearable technology is moving toward the use of flexible and stretchable organic wearables, also known as enhanced wearables. State of the art biosensors are becoming insensitive to strain and can make real-time assessments of the physiological state of subjects, even when worn during normal, everyday activities [50, 66, 162]. Hammock et al. [66, 162] progressed in developing an ultra-thin rechargeable stretchable and self-healable electronic skin (e-skin) akin to human skin that is equipped with thermal and pressure sensors as well as chemical and biological sensing, biodegradability, and self-powering. E-skin allows future biomedical prostheses to naturally feel and communicate human touch which plays a major role in affect regulation. Gao et al. [50] advanced in developing a noninvasive stretchable sweat biosensor that is insensitive to strain to measure the detailed sweat profile of human activities and to make a real-time assessment of the physiological state of the subjects. This provides a potential for real-time biofeedback affect regulation wearables that can be comfortably worn on various body parts and are able to withstand the stress of daily human wear and physical exercise.Though these are not yet market-ready, we can anticipate that they will be in the near future, and can design in anticipation of this.

Looking a bit farther into the future, the distance between the human and the device is decreasing even to the point of implants and the use of electoceuticals [78]. For example, Agrawagl et al. [13] were able to pace the heart of an adult pig with a 2 mm diameter wireless stimulator installed on the animal's vagus nerve. This shows the extreme degree of device miniaturization that can be achieved and what can be enabled for future emotion regulation. One can easily imagine a remote control through which one could directly increase or decrease heart rate or blood pressure. Therefore, the use of wearables seems like a promising approach for affordances that support emotion regulation in the wild.

Of course, it will likely take some time for human augmentation to reach the maturity of first-generation products. For now, portable on-the-skin-surface wearables can provide design guidelines and heuristic measures to build wearables and evaluate the level of wearability. The limitations of wearables is that it needs to conform to socially acceptable monitoring which means that it cannot penetrate the skin and is easily attached, disposed, and will not induce harm.

Recently, there has been considerable work in haptics design for wearability [103]. Understanding this work requires a deeper look into haptic technology. The term haptics is used both to describe the human touch sensation and to describe devices that are built to stimulate human touch. Human touch is divided into two afferent (conducting information to the brain) subsystems: kinesthesia and cutaneous. Kinesthetic sensations are mediated by muscles, tendons, and joints stimulated by bodily movement (e.g., the sensation from playing with a joystick). Cutaneous sensations are felt by the skin, such as pain, pressure, stretch, and temperature; these sensations allow humans to sense spatial forms, texture, movement, flutter, and vibration. Haptic devices are similarly classified into the two groups of kinesthetic and tactile (cutaneous) based on the sensations they create. Kinesthetic haptic devices display force or motion through a tool or to the user's joints, whereas tactile devices stimulate the skin i.e., create a distributed set of forces on the skin. Many kinesthetic haptic devices cannot be considered as wearable because in order to generate a force to display to the user, they must transmit the force from the ground through a fixed base. Kinesthetic haptic devices can be further categorized into three major groups: manipulandums (joystick like devices), gripping devices (e.g. most surgical systems that are manipulated using a device gripped between thumb and index finger), and exoskeleton (e.g., CyberGrasp which is VR glove that delivers reactive force in response to a person's actions inside virtual reality [156]). Kinesthetic exoskeleton devices can be wearable because they are grounded to the body, but they are often heavy and cumbersome due to the motors and power required.

In contrast to kinesthetic devices, tactile haptic devices are more easily designed to be wearable due to the actuators required. Tactile devices include stimulation methods such as normal skin deformation, vibration, temperature display, and skin stretch. One novel method for displaying normal deformation is haptic jamming [154], which is a specialized technology that creates 3-D surfaces with a variable stiffness tactile display using pneumatics and particle jamming. These surfaces are palpated by the hand. Currently there is no wearable haptic jamming device available on the market. However, in the context of emotion regulation, they could take the form of jamming jackets to simulate the sensation of hugging. A common actuator to display normal deformation are arrays of pins that are actuated independently in contact with surface of the skin [139, 134]. A haptic braille watch [42] is an example of a wearable pin stimulation haptic device.

Haptic stimulation devices involve active touch via the fingertips to interpret further meaning, and are a promising approach for implementing reappraisal or distraction emotion regulation tactics. For example, one can imagine a person touching the surface of such a device to be disengaged from the environment by experiencing a gamified task via fingertips (e.g., pressing rising pins as quickly as possible) while attending a tense meeting. Or, a person could receive a braille message with an embedded meaning (e.g., "the faster your heart rate, the slower you should speak"). The limitation with such a haptic device is that the fingertips must be actively involved, which may make the emotion regulation too conspicuous.

Skin stretch devices apply displacement forces tangential to the skin, which are perceived as stretching the skin [132]. Applying skin stretch is being investigated as an alternative to vibrotactile feedback. Skin stretch devices, for example the work by Chinello et al. [34], have similar limitations to normal deformation devices in being inconspicuous.

Temperature devices are silent technologies that are usable in situations in which environmental vibration hinders the utility of vibrotactile approaches. The downside with temperature haptic devices is that environmental temperature can affect the haptic sensation, the temperature change can be slow to actuate, and temperature stimulation can sometimes be uncomfortable if the temperature variation is not carefully controlled.

Vibration haptic devices (vibrotactile) apply motion either directly to the skin or through a mediating structure. Vibrotactile devices are both wearable and can provide passive touch anywhere on body surface, so they do not require the fingertips to be engaged to experience the haptic effects produced. Consequently, the choice of vibrotactile seems more appropriate for emotion regulation in the wild as compared to an exoskeleton or other forms of tactile devices. The choice of the specific vibrotactile actuator to use is critical since they are usually the bulkiest and heaviest components in a wearable device. In general, linear electromagnetic actuators, including voice coils, solenoids, and C-2 tactors, are preferable to non-electromagnetic actuators such as an eccentric rotating mass motor (ERM). This is because most electromagnetic actuators, with the exception of Linear Resonant Actuators (LRA), can produce any vibration profile within their dynamic limitations and are capable of applying a con-stant amplitude vibration. Such degrees of freedom allow for creating rich haptic effects.

In designing a wearable haptic device, the goal is to maximize the level of wearability, portability, mindlessness [65], and the realism of the touch sensation while minimizing the cost. To maximize wearability, Pacchierotti et al. [121] presented a list of usability principles to consider when designing a haptic wearable. The list includes principles such as the device must: be comfortable to wear (ergonomic shape, naturally fits the wearer's body, exerts manageable pressure, comfortable materials used during construction, smooth design); not impair motion; be small and lightweight; be easily activated by the user; use properly chosen actuators (not irritating even when active for a long time, not exceed maximum temperature in contact with skin). Another important principle argues that a haptic effect is more effective when co-located with the desired action or behavior. For example, Brown et. al. [29] showed that locating force-feedback haptics on the same hand that is exploring a virtual object is more effective than locating them on the opposite hand.

In this chapter, we have reviewed the four WEHAB domains and described their importance in understanding and developing technology for affect regulation. In the next chapter, we describe a framework that gives a general approach for designing such technology.

Chapter 3

Conceptual Foundation: WEHAB Framework

3.1 Technology for Affect Regulation

There is more to designing affordances for affect regulation in the wild than understanding the WEHAB space. In this chapter, we describe a WEHAB framework that gives a general approach for designing such affordances. We also present a set of research and development challenges that are suggested by the framework. These challenges are multidisciplinary in nature, and include both the WEHAB solution space as well as other disciplines, such as artificial intelligence.

The WEHAB framework is based on the temporal PM by Gross. As noted in the earlier section on the emotion regulation space, Gross's PM describes how the emotion regulation process unfolds: an emotion is generated, a strategy is selected, the chosen strategy is implemented, and then by monitoring, the strategy is maintained, stopped, or switched. Each point in this model can be augmented with interventions that can involve the user of an affordance (see Figure 3.1). In the WEHAB framework, we considered three types of haptic interventions: (1) cueing, which is used to direct a user towards some strategy; (2) involvement, which guides a user through a tactic; (3) biofeedback, which is used as part of a biofeedback process.

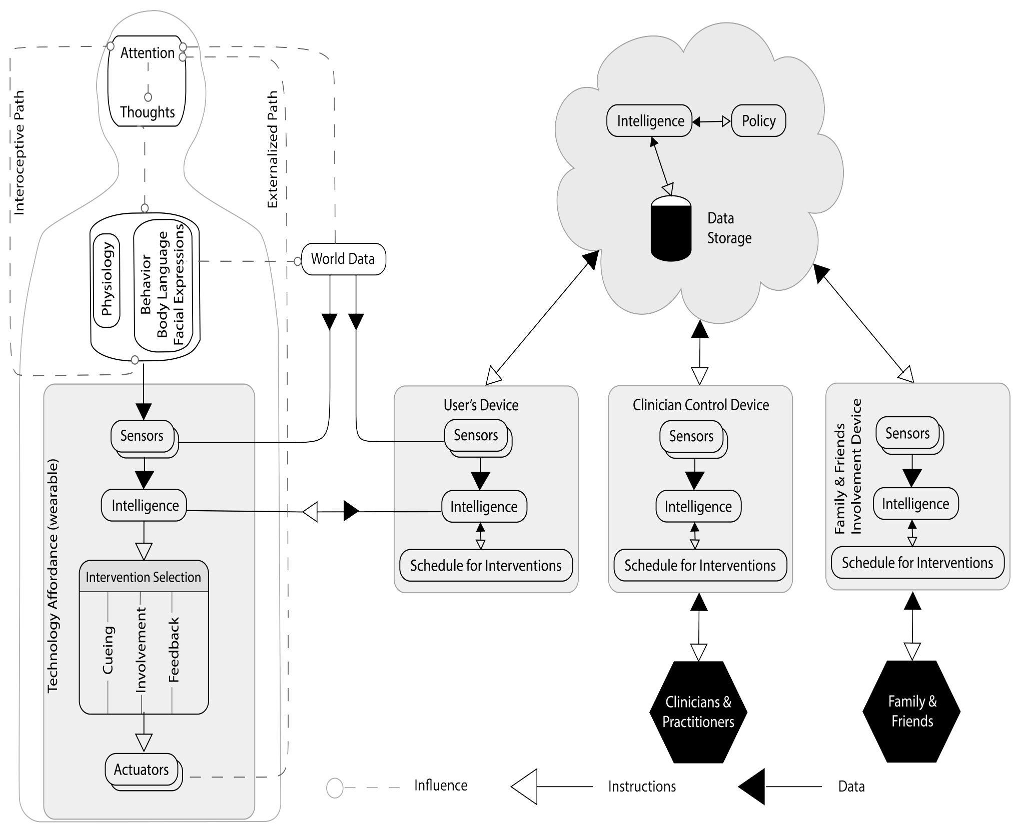


Figure 3.1: WEHAB Emotion Regulation in the Wild Architecture.

There is a considerable design and development work currently taking place in vibrotactile interventions for assisting with emotion regulation. We use the following framework for exploring this broader set of projects and products. This framework is motivated by Gross's process model [60]. We first describe the framework, and then use it to discuss projects and products design for affect regulation using vibrotactcile technology.

Each of the three types of intervention reflects a different way for the user to interact with the device. Two devices that use the same type of intervention share a set of design issues. Viewing this space with this framework encourages designers to think about comparisons between these interventions, and apply techniques that are used for one intervention of a given type to another intervention of that type.

3.1.1 Cueing Interventions

Cueing interventions are based on sensing the need for action, and notifying the user of this need. There is rapid innovation of commercial products that measure physiology and notify users of some situation or desired action: the user is slouching, their heart rate variability (HRV) is poor, their breathing is fast, shallow, or irregular. Examples include Lief Patch [7], Spire Stone [10], and Vitali Sports Bra [11]. All of these devices are meant to be worn all day, and so need to be comfortable to wear, require low power, and have only haptics-based channels of communications with the user. The last of these design constraints arises from needing to be inconspicuous, so that it not be evident a person is using any technology to assist in emotion regulation.

Because they focused on cueing interventions, these projects needed to address sensing problems. The Lief Patch, Vitali Sports Bra, and the Spire Stone sense and analyze the user's breathing wave to determine the need for anxiety regulation, and so placement was largely driven by the need to reliably detect the physiological information of interest.

Automatically detecting when there is a need for emotion regulation is an important problem. Affective computing has been working on the problem of emotion detection for over a decade [129]. There are some promising results that are useful in narrow situations [124, 10]. To the best of our knowledge, these results, including for the Spire and Vitali projects, have yet to be evaluated in terms of their efficacy in reducing anxiety. Issues such as false positives, false negatives, and detecting stress too late for regulation purposes are not yet well understood. We also don't know how they compare with a person's own ability to detect rising emotions in the context of, say, a tense meeting.

3.1.2 Involvement Interventions

Involvement interventions are based on emotion regulation strategies. They can be explicit, in that they lead the user through a process that requires conscious effort for initiation and demands some level of self-monitoring during the implementation of the strategy. (If the device also senses information about the user during the involvement which is used to adapt the user's strategy, then we call the intervention a feedback intervention: see Section 3.1.3.) Or, the intervention can be implicit, in that the vibrotactile effect invokes an unconscious or automatic process that happens without insight, and runs to completion without self-monitoring[1] [65].

Implicit interventions are intriguing because they place few cognitive demands on the user. Examples of projects that used implicit involvement include Doppel [17] and EmotionCheck [37]. Both of these projects used a device worn on the wrist that employed a vibrotactile pattern to present a slow heart rate sensation to the user. The premise was that, by feeling a rhythm that was similar to the heartbeat of a relaxed person, the user's anxiety would be reduced. With Doppel, the user was told that the device measured blood flow, while with EmotionCheck, the user was told that the device reported their true heart rate. In both cases, the rhythm was not the user's heart rate (for Doppel, it was 20% lower than their resting pulse rate, and with EmotionCheck it was 60 beats per minute). Both projects evaluated the effectiveness of their approaches by presenting the user with a stressor and measuring the amount of resulting stress, as compared to users who did not experience the device's haptic sensation during the same stressor. Both found significantly lower self-reported stress in the treatment group as compared to the control group. In addition to self-reported anxiety measure, Doppel found significantly lower Electrodermal Activity (EDA) in the treatment group. Lower EDA is correlated with lower arousal.

A third example of the use of an implicit involvement intervention is Haptic Creature [171]. This was a furry vibrotactile toy, about the size of a cat, that used

[1]Involvement interventions do not require sensing during the intervention, but there may be a need for sensing physiological information before the intervention. For example, PIV (described in Chapter 5) produces a pattern with a certain pace that is personalized for that user. Determining this pace is a sensing problem, and is done during a personalization procedure. EmotionCheck, described below, required no sensing because it used the same sham heartbeat rate for all users.

a vibrotactile device to create an effect similar to a breathing animal. The breathing, combined with the soft texture of the toy, induced a calming effect with the user when they stroked it while the device was on their lap. The study found that the users' arousal and valence decreased during the experiment.

The projects we are aware of that use explicit involvement interventions employ paced breathing.[2] Haptic Chair [125] was an automobile seat that used haptics to generate a dragging sensation on the back: upward represented inhalation and downward represented exhalation. This use case is interesting both because many people spend considerable time driving (and driving can increase anxiety), and also because the researchers demonstrated that stress could be detected by the way the user (the driver) manipulated the steering wheel [124]. This is a clever example of emotion detection in a specialized setting.

Breeze [49] is a vibrotactile pendant that generated a pattern matching another user's breathing pattern (the "sender"). The user (the "receiver") synchronized their breathing with this pattern. The researchers showed that by doing so (and thus sensing the sender's breathing), the sender could encode levels of arousal and valence that were detectable by the receiver. Breeze evaluated the user experiences with three communication channels: audio, visual, and vibrotactile.

Breathe with Touch [173] used tactile (but not vibrotactile) haptics. It consisted of a small rubber bag that inflated and deflated. The user rested their hand on

[2] Lief Patch also implemented a vibrotactile breathing pacer, but we have no information on the haptic pattern outside of it being "gentle" [6]. Lacking information, we don't discuss its utility as a breathing pacer.

the bag and paced their breathing with it. The idea is that the action of inflating and deflating corresponds to breathing, and there is pleasure in feeling the device. Breathe with Touch is envisioned to be used by people who are seated at a computer, and who wish to take a break during which they pace their breathing. The researchers found that participants using this device to pace breathing reduced their stress as measured by heart rate variability and breathing rate, but not as measured by self-reported measures.

3.1.3 Feedback Interventions

Feedback interventions are based on a feedback process. They both guide a person through an emotion regulation strategy and sense some information about the user that is used to adapt that strategy. For example it can inform the user to continue with the selected tactic, or to change something, or to stop. More precisely, we have identified seven ways that biofeedback can assist here. Two of these indicate that the user should continue with the current tactic, and indicate how well the user is doing in terms of attaining the desired emotion goal or motive. For example, it may indicate how well the user, using the tactic of EDA-based biofeedback, is attaining the emotion goal of feeling less angry. Or, it may indicate how well the user is attaining a motive, such as the hedonic motive of feeling pleasure or the instrumental motive of getting better at swimming despite being afraid of water [47].

Three of the ways biofeedback can assist have to do with the user changing something. One communicates whether the user is meeting the required conditions before attending to an involvement haptic (e.g., erect posture, loose clothing, etc. before attending a paced breathing haptic [3, 128, 130]). A second is how well the user is attending to the involvement haptic (e.g., detecting symptoms indicating incorrect breathing when attempting diaphragmatic breathing [76]). The third gives recommendations on how to attend the involvement intervention better (e.g., increasing the exhalation time by slowly pushing the air through pursed lips [76]).

The remaining two have to do with stopping the current tactic. This can include switching to another strategy, or just stopping emotion regulation process altogether either because the desired emotion goal or motives are met or no longer valid [59].

We have found only one project that uses feedback intervention, namely Lief, which used feedback intervention based on a set of three-minute breathing exercises that can affect heart rate variability.

3.1.4 PIV in Relation to Other Devices and Projects

Chapter 5 discusses a specific vibrohaptic breathing pacer, which we call PIV, that we designed and evaluated for user experience and afficacy. PIV uses explicit involvement intervention by providing a breathing pacer. Even though the use of implicit involvement intervention is intriguing, PIV uses the explicit intervention of paced breathing because the efficacy of paced breathing is better studied [106, 157, 30] and known to be effective in reducing arousal.

Table 3.2 summarizes the emotion regulation devices, applications and projects that we discussed in this section. We focus on the properties that are related to our use case. For each device, the following information is given: (1) As well as providing an

	(1) Abilities	(2) Intervention Type	(3) Purpose	(4) Breathing Pacer?	(5) Wearable	(6) Inconspicuous	(7) Placement	(8) Personalizable VT Pattern	(9) Commercial Product
Doppel [9]	intervention	implicit involvement	anxiety reduction	no	yes	somewhat	wrist	yes	yes
Emotion Check [18]	intervention	implicit involvement	anxiety reduction	no	yes	somewhat	wrist	no	no
Haptic Creature [61]	intervention	implicit involvement	anxiety reduction	no	no	no	NA	no	no
Haptic Chair [50]	sensing & intervention	explicit involvement	anxiety reduction	yes	no	no	back	no	no
Breeze [23]	intervention	explicit involvement	anxiety reduction	yes	yes	somewhat	chest	no	no
Breathe With Touch [63]	intervention	explicit involvement	paced breathing to reduce anxiety	yes	no	no	hand palm	no	no
Breathe App [14]	intervention	explicit involvement	paced breathing to reduce anxiety	yes	yes	somewhat	wrist	yes	yes
Lief Patch [3]	sensing & intervention	cueing, explicit involvement, & feedback	paced breathing to reduce anxiety	yes	yes	yes	chest	unclear	yes
Spire Stone [7]	sensing & intervention	cueing	anxiety reduction	no	yes	yes	chest or abdomen	yes	yes
Vitali Sports Bra [8]	sensing & intervention	cueing	anxiety reduction	no	yes	yes	chest	unclear	yes
PIV	intervention	explicit involvement	paced breathing to reduce anxiety	yes	yes	yes	chest, abdomen, or lower back	yes	no

Figure 3.2: List of vibrotactile devices used for anxiety reduction

intervention, does it have additional sensing capabilities? (2) What type of interventions does it use? (3) What is the purpose of the device? (4) Does the device provide a breathing pacer? (5) Is the device wearable? (6) Is the device conspicuous? (7) Where is the device placed or applied? (8) Is the vibrotactile pattern personalizable? (9) Is the product available commercially?

Our immediate goal was not to design a device that improves upon the others listed in this table. Instead, we wished to explore the impact of placement and pattern for inconspicuous devices supporting paced breathing. The impact of haptic pattern in vibrotactile breathing pacers has not been studied before, yet it seems worth examining since sensitivity to haptics is different on different locations on the body [91, 64, 75]. These differences in sensitivities also suggest a closer look at personalization.

Other repetitive activities can be paced with vibrotactile devices, such as walking and rowing. The project described in [74] designed and evaluated a wrist-worn pacer for uniform walking stride frequency. Since this project does not involve emotion regulation, it is not included in Table 3.2. For this project, it was important for the user to walk at the pace the device was generating: for example, to allow the person to reach a destination at a given time. The desired walking pace would not always be the same, and so the researchers were interested in how well a user could meet the requested pace for different steps per minute.

For PIV, which is designed in the context of emotion regulation, it is important that the user practices effortless, uniform slow-paced breathing that is within the range of 4.5 to 9 breaths per minute [76]. This should be a rate comfortable for the user. Breathing at the exact rate the pacer produces is not as important as the breathing being effortless, uniform, and within the target range.

In this chapter, we have presented a framework that gives a general approach for designing affordances for affect regulation and used this framework to describe both existing affordances and the device (PIV) that we present in this dissertation. In the next chapter, we discuss the design and implementation of a scalable, robust biofeed-back haptic system testbed meant to facilitate research-based design.

Chapter 4

HapLand: A Testbed for Prototyping Vibrotactile Systems supporting Affect Regulation

Up to now, we have developed an argument that technology regulation can be supported by technology, and that a promising approach for such technology is vibrotactile-enabled wearables. In this chapter we discuss the design and implementation of HapLand, a scalable, robust biofeedback haptic system testbed that was designed to support research-based design of such technology. HapLand supported vibrotactile pattern generation and visualization as well as physiology capture and analysis. We also discuss some limitations we discovered while using HapLand. These limitations influenced the direction of our future research.

4.1 Background

Technologies and research studies developed to improve affect expression and affective information communication, including those that employ haptics [120, 77, 21, 107, 99, 71, 167], may be useful to facilitate extrinsic affect regulation (i.e., someone else has the goal of regulating your affect or you reach out to someone else to get help with regulating your affect).

However, with the barriers posed by current lifestyles and working conditions, extrinsic regulation of affect through touch in traditional face-to-face communication is not always an option. For that reason, people often need to choose among the various communication media options available today to socially regulate their affect. After choosing a medium, people still have the challenge to produce and maximize "readability"(easy-to-understand representation of emotional information) [174]. In aural and visual communications, readability may come from clear, verbal and salient social cues (e.g., facial expression, voice tone, and body gestures). In text-based communications, readability may be achieved through use of emoticons, capital letters, letter repetition, multiplication of exclamation marks, etc. Yet, extrinsic affect regulation practicality is limited as today's communication media are not designed with the primary goal of accommodating extrinsic regulation of affect. Furthermore, the people we often rely on for extrinsic affect regulation are not always available. In sum, we observed that a large portion of haptic investigations were focused on extrinsic affect regulation, yet haptics for intrinsic (self) affect regulation (in particular via biofeedback) has been relatively less well researched.

Recently, several startups and tech companies have begun to develop various haptic technologies explicitly designed for intrinsic affect regulation, referred to as calming technologies, to facilitate self affect regulation, in particular by aiding response modulation [163, 118, 28, 41, 31]. All these approaches have made important contributions, but none of these have fully addressed the important characteristics of designing a vibrotactile pattern that can regulate affect. A significant challenge is the substantial dimensionality of the problem, which arises from the existence of numerous possible combinations of the factors (such as tactile sensor types, sizes, vibrotactile strengths, durations, location on the skin, etc.) that could play a part in defining the key characteristics of a haptic pattern that may or may not have a significant impact on an on-going emotion. Consequently, it seems unfeasible to launch a study to evaluate each one of the vibrotactile patterns because the operation would be resource-hungry in terms of time, cost, and necessity of having a large sample size. In addition, research is looking into haptics for variety of contexts other than affect regulation, including the use of haptics as a technological aid for enhancing emotional experience while watching a movie or improving visual or hearing-impaired population experiences. With these constraints, each of the earlier studies was forced to choose a limited set of combinations in a particular context, which resulted in sparsely populated datasets compared to the entire universe of possible combinations.

We think that there is a need for a flexible platform that would allow for systematic and conceptually grounded research of vibrotactile aids to intrinsic emotion

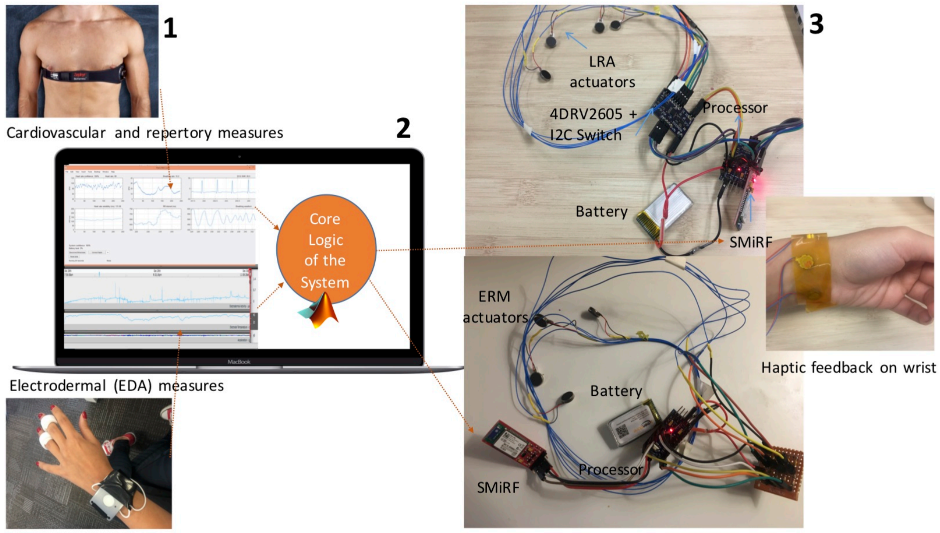


Figure 4.1: 1: Sensing components of HapLand system; 2: Sensed data visualization and is received by a core logic of the system. 3: Two types of vibrotactile wrist bands, one with LRAs and one with ERMs actuators.

regulation as autonomic signals historically have been presented to people in visual or auditory biofeedback modalities rather than haptics. HapLand was developed to meet this demand.

4.2 HapLand System

We designed and built HapLand to be a test-bed apparatus that allows us to explore design parameters – including body location, actuator type, and haptic effect intensity, duration, and pattern – to build an effective emotion regulation wearable system. HapLand provides a platform to create and visualize subtle, quiet, and individualized biofeedback or non-biofeedback haptic patterns. HapLand also allows for implementation of user experience studies in the lab in which the user does not need to sit in front of a screen while a haptic pattern is played on that person's body (i.e., the user may continue engagement with the environment) (unless, of course, sitting in front of a screen it is a requirement of the study). Figure 4.1 illustrates the components of HapLand, which include:

1. Components to capture physiology measures during haptic use, via two sensors: Qsensor [1] and Zephyr Bioharnessr [108]. Qsensor is a Bluetooth compatible device that collects EDA with sampling rates of 8, 12, 16, or 32kHz in realtime and writes them into a file using QLive software. Zephy is a Bluetooth compatible chest harness that logs cardiovascular and respiratory measures. Zephyr sends an ECG packet every 252 milliseconds. Every ECG packet has 63 ECG samples spaced 4 milliseconds apart. Zephyr also sends an R to R packet (the interval between peaks in a ECG waveform) and a Summary packet (heart rate, heart rate confidence, breathing waveform, etc.) every 1008 milliseconds. Every R to R packet has 18 R to R samples spaced 56 milliseconds apart [108].

   Based on Gross's reasoning as to why people fail to regulate their emotions, we concluded that using physiology measurements could help with not only with assessing the efficacy of haptic effects in emotion regulation (i.e., how well a haptic effect can help regulating an emotion), but also could facilitate drawing awareness to emotion dynamics tracking (e.g., biofeedback haptic effects) as well as correctly selecting an emotion regulation strategy (e.g., distraction versus reappraisal when the arousal level is high). Furthermore, there are theoretical and empirical rationales for the use of HRV and electrodermal activity (EDA) as an index of individual differences in emotion regulatory ability. Higher HRV reflects a greater capacity for regulated emotional responses [15, 83, 135] and higher EDA is correlated with higher difficulty in regulating negative emotions [46, 83]. For these reasons, we equipped HapLand with portable cardiovascular measures and EDA collector devices.

2. Core logic of the system that decides which haptic actuator (eccentric rotating mass [ERM] or linear resonant actuators [LRA]) and at which location on the body to activate; how to adjust a haptic pattern (tempo, duration, and intensity) based on collected physiology measures, and which commands to send wirelessly to the haptic wearable. We implemented this core logic in Matlab®.

3. The wearable component that plays the haptic effects (shown in green in Figure 4.1): two wireless wearables, each equipped with four actuators (see Figure 4.1). The two wearables feature different types of actuators. The wearable devices receive haptic commands from the core logic of the system through wireless serial ports (Bluetooth Serial Port Protocol).

4. Component to run experimental designs: Using Psychtoolbox [131], one can design user studies to explore the impact of haptic effects on emotion regulation (e.g., a user study to identify annoyance threshold of LRAs and ERMs).

5. Component to visualize a haptic effect: While a haptic effect is being played, one or more accelerometers, attached to the actuator(s), can collect data on the effect.

4.2.1 Why Use Two Different Types of Actuators?

We designed the HapLand wearable component to use either of two types of electromechanical devices, ERM or LRA. Each system drives four actuators, all either LRA or ERM. ERMs are small DC motors with an off-center mass that vibrate in the x-y plane (parallel to the skin). Vibration amplitude is determined by applied voltage and vibration frequency increases with amplitude. LRAs must be driven by an AC signal at their resonant frequency. LRAs have a lower vibration strength compared to ERMs (0.75G~2G for LRAs and 1G~3G for ERMS). The resulting vibration is along the z-axis (perpendicular to the skin). Each actuator thus creates distinctly different sensations for the wearer, so using both in our testbed provides us with a broader potential palette for designing and testing haptic experiences.

4.2.2 DRV2605 Haptic Driver and PWM

Haptic motors require a driver. The DRV2605 chip from Texas Instruments will drive either an ERM or an LRA. It features a library with 123 built-in effects including clicks, ramps, and buzzes. These effects, however, are intended to create notifications and alerts, such as in cell phones, and are not suitable for creating biorhythm sensations. Instead, we use the pulse width modulation (PWM) input of the DRV2605 to compose our own effects. Doing so requires a microcontroller capable of producing adequate

PWM signals; we chose the ATmega328p made by Atmel. Using PWM, we are able to precisely control haptic strength, duration, and location, and can build concurrent multi-actuator haptic effects. In the case of LRAs, use of the DRV2605 was essential since it detects the resonant frequency of the LRA and converts the PWM signal to an AC drive signal at that frequency. While ERMs it is possible to apply a current buffered PWM signal directly to the actuator, using the DRV2605 in closed-loop mode allows for overdrive at start-up and braking at stop, thus producing more precise effects. Since each DRV2605 can only drive a single actuator, we use four of them in each system.

4.2.3 Tradeoffs and Limitations of Using ATmega328p

To drive LRAs, the DRV2605 requires a PWM frequency of at least 10kHz. The Curie micro controller (mounted on Arduino 101) was not suitable because it did not drive PWM signal at the required frequency base. The Atmel ATmega328p micro controller (used by Arduino Uno, Pro Mini, and Nano), on the other hand, provides PWM frequencies up to 31,250Hz which was more than enough to drive the LRAs. Also, using the Pro Mini or Nano, we could power on the wearable using a single lithium ion battery. However, this decision came with the following tradeoffs: (1) The Atmel ATmega328p microcontroller provides limited RAM space for local variables and thus limits the number of haptic effects we can queue up. (2) No more than four actuators can be driven because the Atmel ATmega328p microcontroller provides 6 PWM pins. We used four of which (pins 9,10,11, and 3) to drive the actuators and the other two (pin 5 and 6) for internal timekeeping. Haptic control signals were transmitted wirelessly to the microcontroller using a Blue SMiRF Gold module which implements a Bluetooth serial port.

If tactors are placed too close together and each tactor is responsible for presenting a unique signal in the scheme of some complex, tactile pattern, the observer will perceive the pattern as one signal and could miss the underlying message generated with the use of two signals. Two-point discrimination acuity is less than 1 mm on the fingers, 35mm to 38mm on the forearm, 15 mm on the forehead, 39 mm for the back, and 45 mm for the calf [104]. Therefore, the choice of four actuators is appropriate assuming that tactors are to be placed around the wrist.

4.2.4 Creating Haptic Effects Based on Acoustic Waves

For creating biorhythm haptic effects, we use acoustic heartbeat and breathing waveforms to define the haptic parameters of duration and intensity. While heartbeat and breathing audio translate readily into recognizable sensations, ECG waveforms, the electrical representation of a heartbeat, do not. Laput et al. have observed that accelerometer data highly resembles audio signals captured via microphone [89] suggesting that compelling haptic sensations can be modeled on audio waveforms.

4.2.5 Scalable Nuanced and Complex Haptic Effects

We designed HapLand to be scalable in terms of being able to create many completely independent effects, as well as sequences of effects, on the four actuators. We provide the three primitive effects of pulse, double pulse, and ramp. All parameters can be specified including strength(s), duration(s) and number of repetitions. Ramps can either increase or decrease in intensity. A heartbeat effect is created using a double pulse, for example, while inhalation and exhalation are modeled using ramps with appropriate beginning and ending intensity. Combinations of the primitive effects can create a large variety of complex effects.

Examples of potential advanced haptic effects include:

1. Distributed (using multiple actuators to distribute a haptic effect): Consider a heartbeat signal with two pulses and a long delay simulated via one actuator versus two actuators. With two actuators, one can simulate the first pulse while the other, adjacent to the first, simulates the second pulse.

2. Bundled: Consider heartbeat and mimicked breathing effects bundled together to allow for focused breathing; as well as feedback that the heart rate is slowing down by gradually decreasing of heart rate effect tempo and intensity. This haptic is richer in context and carries more meaning for a person than a heart rate or breathing rate alone.

3. Gradually Decremented: The aspect of a haptic signal that is decreasing is embedded in amplitude, tempo, or both. It is interesting to ask whether one versus the other is more effective in communicating the message "your body is calming down". Our senses are good at tuning out continuous stimuli (i.e., threshold shift), so varying the amplitude (but not stopping it) makes it difficult to miss an important event occurrence.

4. Truthful versus fabricated versus mixture of both haptic signals: The truthful haptic signal pattern is positively correlated with bodily signals such as HRV, breathing rate variability, and significant EDA changes. Truthful signals can be used as a training aid, helping people learn how to influence affective states in desired directions. Fabricated haptic signals, on the other hand, are those that do not reflect the true physiology state of a person. Such signals reflect a desired state rather than the actual state.

4.2.6 Use of Accelerometer Data to Visualize Haptic Effects

HapLand allows for visualizing the acceleration produced by a haptic effect. We use a MPU9250 accelerometer attached to a 25g reference mass. The actuator is tightly coupled to and the entire setup suspended from the edge of a desk allowing acceleration in all directions to be measured.

Figure 4.2 compares a heartbeat audio waveform with the acceleration produced by both ERMs and LRAs.

4.3 Discussion

We designed and built HapLand as a non-multidisciplinary attempt to develop a technology for affect regulation. The HapLand project exposed some of the limitations of taking a non-multidisciplinary approach to affect regulation which later led us to form a multi-disciplinary advisor team, explore the WEHAB solution space 2, present the WEHAB framework 3, and conduct the PIV study (Chapter 5).

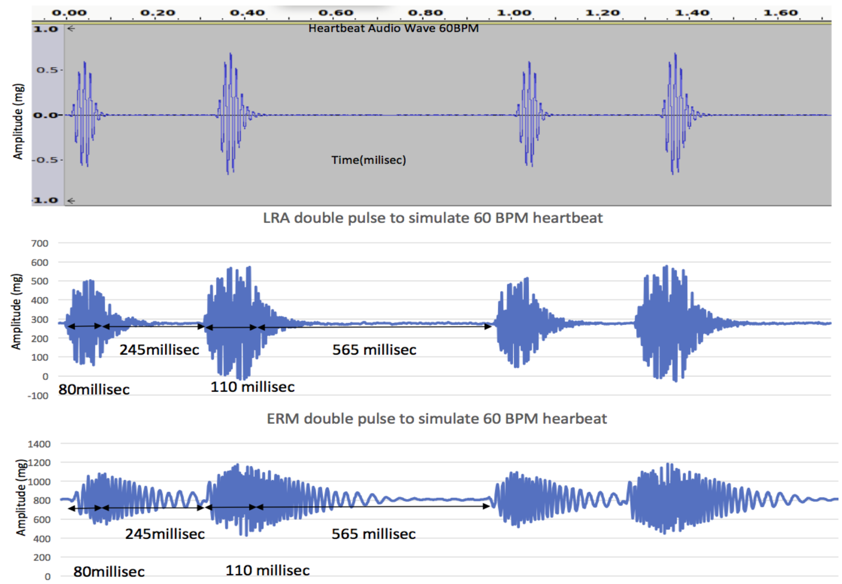


Figure 4.2: Heartbeat audio (top) and acceleration of a reference mass produced along x axis by an ERM (middle) and long z axis by an LRA (bottom)

HapLand presented a platform for running vibrotacticle intervention studies for affect regulation. This platform demanded vibrotactile devices and physiological data collection technology with minimum latency that can be tolerated when reacting to physiological changes, and the need to accurately timestamp physiological data and vibrotactile patterns. Such demands could not be fulfilled because wearable technologies used in HapLand to collect physiology data were not designed to provide real-time data with high sampling rate back to a user. This inhibited providing the ability to evaluate the regulatory effects of a vibrotactile pattern and building feedback technology, both of which require access to physiology in real-time. Emotions are short-lived phenomena and timing for regulating such emotions plays an important role. Another limitation of HapLand was the choice of vibrotacticle tactors for designing a breathing pattern: the C-2 tactor [2] is a better choice because they are optimized for use against the skin.

In the next chapter, we describe the direction we took after building and working with HapLand.

Chapter 5

PIV: Exploring Placement, Pattern, and Personalization of a Vibrotactile Breathing Pacer

5.1 Introduction

Slow-paced breathing has been shown to reduce perceived stress and physiological arousal [106, 157, 30], and it is thus considered to be an effective form of emotion regulation. This raises the question of how technology can assist a person in using slow-paced breathing to regulate unwanted emotions in everyday life.

To motivate this chapter, consider the following use case:

> *You are in a meeting. Your team is behind deadline and your boss is looking for an explanation. Things are getting tense, and your anxiety is increasing. What can you do to reduce your anxiety? You may decide to leave the meeting. You may decide to avoid eye contact. You might start browsing your emails to distract yourself. Although potentially effective at*

decreasing anxiety, all of these decisions could have negative consequences, some more serious than others. Or, you can try slow-paced breathing.

Implementing slow-paced breathing can be challenging when you are stressed. To overcome this challenge, you could seek out biofeedback training, over the course of multiple sessions, to learn how to pace your breathing. Apart from being expensive, training is usually conducted in a controlled environment. This leaves you on your own to implement slow-paced breathing outside of the controlled environment. Alternatively, it would be useful to have a device that assists you in pacing your breathing, and thus helps reduce your anxiety, when in a stressful situation.

Being cued when to start pacing your breathing is also useful. For example, you could use a Spire Stone [10], a vibrotactile wearable that senses your breathing signal and, decides whether you are stressed or not; if so, it cues you with a short private vibration pattern. But because you are anxious, you may need to be repeatedly reminded. It would be better to provide a pacer to which you could pace your breathing, much as a metronome is used by musicians to play music with a steady beat even when anxious.

You could use audible apps designed to practice paced breathing [9] or use the Breathe app [28] if you own an Apple Watch. However, using these could have negative consequences as well; your level of engagement with the meeting might be affected, and your fellow meeting attendees might wonder what you are doing. It would be better to use a breathing pacer that is not obvious to others: then they won't easily see that you have such a pacer because it communicates privately only through an inconspicuous channel, for example with vibrotactile actuators.

There are other meaningful use cases for breathing pacers that reduce anxiety: it is easy to construct scenarios in which an audio pacer would be appropriate, and situations in which inconspicuousness would not be important. In this chapter, we focus on the use case suggested above: the use of vibrotactile technology to inconspicuously interact with the user. This use case is an important one: as we described in Section 3.1, many of the commercial devices appearing on the market that unobtrusively help regulate emotions use vibrotactile technology.

We were drawn to a set of questions arising from this use case. Where should the tactors be placed on the body? Does the choice of body site placement affect the way a person breathes or feels about the device? What kind of haptic pattern is effective in paced breathing? Which patterns are more likely to positively affect the way a person breathes or feels about the device?

One remaining question has to do with personalization. A haptic pattern that some people find ticklish or unbearable others may find pleasurable, and yet others may not even feel it. We also vary widely in how we breathe: a good breathing pace for one could cause another person to hyperventilate. This raises the question of how important is personalization of the pacer prior to practicing paced breathing for it to be effective.

We designed a within-subjects experiment to assess the effects of placement and pattern on pacer experience and efficacy. We investigated how 18 combinations of PIV-specific patterns and placements (3 placements $\times$ 3 shapes $\times$ 2 order values) guided participants' paced-breathing experience and efficacy. The experiment was done in a laboratory setting with the participants comfortably seated.

To investigate which placement $\times$ pattern $\times$ order effect was most effective, we produced covariance pattern models with a heterogeneous compound symmetric error structure for each DV. We further concluded that placement and pattern play a role in breathing experience and breathing efficacy. The details of trends that we found are presented in Section 5.6.

Contributions. This chapter contributes: (1) PIV, a high-fidelity prototype of a personalizable vibrotactile breathing pacer; (2) An effective protocol to design and personalize PIV vibrotactile paced breathing patterns; and (3) A detailed experimental design that enabled us to further analyze the efficacy of different body placement and haptic pattern choices of PIV. In sum, this chapter is about PIV placement, pattern, and personalization.

A unique aspect of our contribution comes from the interdisciplinarity of our team of advisors. Included on our team are experts in emotion regulation, haptics, electrical engineering, HCI, and distributed systems, as well as experts in the clinical application of biofeedback. We believe that such an interdisciplinary approach is necessary for making progress in the development of technology that assists in emotion regulation [114, 113].

5.2 Measures and Models used in PIV

In this section, we briefly describe the models and analytic techniques we used to choose the type of self-reported and physiological measures to answer the research questions listed in Section 5.4. This goal of this section is to make it easier to comprehend the results in Section 5.6.

5.2.1 Emotion Regulation Model

Our work is based in part on the model of emotion regulation by James Gross [60, 59]. This model describes the internal (and typically unconscious) process through which people regulate emotions as consisting of three steps: the perception (P) step in which someone perceives a psychologically relevant situation; the valuation (V) step in which the person evaluates and interprets the situation to determine which actions should be taken; the action (A) step in which the person implements a specific action. This action can cause a change to the situation which can lead to the generation of a new emotion.

We were motivated by this model when determining the set of self-reported measures. In a similar way, a participant goes through three steps when experiencing the pacer. We ask how well the participant attended the pacer (perception), how well they could differentiate between the inhalation and exhalation waves (valuation), and how well they could synchronize their breathing with the pacer (action).

5.2.2 Unipolar Valence Model for Emotion Self-report

The Unipolar Valence Model is used to capture, via self-reports, the conscious experience of emotions. It allows for expressing both positive affect (PA) and negative affect (NA) using two separate axes. Doing so addresses the evidence that suggested individuals can experience mixed emotional states, such as guilty pleasure [90, 87, 19, 67].

Kron [84, 85] encouraged using unipolar-valence model to measure emotional experience. For example, Kron et. al. found that valence measured using the bipolar scale of valence-arousal as well as EMG measures (physiological measure of valence) were highly correlated with the difference between PA and NA scores (i.e., PA − NA). In addition, the arousal measured using the bipolar scale of valence-arousal as well as EDA were highly correlated with the sum of PA and NA scores [84, 85].

Given Kron's result, and the relative ease of explaining to participants about

PA and NA, we used the Unipolar Valence model to form two questions on the self-reported feelings.

5.2.3 Linear Mixed Model and Covariance Pattern Model

When there is no missing data, the Multivariate analysis of variance (MANOVA) models is appropriate to use. The MANOVA model does not assume equal variances and covariances, and it uses list-wise deletion so that any subject that has a missing value in any of its conditions is removed from the analysis. Because of its use of list-wise deletion in the presence of missing data, the MANOVA model has relatively low power to detect interaction effects and main effects.

Linear Mixed models (LMMs), on the other hand, allow for different source of variation in data, and they can accommodate missing data in an effective way. Such models assume that the observations are not independent from each other and that the residuals may be correlated. LMM assume normally distributed responses that incorporate observational blocking (e.g., responses are nested within participants). LMMs consist of fixed effects (variables that are expected to have an effect on the dependent variables) and random effects (grouping factors for which we are trying to control). The incorporation of random effects accounts for the fact that multiple responses from the same person are more similar than responses from different people. LMMs produce quantitative parameter estimates that describe both how the response variable changes as a function of the fixed predictor variables (e.g., body placement and pattern), and the variability among the levels of the random effect (e.g., subject differences).

There are multiple ways of performing mixed modeling. One way is using a mixed linear model with random intercept. This model assumes compound symmetry, that is, equal variances and equal covariances for predicted errors. This assumption is often unrealistic because the observations of the dependent variable for the same subject are assumed to have equal covariances, regardless of how far apart the measurements were taken. And, a violation of this assumption can give misleadingly small p-values. This model also assumes that each dependent variable is approximately normal within each of the 18 conditions which may not hold true in all situations.

This model is appropriate to use when reporting how much of the variability of each penalization parameter is explainable by the body placement and the individual differences. We used this model to report the findings in section 5.6.2.

A third approach is to use a covariance pattern model, which is appropriate to analyze the dependent variables of self-reported and physiological measures in our study. This model takes into account the covariances between the repeated measures. That is, the observations for the same subject are assumed to have a specific pattern of covariance across the trials. There are several different covariance structures commonly used, including unsecured, compound symmetry, Toeplitz, first order autoregressive, heterogeneous compound symmetry, etc. In a within-subjects design where subjects are tested under conditions in random order, the Toeplitz and first order autoregressive structures are seldom appropriate; these are instead more useful for longitudinal designs. For our study, the unstructured and heterogeneous compound symmetric structure are more appropriate.

If the amount of missing data is too high, the unstructured method can take a very long time to converge. We found this to be the case, and so we used the covariance pattern model with a heterogeneous compound symmetric error structure, which converges quickly. The heterogeneous compound symmetry assumes specific variance for each trial, and a specific constant correlation between each pair of 18 observations within a subject. It uses all of the available data and does not assume equal variances. We computed (in SPSS) the Satterthwaite degree of freedom for this type of model, which improves the small-sample performance.

We used this covariance pattern model to determine which, if any, interaction effects are present. With this information, we proceeded to examine the appropriate effects (simple-simple main, simple main, or main) by reporting the traditional p-value in addition to the confidence interval (CI) for each effect.

With this approach, one starts with a model with all main effects and all interaction effects. Then, any interaction effect that is non-significant is dropped from the model and the model is run again. The decisions about what effects to report (assuming the second model includes one or more interactions) is based on the results of this second model. We performed this exploratory model selection to decide if some or all interaction effects could be deleted from the model.

5.2.4 EDA and Continuous Decomposition Analysis

Electrodermal activity (EDA) refers to the phenomena of the variation of the electrical properties of the skin in response to sweat secretion [48]. The most widely studied electrical property of skin is the Skin Conductance (SC) signal, which can be quantified by applying a constant low voltage between two points of skin contact and measuring the resulting current flow between them. A SC signal is usually characterized by a sequence of overlapping phasic (fast changing) skin conductance responses (SCRs) overlaying a tonic (slower acting) component. An SCR shows a steep incline to the peak and a slow decline to the baseline. The succession of SCRs usually results in a superposition of subsequent SCRs, as one SCR arises on top of the declining trail of the preceding one (see Figure 5.1 and the red circled areas of the purple curve in the lower part of Figure 5.7(c)).

To analyze the SC data, the standard peak detection method (trough-to-peak) defines the SCR amplitude as the difference of the SC values at its peak and at the preceding trough [27, 44]. This technique, however, can be limiting in the case of closely superposing SCRs [86, 58]. The issue of superposing responses motivated us to use other methods that offer a more precise assessments of the SCR amplitude.

Continuous Decomposition Analysis [22, 23] is a method for decomposing a SC signal into continuous tonic and phasic activities (tonic activity shown in gray and phasic activity shown in blue shown in Figure 5.1). This method is useful especially in situations with high phasic activity. The tonic activity gives basic level of skin conductance level and varies, depending on the individual, between 2 to 20 microSiemens (μ S). The phasic activity is a marker of the activation component of an emotional episode aroused by a presentation of a stimulus [32]. In this study, we used this method to analyze the phasic component of the SC signal. More specifically, we used the Matlab-based LedaLab

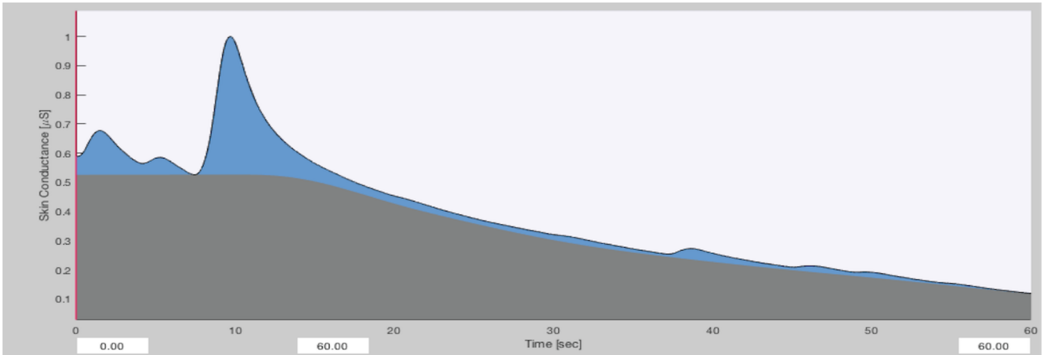


Figure 5.1: Skin conductance from one of our trials as displayed by the Ledalab analysis software. The blue area indicates the phasic component of the signal, and the grey area represents the tonic component.

software [5] to calculate the average phasic drive within a response window (CDA.SCR, in μ S). We used a response window of 60 seconds. Decreased CDA.SCR is observed when participants downregulate emotions as compared to upregulating [43, 79].

5.3 The Design of the Breathing Pacer

In designing the breathing pacer, we adopted five design guidelines: using haptic intervention, being inconspicuous while being effective in paced breathing, using a pattern that supports based breathing, being personalizable, and being usable at any place and time.

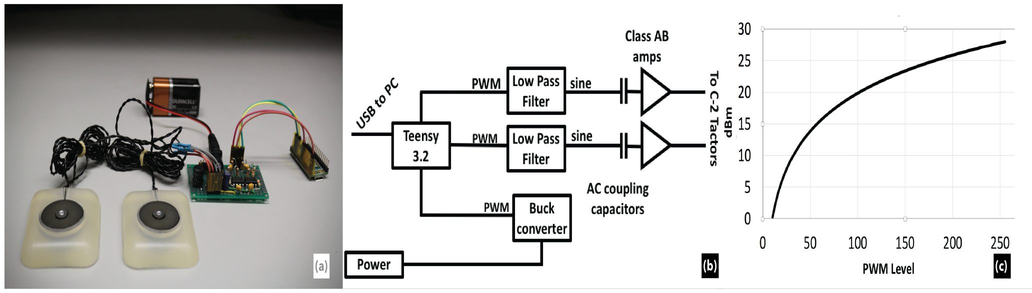


Figure 5.2: PIV device (a); PIV circuit board design (b); C-2 power in terms of PWM levels (c)

5.3.1 Using Haptic Intervention

There are several advantages in using haptics to build a breathing pacer. Haptic signals can be quick to understand, which make them attractive for use in technological aids [51] especially when visual and auditory channels are busy, overloaded, or unreliable [137, 73]. In particular, the choice of a vibrotactile signal seems more appropriate for emotion regulation in everyday life than an exoskeleton or other forms of tactile devices due to size and power consumption. The choice of the specific vibrotactile actuator to use is critical since they are usually the bulkiest and heaviest components in a wearable device. In general, linear electromagnetic actuators, including voice coils, solenoids, and C-2 tactors, are preferable to non-electromagnetic actuators such as an eccentric rotating mass motor (ERM). This is because most electromagnetic actuators, with the exception of Linear Resonant Actuators (LRA) [8], can produce any vibration profile within their dynamic limitations. Such degrees of freedom allow for creating rich haptic patterns.

We used a pair of C-2 tactors [4] to build PIV. This tactor is a spring moving-magnet actuator that has been optimized for use against the skin. It has a primary resonance between 200 Hz to 300 Hz, but it can be sensed when driven between 10 Hz and 320 Hz. The vibration can be played at different amplitudes (or, equivalently, different powers), specified by Pulse Width Modulation (PWM) duty cycles. In the PIV prototype, the PWM signal (which has a switching frequency of 100Khz) is filtered to produce an analog voltage that is directly proportional to the PWM duty cycle. The maximum drive voltage (2.5 V RMS) is delivered when PWM is 255, at which point the power is 625 milliwatts.

The C-2 tactor is a good choice to create a biphasic vibrotactile pattern because of its ability to play vibrations at different frequencies and still be easily sensed, and its effectiveness in implementing short pauses. We could have used tactors with fewer degrees of freedom, but doing so would have required additional ways of distinguishing between inhalation and exhalation. This could be done using multiple tactors to provide, for example, an illusion of motion [123], but doing so would take more space on the body which could impact wearability and inconspicuousness.

People perceive increases in power, and so we briefly describe the relationship between PWM and power. Figure 5.2 shows this relation, with power expressed in terms of dBm (decibels with a reference power of 1 milliwatt).[1] The maximum power in this

[1]Perception also depends on the efficiency of the C-2 tactor, which is not taken into account in Figure 5.2. This figure was derived as follows. $dBm(P) = 10\log_{10} P$ with P expressed in milliwatts, and $P = V^2/R$. For the circuit, $R = 10\Omega$. Given the maximum drive current is 250 mA RMS and $V = IR$, the maximum drive voltage is 2.5 V RMS. This gives $dBm(\text{PWM}) = 10\log_{10}(((2.5 * \text{PWM}/255)^2/10) * 1000) = 20\log_{10}\text{PWM} - 20.172$.

scale is 27.6 dBm. In the result section, we reported the amplitude values of personalized haptic shapes in units of PWM level.

The C-2 tactor can be driven using a stock controller available from Engineering Acoustics Incorporation. This controller provides the hardware and software needed to drive up to eight tactors, but it is large, expensive, and needs 110 volts; as such, it not appropriate for a wearable. The Macaron approach [140] of using a USB powered Class D amplifier to drive a tactor would reduce the size, cost and power requirements, but it would also reduce the fidelity of the haptic effect. So, we designed a custom 9 volt circuit board that uses a Class AB amplifier[2] to produce a clean sine wave. This board drives two C-2 actuators simultaneously (see Figure 5.2(b), upper right) and is powered by a battery or a 9 volt adaptor charger.

We also wrote a driver, run by a Teensy 3.2 processor, that receives vibrotactile pacing commands. A pacing command encodes a continuous inhalation and exhalation pattern with pauses between them. The pacing command also includes the pattern pace (BPM and *br*). When the driver is instructed to start playing a new pattern, it delays doing so until the currently playing pattern reaches the end of an exhalation wave so as to keep the breathing rhythmic. The driver provides other commands as well, including one that terminates any playing pattern and flushes any queued-up patterns.

To be able to run the personalization routine, we wrote controller software that sends commands to the processor via a mini-USB connector. The controller software is written in Matlab. This software implements a user interface that allows the experi-

[2]We used On Semiconductor L272M amplifiers.

menter to adjust the breathing pattern (e.g., on the basis of the participant's feedback) during the personalization routine. The software also automates major parts of the experimental protocol, including generating the patterns played to the participant and capturing the participant's ratings after each pattern is played.

5.3.2 Being Inconspicuous while being Effective in Pacing Breathing

There are many factors to consider when choosing a body site for placement, including one's ability to detect and react to vibrotactile effects at that body site under different conditions (i.e., while seated, while walking, and while distracted) [75]. For our use case, the body site should lend itself to making PIV inconspicuous to others because, for the most part, we envision it being used in social settings. In addition, the PIV tactors should be located in a place that is effective in pacing breathing [117, 29]. The second condition implies choosing a body location that is involved with breathing.

Based on this reasoning, we did not include the wrist: it is not involved in breathing and it may not be inconspicuous. Wrist placement could also result a body position that restricts breathing [100], since one often looks at a wrist-mounted device by bending the head down.

5.3.2.1 Placement Symmetry

Because breathing is a symmetric experience – we have two lungs and two nostrils – we decided to use pair of symmetrically placed C-2 tactors to generate the pacing pattern on the selected body sites. Indeed, when we tried a single tactor placed on the midline on me and my research assistants, we all preferred to have two symmetrically placed tactors at least 2 to 3 inches from the midline. This is consistent with advice from my advisors who are biofeedback breathing practitioners: they touch patient with both hands at symmetrical places on the abdomen rather than with only one hand. We control the tactors' amplitudes and frequencies in tandem: the two tactors always generated the same vibrotactile pattern at all times.

5.3.2.2 Placement Body Sites

The three body sites we chose to investigate for PIV placement were the abdomen, the lower back (the Dimples of Venus), and the chest. These sites are shown in Figure 5.3(a–c).

- Abdomen. When a practitioner teaches abdominal breathing, they often touch the patient's abdomen or encourage them to place their hands on their abdomen to feel if it is moving [128]. We adopted this idea, and chose points roughly one third of the way along a line from the umbilicus to the anterior superior iliac spine. These points are easily found, are sensitive to touch, and are not too far down the torso to make it difficult or embarrassing to attach the tactors on a person who is wearing pants.

- Lower back. This location is sometimes called the Dimples of Venus. Practitioners often find it effective to encourage abdominal breathing by asking the patient to envision a balloon in their abdomen, inflating with each inhale [76]. Such a balloon would put pressure on the immobile parts of the abdomen, as well as the corresponding area on the back. This suggests an alternate back location that mirrors the two points on the abdomen. We chose the Dimples of Venus because they are on the lower trunk and easy to locate. The point localization threshold of the back is similar to that of the abdomen [92] and so this spot should be sufficiently sensitive to be useful.

- Chest. The first two locations are on the lower trunk. We were interested to know whether placing the tactors on the upper trunk would make a difference. So, we chose a spot two inches below the midpoints of the clavicles. This spot is easy to locate across different individuals.

These body sites don't contradict the results of [75]. In this work, they found that of the 12 body sites they investigated, the wrists and the spine were the best in terms of detecting vibrotactile pulses, the feet and thigh were the worst, and the other sites were approximately the same. Our abdomen body sites are their sites 7-8, and our chest sites are their sites 10-11. They did not consider a site close to the lower back sites we used; the spine and the lower back are the only sites either study considered that are on the dorsal side.

5.3.3 A Pattern that Supports Paced Breathing

We are interested in a purely tactile-based pacer: a pacer generating a noise would be conspicuous to others. To ensure no audible noise during the study, we selected

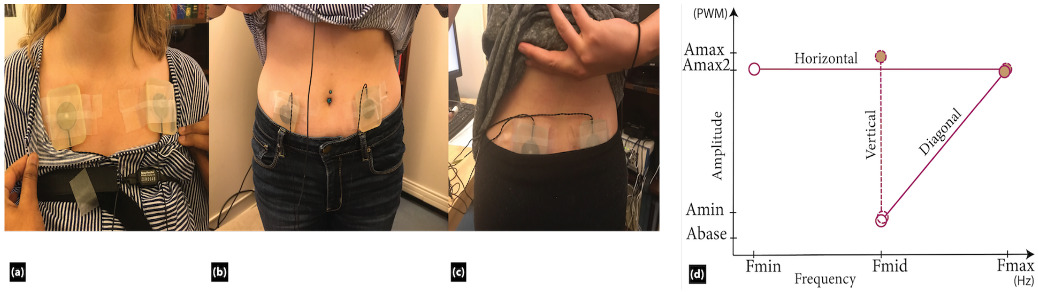


Figure 5.3: C-2 tactor chest placement (a); Abdomen placement (b); Lower back placement (c); Frequency - Amplitude representations of the the three shapes (d).

a range of frequencies and amplitudes that were easily noticeable while, with some noise shielding around the tactors, would be inaudible. The PIV device, however, is a prototype: the noise shielding around the tactors is much less than what exists for devices like the Spire Stone. To compensate for this lack of shielding, we placed noise cancelling headphones on the participant. Doing this allowed us to explore frequencies that should be inaudible in properly shielded devices.

We distinguish between the *shape* of a pattern, which is the property of the pattern that encodes when to inhale and exhale, and the *pace* of a pattern, which determines the timing of the inhalations and exhalations. We express the pace of a pattern in terms of the breaths per minute (BPM) and the breath ratio (br), which is the ratio of the inhale time to the exhale time. For a pace of a pattern to be effective, one must determine an appropriate BPM and br at which a user can comfortably synchronize breathing and not feel rushed.

5.3.4 Piloting the Shape

We did not find it straightforward to choose an effective shape. We first explain how we explored different shapes through piloting the design, and then describe the shape we ultimately used.

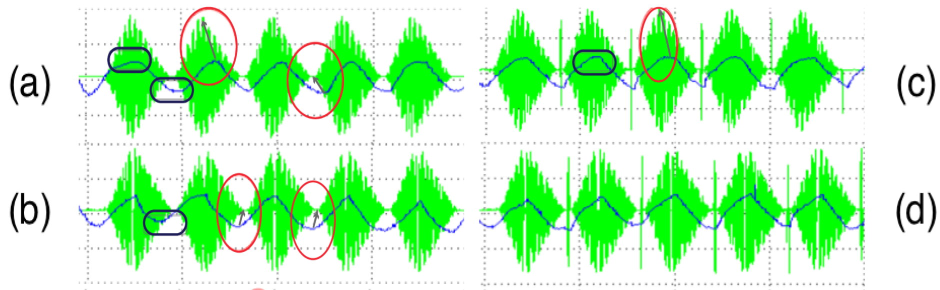


Figure 5.4: Accelerometer data showing a user's breathing signal (shown in blue) overlayed with the haptic pacing pattern waveform (shown in green) the user was pacing with. The x axis represents time and the y axis represents PWM level. The breathing signal and the haptic pattern were not in phase, as noted in the circles. The transition between the inhalation and exhalation phases was not easy for the user to notice, which led to breath holding as noted in ovals.

We first piloted different shapes with five of the authors and RAs, and iterated on how well participants could synchronize their breathing with each shape using self-reported information. Using our high-fidelity prototype, we initially tried the shape of a wave consisting of a linear ramp up followed by a linear ramp down. The ramp up is the inhale phase, and the ramp down the exhale phase. An example is in Figure 5.4(a), which, like all of the waves in this figure, has a pace of BPM = 8.5 and br = 2/3.

The green curves show the waves, and the blue curve is the actual breathing pattern as measured by an accelerometer placed on a participant's chest. We observed that participants struggled to determine when to start inhaling or exhaling, which led to breath holding (highlighted with ovals) during the transition between inhaling and exhaling, and occasionally to taking a short inhale to sync up with the pacer. In addition, the breathing wave and the haptic wave were not in phase, as noted in the circles. The reason for this delay is explainable: [126] suggests that at least 20% to 30% of a difference in amplitude or frequency is necessary for robust discrimination between vibrotactile stimuli in practical application; this is called the "just noticeable difference". Note that the participant started inhaling or exhaling when the amplitude of the haptic effect had changed by approximately 20% - 50%.

To more clearly indicate the transition from the inhale to exhale phase, we added a 100 ms pause between the ramp up and ramp down. This was useful: as can be seen in Figure 5.4(b), the participant deliberately began exhaling at the correct times (see the sharper inflections in the blue curve). He did not appear to be confused about when to start exhaling, but was still uncertain about when to start inhaling. We then added a 100 ms pulse with a high amplitude to indicate when to start inhaling (Figure 5.4(c)). This also worked well: as can be seen, he deliberately began to inhale at the correct times. Figure 5.4(d) shows the results of using a pacer with both the pause and the pulse.

A biofeedback advisor, however, observed that the participant was breathing with effort, as can be seen by the sharp inflections in the waveforms. The practitioner noted that when breathing is effortful, the benefit it has in regulating emotions is decreased. He advised that the pacer amplitude should become zero during the transitions between inhalation and exhalation phases. Doing so signals a brief pause at the end of each inhalation and exhalation, which would result in smooth and effortless breathing. We chose a pause of 300 ms between the inhalation and exhalation phases, and 200 ms between the exhalation and the next inhalation phase. When we calculate br, we include the 300 ms pause with the inhalation time, and the 200 ms pause with the exhalation time.

5.3.5 Final Pacing Shape

The biofeedback practitioners guided us in choosing the shape we used in this study. The shape is reminiscent of the sound of breathing. Figure 5.5 gives an amplitude - time plots of three patterns. These are biphasic, with each phase being a sinusoidal vibration with some frequency and defined by a minimum amplitude A_{base} and a maximum amplitude. The envelope increases linearly from A_{base} to the maximum amplitude for the first half of the phase, and then linearly decreases back to A_{base} to complete the phase.

With respect to order, we did not know whether inhalation or exhalation would be better represented by the stronger sensation: individuals might differ in their preferences. For example, we were curious whether a stronger inhalation wave would be easier to synchronize with (since each breathing cycle starts with inhalation), or a stronger exhalation would be easier (because exhalation is pushing air out of the body).

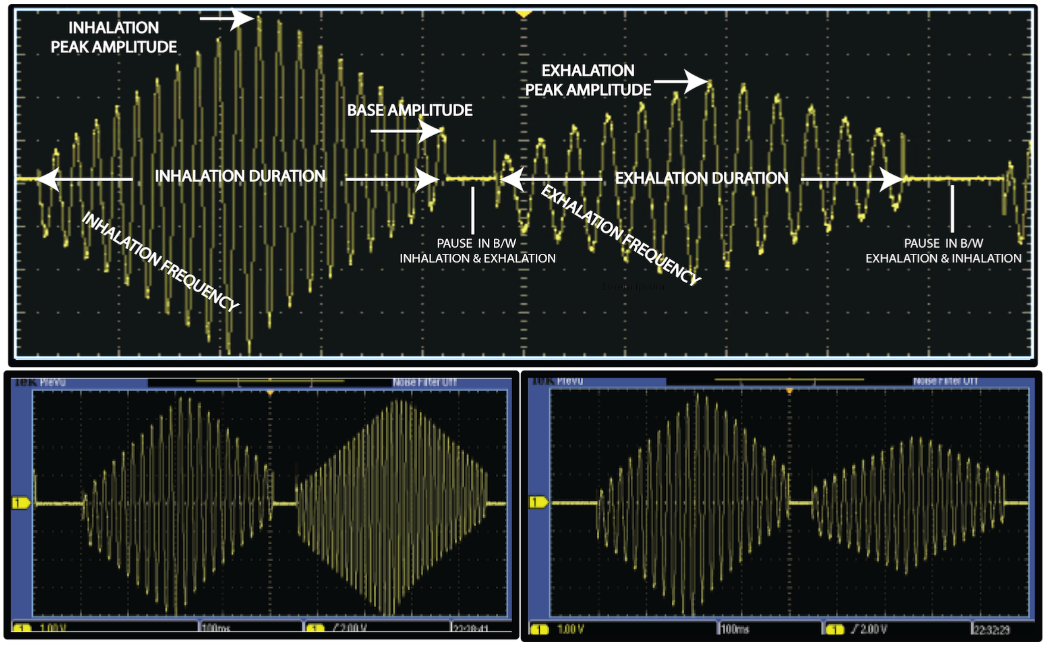


Figure 5.5: Three breathing patterns. The top is a diagonal shape with order = strong inhale, the bottom left is a horizontal shape with order = strong exhale, and the bottom right is a vertical shape with order = strong inhale.

Figure 5.3(d) shows the frequencies and maximum amplitudes associated with each shape. This figure shows six points in frequency - amplitude space, where each point represents an inhale or exhale phase. A line connecting two points represents a shape, with one end being the inhale phase and the other being the exhale phase. The label on the line is our name for the shape (e.g., a shape that has both phases with the same frequency is a "horizontal" shape because the line representing this shape in frequency - amplitude space is horizontal). For each line, the point that feels more intense is filled in. If this point represents the inhale phase, then the pattern has order = strong inhale;

otherwise it has order = strong exhale.

5.3.6 Being Personalizable

Given a pattern, the pacer needs to be personalized for the participant. One part of the personalization process involves finding their breaths per minute BPM and breath ratio br. As we observed in Section 3.1.4, the goal is for the user to practice effortless, uniform slow-paced breathing that is within the range of 4.5 to 9 breaths per minute [76]. Thus, one part of personalization is to find a pace that the participant finds comfortable.

The other part of personalization involves determining the frequencies and amplitudes associated with the shape (that is, the points in Figure 5.3(d)). For this, it is important that the participant cannot hear the vibrotactile pattern, can easily distinguish the inhalation phase from the exhalation phase, and can easily synchronize their breathing with the pattern without feeling rushed.

The detailed steps of our personalization routine are presented in Section 5.5.2 and Algorithm 1. We assessed whether there is variability across subjects in these parameters in Section 5.6.

5.4 Research Questions

We used a lab-based no-stressor approach to investigate pattern and placement as a function of PIV experience and efficacy.

In terms of PIV efficacy, we looked at the physiological data of the breathing waves, primarily at the regularity of breath duration and the regularity of breath depths. Irregularities of these values indicate the difficulty the participant was having in pacing their breathing. In addition, we looked at the ratio of chest to abdomen breathing: breathing slowly, regularly, and more with the abdomen is commonly advised as a way to reduce anxiety [30, 76, 106, 157]. Hence, we would prefer to use a placement that results in a higher abdomen to chest breathing ratio, while also minimizing breathing irregularity.

We also measured SC to determine whether it decreased during paced breathing: reduced SC is associated with reduced arousal, which is a measure of anxiety reduction. More reduction of SC during a trial reflects more effective paced breathing which in turn results in better down regulation of emotion during that trial.

Thus, we addressed the following three research questions:

1. How important is personalization of the vibrotactile pattern for each body site? See Section 5.6.2.

2. How do the choices of body site and breathing vibrotactile pattern influence participant affect as well as the ability to attend to the pacer, to differentiate the cues for inhaling and exhaling, and to synchronize breathing with the pacer? See Section 5.6.4.

3. How do the choices of body site and breathing vibrotactile pattern influence participant SC level and the manner in which they breathe (the degree of chest to abdominal breathing, the regularity of their breathing, and the depth of their

breaths)? See Section 5.6.5.

5.5 Experiment

A total of 36 volunteers (14 Female; 22 Male; $Mean_{age} = 27.92, SD_{age} = 9.15$) took part in the study. We recruited individuals through a university pool of students and through a Facebook ad. Compensation was either $20/hour or two university course credits. Volunteers were asked to fill out an eligibility survey. Those who met the criteria were invited to participate in an on-site 2 hour session. Volunteers were excluded if they were under 18; pregnant or breastfeeding; experience cardiovascular, respiratory, or psychological/neurological disorders; or smoked over five cigarettes a day.

Each experiment was controlled by two experimenters. The experiment was run with the participant in an experiment room and the experimenters in an adjacent control room. The experimenters only went to the experiment room to help the participant relocate the actuators. The control room contained two computers. One computer ran software from Thought Technology[3] to collect, with a sampling rate of 256Hz, the physiology data collected from the participant during the experiment. One of the experimenters used this computer to label each trial and to monitor the data being collected. The other computer ran the breathing pacer controller software. It was connected to two monitors, mice, and keyboards, with one set in the control room and the other set in the experiment room. At different times, either the second experimenter or the participant controlled the software with their keyboard and mouse.

[3]http://thoughttechnology.com/

The experimenters watched the participant via two cameras. One camera was placed behind the participant so the experimenters could watch what the participant was looking at on the screen and what they were typing, and the other was in front of the participant so that the experimenters could see the participants facial expressions. The experimenters could hear the participant via a microphone in front of the participant, and the experimenters communicated with the participant through noise-cancelling headphones that the participant were wearing. The C-2 tactors were connected to the custom circuit board, which was in the experiment room. The circuit board, being a piece of unprotected electronics, was hidden in a box on the table with the monitor and keyboard.

5.5.1 Experimental Protocol

The protocol is shown in Figure 5.6. It had a 3 factor within-subjects design. The factors were placement (chest, abdomen, lower back), shape (vertical, horizontal, and diagonal), and order (strong inhale, strong exhale). The order of the placements and the patterns for each body site were chosen at random for each participant to equalize any ordering effects.

We first instrumented the participant with a chest breathing strap, an abdomen breathing strap, two electrodermal activity (EDA) electrode patches on the index finger and one of the ring fingers, a pulse sensor on the index finger, and a temperature sensor on their little finger, all on the left hand. We then placed the tactors on the first of the three randomized placements (Figure 5.7(a-b)). When attaching the tactors to a

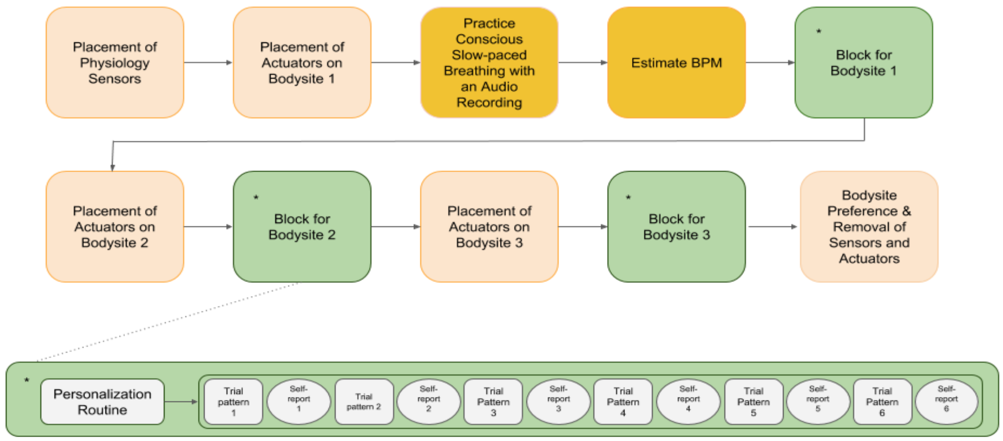


Figure 5.6: Experimental protocol for each participant. The beige boxes are the actions that involve the research assistant working with the participant on experimental setup and pacer placement. The gold boxes are actions with the research assistant in the control room and the participant alone in the experimental room. The green boxes, exploded in the bottom, include the vibrotactile personalization routine for that placement followed by six randomized pairs of trials and self-reported responses.

participant, we placed each in a silicone gel snap-in mounting pad because we found that users found the sensation more pleasant using the mounting pads than not using them. We used surgical tape to attach the tactors to the participant: given our goal to learn about the potential tactors placement body sites before making a more high-fidelity prototype, we chose this expeditious approach.

The participant sat in front of the monitor and keyboard with noise cancelling headphones on their head. The participant was informed that the experimenters could see and hear them from the control room, and that the session would be recorded for later analysis.

The participant then listened to a five minute recording that led them through a mindful, slow paced breathing exercise. The participant was asked to practice these breathing techniques for two minutes while listening to text from [38] on mindful slow breathing. During the last 30 seconds of this exercise, their breathing pattern was captured to estimate the participant's BPM. The BPM was always in the range of 4.5 to 9 BPM, which is consistent with the literature [76]. The breath ratio br was initially set to 1.0.

At this point, an experimenter worked with the participant to measure the parameters of the pacer's shape for the randomly-chosen body site. We called this phase of the protocol the *personalization routine*. The detailed steps of this routine are presented in Section 5.5.2 and the pseudocode is presented in Appendix A.1 as Algorithm 1.

The next step of the protocol was to have the participant pace their breathing with each pattern. The participants were informed that the patterns would be presented in a random order so that they did not assume that the sequence of patterns would become more personalized based on their comments.

Before starting a pattern, the participant was asked to take a deep inhale and a deep exhale, and an experimenter in the control room labeled the current recorded physiology with information about the pattern (the body site, shape, and strength). The pattern was played for 90 seconds during which the participant paced their breathing with it. After the pattern concluded, the experimenter again labeled the current recorded physiology and the participant answered a set of questions on the monitor: (1) How well they attended the pacer; (2) How well they differentiated between the two waves; (3) How well they could synchronize their breathing with the pacer; (4) How positive (PA) and negative (NA) they felt right after the pacing. The sequence of questions was counterbalanced to ensure that it had no effect on the ratings. The first three questions were presented as a continuous Likert scale from 0-100 with the 7 labels of extremely easy, moderately easy, slightly easy, neither easy nor difficult, slightly difficult, moderately difficult, and extremely difficult (0 represents extremely easy, 14 represents moderately easy, and so on). PA and NA were each presented as a scale from 0-100, with 0 labeled as not at all and 100 labeled as extremely.

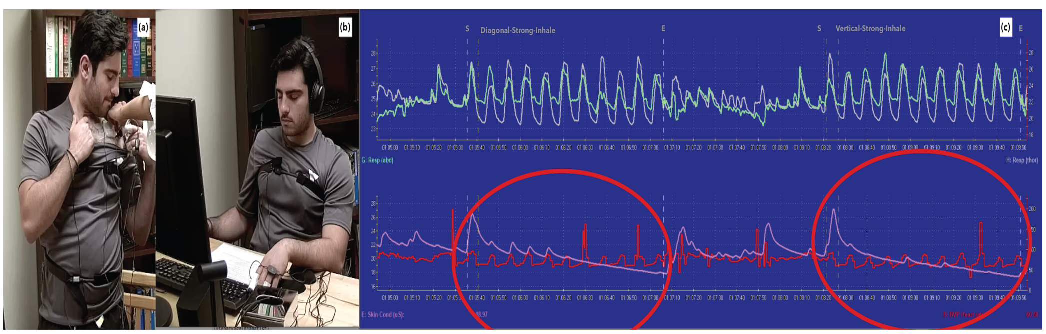


Figure 5.7: C-2 tactor placement on the chest (a); participant performing paced-breathing during a trial (b); physiology measurements of the participant during two trials (c). The top graph shows the breathing curves: the teal curve is for the abdomen and the gray curve for the chest. The lower graph shows the pulse rate (red) and SC (purple).

These steps, from personalizing the shapes to evaluating the patterns and the body site, were repeated for the other two placements. For each new placement, an experimenter assisted the participant in moving the tactors to the new location. Once all three placements were explored, the participant was asked which body site placements they liked best and worst.

After that, the experimenters stopped the video recording and physiology data collection; helped the participant remove the attached sensors and tactors; compensated the participants; and saved all the data on the secure server.

5.5.2 The Personalization Routine

In this section, we describe the personalization routine. This routine was conducted for each placement. The pseudocode for Algorithm 1 can be found in Appendix A.1. The goal of this routine is to determine the six points in frequency - amplitude space shown in Figure 5.3(d).

The participant was instructed to let the experimenters know any time during the personalization routine if they could hear the tactors: if so, then the experimenter adjusted the parameters so that the participant could hear no sound.

First, the tactors played a set of patterns with high amplitude and increasing frequency from 30 Hz to 255 Hz for approximately 40 seconds to familiarize the participant with the sensation and to show that at high enough frequencies they could hear the tactors as well as feel them (lines 56-61 of Algorithm 1).

After this period, the personalization routine followed two steps. In the first step (lines 63-73), F_{min} was determined by playing a pattern with a low frequency and a high amplitude. The frequency was increased until the pattern was easily noticeable. F_{min} is the frequency that was used in creating a horizontal shape. Then, A_{base} was determined by first playing a pattern with a low amplitude and frequency F_{min}. The amplitude was increased until the pattern was barely noticeable (lines 76-82). This amplitude was recorded, the amplitude was increased by 50 PWM levels and then decreased until the pattern was no longer noticeable (lines 83-90). A_{base} was computed as the average of this amplitude and the previously recorded amplitude plus 20 (line 93). This calculation guaranteed that the A_{base} was just noticeable.

Once F_{min} and A_{base} were found, the Matlab controller automatically generated estimates for five additional parameters: three for amplitudes ($A_{min}, A_{max}, A_{max2}$) and two for frequency (F_{mid}, F_{max}). We based these estimates on the values found to be generally acceptable to participants during pilots of the protocol with the first seven participants[4]. These parameters were used as follows (see Figure 5.3(d)):

- The horizontal shapes had both waves with an amplitude A_{max}. One wave had frequency F_{min} and the other F_{max}. One shape (*order* = strong inhale) has the inhale wave with frequency F_{max}, and the other shape (*order* = strong exhale) had the exhale wave with frequency F_{max}. See lines 31-34 of Algorithm 1.

- The vertical shapes had both waves with a frequency F_{mid}. One wave had amplitude A_{min} and the other A_{max2}. One shape (*order* = strong inhale) has the inhale

[4]These participants were excluded from the study: note that the first Subject ID we report is numbered 8.

wave with amplitude A_{max2}, and the other shape (*order* = strong exhale) had the exhale wave with amplitude A_{max2}. See lines 35-38 of Algorithm 1.

– The diagonal shapes had one wave with frequency F_{mid} and amplitude A_{min}, and the other wave F_{max} and A_{max}. One shape (*order* = strong inhale) had the inhale wave with frequency F_{max} and amplitude A_{max}, and the other shape (*order* = strong exhale) had the exhale wave with frequency F_{max} and amplitude A_{max}. See lines 39-42 of Algorithm 1.

During the second step of the calibration routine, an experimenter led the participant through trials of breathing with a set of patterns, and adjusted the pacer's parameters, as well as BPM and *br*, based on comments by the participant. This approach is informed by [76]. In our study, the majority of the participants had no prior experience with paced-breathing and found $br = 1.0$ to be a comfortable value. This breathing pace was used for rest of the patterns played with this placement. (See lines 95-113 and 115-134 of Algorithm 1).

5.6 Results and Discussion

In this section, we will be answering the research questions specified in Section 5.4.

5.6.1 Inclusion and Exclusion

In total, we excluded 78 of the 648 trials (12 percent) because of procedural errors. In these trials, either the pacer was incorrectly configured during the personalization phase or there was a software bug.

For 22 additional trials, we excluded the use of dependent variables that were computed from chest or abdomen wave by identifying those trials that had anomalous BPM values. Figure 5.8 shows these trials. On the left, we present the 22 trials whose measured BPM are outside of the range of 5 to 9 BPM[5] On the right, we show two of these problematic trials. The top trial shows the SC, the chest wave, and the abdomen wave. Note that the chest wave is noisy, which made it difficult to computationally locate the peaks, which is why the observed chest BPM was computed to be 4. Otherwise, it appears that the participant was breathing well and SC dropped during the trial. We don't know what caused the noise in the chest wave. The bottom trial has both the chest and abdomen waves noisy. In addition, the SC increases during the trial, which indicates increased arousal. Again, we don't know what caused the irregular breathing waves. For the upper trial, we excluded the use of any DV that is based on chest wave data. For the lower trial, we also excluded the use of any DVs that are based on abdomen wave data.

We then examined the trials that had high values of at least one breathing measure. We chose bounds that included the values that appeared to be much larger

[5]To compute the person's observed BPM, we measured the time between peaks and rounded to 2 significant digits. The mode of this set of values was used to compute the observed BPM.

than most. The bounds we chose that triggered further inspection were[6]:

mean_abd_movement > 12
sd_abd_movement > 3.5
sd_abd_time > 1000
mean_cst_movement > 14
sd_cst_movement > 19
sd_cst_time > 1000

Applying these bounds resulted in us visually inspecting 35 additional trials. Of these, we could see no obvious problem with 19 of them. The following 16 trials were amended or removed for the following reasons:

– Both the abdomen and chest breathing waves were highly irregular, and so all breathing-related DV measurement were removed:

[6]Section 5.6.5.1 defines the seven breathing measures used in this study.

Subject ID	trial
s009	Horizontal, strong inhale, abdomen
s012	Vertical, strong exhale, abdomen
s012	Diagonal, strong inhale, chest
s012	Horizontal, strong exhale, chest
s013	Horizontal strong exhale, chest
s015	Diagonal, strong exhale, abdomen
s035	Diagonal, strong exhale, chest
s035	Diagonal, strong inhale, chest
s035	Horizontal, strong exhale, chest
s035	Vertical, strong exhale, chest

– The abdomen breathing wave was highly irregular, and so all abdomen-related breathing DV measurements were removed:

Subject ID	trial
s009	Horizontal, strong inhale, abdomen
s009	Diagonal, strong exhale, chest
s009	Diagonal, strong inhale, chest
s012	Horizontal, strong inhale, chest

– The abdomen breathing wave was too shallow to allow for precise peak detection, and so the ab_std_time measurement was removed:

Subject ID	trial
s012	Diagonal, strong inhale, abdomen
s012	Vertical, strong inhale, abdomen

Finally, for each DV, we computed the skewness for the differences between each pair of placements (e.g., attend for chest placement minus attend for abdomen placement). For each difference value, we identified those with skewness either greater than 0.8 or less than -0.8. For each such value, and then identified any participants that had a mean value for the difference that was at least 3 standard deviations from the group mean. In all but one case, there was no more than one such participant. For mean_abd_movement, we needed to iteratively remove subject ids s037, s022 and s019 before the resulting skewness was acceptably low. In each case, we removed a subject for the DV under consideration by replacing its mean measurement with NA.

Figures A.1–A.9 in Appendix A.4 show the results for one-sample t-tests for each dependent variable after any identified outliers were removed.

For the purposes of further analysis, we used $\log_{10}$ transformations for the four DVs that measured standard deviations: sd_abd_movement, sd_chest_movement, sd_abd_time, and sd_chest_time.

5.6.2 Personalization

The first research question we addressed was the importance of personalization in this study. We found participants differed in the values produced by the personalization procedure, the statistics of which are shown in Table 5.1. These differences can be seen in Figure 5.9. The variance in the personalization parameters values suggested that people do differ in their sensitivity ranges, and so, as we expected, personalization for each individual is important. The two threshold values, A_{base} (SD = 26.24) and F_{min}

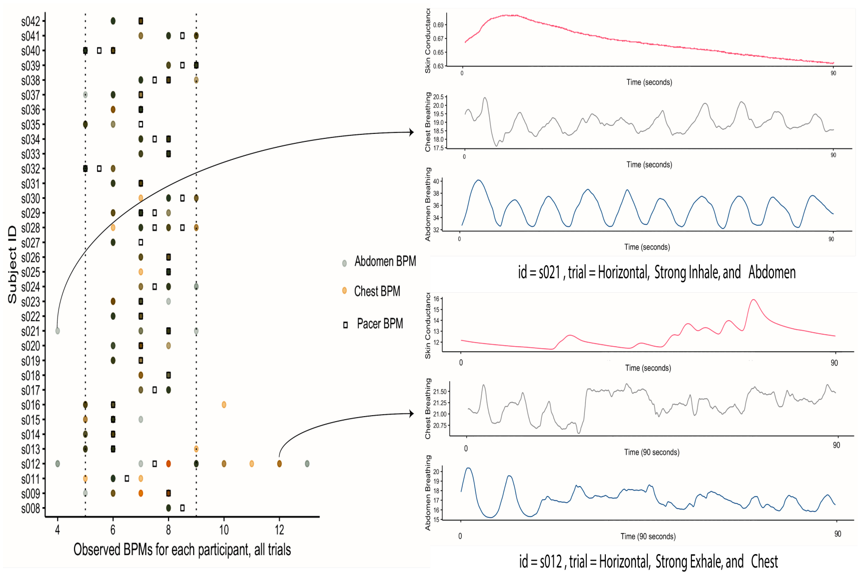


Figure 5.8: Left: the pacer's BPM (unfilled squares) and approximate measured BPM (colored squares) for all the trials. Right: two of the 22 trials that lie outside of the range of 5-9 BPM. See discussion section.

(SD = 20.03), had the highest variability among all the parameters. Note that both of these values have to do with the sensitivity of the individual to vibrotactile effects.

Next, we investigated the sources of the variances both for the four amplitude-based parameters, and separately for the three frequency-based parameters. For each of these two sets of parameters, we fit a linear mixed model with body site as the fixed effect and id as the random effect[7]. And, we used a one-way mixed ANOVA analysis of variance to compare the measures of the parameters to the three body sites (as the fixed effect) and to subject ID (as the random effect)[8]. We found that all seven parameters

[7]This is the formula we used (lmer function in the lme R package) to perform this test: $DV \sim bodysite + (1|id)$

[8]This is the formula that we used in R to perform this test: tab_model(model.fit, show.std = "std2",

Personalization Parameters	Mean	SD	CI	Range
A_{base}	98.90	26.24	[90.38,106.99]	[30, 215]
A_{min}	178.08	14.27	[173.34,182.28]	[120,245]
A_{max}	247.76	11.32	[243.90,247.78]	[180,255]
A_{max2}	243	16.09	[237.26,247.72]	[180,255]
F_{min}	133.4	20.03	[127.58,140,14]	[75,200]
F_{mid}	163.09	15.65	[158.17,168.89]	[107,235]
F_{max}	186.16	16.07	[181.14,191.23]	[135, 255]

Table 5.1: Descriptive Statistics of Personalization Parameters

differed significantly between body sites, but the variance due to individual differences is at least 4 to 5 times larger than the variance due to body site. Table 5.2 summarizes the results.

Comparing the last two columns in Table 5.2, it is readily apparent that the variance due to individual differences is at least 4 to 5 times larger than the variance due to body site. This result emphasizes the importance of personalization: a lack of individualization could result in variances in the dependent variables that may have nothing to do with the main effects of interest.

---

p.val = "kr", show.adj.icc = TRUE, show.df = TRUE)

Personalization Parameters	$F(2, 610)$	Explained Variance	Due to Position	Due to Individual Differences
A_{base}	57.97	54%	8.3%	45.7%
A_{min}	8.15	44%	1.4%	42.6%
A_{max}	14.97	52%	2%	50%
A_{max2}	57.97	67%	1%	66%
F_{min}	57.60	61%	6.9%	54.1%
F_{mid}	36.98	53%	5.3%	47.7%
F_{max}	37.21	55%	5.2%	49.8%

Table 5.2: Sources of Variance on Calibration Parameters. The values, from left to right, are F test, conditional R^2, marginal R^2, and the difference between conditional and marginal R^2. For all F values, $p < 0.0001$.

5.6.3 Model Fitting for Pacer Experience and Pacer Efficacy

To understand the impact of body location and pattern, we analyzed the physiology and self-reported measures using a covariance pattern model with heterogeneous compound symmetric error structure. First, we removed the outliers as described in Section 5.6.1. For all the measurements that were a standard deviation (i.e., sd_abd_movement, sd_cst_movement, sd_abd_time, and sd_cst_time), we performed a $\log_{10}$ transform. Then, for each of the DVs and log-transformed DVs, we fit a model with all main effects and all interaction effects. Any interaction effect that were non-significant were then dropped from the model, and the model was re-run. The decisions about which effects to report were based on the results of this second model.

The main effect results are listed in Table 5.4, the simple main effects in Table 5.5, and the simple-simple main effects in Table 5.6.

5.6.4 Pacer Experience: Self-reported Measures

5.6.4.1 Descriptive Analysis

Figures A.10–A.13 in Appendix A.6 show the values of Attend, Differentiate, Synchronize, and PA $-$ NA for each trial of each subject. The range of possible values for all five measures was $[0, 100]$, and so the range of possible values for PA $-$ NA is $[-100, 100]$. For synchronize, attend, and differentiate, higher values indicated more difficulty in performing that action. High PA values indicated high positive affect, high NA values indicated high negative affect, and high values of PA $-$ NA indicate high valence.

We used the summary measure PA $-$ NA rather than the individual measures of PA and NA from our observations of the participants reporting of NA. Specifically, some participants did not use the NA slider at all, and instead reduced their self-reported PA value to indicate that they weren't feeling as positive as before about a pattern. Thus, we felt the use of PA $-$ NA was more interesting than PA and NA separately.

The left-hand part of each figure groups the measures first by placement and then by shape, while the right-hand part groups the values first by shape and then by placement. In both cases, the shape of the endpoint distinguishes between strong inhale and strong exhale patterns. Outlier values have not been removed. From these figures, one can readily see the range of measures reported by individuals as well as how they changed over different factors. For example, from Figure A.11a, one can readily see that with chest placement, most participants found it easier to differentiate horizontal shapes as compared to vertical shapes. But, there were several subjects who had the opposite experience: they found it much harder to differentiate horizontal shapes as compared to vertical shapes.

The descriptive statistics for self-reported measures are shown in Table 5.3, Figure 5.10 and Figure 5.11. Note that attend, differentiate, and synchronize are clustered around the less difficult end, and NA is for the most part very low. This is because all these four measurements came from distributions that were inflated with zeros (see Figures 5.10 and 5.11). This indicates that there were many trials that participants reported as being easy to attend to, easy to differentiate the inhalation from the exhalation phases, and easy to synchronize the breathing with.

In retrospect, the goal of personalizing the pacer for each body site makes it easy to attend, easy to differentiate between the inhalation and exhalation phases, easy to synchronize breathing with, and to generate low negative affect. The self-reported values for attend, differentiate, synchronize, and PA $-$ NA all suggest that after personalization, the pacer was well calibrated for the participant.

Measure (raw)	Mean	SD	CI	Range
Attend	17.93	13.48	[13.39,22.48]	[0, 88]
Differentiate	17.24	11.96	[13.48,20.70]	[0, 100]
Synchronize	21.33	14.61	[16.73,26.06]	[0, 100]
Positive affect (PA)	47.02	24.84	[47.03, 54.78]	[0, 100]
Negative affect (NA)	8.61	10.33	[5.51, 12.14]	[0, 76]
PA - NA	38.37	27.88	[29.90, 38.58]	[-74, 100]

Table 5.3: Descriptive statistic on self-reported measures

5.6.4.2 Model Summary

Table 5.4 includes the significant results for the DV differentiate, and Table 5.5 reports the significant results for the DV synchronize. For the DVs of attend and PA $-$ NA, we failed to find evidence that the model could explain the variability of these two dependent variables.

The visualization of the main effects for differentiate is reported in Figure 5.12 and the simple main effects for synchronize are reported in Figure 5.13 and Figure 5.14. The results suggest that the shape of the pattern plays an important role in how well the participants can differentiate between the inhale and the exhale phases. In particular, the vertical (amplitude-based) patterns are harder to differentiate as compared to horizontal (frequency-based) and diagonal patterns (both frequency and amplitude based).

The Cohen's d values shown in Figure 5.12 and reported in Table 5.4 suggest that, for differentiate, the mean for vertical shapes is approximately 30 percent of a standard deviation shifted from the means for the other two shapes. This represents

Dependent variables	Mean difference	Mean difference value	Std. Error	df	p-value	CI Lower	CI Upper	Cohen's d
Mean of ab movement	Ab vs LB	-.428	.135	85.813	.002	-.695	-.16	.24*
	Chest vs LB	0.233	.124	192.085	.062	-.012	.477	.12
	Ab vs Chest	.660	.118	160.421	0	.428	.893	.40*
Mean of chest movement	Ab vs LB	- .520	.159	372.81	.001	-.833	-.208	.21*
	Chest vs LB	-.283	.154	283.767	.069	-.589	.022	.12
	Ab vs Chest	-.238	.155	298.292	- .543	.068	.588	.09
	Str Ex vs Str In	-.154	.065	202.573	.019	-.282	-.025	.13
Chest to ab movement Ratio	Ab vs LB	.175	.121	90.83	.151	-.065	.415	.25*
	Chest vs LB	-.152	.068	336.68	.028	-.288	-.017	.12
	Ab vs Chest	-.328	.119	99.10	.007	-.564	-.092	.34*
	Str Ex vs Str In	-.154	.065	202.57	.019	-.282	-.025	.13
Differentiate	Vert vs Horiz	6.36	2.191	326.497	.004	2.056	10.677	.32*
	Vert vs Diag	5.55	2.166	266.919	.011	1.287	9.817	.31*
	Horiz vs Diag	-.814	1.936	339.081	.674	-4.622	2.994	.2*
CDA.SCR	Ab vs LB	-.048	.017	185.823	.005	-.082	-.015	.24*
	Chest vs LB	-.026	.016	213.40	.12	-.058	.007	.15
	Ab vs Chest	-.023	.014	313.568	.099	-0.049	0.004	.09

Table 5.4: Significant main effects of all dependent variables. We did not find significant main effects for the DVs not listed in this table. The Cohen's d values with an asterisk suggest substantial shift between the two mean distributions.

approximately a 1 to 10 points difference in the self-reported measure, which is a small to moderate difference.

This observation suggests that both the horizontal and diagonal shapes were easier to differentiate as compared to vertical shapes. We conjecture that this arose from a limitation of the C-2 tactors. The average value of A_{min} was 178. As one can see in Figure 5.2(c), for a PWM level of 178, over 88% of the dynamic range of the C-2 tactor has been reached. The lack of remaining dynamic range makes differentiating between

Dependent parameter	Mean difference	Cohen's d
Synchronize	Chest, strong inhale vs ab, strong inhale	.02
	Chest, strong exhale vs abdomen, strong exhale	.07
	Chest, strong inhale vs lower back, Strong inhale	.30
	Chest, strong exhale vs lower back, strong exhale	.15
	Ab, strong inhale vs lower back, strong exhale	.32
	Ab, strong ex vs lower back, strong exhale	.07
Synchronize	Abdomen diagonal vs chest diagonal	.33
	Abdomen horizontal vs chest horizontal	.11
	Chest diagonal vs lower back diagonal	.07
	Chest horizontal vs lower back horizontal	.30
	Abdomen diagonal vs lower back diagonal	.38
	Abdomen horizontal vs lower back horizontal	.19

Table 5.5: Significant simple effects of all dependent variables with interaction effect

the two waves in the vertical pattern difficult. Further evidence that there is a lack of dynamic range is that during the personalization routine for vertical shapes, participants frequently requested higher values of both A_{min} and A_{max2} even though the A_{max2} was already at the maximum PWM level of 255.

The results also suggest the existence of an interaction effect between body site and order (see Figure 5.14) for the self-reported measure of synchronize. The order of a pattern (that is, the intensity of inhale versus the exhale phase) seems not to matter much when either the abdomen or the chest is chosen for placing the tactors. However, when the lower back is selected, synchronizing with the order of strong inhale is significantly more difficult as compared to the order of strong exhale (Cohen's d of .30).

In addition, the results also suggest the existence of an interaction effect between body site and shape (Figure 5.13). Given that we have already concluded that vertical shapes are harder to differentiate, the Cohen's d values for the vertical shape are not shown in this figure. For a diagonal shape, the placement of tactors on the abdomen results in easier synchronization as compared to placement on the chest ($d = .33$) or on the lower back ($d = .38$). For horizontal shapes, the placement on the lower back results in harder synchronization as compared to placement on the chest ($d = .30$) or abdomen ($d = .19$).

Lastly, in looking at the self-reported preferences for body site collected from each participant at the end of the protocol, we could find no evidence to support the notion that a particular body site was significantly preferred by a majority of the participants. A Chi-Square test did not show any significant difference ($\chi^2 = .30, df = 2, p = .850$) among the three body sites.

Based on these findings with the self-reported measures, it is hard to make strong conclusions about the optimal choices of pattern and body site. In retrospect, this is not a surprising result. By personalizing the pacer for each body location, we were explicitly attempting to make the pacer induce positive affect, be easy to attend, be easy to differentiate between the inhalation and exhalation phases, and be easy to synchronize breathing with. Thus, using self-reported measures only to determine the best pattern and placement may not be the right approach to tease apart small differences between different body sites and patterns.

5.6.5 Pacer Efficacy: Physiological Measures

The third research question was how the choices of body site and breathing vibrotactile pattern influenced participant physiology measures. To answer this question, we analyzed the physiology measures of skin conductance (SC) and the manner in which participants breathed (i.e., the degree of chest to abdominal breathing, the regularity of their breathing pace, and the regularity of their breathing depths).

Figure 5.15 shows an example of breathing signals collected from Subject 18 during a trial. The breathing signal is collected from the abdomen (in blue) and from the chest (in orange). Figure 5.1 and the purple curve in the lower part of Figure 5.7(c) are examples of SC signals collected during a trial from Subject 21.[9].

5.6.5.1 Chest and Abdominal Breathing Measures

To understand breathing behavior, we deconstructed the chest and abdomen breathing waves into measures related to time (horizontal axis) and breathing depth (vertical axis). We calculated, for each trial, the means and standard deviations of the valley-to-peak heights of the chest and abdomen waves (see Figure 5.15). The valley-to-peak height is measured from a valley to the immediately following peak. These heights represent the depths of chest and abdomen expansion and contraction during breathing. The mean of the valley-to-peak measurements represents the average breathing

[9] As noted in Section 5.5, SC and breathing data was collected via a Thought Technology system with a sampling rate of 256Hz.

depth (chest or abdomen) while pacing breathing during a trial (*mean_abd_movement*, *mean_cst_movement*). The standard deviation of the valley-to-peak represents the amount of irregularity in breathing depth (*sd_abd_movement*, *sd_cst_movement*). We also calculated, for each trial, the standard deviations of time between each pair of consecutive peaks. This represents how well a participant paced their breathing: the lower the standard deviations, the better the pacing (*sd_abd_time*, *sd_cst_time*). To compare the amount a participant breathed with their abdomen as compared with their chest (*Ch2Ab ratio*), we measured the valley-to-peak heights, saved them each in a separate vector, element-wise divided chest to abdomen vectors, and then averaged the result.

The irregularity of breath durations and the irregularity of the breath depths were collected to determine how difficult the participant found pacing their breathing: the higher the irregularity, the more difficult the paced breathing. In addition, the ratio of chest to abdomen breathing and the average depth of chest and abdomen breathing were collected to give us ideas about the choice of body location that resulted in relatively more abdominal breathing. This is interesting because abdominal breathing is commonly advised as a way to reduce anxiety [30, 76, 106, 157].

Figures A.14–A.20 in Appendix A.6 show the values of the seven breathing measures for each trial of each subject. As with the self-reported measures, the left-hand part of each figure groups the measures first by placement and then by shape, while the right-hand part groups the values first by shape and then by placement. In both cases, the shape of the endpoint distinguishes between strong inhale and strong exhale patterns. Outlier values have not been removed.

The main effects and the simple-simple main effect are listed in Table 5.4 and Table 5.6. We failed to find evidence that the model could explain the variability of the breathing-related dependent variables not listed in these two tables.

We found the following results:

- The mean of the chest movement as well as the ratio of chest to abdomen breathing are both reduced significantly when a pattern's order is strong inhale as compared to strong exhale (see Figure 5.17 and Figure 5.18). Given that the Cohen's d for both of these DVs is around .13, we consider these as negligible effects, yet worth further exploring in future studies (see Table 5.4).

- The ratio of chest to abdomen breathing is significant when the tactors are placed on the abdomen as compared to the chest or the lower back. We also observed that the amount of chest movement decreases when the tactors are placed on the abdomen as compared to the lower back. In addition, the amount of abdomen movement significantly increases when the tactors are placed on the chest as compared to the lower back (d = .24) or abdomen (d = .4). These results suggest that when tactors are moved to the abdomen, the amount of chest and abdomen breathing both decrease, but the the abdomen movement decreases relatively more, given that the ratio of chest to abdomen breathing is higher as compared to the other two body sites.

- If the abdomen is chosen for tactors placement and the vertical shape is chosen for the vibrotactile pattern, then the order of strong inhale results in less chest movement irregularity as compared to order of strong inhale. The opposite of this effect is observed when the tactors are placed on the lower back. When the vertical shape is chosen for the lower back, then the strong inhale order results in less chest movement irregularity. When the tactors are placed on the abdomen, the use of the vertical strong exhale pattern results in less irregularity as compared to the other pattern combinations. When the tactors are placed on the chest, the type of the pattern does not influence the irregularity of the chest movement. And, when the tactors are placed on the lower back, the choice of a vertical pattern with strong inhale seems to result in less chest movement irregularity (See Figure 5.16).

Together, these three points do not strongly suggest a benefit of using one body site or order as compared to the other alternatives. We have not corrected for multiple comparisons, however, and so the the analysis, while suggestive, requires replication.

5.6.5.2 SC Measures

For most trials of paced breathing, the skin conductance (SC) signal dropped during the trial. Examples are shown in Figure 5.1 and in purple in the lower part of Figure 5.7(c). Recall that a dropping SC signal is associated with reduced sympathetic nervous system arousal. To examine this further, we fit a linear regression model to the SC for each trial. A negative slope for this model indicated a calming effect. For the 438 trials in which we had SC information (see Figure 5.21), only 30 trials had linear regressions with non-negative slopes. One example of such a trail is shown in the right hand side of Figure 5.21, which illustrates the SC and breathing waves for a trial by Subject ID 8 (placement = abdomen, shape = horizontal, order = strong inhale). We visually examined all 30 cases to understand whether the BPM or the breathing waves influenced the positive slope but we unable to ascertain what caused SC to be increasing.

We also calculated skin conductance response (CDA.SCR) using the CDA method implemented in Ledalab software. Similar with the previously-discussed measures, Figures A.21 and A.22 in Appendix A.6 show the values of these two skin conductance measures for each trial of each subject.

We failed to find any significant results with regards to speed of arousal drop represented by the SC slope. This suggests that we couldn't find evidence that arousal drops faster on one body site compared to another.

However, we found that when the tactors were placed on the abdomen as compared with when they were placed on the lower back, CDA.SCR was significantly less, which indicates less tonic activity. In other words, it appears that less arousal was observed when the tactors were placed on the abdomen as compared to when they were placed on the lower back. Table 5.4 and Figure 5.20 summarizes the results. Recall that we had already observed that tactor placement on the abdomen resulted in less chest movement, less abdominal movement, and less irregularity in the breath depth. The SCR information gives additional information for the choice of the abdomen for placement as compared to lower back.

5.7 Discussion

5.7.1 Preferred Choices of Body Site and Pattern

We couldn't find a strongly more appropriate choice of the tactors placement after analizying both self-reported as well as the physiological measures. The analysis of the breathing signal suggested that placement on the abdomen resulted in less chest and abdominal movement, and larger ratio of chest to abdomen breathing compared to the other two body sites. However, these observations are not sufficient to suggest that abdomen is a better choice compared to the other two body sites. We think that less chest and abdominal movement resulted in less irregularity of breath depths, which further supported the choice of the abdomen as the preferred location over the chest and lower back. But, further investigations are required.

We do think that the lower back is less an appropriate body site to place the tactors as compared to the abdomen. This suggestion is motivated by the results of SC signal analysis. Placing the tactors on the lower back results in more tonic activation as compared to placing the tactors on the abdomen. Furthermore, synchronize breathing with the pacer becomes harder when tactors are placed on the lower back with the pattern order of strong inhale as compared to the other two body sites regardless of the order.

We failed to find evidence that any of the body site placements were significantly more preferred by the participants when we asked them at the end of the study. We also failed to find evidence that any of the placements could explain variability in self-reported measures of attend and PA $-$ NA.

As for the shape, we did find enough evidence to prefer one shape over another. Comments from participants led us to suspect that the vertical pattern was perhaps harder to differentiate as compared to the frequency-based horizontal and diagonal patterns. We also did find statistical support for these observations in how well the participants could differentiate between the inhalation and exhalation phases of the pacer. We think that the results that we observed were due to the C-2 tactor's mechanical limitations. Between the diagonal and the horizontal patterns, we do not have enough evidence that one is better than the other in all situations. The diagonal shape on the abdomen results in less chest movement irregularity as compared to vertical and horizontal patterns on the abdomen. But, on the chest, there is not much of difference between the shapes. As described in Appendices A.2.5 and A.2.6, two fine-tuning procedures are needed for the diagonal patterns, but only one fine tuning procedure is needed for the horizontal patterns. Because the personalization routine procedure is shorter for a horizontal pattern than for a diagonal pattern, using a horizontal pattern is attractive.

As for the order of the inhale versus exhale phases, we found that the strong exhale resulted in less chest movement and chest to abdomen ratio of movement but these effects are negligible. On the other hand, based on chest SD of movement results, we think that when tactors are placed on the lower back, strong exhale is more preferred when the shape is diagonal or horizontal, but for the vertical shape, strong inhale is preferred. This observation does not hold when the tactors are placed on the abdomen. On the abdomen, only when the vertical shape is used, the strong inhale order is preferable to the strong exhale order.

In sum, we think that frequency-based patterns are the right choices for designing a vibrotactile pacer, but for choosing the body site and order, multiple trade offs are involved. If the goal is to reduce the irregularly of abdomen and chest movement, then abdomen is a better place for placing the tactors are compared to the lower back and chest. If the goal is to have less skin conductance response, then abdomen is more preferred than the lower back.

5.7.2 Design Implications

Personalization matters Our findings suggest that personalization is important in the design of a vibrotactile intervention for emotion regulation. The lack of a personalization routine could diminish the accurate estimate of the regulatory effect size of a vibrotactile intervention. For example, the lack of a personalization routine could explain the results in [49] in which they found vibrotactile interventions were less effective than auditory interventions.

The design of an effective personalization routine is challenging and requires more than simply providing knobs for the user to tune on their own as they explore a multidimensional space of vibrotactile patterns. In this study, we went through many iterations of the personalization routine to make it both effective and efficient.

In practice, personalization will not be a one-time procedure. The changing presence of stressors and distractors in everyday life, and the amount of training, practice, and habituation a user has in using the device, will likely require continued changes in the vibrotactile patterns. In this study, we strategically controlled for such confounding variables, but longitudinal studies in real-world settings will need to accommodate for changes in them.

Details matter In reviewing the literature on other vibrotactile devices that assist in emotion regulation (see Table 3.2), we found very little discussion about the design of the vibrotactile pattern or on the physiological impact of where the device was placed (one example of the physiologic effect of a haptic pattern is in [158]). In this chapter, we show that pattern and placement have impact. For example, the relative strength of the inhale and exhale waves had an effect on the regularity of breathing, and placing the tactors on the abdomen reduced abdominal movement. More discussion and perhaps research is warranted. For example, wearing a device on the wrist has many advantages: because of the normalization of wearing watches, the wrist is a natural location and the habit of wearing a device on the wrist is usually easily adopted. But, there could be physiological consequences of using the wrist, such as a reduction of the tidal volume of the breath arising from the posture of some users.

Explicit versus implicit involvement Recall that an implicit involvement intervention is a process that is evoked automatically by the vibrotactile effect, runs to completion without monitoring, and can happen without insight [37, 17]. They are intriguing because they demand so little from the user. But, less is known about their efficacy both over the short term and the long term.

Paced breathing, on the other hand, is a well studied explicit intervention [106, 157, 30] But, little is known about the long term use of a breathing pacer. As discussed above, there are consequences of pattern and placement on breathing, but such conditions may change or even disappear with habitual use.

In the near term, we plan to do a study of PIV under conditions similar to the Doppel study [17] to compare the effect size of implicit and explicit involvement interventions. In the long term, the two approaches should be studied longitudinally and in everyday life.

5.8 Conclusion

This chapter described a study on the design, pattern and placement of a personalizable, inconspicuous vibrotactile breathing pacer (PIV). The choice in tactors' placements came from the need to be inconspicuous, and the desire to aid in effective paced breathing.

We showed how important having a personalization routine is: most of the explainable variance in the pattern configuration parameters arose from individual differences rather than the body placement. This means that the personalization phase is very important and should not be skipped when designing a vibrotactile breathing pacer. We also observed that the self-reported measures, except for positive affect, were skewed towards zero, which indicated that the personalization routine was successful.

We showed that once the parameters of the pattern are personalized, self-reported measures of differentiate and synchronize could facilitate explaining the choices of pattern and placement but not the affect (PA − NA) and attend self-reported measures. We found no evidence that any of the body placements were preferable when we asked participants their preferences at the end of the study. This encouraged us to incorporate physiology data analysis to draw further conclusions about how placement and pattern influence the breathing efficacy.

After incorporating the physiology measures analyses, the results of skin conductance response (CDA.SCR) and chest SD of movement (sd_chest_movement) discouraged us from considering lower back for tactors placement as an appropriate body site as compared to abdomen and chest. And between the chest and abdomen, the results of chest SD of movement suggests use of diagonal shapes on the abdomen and use of either diagonal or horizontal shape on the chest. In both cases, the order does not matter.

In terms of the shape of the patterns, we found evidence that the vertical shape is less appropriate than horizontal and diagonal shapes for a vibrotactile breathing pacer. Perhaps due to the physical limitations of the C-2 tactor, participants preferred amplitude-based less than frequency-based or frequency-and-amplitude shapes to differentiate between inhaling and exhaling phases. We have enough reason to believe this is accurate; the participants requested frequency enhancement during the personalization routine when the C-2 tactors couldn't provide higher amplitudes.

Several researchers have observed that that vibration is effective for eliciting higher arousal (and often unpleasant) emotions [172, 146, 170]. Despite this concern, we did not receive any comments from participants indicating that they found PIV's use of tactors annoying. Indeed, we received comments to the contrary. We suspect that this is a consequence of the personalization routine and the act of slow-paced breathing during the experiment: slow-paced breathing reduces affect.

Going forward, we have yet to study the PIV prototype device in the context of a stressor, which is an important next step. Studying PIV's calming effect in the presence of a stressor requires a different experimental design study in which the placement and the pattern of PIV are fixed, and in which the goal is to study the interaction effect between groups (treatment and control) and time (pre- and post- stressor). After that, we plan build a self-contained prototype that can be used in everyday life to better understand the efficacy of the pacer in terms of reducing anxiety in daily activities.

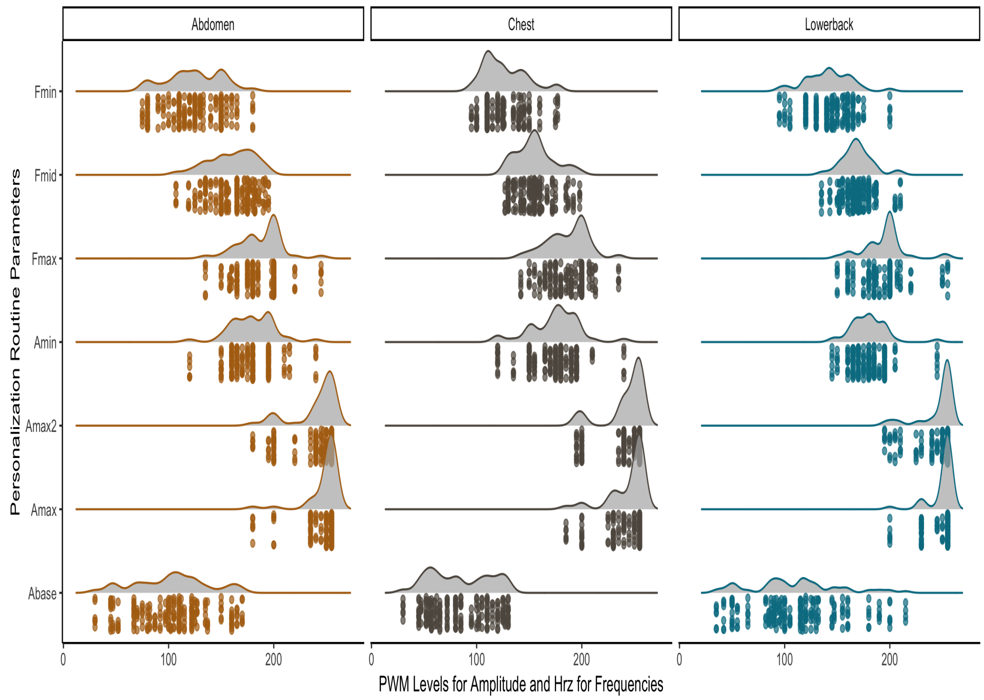


Figure 5.9: Distributions of each personalization parameter (both frequencies and amplitudes) on three body sites. The top three lines refer to frequencies and the remaining four refer to amplitudes. In the case of frequencies, the x-axis is measured in Hz; in the case of amplitudes, the x-axis is PWM levels. Fmin (the top row) and Abase (the bottom row) have the largest spreads that indicate individual differences. These were the two values that were measured using staircasing. In addition, the shapes of Fmin and Abase distributions differ between the chest and lower back. This illustrates the effect of body placement.

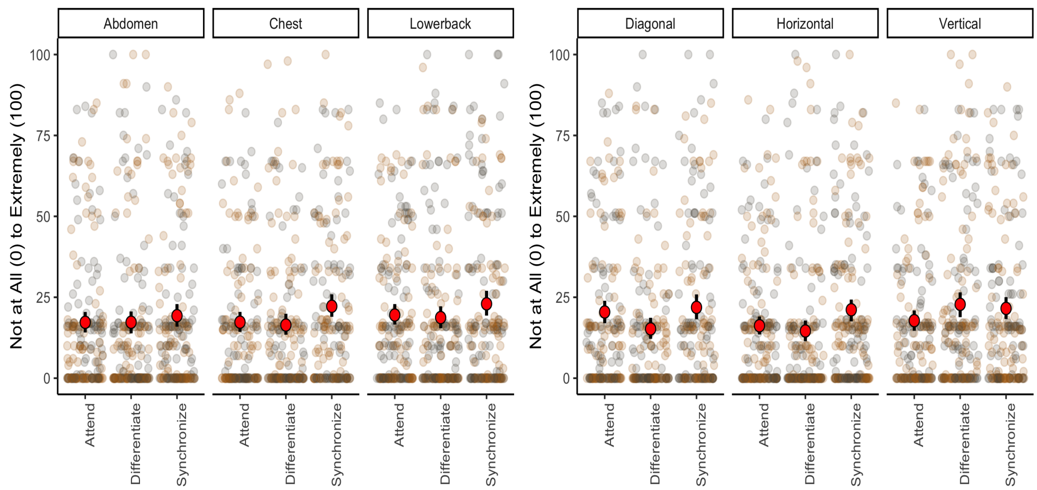


Figure 5.10: Descriptive statistics of the self-reported measures of attend, differentiate, and synchronize. Note that the higher the y axis value, the harder it was to attend, differentiate, or synchronize with a pattern. See the caption of Figure 5.9 for the explanation of this diagram.

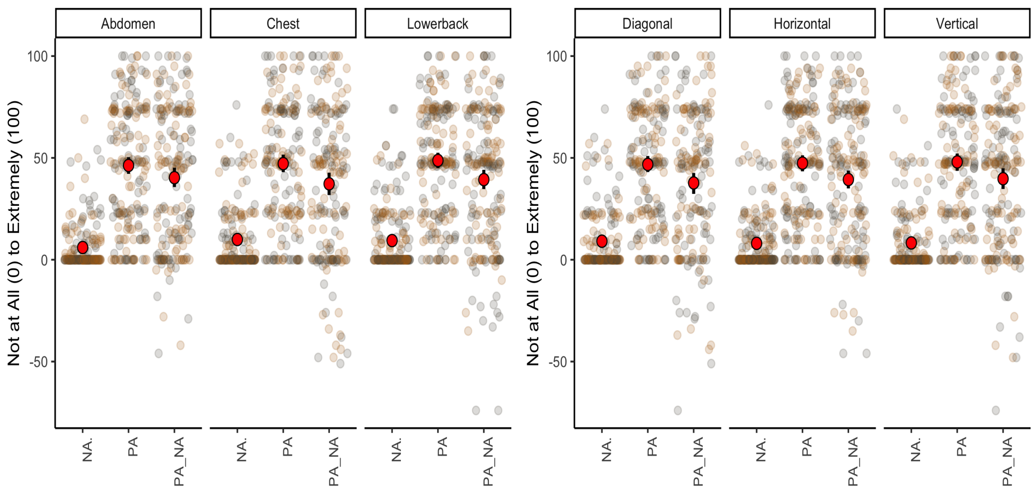


Figure 5.11: Descriptive statistics of the self-reported measures of Positive Affect (PA), Negative Affect (NA), and the difference between PA and NA. Higher y axis indicates more extreme reports of PA, NA, and PA - NA. See the caption of Figure 5.9 for the explanation of this diagram.

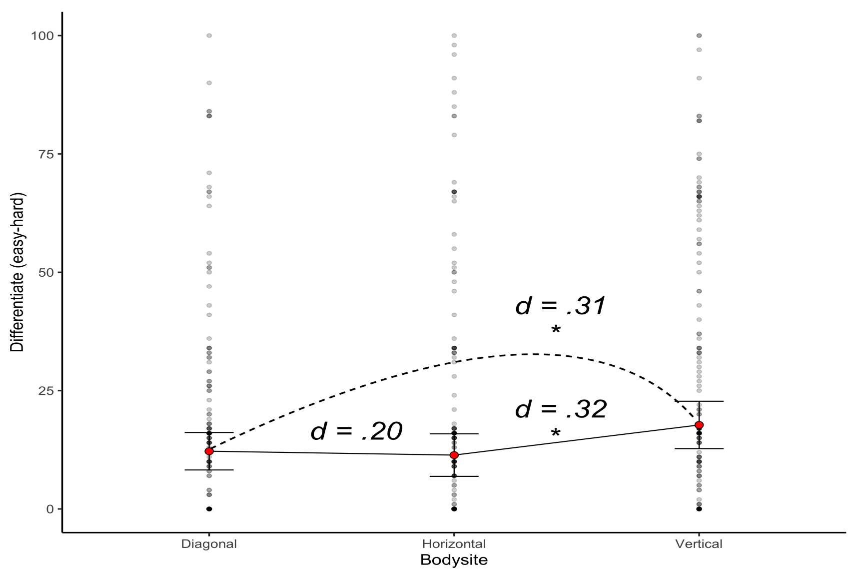


Figure 5.12: Shape of a vibrotactile pattern has a main effect on the dependent variable of differentiate. Differentiating vertical patterns are significantly harder that horizontal or vertical shapes.

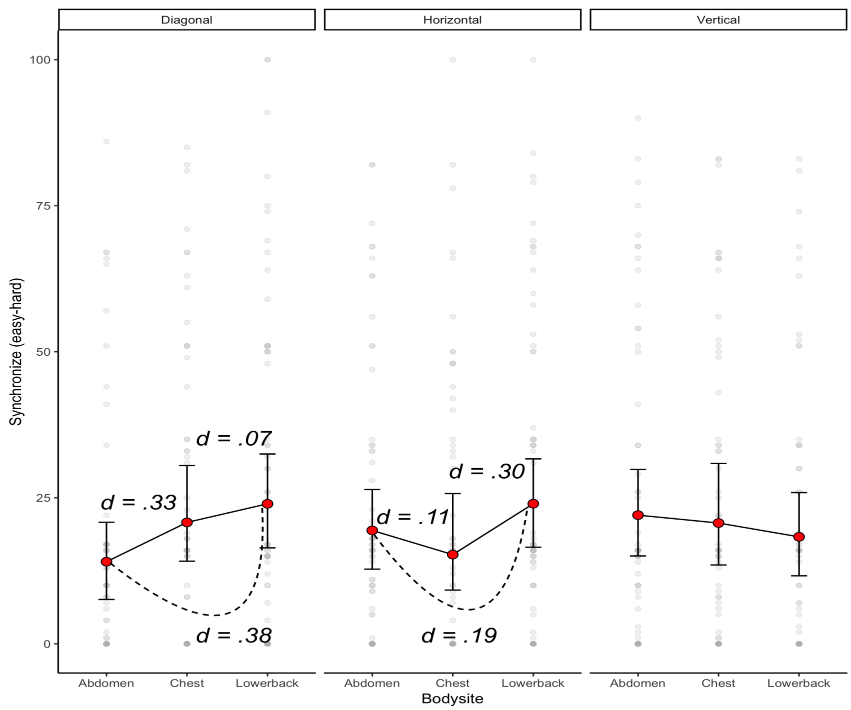


Figure 5.13: The placement and shape interaction suggest that if diagonal shapes are used in a breathing pacer design, then placement on the abdomen result in easier synchronization with the pattern as compared with placement on the chest or the lower back. If on the other hand, a horizontal shape is selected, then placing on the lower back is not recommended.

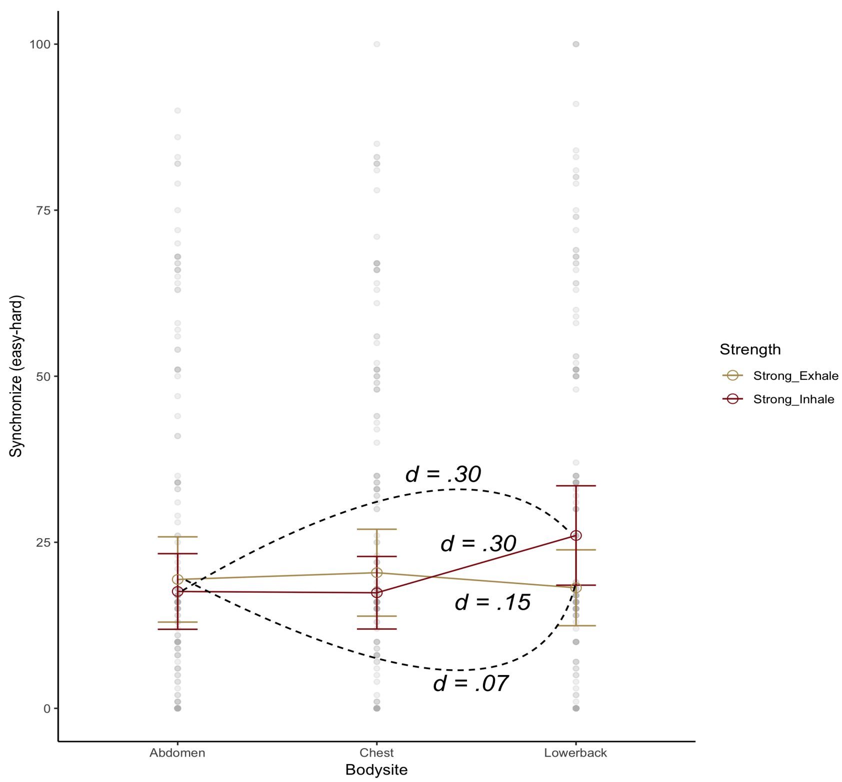


Figure 5.14: The order of a pattern does not matter much when the abdomen or chest body site are chosen. However, on the lower back, synchronizing with order of strong inhale is significantly more difficult as compared to strong exhale.

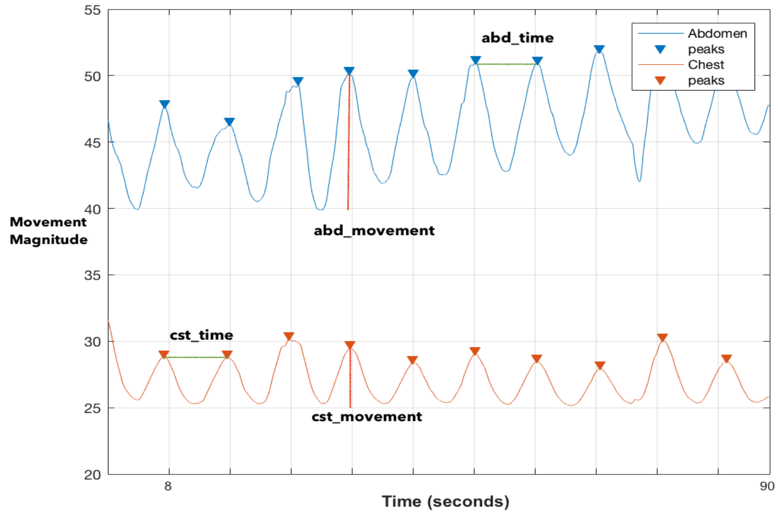


Figure 5.15: Breathing waves from Subject ID 18, with abdomen placement, vertical shape, and strong inhale; To convert the sample to time units (seconds), divide by 256.

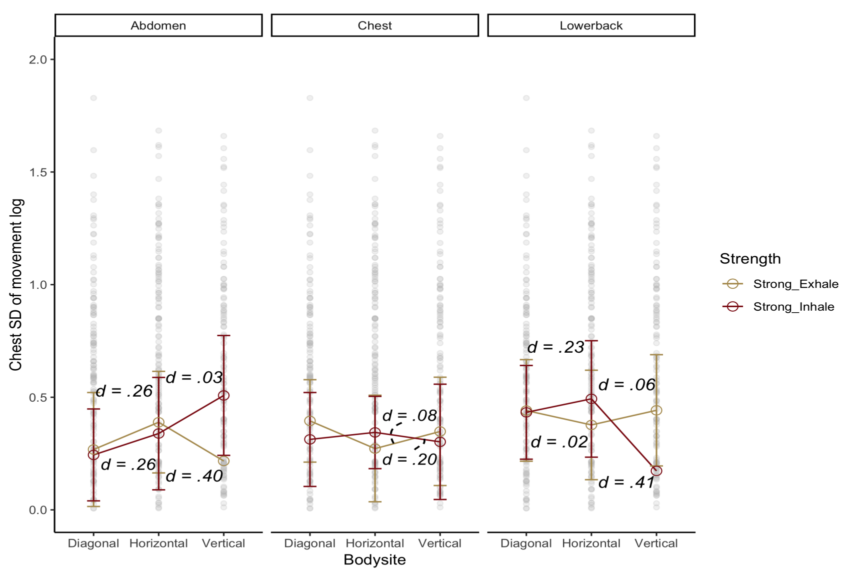
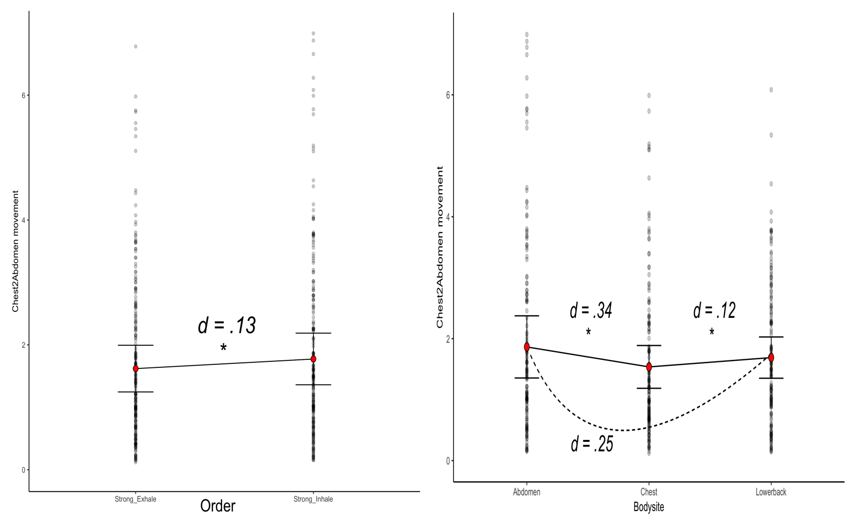


Figure 5.16: Chest SD of movement (log transformed)

Dependent parameter	Mean difference	Cohen's d
SD of Chest Movement (log transformed)	Ab, Horiz, Strong In vs Ab, Vert, Strong In	.03
	Ab, Horiz, Strong Ex vs Ab, Vert, Strong Ex	.40
	LB, Horiz, Strong In vs LB, Vert, Strong Ex	.14
	LB, Horiz, Strong In vs LB, Vert, Strong Ex	.08
	Ab, Diag, Strong In vs Ab, Vert, Strong In	.30
	Ab, Diag, Strong Ex vs Ab, Vert, Strong Ex	.20
	LB, Diag, Strong In vs LB, Horiz, Strong In	.41
	LB, Diag, Strong Ex vs LB, Horiz, Strong Ex	.06
	LB, Diag, Strong In vs LB, Horiz, Strong In	.23
	LB, Diag, Strong Ex vs LB, Horiz, Strong Ex	.02
	Chest, Diag, Strong In vs LB, Horiz, Strong In	.04
	Chest, Diag, Strong Ex vs LB, Horiz, Strong Ex	.16
	Ab, Diag, Strong In vs LB, Horiz, Strong In	.26
	Ab, Diag, Strong Ex vs LB, Horiz, Strong Ex	.19

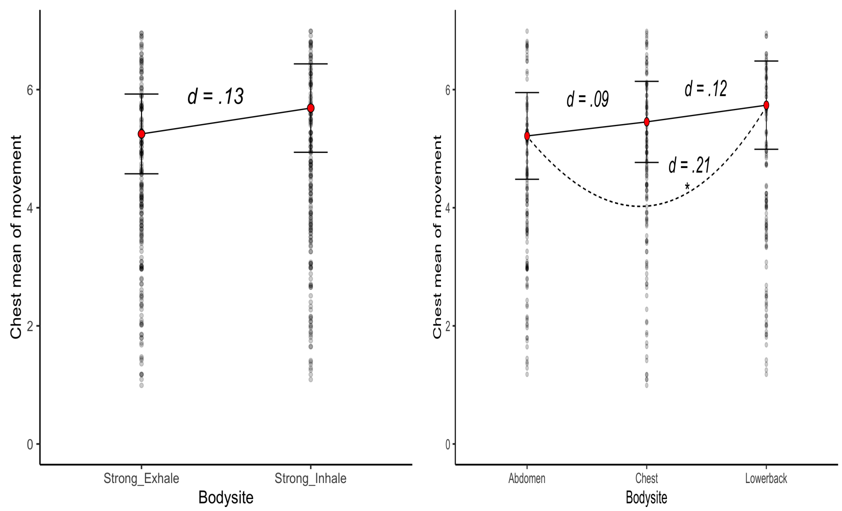
Table 5.6: Significant simple-simple effects of SD of chest mean movement after log transformation.



(a) Main effect of tactors placement

(b) Main effect of order

Figure 5.17: Main effect of pattern order and placement on the chest to abdomen movement ratio ($Ch2Ab\ ratio$). When the tactors are placed on the abdomen, the amount of chest to abdominal breathing is higher than when the tactos are placed on the lower back or on the chest (a). When the inhalation phase feels stronger, the amount of chest to abdominal breathing is higher than when the exhalation phase feels stronger (b).



(a) Main effect of order (b) Main effect of tactors placement

Figure 5.18: Main effect of order and placement on chest mean movement. When the tactors are placed on the abdomen, the amount of chest mean movement is lower than when the tactors are placed on the other two body sites (a). When the inhalation phase feels stronger, the amount of chest breathing is higher than when the exhalation phase feels stronger (b).

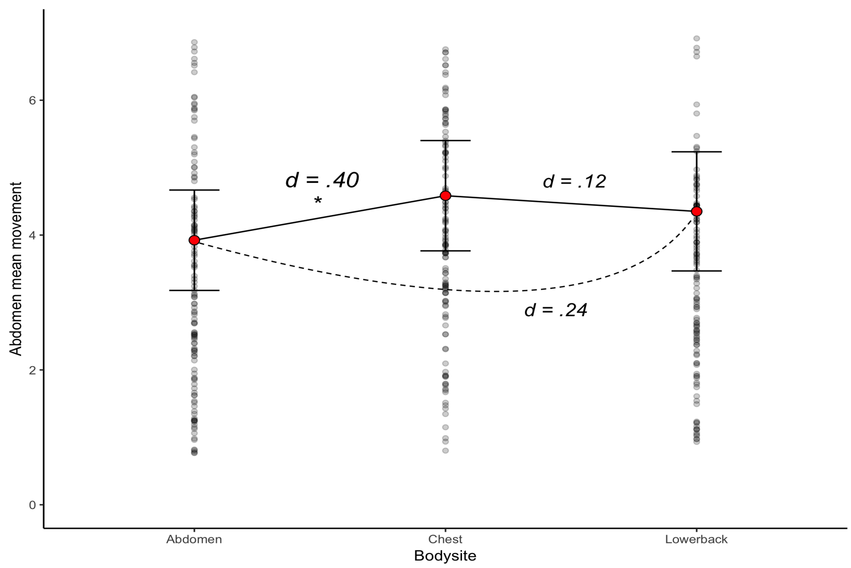


Figure 5.19: Main effect of tactor placement on the abdomen mean movement. When tactors are placed on the chest, the amount of abdominal movement is larger as compared to when the tactors are placed on the abdomen ($d = .4$) or the lower back ($d = .24$).

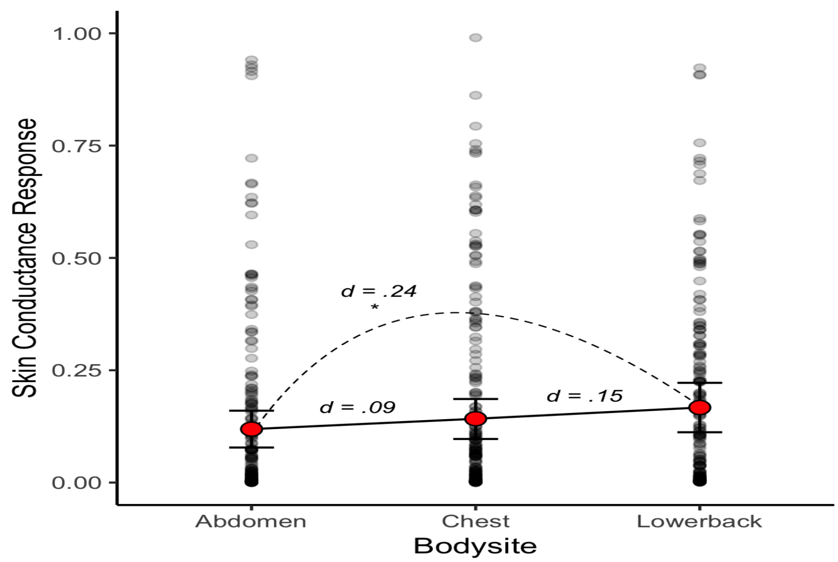


Figure 5.20: Main effect of tactors placement on Skin Conductance Response (CDA.SCR). When tactors are placed on the chest, the tonic activity is lower as compared to when they are placed on the lower back.

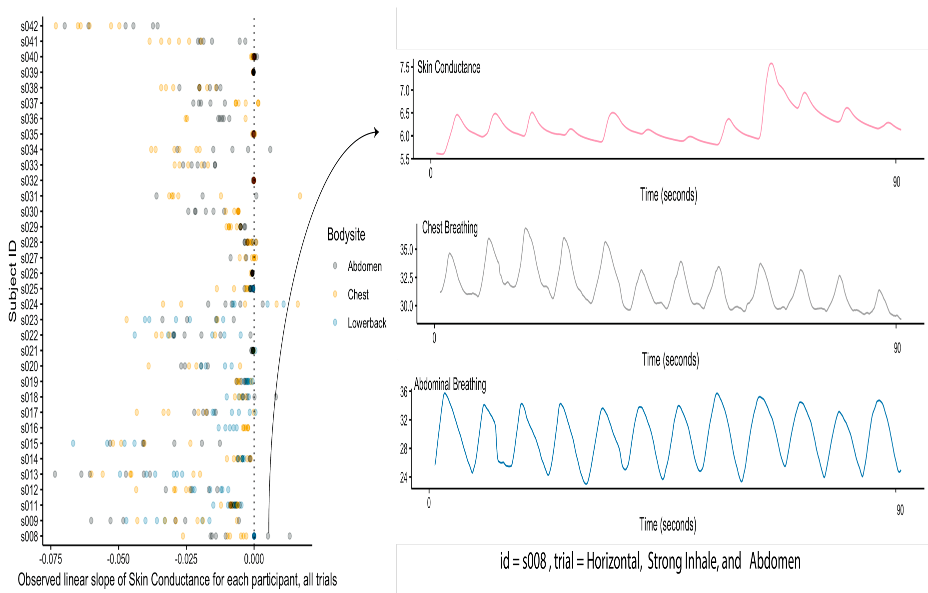


Figure 5.21: A negative slope of the linear regression for SC indicated a calming effect for that trial (image on the left). There were 30 trials in which the slope was greater than zero. The image on the right illustrates one of such trial (Subject ID 8, placement = abdomen, shape = horizontal, order = strong inhale).

Chapter 6

Conclusion

Motivated by the prevalence and adverse impact of anxiety and anxiety disorders, I have been advised by a set of experts in building, designing, and evaluating a vibrotactile technology to facilitate affect regulation. The areas of expertise represented by my advisors include emotion regulation, haptics, electrical engineering, HCI, and distributed systems, as well as the clinical application of biofeedback. A unique aspect of this dissertation contribution comes from this multidisciplinarity. We believe that such a multidisciplinary approach is necessary for making progress in the development of technology that assists in affect regulation.

The multidisciplinarity of my research has resulted in challenges and generated insights. In this chapter, I present three gaps from the perspective of the more technical members of HCI community[1]. The three gaps are: (1) The JITAI chimera, which argues

[1]The HCI community is made up of many disciplines, including the social sciences. When I refer to the HCI perspective here, however, I am focusing on those who come from the computer science community.

that the ideal of "just in time intervention" for affect regulation is too late; (2) The issues of tactor placement, which describes how interdisciplinary research can reveal different values in research questions; and (3) The geometric structure of subjective affect, which discusses two models for capturing subjective emotional responses, one of which is not well known to the HCI community.

I then conclude this chapter by summarizing the dissertation.

6.1 Three Challenges of Multidisciplinary Approach in Building Technology for Affect Regulation

In this section, I present three gaps that I came across during the dissertation research.

6.1.1 The JITAI Chimera

The material in this section (as well as the next two sections) is from a submission to the *Affective Computing and Intelligent Interaction* 2019 Conference.

An influential idea in health technology HCI is Just-in-Time Adaptive Interventions (JITAIs). The term JITAIs was first introduced by Susan Murphy [153], and is defined as individualized, context-specific, and real-time interventions delivered by mobile technology. The efficacy of such interventions depends strongly on the sensing component of the mobile system that decides the type and the timing of such interventions. Examples of sensory inputs to the sensing component of the system include situational context, self-reported measures, user geographical location, weather, social setting, user stress and mood, user behaviors, user engagement, and so on.

Although useful in some circumstances, JITAIs may not apply for affect regulation. Consider a widely used process model of affect regulation [59]. The process model of emotion regulation defines five families of regulatory strategies one can deploy to change one's emotion. These include: situation selection (e.g., avoidance of the situation altogether), situation modification (e.g., changing specific aspects of a situation), attentional deployment (e.g., thinking of errands unrelated to the situation to distract oneself), cognitive change (e.g., reinterpreting the meaning of the situation), and response modulation (e.g., suppressing the bodily expressions of the emotion). These strategies are hypothesized to operate by interfering at different points in the emotion generation process. The model also suggests that strategies that intervene at earlier stages of emotion generation tend to require less effort and be more effective than strategies that intervene later. That is, situation selection and situation modification require the least effort; attentional deployment requires more effort; cognitive change even more effort, and response modulation is the most effortful [59].

Let's assume that it is possible to sense when an emotion should be regulated. When such sensing relies upon emotional expression or behavior, the detected emotion will have already surfaced by the time it has been detected. Given that strategies for regulating emotions become more difficult the later they are applied in the emotion generation process, the sensing would occur at a point where regulation would be more difficult. That is, from a sensing point of view, detecting an emotion is easier later in the emotion generation process, while from the process model of emotion regulation point of view, regulation becomes much harder in the emotion generation process. Thus, when it comes to emotion regulation, JITAIs interventions may be too late to be truly effective (because it would be detected too late).

In fact, to increase the likelihood of success in affect regulation, it would be better for a JITAI intervention to begin before a predicted (e.g., high arousal negative) emotion is even generated. Currently, this is best done by the individual themself, rather than by technology. Right before the generation of an expected emotion, an individual's emotional arousal level can still be relatively low, and so their cognitive abilities would be intact enough for a person to initiate the technology-supported intervention on their own, rather than relying on a sensing component to automatically trigger the intervention.

There is a deep belief in the HCI community that technology can do a more effective job in sensing than individuals can, and so triggering interventions should be left to technology. This belief takes away from a person the responsibility of determining when emotion regulation might be needed. In some cases, a person can predict the situations in which emotions will arise and trigger an intervention early on. By taking on this responsibility, the person can also learn how to manage their emotions better with a device-based intervention. Of course, there will always be cases where such prediction can be hard, such as suddenly encountering a person you were not expecting and with whom you have a tense relationship.In such situations, interventional technology would need to offer extra help to a user, but we believe at no time should an individual feel controlled by their technology.

This was indeed an eye opening observation for me. Giving the responsibility to an individual to trigger an intervention is helpful to change their potential core belief that they lose control over their emotions in certain situations. By retaining this responsibility, it seeds a belief that they are in control to intervene if and whenever they want. Similar to how emotions do not simply happen to us, interventions should not simply happen to us as well.

6.1.2 Where to Wear the Device

One of the goals of my research was to determine where to place the device's tactors. The choices were driven by our experiences:

– My emotion regulation advisors suggested thinking about inconspicuousness in social settings. When used in a public setting, an affect regulation device should not be seen or sensed by others nearby the user. This is because in such settings, users may find it embarrassing or stressful if it is obvious they possess or are using technology that is meant to help regulate their emotions.

– The biofeedback experts suggested placing the device on body sites that are involved in breathing. Their idea was drawn from their practical experiences working with clients while teaching them biofeedback. For example, one of our experts mentioned that he taps the abdomen area of the patient to draw awareness to that body location; doing so encourages abdominal breathing. Both experts suggested the lower back area because it is common practice to encourage abdominal breathing by asking the patient to envision a balloon in their abdomen, inflating with each inhale [76]. Such a balloon would put pressure on the abdomen (thus causing it to move out), as well as the corresponding immobile area on the back.

– Our haptics expert also suggested placing the device on body sites that are involved in breathing, but for a somewhat different reason. The haptics literature defines a concept as co-located haptic feedback, which means that the haptic signal occurs close to the body location involved with a specific desired action [29, 101].

– There was some evidence that immobile locations, such as the lower back, might be a better location than mobile locations such as the abdomen and the lower back. We noticed, for example, that if a participant was simply attending to a vibrotactile signal, they could feel a fairly weak vibration, but once they started trying to breathe with it on a mobile site, the signal needed to be made stronger. This observation is consistent with the work presented in [74] which designed and evaluated a wrist-worn pacer for uniform walking stride frequency. The authors avoided placing tactors on the feet and other moving parts of the body because body motion makes more difficult the detection of vibro- or electrotactile stimuli [75].

Given these observations, the abdomen, the chest, and the lower back were three obvious choices for placement. These sites are shown in Figure 5.3. We agreed that these placements were interesting and would give some evidence about the utility of our prior experiences.

We did, however, receive a high level of criticism from HCI researchers for not including the wrist. Using the logic that resulted in our choices for placement, the wrist is not a good location: it's not involved in breathing, it's not inconspicuous to the level we were considering (if it is easy to do so, people often look at devices when they vibrate). In addition, if one were to look at a wrist device, it would result in a body position that restricts breathing [100]. Given these observations, the wrist was not an interesting placement.

On the other hand, from an HCI point of view, the wrist is a very interesting placement. Considering the principles often used to characterize wearable haptic devices [121], a wrist placement is a location that makes it easy to attach and carry a device, does not impair the wearer's motion, is easily activated by the user, and naturally fits the wearer's body. Thus, while I was never asked by our psychologist colleagues whether we were considering the wrist as a placement, I was frequently asked by our HCI colleagues whether we were considering a wrist placement.

This is an example of the kind of gap that can arise in multidisciplinary research and design. It would indeed be interesting to compare wrist placement with the three body sites we chose.

6.1.3 The Geometric Structure of Subjective Affect

When running an experiment, it is often necessary for participants to self-report their conscious experiences of affect. The most common model used by HCI researchers for representing this information is the three-dimensional model of valence-arousal-dominance. These three dimensions are independent and bipolar (that is, zero is the midpoint value). Valence measures pleasantness-unpleasantness, arousal measures the degree of arousal, and dominance measures a sense of being influential and in control. Together, the three are useful in defining emotional states [138]. Because dominance measures a sense of control, it is often not relevant and therefore not used, including in this dissertation. It has also been shown that valence is correlated with facial electromyography (fEMG), for example with the corrugator supercilii muscle, and arousal is correlated with skin conductance (SC) [133].

It is often difficult to explain to participants the meanings of valence and arousal. For some, part of the problem is that valence and arousal are not independent. As people feel more pleasant or unpleasant feelings, they tend to experience, on average, higher levels of arousal as well. Likewise, feelings of higher arousal are more likely to be accompanied by higher valenced feelings, both positive and negative [87]. This leads to a V–shaped relation between valence and arousal. Yet, when we instruct participants on valence and arousal, we present them as independent values even though they are not. Note that this V-shaped relation is subject to individual differences and culture [88, 87], which adds to the difficulty of explaining the meanings of valence and arousal to participants.

Another model, called the Unipolar Valence Model, does not treat valence as being either more negative or positive. Instead, it separates valence into two independent measures. This model asks the participant to rate their conscious experience of emotion in terms of positive affect (PA) and negative affect (NA). In practice, participants often find PA and NA easier to grasp than valence and arousal. It also allows the participant to more easily express mixed valence emotions, such as the feeling of being both happy and guilty while enjoying a bar of chocolate [67]. It has been shown that PA-NA is correlated with fEMG (and thus their difference is a measure of valence) and PA+NA is correlated with SC (and thus their sum is a measure of arousal) [84]. Because of this, the Unipolar Valence Model is sometimes described as a 45 degree rotation of the Valence-Arousal Model.

We used the Unipolar Valence model and formed questions on the self-reported feelings, i.e., how positive (PA) and negative (NA) the participant felt right after the pacing segment. We encouraged the participants to use both scales. We reinforced this encouragement by requiring the participant to set both PA and NA to some value, including zero, rather than having zero be the default value.

Because of the ease in describing it to participants, we encourage others who are using valence-arousal to consider using the Unipolar Valence model instead.

6.2 Summary

Failures of affect regulation are both common and costly. This thesis emphasizes the importance of a multidisciplinary approach for designing affordances that assist people to regulate their emotions in the wild. We identified four disciplines—two technical (wearables and haptics) and two psychological (emotion regulation and biofeedback) and reviewed the parts of these that are important to the problem at hand. We call these parts of the four disciplines the WEHAB solution space. By exploring this multidisciplinary solution space, designers can deploy tradeoffs across all four disciplines, as compared to optimizing along a smaller set of disciplines.

After reviewing existing work in the context of the WEHAB solution space, we presented a conceptual framework that provides structure for exploring the use of haptic-based technology for emotion regulation. This WEHAB framework pinpoints common failures in emotion regulation and identifies different kinds of technology interventions to facilitate emotion regulation. We concluded with three example of using the WEHAB approach that illustrates the value of multidisciplinarity. Our hope is that the WEHAB approach will enable more effective research and development in the area of wearables for emotion regulation in the wild.

In thinking about how technology can facilitate affect regulation, we found the WEHAB framework useful. This model clusters the objectives of technologies for affect regulation into three types: *cueing*, which directs someone towards an affect regulation strategy; *involvement*, which guides someone through a strategy (either explicitly or implicitly); and *feedback*, which assists in a biofeedback process. Each of these types reflects a manner in which the user interacts with a device in the support of affect regulation. Two projects or products that use the same type of objective share a set of design issues. Viewing this space with this framework encourages designers to think about comparisons between these objectives, and to consider applying techniques that are used for one to be used for another.

We have discussed three knowledge gaps we came across in this research. We feel that much of the richness and complexity of the field of affective science is lost when viewed solely through the lens of current HCI research. We hope that there will be increasing collaboration across relevant fields as each can learn much from the other.

6.3 Future Work

I foresee three projects that I can conduct which will will build on the research presented in this dissertation.

The first is a study that evaluates the experience and efficacy of the PIV pacer in the presence of cognitive stressors. Such a study would allow us to evaluate PIV in a scenario comparable with those used for other affect regulation technology [37, 17]. Given the strong arousal reducing abilities of paced breathing, we expect that this study will show that the PIV pacer is effective.

The second is a study that evaluates the experience and efficacy of the PIV pacer in a target population. Interesting populations include people on the autistic spectrum and people recuperating from cardiac surgery. Both of these populations experience periods of high negative arousal, and for which the PIV pacer may be an appropriate affect regulatory approach. I have begun conversations with researchers at another university to provide such a target population and the facilities to run this study.

The third is a study that evaluates the experience and efficacy of the PIV pacer in everyday life—what we have called "in the wild". To support this study, we would design and build a mobile app that collects information about the use cases of the breathing pacer in the wild as well as affect regulation success rate when using it. Collecting such data would provide the base data that would be used in constructing a causal model that capture a person's activities and self reports and is used as a basis to make affect regulation recommendations.

Appendix A

Supplementary Materials

A.1 Personalization Routine: Pseudocode

In this section we present the personalization routine as pseudocode. The personalization routine involves several agents: the two research assistants (referred to collectively as "experimenter" in the pseudocode), a participant, the controlling Matlab software, and the device and its processor.

The two functions playPattern and stopPattern refers to code executed by the Matlab software that sends commands to the device. The procedures refer to major steps of the personalization routine. The steps of the personalization routine are executed in the order the procedures are listed below. Thus, the logic of the main steps of the personalization routine can be determined by simply reading the procedures in order. However, for the most part, the agent that executes each action in a procedure is not readily apparent. To more fully understand the personalization routine and the details of each agent's responsibility in the personalization routine, please refer to Section A.2.

A.2 Personalization Routine: Script

This section contains the script that the research assistants (RAs) read to the participant and also describes the actions the RAs took. The text in normal face are those by RA1, and those in bold face are by RA2. This script is parameterized by the value <position>, which stands for the body location on which the tactors were currently attached.

A.2.1 Instructions

– Before we start, please try to touch the tactors on your <position>. Do you feel like they are well secured? Great. From past experience, the vibrating device does not fall or get loose when you move around. So try to feel relaxed and comfortable. If they are becoming loose, please let us know.

– We will now begin step 0 of the study. Feel free to follow along with the sheet in front of you.

– This phase of the study will be a warm-up. Think of the vibrating device on your <position> as a speaker. We'll be adjusting how loud it plays, and also the pitch of the note it plays. You won't be listening for the notes with your ears, but rather feeling it with your skin, which is why we have placed noise-cancelling headphones on you. If at any time you can hear the vibrations through the headphones, please

Algorithm 1 Personalization routine: Global variables.

global variables

// *frequencies are in Hzs and amplitudes are in PWM level units*

// *parameters to construct a biphasic breathing pattern*

F_{in} // *frequency of inhale wave*

A_{in} // *peak amplitude of inhale wave*

F_{ex} // *frequency of exhale wave*

A_{ex} // *peak amplitude of exhale wave*

$A_{base} \leftarrow 50$ // *base amplitude of both inhale and exhale waves*

In2ExDelay $\leftarrow 300$ // *delay between inhale and exhale*

Ex2InDelay $\leftarrow 200$ // *delay between exhale and inhale*

// *parameters to construct a shape*

F_{min} // *frequency used for horizontal shape*

$F_{max} \leftarrow 200$ // *frequency used for horizontal and diagonal shapes*

$A_{max} \leftarrow 255$ // *amplitude used for horizontal shape*

F_{mid} // *frequency used for vertical and diagonal shapes*

$A_{min} \leftarrow 195$ // *amplitudes used for vertical and diagonal shapes*

$A_{max2} \leftarrow 255$ // *frequency used for horizontal and diagonal shapes*

Algorithm 1 Personalization Routine: Functions.

Frq // frequency of default pattern

Amp // peak amplitude of default pattern

$BPM \leftarrow 7.5$ // *number of breaths per minute*

$BR \leftarrow 1$ // *ratio of inhale to exhale duration*

function PLAYPATTERN(shape, strength, repetition)

 // *pattern is [$F_{in}, A_{in}, F_{ex}, A_{ex}$, BPM, BR]*

 // *command is [pattern, inhale to exhale delay, exhale to inhale delay, repetition]*

 if (shape = horizontal) $\wedge$ (strength = inhale) **then**

  pattern $\leftarrow [F_{max}, A_{max2}, F_{min}, A_{max2}, A_{base}, BPM, BR]$

 else if (shape = horizontal) $\wedge$ (strength = exhale) **then**

  pattern $\leftarrow [F_{min}, A_{max2}, F_{max}, A_{max2}, A_{base}, BPM, BR]$

 else if (shape = vertical) $\wedge$ (strength = inhale) **then**

  pattern $\leftarrow [F_{mid}, A_{max}, F_{mid}, A_{min}, A_{base}, BPM, BR]$

 else if (shape = vertical) $\wedge$ (strength = exhale) **then**

  pattern $\leftarrow [F_{mid}, A_{min}, F_{max}, A_{max}, A_{base}, BPM, BR]$

 else if (shape = diagonal) $\wedge$ (strength = inhale) **then**

  pattern $\leftarrow [F_{max}, A_{max2}, F_{mid}, A_{min}, A_{base}, BPM, BR]$

Algorithm 1 Personalization routine: Procedures (1).

```
        else if (shape = diagonal) ∧ (strength = exhale) then
            pattern ← [F_mid, A_min, F_max, A_max2, A_base, BPM, BR]
        else
            // pattern has identical inhale and exhale waves and
            //      is only used to habituate users to the tactors
            pattern ← [Frq, Amp, Frq, Amp, A_base, BPM, BR]
        end if
        command ← [pattern, In2ExDelay, Ex2InDelay, repetition]
        send command to processor
    end function

    function stopPattern
        instruct processor to finish currently playing pattern
        clear all queued patterns
    end function
    procedure Warm-up // Habituate the participant with the tactors' vibration range
        Amp ← 255
        for Frq in range (30,255,5) do playPattern(NULL, NULL, once)
        end for

```

Algorithm 1 Personalization routine: Procedures (2).

```
        wait until patterns complete
    end procedure
    procedure FIND F_min // Determine a low frequency that can be vividly felt
        Frq ← 25
        Amp ← 255
        repeat
            Frq ← Frq + 5
            playPattern(NULL, NULL, continuously)
            Wait 8 seconds
        until participant perceives pattern vividly
        F_min ← Frq
        stopPattern()
    end procedure

    procedure FIND A_base // Determine an amplitude that can be barely noticed
        Amp ← 5
        Frq ← Fmin
        repeat
            Amp ← Amp + 5
            playPattern(NULL, NULL, continuously)
            Wait 8 seconds
```

Algorithm 1 Personalization routine: Procedures (3).

participant barely notices pattern

$A_{hi} \leftarrow Amp$

stopPattern()

$Amp \leftarrow A_{low} + 55$

repeat

  $Amp \leftarrow Amp - 5$

  playPattern(NULL, NULL, continuously)

  wait 8 seconds

until participant can no longer notice pattern

$A_{low} \leftarrow Amp$

stopPattern()

$A_{base} \leftarrow (A_{low} + A_{hi})/2 + 20$

procedure FINE TUNE HORIZONTAL PATTERN

  $BPM \leftarrow$ participant's estimated breaths per minute

  playPattern(horizontal, exhale, continuously)

  Experimenter repeatedly asks participant how the pattern is

    perceived and adjusts F_{min}, A_{max}, and F_{max} accordingly

Algorithm 1 Personalization routine: Procedures (3).

repeat

  with probability .5

    playPattern(horizontal, inhale, continuously)

   or playPattern(horizontal, exhale, continuously)

  end with

until participant correctly detects which of the two waves is stronger 3 times in a row

stopPattern()

playPattern(horizontal, exhale, continuously)

Experimenter asks participant to breath with the pattern

wait 4 breaths

Experimenter asks participant about any issues they have with the pattern, and adjusts $F_{min}, A_{max}, F_{max}, BPM$ and BB accordingly

stopPattern()

procedure FINE TUNE VERTICAL PATTERN

  $BPM \leftarrow$ participant's estimated breaths per minute

  playPattern(vertical, exhale, continuously)

  Experimenter repeatedly asks participant how the pattern is perceived and adjusts F_{min}, A_{max}, and F_{max} accordingly

Algorithm 1 Personalization routine: Procedures (3).

1: **repeat**

2: **with** probability .5

playPattern(vertical, inhale, continuously)

or playPattern(vertical, exhale, continuously)

`participant correctly detects which of the two waves is stronger 3 times in a row`

stopPattern()

playPattern(vertical, exhale, continuously)

`Experimenter asks participant to breath with the pattern`

`wait 4 breaths`

`Experimenter asks participant about any issues they have with the pattern, and adjusts` $F_{min}, A_{max}, F_{max}, BPM$ `and` BB `accordingly`

stopPattern()

=0

let us know. As for the vibrations, they may feel strong or very subtle to the point where you may not notice them at all, but at no time should it be painful – it's been designed to safely vibrate on people's skin. If at any time it feels too uncomfortable, just let us know and we will stop it. Okay? This is in no way designed to test your tolerance or distract you. Our goal is to find the range of vibration where you are still able to remain focused, so that we can personalize your range to use for the remaining phases of the study.

– We'll be using the words *frequency* and *amplitude* a lot. To make this easier for you to understand, think of frequency as *how fast* the vibration is, and amplitude as how *intense* the sensation is. Sounds good?

A.2.2 Warm-Up

– We'll begin this study by giving you a warm-up. We will play a range of vibrations with lower frequencies and slowly progress to higher frequencies. This is just to give you a feel for what to expect during the study. We will not go beyond this frequency during the study. Please let me know if it feels uncomfortable at any time and we'll stop right away. Are you ready? Great, we'll now begin.

– **RA2 starts executing procedure Warm-Up.**

– Let me know when you begin to feel it.

If they expressed concern, "No worries, this is just a warm up to get you habituated with the vibration range. We will not go beyond this range throughout the study."

– {When procedure Warm-up ends.} How are you doing so far? Great, now moving on to step 1.

A.2.3 Find $\mathbf{F}_{\mathrm{min}}$

– We'll begin with a low frequency and slowly progress to higher frequencies. Let me know when the vibration is easily and vividly noticeable. Wait until you can feel a steady vibration, that you can no longer tune it out, not just the first moment you can perceive a vibration. Ready? Alright, hang on.

– **RA 2 starts executing procedure Find F_{min}**

– {When procedure Find F_{min} ends} Great job, thank you. Moving on to step 2.

A.2.4 Find $\mathbf{A}_{base}$

– In step 2, we will find an amplitude that is just noticeable. Let me know as soon as you start feeling the vibration. It may be barely noticeable. Ready? Alright, hang on.

– **RA 2 starts executing procedure Find A_{base}**

– {When line 80 is reached}

RA2 saves the upper bound for A_{base} (line 83).

Great, now please, let me know as soon as you can no longer feel the vibration.

– {When line 88 is reached}

RA2 saves the lower bound for A_{base} (line 91).

Thank you, we'll now be moving onto step 3.

A.2.5 Fine tune Horizontal pattern

– We will now be playing a repeating pattern of wave-like vibrations. The waves come in pairs. Each time we start playing a new pattern, the waves can be different – sometimes, the first wave will feel stronger, and other times the second wave will feel stronger. Our goal right now is to try to adjust the waves so it is comfortable and personalized to you ... Ready?

– **RA2 starts executing procedure Fine tune Horizontal pattern.**

– {After seeing 3-4 breaths on the physio screen, and while the wave is playing, ask the following questions (lines 98-99)}

Are you able to feel the waves?

Are you able to hear the waves?

Are you able to notice that there are two waves with a pause in between?

Do the waves feel too weak, too strong, or just right for you?

RA2 adjusts the waves accordingly.

Could you easily distinguish the first wave from the second wave?

Which of the two vibrations felt stronger? First one, or second one?

- Now, I am going to stop and play a different pattern. Let me know which vibration feels stronger? First one or second one? Ready?

  RA1 and RA2 executes lines 100-105

  {The participant needs to differentiate the waves correctly at least three times.}

  If the participant couldn't easily differentiate, RA2 will make further adjustments.

- **RA1 and RA2 executes lines 110-112**

- Would you like me to make any further adjustments?

A.2.6 Fine tune Vertical pattern

- We will now be playing another repeating pattern of wave-like vibrations. Just like before, the waves come in pairs. Each time we start playing a new pattern, the waves can be different – sometimes, the first wave will feel stronger, and other times the second wave will feel stronger. Our goal right now is to try to adjust the waves so it is comfortable and personalized to you ... Ready?

- **RA2 starts executing procedure Fine tune Vertical pattern.**

- {After seeing 3-4 breaths on the physio screen, and while the wave is playing, ask the following questions (lines 118-119)}

  Are you able to feel the waves?

  Are you able to hear the waves?

Are you able to notice that there are two waves with a pause in between?

Do the waves feel too weak, too strong, or just right for you?

RA2 adjusts the waves accordingly.

Could you easily distinguish the first wave from the second wave?

Which of the two vibrations felt stronger? First one, or second one?

- Now, I am going to stop and play a different pattern. Let me know which vibration feels stronger? First one or second one? Ready?

  RA1 and RA2 executes lines 120-125

  {The participant needs to differentiate the waves correctly at least three times.}

  If the participant couldn't easily differentiate, RA2 will make further adjustments.

- **RA1 and RA2 executes lines 130-131**

- Would you like me to make any further adjustments?

A.2.7 Prepare for the trials

- You will now experience a set of randomized trials, with a different pattern for each trial. These trials are in no particular order, so do not think of these sequences as getting more personalized to you, as some may feel more pleasant to you than others. You will have a chance after each trial to give us your feedback on your experience, so go ahead and let us know which trials you liked and which you did not, and feel free to also explain why in the comment section.

– I will give you some tips on how to make the best out of your experience. First, before each trial inhale and exhale so that after you start each trial, you can begin with an inhalation. It will help you pace yourself throughout these trials.

– Please maintain the same steady posture and keep your left hand still throughout these trials.

– Please relax like you did at the beginning of the study, and sync your breathing with the vibrations.

– You may click on the begin button to start.

A.3 Conscious Slow-paced Breathing Script to Determine BPM

– We begin by teaching you a few breathing techniques. Let's practice these techniques together as I explain. Please sit comfortably and relax, and feel free to close your eyes. I find this great for clearing my thoughts. First, let's start by becoming aware of your breathing. You can do this by placing one hand over the strap on your belly and try to slowly inhale and exhale.

– «speak in a slow pace and with a soft manner» The first technique I will suggest is to imagine you have breathing holes in the bottom of your feet, like a whale.

Take a deep breath through your feet... and up to your abdomen... then... on the exhale, reverse and release this breath out from your feet.

- The next technique that might be helpful is to take a deep breath in and then imagine fogging up a mirror, When you exhale, make a (whisper) "haaa" sound, or, you could take a deep inhale and exhale while making a hissing sound, "Sssss..". Try to make sure your exhales are slow... and long... To validate whether you are doing them correctly, these exercises should feel effortless and you should not feel rushed at any time. Shall we begin? Let us begin together. Let's being with an inhaleeee.. "Sssssu" and hold... And when you're ready... exhaleeeee, "Haaa..." And repeat... inhale... "Sssssu," and... exhale... "Haaa..."
- «softly» Great job.
- We will now begin by recording your breathing for about 2 minutes. Please remain still during this time: we will let you know once the time is up. We want you to breathe smoothly, consciously, and effortlessly. Please sit comfortably and relax and feel free to close your eyes. I will help guide your breathing as we go along. Are you ready to begin? Great.

  RA1 Set a timer to 2 minutes.

  RA2 Press "play icon" to start BPM recording session.
- Now, let us start by becoming aware of our breathing... Without trying to change your breathing, simply notice... how you are breathing... Notice, where you are

breathing from... whether your shoulders are rising and falling... whether your chest, is rising and falling... or perhaps... your belly is rising... and falling. (PAUSE) Now... as you slowly inhale... imagine the air... flowing deeper into your belly. Pause... at the top of your breath, and then follow your breath out as you completely exhale when you are ready... Think of the air as oozing... and escaping... from your nose or mouth... Slowly take a breath in... Let any tension melt away as you relax more with each breath... (PAUSE) Notice how the cool fresh air enters your nose...

– Notice what happens as that breath of fresh air enters your lungs... Notice... what happens when you exhale... Feel the temperature of each breath... cool as you inhale... and warm as you exhale. As your breathing becomes smooth and slow, feel yourself releasing all tension... as you become more relaxed with each breath.

  «give the participant some quiet time as they continue their breathing and wait for the 2 minutes to be up if not yet» Great job.

– RA1 focus on the last 30 seconds of breathing wave on the screen to estimate the BPM.

– **RA2 enters the BPM into the Matlab program.**

– Two minutes are up, thank you.

A.4 Skewness test for each of the Dependent Variables

For each DV, we conducted a one-sample t-test for the differences between each pair of placements. For each difference value, we identified those with skewness either greater than 0.8 or less than -0.8, and then identified any participants that had a mean value for the difference that was at least 3 standard deviations from the group mean. In all but one case, there was no more than one such participant. For abdomen_mean_movement, we needed to iteratively remove subject ids s037, s022 and s019 before the resulting skewness was acceptably low. In each case, we removed a subject for the DV under consideration by replacing its mean measurement with NA.

Figures A.1–A.9 show the results of one-sample t-tests for each dependent variable after any identified outliers were removed.

abd_sd_time_log								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Abdomen	6.234977089	0.4509562	0.4509562	33	1.693889	5.4711075	**6.9988467**	1.9247705
AvsC	-0.011520085	0.3632959	0.3632959	33	1.693889	-0.626903	0.6038628	-0.8365167
AvsL	0.002169462	0.2872826	0.2872826	33	1.693889	-0.4844553	0.4887943	0.2447229
Chest	6.205279025	0.3402848	0.3402848	33	1.693889	5.6288744	**6.7816837**	1.5077872
CvsL	0.023370049	0.3241984	0.3241984	33	1.693889	-0.525786	0.5725261	0.9186471
Lowerback	6.167276313	0.2772975	0.2772975	33	1.693889	5.6975652	**6.6369874**	-0.5791878
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
AvsC	-0.01152008	-0.1765534	0.8610457	30	-0.1447781	0.1217379	One Sample t-t	two.sided
AvsL	0.002169462	0.04136216	0.9672906	29	-0.1051036	0.1094426	One Sample t-t	two.sided
CvsL	0.02337005	0.4013559	0.6910029	30	-0.09554689	0.142287	One Sample t-t	two.sided

Figure A.1: Skewness for abd_sd_time after $\log_{10}$ transformation.

Abd_sd_movement_log aftre id=s027 is removed								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Abdomen	-0.002292534	0.6528269	0.6528269	33	1.693889	-1.1081086	1.1035236	-0.74878451
AvsC	-0.092824515	0.3820266	0.3820266	33	1.693889	-0.739935	0.554286	-0.36522125
AvsL	0.019803658	0.4781864	0.4781864	33	1.693889	-0.7901908	0.8297981	0.09074851
Chest	0.152886146	0.5871086	0.5871086	33	1.693889	-0.8416106	1.1473829	-0.42371867
CvsL	0.090028442	0.3023551	0.3023551	33	1.693889	-0.4221274	0.6021843	-0.21388068
Lowerback	0.045020096	0.5583234	0.5583234	33	1.693889	-0.9007176	0.9907578	-0.28425309
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
AvsC	-0.09282451	-1.330852	0.1936074	29	-0.2354756	0.04982655	One Sample t-t	two.sided
AvsL	0.01980366	0.2230218	0.8251376	28	-0.1620887	0.201696	One Sample t-t	two.sided
CvsL	0.09002844	1.630884	0.1137293	29	-0.02287279	0.2029297	One Sample t-t	two.sided

Figure A.2: Skewness for abd_sd_movement after removing the outlier subject id 27.

A.5 Mean and standard deviance of all significant Dependent Variables

For each of the DVs and level of that DV for which there was a significant finding, we computed for each subject the mean and standard deviation of the DV and level of interest as well as the standard deviations of the pairwise differences. Tables A.1–A.8 shows these values.

A.6 Dependent variable measurements for each participant

Figures A.10–A.13 show the values of all the DVs used in the analysis presented in this dissertation. The left-hand part of each figure groups the measures first by placement and then by shape, while the right-hand part groups the values first by shape and then by placement. In both cases, the shape of the endpoint distinguishes between

CDA.SCR after removing id = s009								
Placement	**Mean placement**	**SD placement**	**SE mean**	**n**	**t**	**CI_lower**	**CI_upper**	**Skewness**
Abdomen	0.14430896	0.17193402	0.17193402	33	1.693889	-0.1469281	0.4355461	1.16912776
AvsC	-0.02406729	0.09172189	0.09172189	33	1.693889	-0.179434	0.1312994	-0.22852889
AvsL	-0.05484757	0.16120021	0.16120021	33	1.693889	-0.3279028	0.2182077	0.65774963
Chest	0.16655553	0.18249922	0.18249922	33	1.693889	-0.1425778	0.4756889	1.10259996
CvsL	-0.0259785	0.14194188	0.14194188	33	1.693889	-0.2664122	0.2144553	-0.07873803
Lowerback	0.19777877	0.20608766	0.20608766	33	1.693889	-0.1513108	0.5468683	1.41356781
	Estimates	**Statistic**	**p.value**	**n**	**Conf.low**	**Conf.high**	**Method**	**Alternative**
AvsC	-0.02406729	-1.484326	0.1478204	31	-0.05713656	0.009001975	One Sample t-te	two.sided
AvsL	-0.05484757	-1.863599	0.07253272	29	-0.1150407	0.005345577	One Sample t-te	two.sided
CvsL	-0.0259785	-1.019024	0.3163397	30	-0.0780432	0.0260862	One Sample t-te	two.sided

Figure A.3: Skewness for CDA.SCR after removing the outlier subject id 9.

strong inhale and strong exhale patterns. Outlier values (see Section 5.6.1 for details) have not been removed from these graphs.. From these figures, one can readily see the range of measures reported by individuals as well as how they changed over different factors. For example, from Figure A.11a, one can readily see that with chest placement, most participants found it easier to differentiate horizontal shapes as compared to vertical shapes. But, it is also clear that there were several subjects who had the opposite experience: they found it much harder to differentiate horizontal shapes as compared to vertical shapes.

Synchronize after removing id = s028								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Abdomen	20.042857	16.35726	16.35726	35	1.690924	-7.616034	47.70175	0.6120977
AvsC	-1.691429	13.35677	13.35677	35	1.690924	-24.276723	20.89387	-0.6423092
AvsL	-3.675238	14.68364	14.68364	35	1.690924	-28.504164	21.15369	-0.4453478
Chest	21.734286	18.2375	18.2375	35	1.690924	-9.103953	52.57252	0.4651025
CvsL	-1.98381	16.9527	16.9527	35	1.690924	-30.649539	26.68192	0.2891227
Lowerback	23.718095	17.8393	17.8393	35	1.690924	-6.446815	53.88301	0.2340627
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
AvsC	-1.691429	-0.7491798	0.4589011	34	-6.279641	2.896784	One Sample t-t	two.sided
AvsL	-3.675238	-1.480764	0.1478779	34	-8.719246	1.368769	One Sample t-t	two.sided
CvsL	-1.98381	-0.6923013	0.4934495	34	-7.807265	3.839646	One Sample t-t	two.sided

Figure A.4: Skewness for Synchronization after removing the outlier subject id 28.

PA - NA after removing id=028								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Abdomen	-13.748095	30.21372	30.21372	35	1.690924	-64.8372	37.34101	-0.20615548
AvsC	2.558095	12.81883	12.81883	35	1.690924	-19.11757	24.23376	-0.22010554
AvsL	2.048095	16.4161	16.4161	35	1.690924	-25.71028	29.80647	0.30899863
Chest	-16.30619	29.98024	29.98024	35	1.690924	-67.00051	34.38813	-0.36180121
CvsL	-0.51	18.42356	18.42356	35	1.690924	-31.66284	30.64284	-0.48351926
Lowerback	-15.79619	29.01178	29.01178	35	1.690924	-64.85292	33.26054	-0.06481675
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
AvsC	2.558095	1.180599	0.2459556	34	-1.845326	6.961517	One Sample t-t	two.sided
AvsL	2.048095	0.7380984	0.465519	34	-3.591032	7.687222	One Sample t-t	two.sided
CvsL	-0.51	-0.1637686	0.870883	34	-6.838714	5.818714	One Sample t-t	two.sided

Figure A.5: Skewness for PA - NA after removing the outlier subject id 28.

Attend								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Abdomen	17.7060185	16.19128	16.19128	36	1.689572	-9.65033	45.06237	0.877226
AvsC	0.8986111	16.92817	16.92817	36	1.689572	-27.70276	29.49998	0.07558283
AvsL	-1.9916667	14.5402	14.5402	36	1.689572	-26.55839	22.57506	-0.08347694
Chest	16.8074074	17.57362	17.57362	36	1.689572	-12.8845	46.49932	**0.92160165**
CvsL	-2.8902778	18.85134	18.85134	36	1.689572	-34.74098	28.96042	0.51270369
Lowerback	19.6976852	16.77946	16.77946	36	1.689572	-8.65242	48.04779	0.53808742
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
AvsC	0.8986111	0.3185027	0.7519966	35	-4.829057	6.626279	One Sample t-t	two.sided
AvsL	-1.991667	-0.8218593	0.4167207	35	-6.911363	2.92803	One Sample t-t	two.sided
CvsL	-2.890278	-0.9199171	0.3639132	35	-9.268652	3.488097	One Sample t-t	two.sided

Figure A.6: Skewness for Attend

SC_slope								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Abdomen	-0.0129055622	0.01408683	0.01408683	34	1.69236	-0.03674555	0.01093443	**-1.2957861**
AvsC	0.0026460724	0.008156622	0.008156622	34	1.69236	-0.01115787	0.01645002	-0.03864889
AvsL	0.0018358417	0.008951899	0.008951899	34	1.69236	-0.013314	0.01698568	-0.09480995
Chest	-0.0151849114	0.01507953	0.01507953	34	1.69236	-0.04070491	0.01033509	**-0.99394563**
CvsL	-0.0006745223	0.008164608	0.008164608	34	1.69236	-0.01449198	0.01314294	-0.10973802
Lowerback	-0.0149638077	0.015232821	0.015232821	34	1.69236	-0.04074323	0.01081561	**-1.20038614**
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
AvsC	0.002646072	1.863581	0.07157939	32	-0.0002461398	0.005538285	One Sample t-t	two.sided
AvsL	0.001835842	1.160099	0.2548654	31	-0.001391662	0.005063346	One Sample t-t	two.sided
CvsL	-0.0006745223	-0.4745893	0.6383026	32	-0.003569566	0.002220522	One Sample t-t	two.sided

Figure A.7: Skewness for Skin Conductance Slope

Differentiate								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Diagonal	15.38619	15.8862	15.8862	36	1.689572	-11.454698	42.22708	1.0726304
Horizontal	14.113426	13.84806	13.84806	36	1.689572	-9.283872	37.51072	0.6310358
HvsD	-1.155238	11.49032	11.49032	36	1.689572	-20.568972	18.2585	-0.0285316
HvsV	-9.10787	20.79113	20.79113	36	1.689572	-44.23599	26.02025	-0.1698989
Vertical	23.221296	17.81555	17.81555	36	1.689572	-6.879362	53.32196	0.7588126
VvsD	8.241429	19.00733	19.00733	36	1.689572	-23.872836	40.35569	0.5798699
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
HvsV	-9.10787	-2.628391	0.01265433	35	-16.14258	-2.073164	One Sample t-t	two.sided
HvsD	-1.155238	-0.5948032	0.5559131	34	-5.102302	2.791826	One Sample t-t	two.sided
VvsD	8.241429	2.565165	0.01489649	34	1.712182	14.77068	One Sample t-t	two.sided

Figure A.8: Skewness for Differentiation

abd_mean_movement after removing id = s037, s022, and s019								
Placement	Mean placement	SD placement	SE mean	n	t	CI_lower	CI_upper	Skewness
Abdomen	3.8696182	2.41115	2.41115	31	1.697261	-0.222732	7.961968	0.5739666
AvsC	-0.6740273	1.111776	1.111776	31	1.697261	-2.5610019	1.212947	-1.0589351
AvsL	-0.4672218	1.289799	1.289799	31	1.697261	-2.6563475	1.721904	-0.3656196
Chest	4.820498	2.637716	2.637716	31	1.697261	0.3436058	9.29739	0.5488665
CvsL	0.1402704	1.316437	1.316437	31	1.697261	-2.0940665	2.374607	0.1284078
Lowerback	4.7380954	2.891642	2.891642	31	1.697261	-0.1697756	9.645966	0.6870236
	Estimates	Statistic	p.value	n	Conf.low	Conf.high	Method	Alternative
AvsC	-0.6740273	-3.208034	0.003429782	27	-1.105129	-0.2429254	One Sample t-t	two.sided
AvsL	-0.4672218	-1.882274	0.07103676	26	-0.9774494	0.04300572	One Sample t-t	two.sided
CvsL	0.1402704	0.5638257	0.5775264	27	-0.3701906	0.6507313	One Sample t-t	two.sided

Figure A.9: Skewness for abd_mean_movement after removing outliers subject id s037, s022, and s019

id	Mean Strong Inhale	SD Strong Inhale	Mean Strong Exhale	SD Strong Exhale	SD Strong Exhale vs Strong Inhale
s007	NA	NA	NA	NA	NA
s008	2.018	0.64	2.148	0.769	0.558
s009	2.786	NA	NA	NA	NA
s010	NA	NA	NA	NA	NA
s011	0.209	0.062	0.171	0.03	0.078
s012	2.656	0.828	2.986	0.872	0.875
s013	1.505	0.696	1.457	0.649	0.697
s014	1.409	1	1.54	1.065	0.345
s015	1.478	0.207	1.455	0.552	0.425
s016	1.358	0.283	1.067	0.128	0.314
s017	0.715	0.327	0.64	0.228	0.164
s018	0.524	0.241	0.481	0.185	0.213
s019	0.572	0.234	0.78	0.703	0.663
s020	1.173	0.451	1.099	0.2	0.384
s021	5.039	1.12	4.281	0.983	1.449
s022	1.534	0.824	1.469	0.523	0.542
s023	2.761	0.338	2.619	0.836	0.766
s024	1.295	0.239	1.292	0.211	0.228
s025	0.436	0.176	0.476	0.143	0.103
s026	6.456	1	4.619	1.576	2.941
s027	0.874	0.175	0.654	0.223	0.152
s028	1.63	1.074	1.252	0.58	0.662
s029	1.165	0.704	0.923	0.187	0.637
s030	1.65	0.535	1.305	0.295	0.323
s031	2.101	0.432	2.174	0.555	0.599
s032	0.565	0.17	0.594	0.216	0.138
s033	2.921	1.056	3.158	1.487	1.369
s034	3.635	1.526	3.045	0.644	1.273
s035	3.965	0.273	3.767	0.663	0.39
s036	1.573	0.302	1.407	0.45	0.467
s037	2.985	1.94	1.635	1.153	1.081
s038	0.669	0.408	0.588	0.333	0.191
s039	NA	NA	NA	NA	NA
s040	1.816	0.821	1.682	0.839	0.651
s041	1.466	0.284	1.464	0.452	0.35
s042	4.568	1.79	4.538	1.921	1.047

Table A.1: Ch2Ab individual difference

id	Mean Abdomen	SD Abdomen	Mean Chest	SD Chest	Mean Lowerback	SD Lowerback	SD Abdomen vs Chest	SD Abdomen vs Lowerback	SD Chest vs Lowerback
s007	NA	NA	NA	NA	NA	NA	NA	NA	NA
s008	1.581	0.658	1.732	0.409	0.894	0.21	0.792	0.628	0.564
s009	0.466	NA	NA	NA	NA	NA	NA	NA	NA
s010	NA	NA	NA	NA	NA	NA	NA	NA	NA
s011	1.267	0.475	1.259	0.237	1.57	0.535	0.687	0.848	0.612
s012	0.161	0.025	0.352	0.211	0.375	0.047	NA	0.003	0.184
s013	0.951	0.544	0.471	0.301	0.5	0.344	0.766	0.679	0.504
s014	1.676	0.578	1.296	0.569	1.284	0.389	0.969	0.912	0.67
s015	1.679	0.334	1.305	0.435	1.379	0.332	0.485	0.439	0.668
s016	NA	NA	1.814	0.892	1.322	0.804	NA	NA	1.106
s017	2.008	0.635	2.156	0.784	2.136	1.15	0.541	0.734	1.322
s018	1.557	0.515	1.157	0.6	0.888	0.323	0.11	0.691	0.797
s019	1.357	0.457	1.843	0.48	2.619	0.992	0.338	0.512	0.431
s020	1.183	0.348	1.154	0.426	1.348	0.381	0.423	0.177	0.322
s021	0.527	0.306	0.769	0.447	0.516	0.128	0.625	0.417	0.554
s022	2.198	0.744	3.302	1.561	2.291	0.672	1.608	0.645	2.082
s023	0.912	0.122	0.809	0.425	0.615	0.187	NA	0.2	0.301
s024	0.981	0.271	0.847	0.428	1.576	0.222	0.325	0.335	0.536
s025	2.259	0.577	1.913	0.263	2.125	0.384	0.386	0.751	0.53
s026	1.55	0.608	1.284	0.16	0.959	0.334	NA	0.714	NA
s027	0.833	0.331	0.67	0.503	1.634	0.842	0.393	NA	1.049
s028	2.451	0.884	3.219	0.485	2.562	0.815	1.33	1.077	0.916
s029	1.534	0.655	2.577	0.64	1.988	0.625	1.015	1.102	0.628
s030	0.64	0.231	0.688	0.208	0.861	0.327	0.36	0.235	0.409
s031	0.818	0.201	0.927	0.223	0.877	0.31	0.169	0.443	0.337
s032	0.883	0.191	1.85	0.259	1.817	0.43	0.372	0.29	0.639
s033	0.388	0.198	0.699	0.229	0.792	0.18	0.337	0.191	0.296
s034	1.305	0.326	1.322	0.196	1.204	0.509	0.213	0.856	0.629
s035	0.765	0.192	2.001	0.257	NA	NA	0.1	NA	NA
s036	0.497	0.113	0.533	0.203	0.394	0.112	0.131	0.126	0.157
s037	3.211	1.436	1.944	0.395	1.321	1.036	1.311	1.808	1.301
s038	1.486	0.586	1.435	0.424	1.32	0.463	0.81	0.666	0.712
s039	0.45	NA	NA	NA	NA	NA	NA	NA	NA
s040	1.674	0.458	1.393	0.569	0.728	0.201	0.976	0.627	0.733
s041	1.253	0.383	1.588	0.586	1.422	0.455	0.834	0.318	0.762
s042	0.389	0.084	0.417	0.123	0.47	0.109	0.14	0.11	0.224

Table A.2: Ch2Ab individual difference

id	Mean Abdomen	SD Abdomen	Mean Chest	SD Chest	Mean Lowerback	SD Lowerback	SD Abdomen vs Chest	SD Abdomen vs Lowerback	SD Chest vs Lowerback
s007	NA	NA	NA	NA	NA	NA	NA	NA	NA
s008	2.210	0.418	1.288	0.247	2.752	0.260	0.365	0.559	0.375
s009	2.786	NA	NA	NA	NA	NA	NA	NA	NA
s010	NA	NA	NA	NA	NA	NA	NA	NA	NA
s011	0.174	0.014	0.195	0.050	0.201	0.075	0.046	0.072	0.080
s012	3.172	1.048	3.502	0.511	2.219	0.278	2.442	0.798	0.848
s013	0.890	0.348	1.647	0.465	1.938	0.612	0.699	0.702	0.704
s014	2.811	0.871	0.857	0.269	1.064	0.207	1.051	0.746	0.423
s015	1.248	0.322	1.405	0.187	1.805	0.429	0.222	0.772	0.613
s016	NA	NA	1.292	0.339	1.133	0.137	NA	NA	0.330
s017	0.690	0.118	0.396	0.034	0.945	0.133	0.142	0.155	0.143
s018	0.719	0.207	0.451	0.084	0.338	0.062	0.172	0.172	0.109
s019	0.253	0.035	0.766	0.148	0.898	0.682	0.173	0.105	0.225
s020	0.914	0.181	1.280	0.304	1.161	0.503	0.427	0.764	0.458
s021	5.096	1.329	4.433	0.595	4.484	1.328	1.396	1.968	1.849
s022	2.141	0.487	0.662	0.078	1.566	0.177	0.498	0.585	0.217
s023	2.910	0.503	3.401	0.328	2.306	0.485	NA	0.505	0.133
s024	1.103	0.183	1.341	0.135	1.471	0.180	0.228	0.376	0.261
s025	0.505	0.054	0.591	0.098	0.268	0.065	0.101	0.096	0.093
s026	5.362	1.982	5.862	0.182	3.929	NA	NA	NA	NA
s027	0.960	0.073	0.868	0.160	0.539	0.144	0.211	NA	0.158
s028	1.473	0.591	0.667	0.064	2.294	0.769	0.604	0.724	0.735
s029	0.936	0.099	0.758	0.071	1.440	0.767	0.092	0.778	0.813
s030	1.697	0.232	1.759	0.436	0.977	0.083	0.318	0.261	0.423
s031	2.428	0.596	2.448	0.232	1.688	0.235	0.553	0.587	0.161
s032	0.492	0.079	0.812	0.092	0.434	0.090	0.132	0.141	0.061
s033	4.324	1.119	1.969	0.257	2.668	0.741	1.233	0.893	0.741
s034	4.173	1.655	2.377	0.313	3.559	0.257	1.675	1.571	0.312
s035	3.866	0.429	NA	NA	NA	NA	NA	NA	NA
s036	1.803	0.033	1.381	0.410	1.259	0.359	0.421	0.408	0.191
s037	0.450	0.092	3.751	1.184	2.170	0.952	1.048	0.875	0.916
s038	1.080	0.163	0.283	0.055	0.522	0.133	0.181	0.152	0.134
s039	NA	NA	NA	NA	NA	NA	NA	NA	NA
s040	1.138	0.323	1.569	0.574	2.662	0.572	0.695	0.499	1.227
s041	1.570	0.180	1.083	0.277	1.742	0.259	0.380	0.385	0.390
s042	6.871	0.918	3.147	0.533	3.641	0.293	1.179	0.853	0.732

Table A.3: abd_sd_movement individual difference

id	Mean Abdomen	SD Abdomen	Mean Chest	SD Chest	Mean Lowerback	SD Lowerback	SD Abdomen vs Chest	SD Abdomen vs Lowerback	SD Chest vs Lowerback
s007	NA	NA	NA	NA	NA	NA	NA	NA	NA
s008	4.291	0.566	5.387	0.479	3.092	0.427	0.516	0.956	0.752
s009	0.962	NA	NA	NA	NA	NA	NA	NA	NA
s010	NA	NA	NA	NA	NA	NA	NA	NA	NA
s011	8.183	0.746	9.015	0.652	9.49	1.835	0.866	2.29	1.871
s012	0.789	0.022	0.98	0.174	1.056	0.092	NA	0.064	0.128
s013	3.233	1.139	1.89	0.386	2.334	0.701	0.864	1.433	0.96
s014	2.844	0.675	6.536	0.675	3.993	0.356	0.741	0.632	0.177
s015	4.986	1.52	4.977	0.78	4.155	0.206	1.305	1.707	0.852
s016	NA	NA	6.615	1.309	7.413	0.46	NA	NA	1.625
s017	9.018	1.149	9.915	0.93	10.329	1.32	1.032	0.61	0.999
s018	5.573	1.458	5.672	0.592	4.993	0.218	1.073	1.519	0.583
s019	7.698	0.685	6.41	0.926	11.895	1.49	1.539	2.056	2.289
s020	4.102	0.546	4.202	0.354	4.496	0.905	0.431	1.413	0.922
s021	1.193	0.244	1.499	0.341	1.275	0.354	0.484	0.438	0.598
s022	5.507	1.196	14.052	1.029	7.434	1.177	1.926	1.926	2.077
s023	1.732	0.233	1.723	0.351	2.193	0.179	NA	0.365	0.464
s024	3.295	0.532	3.611	0.418	3.732	0.413	0.469	0.966	0.755
s025	8	0.551	8.963	1.243	9.782	0.557	0.936	0.644	0.935
s026	2.264	0.603	1.837	0.092	1.365	0.493	NA	0.223	NA
s027	5.307	0.55	5.955	0.194	9.142	0.709	0.739	NA	0.643
s028	6.928	1.69	8.84	2.366	5.584	1.316	1.982	2.22	1.804
s029	6.389	0.93	10.031	0.783	9.19	1.447	0.59	1.661	1.182
s030	2.961	0.294	3.517	0.487	4.536	0.344	0.432	0.6	0.724
s031	3.076	0.576	3.432	0.406	4.331	0.393	0.925	0.681	0.692
s032	7.83	0.848	7.196	0.566	9.154	0.807	1.047	1.414	0.91
s033	1.732	0.342	3.12	0.255	2.615	0.389	0.476	0.38	0.38
s034	2.709	0.539	4.016	0.503	2.551	0.123	1.007	0.654	0.471
s035	1.669	0.365	3.2	0.534	NA	NA	0.732	NA	NA
s036	2.482	0.152	3.113	0.154	3.255	0.304	0.246	0.37	0.211
s037	10.608	1.283	4.268	0.812	4.932	1.646	1.471	1.423	2.064
s038	4.779	0.728	4.476	0.84	4.675	0.383	0.608	0.566	0.939
s039	0.82	NA	NA	NA	NA	NA	NA	NA	NA
s040	5.098	0.602	4.476	0.687	3.015	0.414	1.111	0.775	0.799
s041	2.696	0.475	3.444	0.449	3.143	0.42	0.844	0.591	0.661
s042	1.149	0.111	2.158	0.276	1.779	0.132	0.32	0.136	0.302

Table A.4: abd_mean_movement individual difference

id	Mean Abdomen	SD Abdomen	Mean Chest	SD Chest	Mean Lowerback	SD Lowerback	SD Abdmen vs Chest	SD Abdomen vs Lowerback	SD Chest vs Lowerback
s007	NA	NA	NA	NA	NA	NA	NA	NA	NA
s008	9.129	1.495	6.717	0.826	7.942	1.043	1.231	2.165	1.439
s009	2.613	0.367	4.883	0.720	3.620	0.237	0.976	0.498	0.720
s010	NA	NA	NA	NA	NA	NA	NA	NA	NA
s011	1.401	0.193	1.705	0.387	1.795	0.490	0.327	0.468	0.728
s012	2.353	0.502	3.802	0.902	2.336	0.279	1.185	0.415	0.877
s013	2.521	0.416	2.970	0.614	4.175	0.764	0.905	0.720	1.110
s014	5.959	0.415	5.397	1.095	3.775	0.251	1.136	0.233	1.267
s015	5.490	0.882	6.705	0.477	6.761	0.622	1.228	1.360	0.500
s016	NA	NA	8.325	1.465	8.278	1.256	NA	NA	0.747
s017	6.537	2.056	4.020	0.382	9.861	2.140	2.171	1.900	2.182
s018	3.338	0.508	2.553	0.519	1.660	0.325	0.487	0.823	0.780
s019	1.893	0.113	4.805	0.963	7.316	0.812	0.900	0.908	1.690
s020	3.177	0.308	4.608	0.730	4.733	1.047	0.739	1.247	1.252
s021	5.555	0.902	6.487	1.389	5.148	0.743	1.705	0.931	2.089
s022	11.049	0.970	9.162	0.962	11.225	1.669	0.987	1.994	1.652
s023	4.974	0.607	5.060	0.545	4.921	0.842	NA	0.561	0.422
s024	3.490	0.544	4.815	0.739	5.398	0.501	0.899	0.977	1.072
s025	3.736	0.284	4.798	0.464	2.464	0.422	0.635	0.614	0.917
s026	10.847	1.652	10.757	0.203	9.280	1.422	NA	1.054	NA
s027	4.878	1.153	5.049	0.837	4.770	0.927	0.367	NA	1.023
s028	8.592	2.387	5.715	1.686	9.209	1.862	1.394	2.550	1.940
s029	6.025	1.209	7.552	1.154	10.493	2.072	0.378	2.127	2.280
s030	4.919	0.601	5.930	1.143	4.399	0.315	0.941	0.660	0.898
s031	7.284	1.057	8.061	0.919	7.388	1.273	1.207	1.074	1.430
s032	3.765	0.389	5.825	0.537	3.963	0.578	0.373	0.777	0.650
s033	7.073	0.701	6.092	0.380	6.698	1.281	0.715	1.065	1.224
s034	9.708	0.529	8.820	0.563	8.816	0.761	0.805	0.596	0.884
s035	6.343	0.768	4.670	0.169	NA	NA	NA	NA	NA
s036	4.292	0.115	4.136	0.950	3.772	0.701	1.000	0.487	0.585
s037	4.750	0.522	11.814	1.268	7.726	1.295	1.538	1.118	2.604
s038	5.266	1.163	1.260	0.251	2.463	0.820	1.099	0.656	0.658
s039	3.280	0.317	4.594	0.535	6.608	0.746	0.780	0.736	0.669
s040	5.814	1.688	6.537	1.151	8.207	2.284	1.822	1.873	3.462
s041	4.190	0.483	3.160	0.372	5.237	0.713	0.532	0.617	0.871
s042	7.291	0.382	6.495	0.545	6.182	0.389	0.665	0.200	0.582

Table A.5: abd_mean_movement individual difference

id	Mean Abdomen	SD Abdomen	Mean Chest	SD Chest	Mean Lowerback	SD Lowerback	SD Abdomen vs Chest	SD Abdomen vs Lowerback	SD Chest vs Lowerback
s007	NA	NA	NA	NA	NA	NA	NA	NA	NA
s008	0.280	0.122	0.162	0.090	NA	NA	0.189	NA	NA
s009	1.359	0.627	0.511	0.148	0.608	0.168	0.627	0.552	0.284
s010	NA	NA	NA	NA	NA	NA	NA	NA	NA
s011	0.022	0.016	0.046	0.023	0.035	0.023	0.032	0.028	0.032
s012	0.562	0.330	0.437	0.254	0.128	0.083	0.408	0.340	0.307
s013	0.504	0.627	0.298	0.348	0.194	0.077	0.791	0.580	0.394
s014	0.025	0.019	0.039	0.030	0.012	0.009	0.031	0.018	0.028
s015	0.110	0.082	0.285	0.119	0.184	0.095	0.135	0.126	0.143
s016	NA	NA	0.108	0.039	0.154	0.035	NA	NA	0.080
s017	0.217	0.170	0.294	0.239	0.423	0.121	0.143	0.211	0.316
s018	0.043	0.028	0.030	0.016	0.015	0.014	0.031	0.017	0.016
s019	0.016	0.012	0.075	0.042	0.010	0.006	0.053	0.014	0.039
s020	0.132	0.041	0.152	0.121	0.289	0.138	0.144	0.131	0.259
s021	0.004	0.002	0.004	0.002	0.006	0.003	0.001	0.005	0.005
s022	0.527	0.097	0.654	0.152	0.501	0.224	0.213	0.285	0.140
s023	0.235	0.112	0.243	0.169	0.222	0.104	NA	0.130	0.167
s024	0.214	0.029	0.457	0.234	0.426	0.116	0.245	0.123	0.287
s025	0.004	0.001	0.029	0.024	0.005	0.003	0.027	0.003	0.024
s026	0.004	0.003	0.004	0.001	0.024	0.018	NA	0.018	NA
s027	0.124	0.074	0.121	0.042	0.236	0.089	0.104	NA	0.084
s028	0.014	0.011	0.061	0.083	0.038	0.044	0.092	0.041	0.097
s029	0.037	0.039	0.059	0.024	0.272	0.101	0.035	0.076	0.090
s030	0.053	0.057	0.015	0.011	0.149	0.217	0.054	0.238	0.211
s031	0.287	0.090	0.519	0.089	0.259	0.108	0.093	0.214	0.155
s032	0.002	0.000	0.002	0.001	0.002	0.000	0.001	0.001	0.001
s033	0.015	0.019	0.035	0.065	0.196	0.244	0.063	0.246	0.282
s034	0.310	0.120	0.335	0.150	0.705	0.414	0.196	0.371	0.436
s035	0.006	0.004	0.009	0.006	NA	NA	0.007	NA	NA
s036	0.090	0.037	0.223	0.025	0.240	0.176	0.006	0.189	0.170
s037	0.043	0.015	0.090	0.039	0.113	0.113	0.038	0.125	0.138
s038	0.070	0.023	0.061	0.029	0.096	0.061	0.033	0.049	0.079
s039	0.002	0.001	0.002	0.001	0.004	0.003	0.000	0.003	0.003
s040	0.005	0.002	0.010	0.005	0.066	0.103	0.005	0.103	0.114
s041	0.182	0.214	0.097	0.106	0.286	0.258	0.270	0.218	0.325
s042	0.479	0.229	0.538	0.189	0.841	0.326	0.273	0.244	0.327

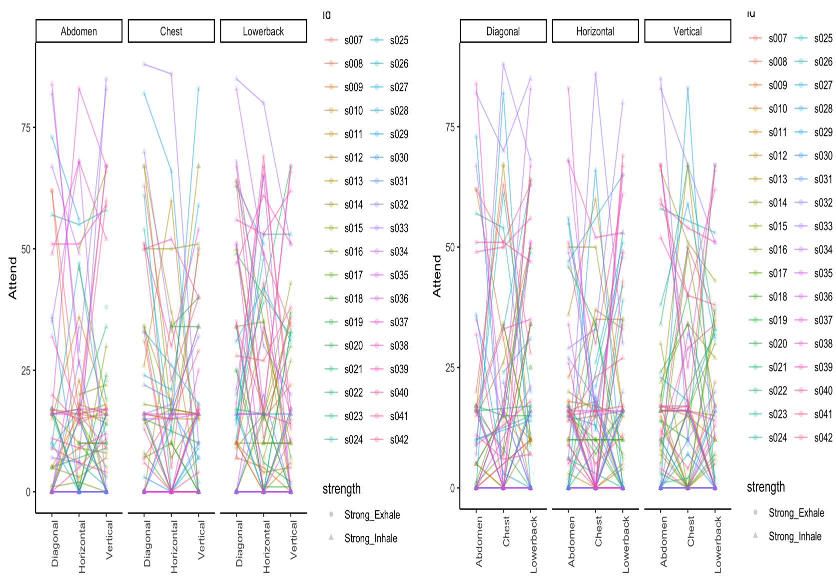
Table A.6: CDA.SCR individual difference

id	Mean Abdomen	SD Abdomen	Mean Chest	SD Chest	Mean Lowerback	SD Lowerback	SD Abdomen vs Chest	SD Abdomen vs Lowerback	SD Chest vs Lowerback
s007	19.167	33.493	50.000	70.711	32.833	37.472	105.359	47.936	108.187
s008	19.500	25.074	16.833	18.638	0.000	0.000	29.998	25.074	18.638
s009	19.833	25.007	30.833	30.301	2.500	2.168	36.644	24.606	31.226
s010	15.750	0.500	16.333	1.211	15.400	0.548	0.957	0.500	1.304
s011	14.333	18.769	16.000	22.136	34.000	18.450	14.208	24.163	25.892
s012	44.833	24.991	43.833	30.590	26.833	26.095	17.401	41.766	43.904
s013	6.833	2.563	0.000	0.000	0.000	0.000	2.563	2.563	0.000
s014	35.000	18.547	41.000	15.139	26.500	20.207	10.985	20.535	15.067
s015	4.167	10.206	0.000	0.000	0.000	0.000	12.500	10.206	0.000
s016	5.333	6.743	19.500	12.046	17.333	20.017	14.120	23.673	26.821
s017	4.750	6.602	15.167	25.694	32.333	29.521	10.751	29.307	47.847
s018	7.000	3.559	5.500	5.196	16.000	12.000	5.802	14.855	15.588
s019	25.000	25.495	35.000	9.557	17.167	13.556	17.263	24.622	8.808
s020	5.400	8.142	6.000	7.348	42.500	21.947	13.077	18.661	21.032
s021	16.667	10.764	58.500	12.021	13.800	14.584	0.707	14.053	NA
s022	5.333	8.287	0.000	0.000	16.000	18.276	8.500	16.354	21.213
s023	3.400	4.980	3.500	4.950	1.667	2.875	0.707	5.505	2.121
s024	3.200	7.155	0.000	0.000	7.750	8.958	7.155	8.958	8.958
s025	36.400	21.594	30.000	31.249	33.000	26.048	42.406	24.193	47.809
s026	30.400	32.784	37.000	38.184	30.750	35.566	NA	56.835	NA
s027	41.500	17.678	30.500	17.997	39.400	14.977	13.435	NA	28.420
s028	0.000	0.000	54.500	34.093	0.000	0.000	34.093	0.000	23.702
s029	10.000	13.856	14.500	26.591	23.167	36.058	12.418	48.489	53.042
s030	13.500	12.645	7.500	8.240	2.667	6.532	17.053	13.659	7.910
s031	0.000	0.000	3.500	6.442	3.167	7.757	7.544	9.500	11.325
s032	3.667	5.820	8.167	8.998	0.000	0.000	9.649	5.820	8.998
s033	47.500	42.978	56.800	33.641	47.333	38.166	69.888	63.405	36.329
s034	43.800	20.092	16.167	11.125	50.600	20.219	26.848	16.840	19.882
s035	0.000	0.000	0.000	0.000	10.167	15.753	0.000	16.709	13.864
s036	31.000	25.904	6.400	8.764	11.333	14.137	31.429	33.080	19.435
s037	36.400	37.454	44.833	24.951	56.600	41.914	25.811	63.570	51.267
s038	23.500	27.891	15.333	15.319	38.500	29.283	31.231	45.255	17.394
s039	59.000	11.730	48.667	5.785	58.500	10.710	15.148	15.215	13.348
s040	45.500	20.753	32.833	15.549	36.333	26.763	29.289	31.524	27.135
s041	6.167	5.076	7.833	9.517	36.000	24.470	6.377	22.338	20.331
s042	17.667	12.176	42.667	22.642	50.000	22.548	33.722	30.781	25.375

Table A.7: Synchronize individual difference

id	Mean Vertical	SD Vertical	Mean Horizontal	SD Horizontal	Mean Diagonal	SD Diagonal	SD Vertical vs Horizontal	SD Vertical vs Diagonal	SD Horizontal vs Diagonal
s007	0.000	0.000	37.667	48.735	5.000	5.774	47.216	5.774	50.027
s008	13.000	21.753	8.667	21.229	0.000	0.000	34.558	21.753	21.229
s009	20.833	37.960	2.333	3.830	16.167	24.790	38.919	52.489	25.031
s010	15.833	0.983	15.167	1.472	13.000	2.646	1.033	1.155	1.155
s011	14.000	26.840	45.500	16.171	28.833	30.420	36.341	13.891	33.435
s012	34.500	28.662	23.333	27.362	41.333	31.519	11.303	52.082	53.673
s013	3.833	6.585	2.167	3.710	1.000	1.549	2.875	5.231	2.401
s014	29.167	19.773	23.000	22.909	59.000	11.314	22.702	1.414	46.669
s015	2.500	6.124	0.000	0.000	0.000	0.000	6.124	7.500	0.000
s016	11.667	16.669	1.667	4.082	10.667	14.250	13.008	19.267	15.310
s017	5.333	8.262	27.333	28.040	16.750	15.987	32.515	10.689	41.428
s018	9.000	12.182	10.000	0.000	NA	NA	12.182	NA	NA
s019	15.167	11.321	26.167	18.357	26.000	0.000	18.232	1.414	9.899
s020	7.800	6.099	0.000	0.000	10.500	7.064	NA	11.167	10.607
s021	40.000	19.300	8.000	9.238	12.250	8.180	9.292	9.866	15.586
s022	4.000	8.000	0.000	0.000	7.500	8.240	8.000	0.500	8.240
s023	6.833	7.521	4.000	8.000	0.000	0.000	7.848	8.963	0.000
s024	2.000	2.828	5.167	8.010	4.167	7.055	2.828	2.828	12.869
s025	44.333	36.474	6.500	4.461	16.667	15.280	30.265	31.097	16.702
s026	34.333	24.826	0.000	0.000	0.000	0.000	NA	NA	0.000
s027	34.800	24.591	25.250	10.112	24.250	3.594	33.975	31.770	8.042
s028	19.600	36.032	2.167	5.307	2.333	5.715	30.332	29.895	0.408
s029	27.200	26.224	0.000	0.000	0.000	0.000	26.224	26.224	0.000
s030	10.667	8.287	10.333	8.017	10.833	8.400	9.852	10.128	14.335
s031	16.500	27.377	0.000	0.000	0.000	0.000	27.377	32.500	0.000
s032	17.000	9.633	5.667	13.880	5.167	12.656	13.292	12.400	1.225
s033	37.600	44.892	28.833	29.376	17.667	7.202	66.169	49.251	30.023
s034	12.500	16.197	41.167	29.822	44.667	27.725	36.724	46.757	38.723
s035	18.800	15.156	17.500	38.625	9.600	9.813	39.366	11.446	38.850
s036	70.250	37.098	0.000	0.000	0.000	0.000	37.098	37.098	0.000
s037	50.750	34.248	37.833	40.415	48.167	47.592	38.100	39.183	50.091
s038	49.500	37.893	13.667	26.808	16.667	27.732	54.098	59.318	16.297
s039	52.833	11.856	23.833	19.229	32.500	17.237	29.611	26.934	3.670
s040	32.167	26.529	27.833	37.510	13.667	4.676	36.043	29.194	41.997
s041	16.167	24.943	0.000	0.000	2.667	6.532	24.943	27.718	6.532
s042	55.500	23.864	27.333	36.456	41.500	33.441	43.120	32.305	38.249

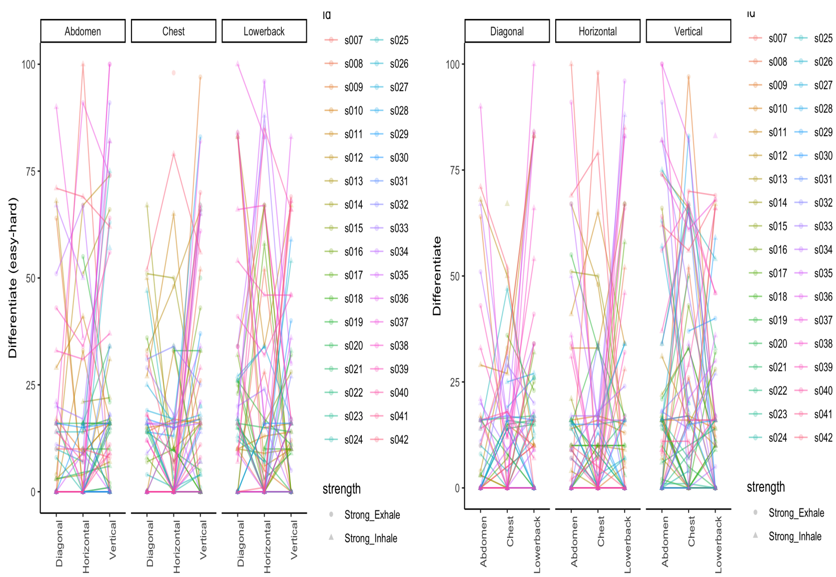
Table A.8: Differentiate individual difference



(a) By position

(b) By shape

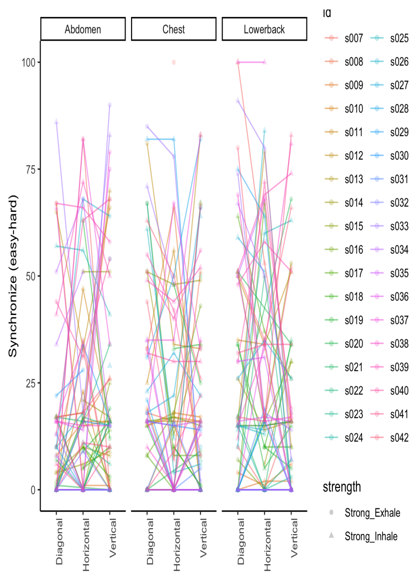
Figure A.10: Attend



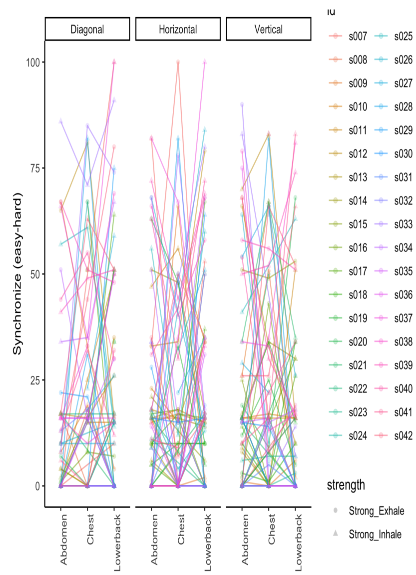
(a) By position

(b) By shape

Figure A.11: Differentiate

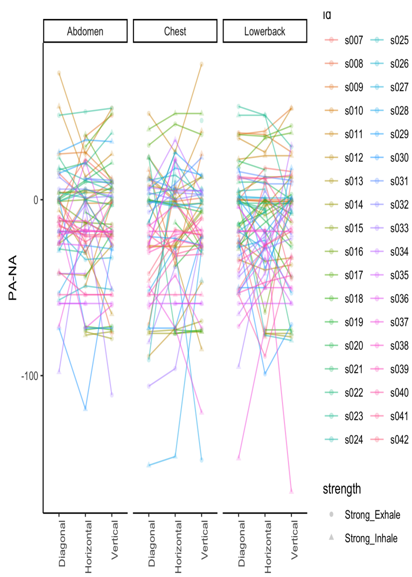


(a) By position

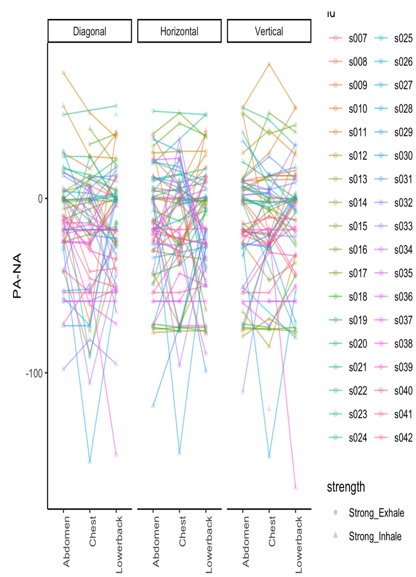


(b) By shape

Figure A.12: Synchronize

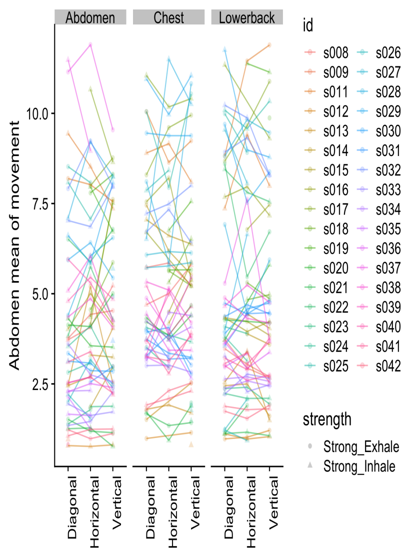


(a) By position

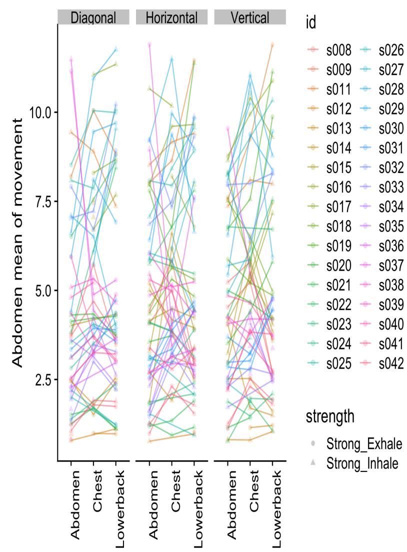


(b) By shape

Figure A.13: PA−NA

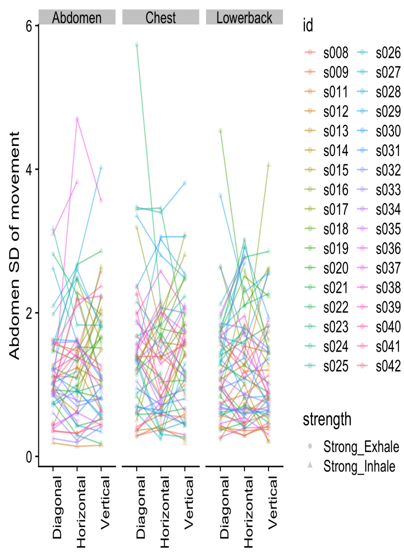


(a) By position

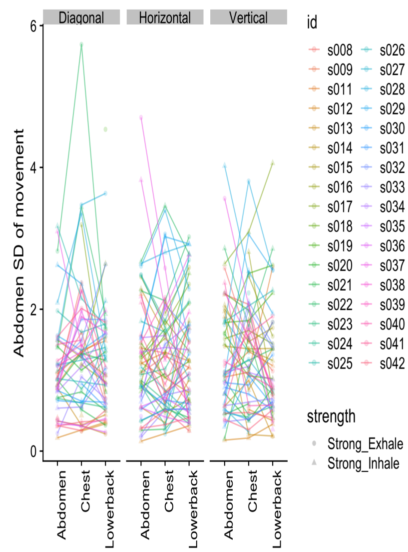


(b) By shape

Figure A.14: Abdomen, mean movement

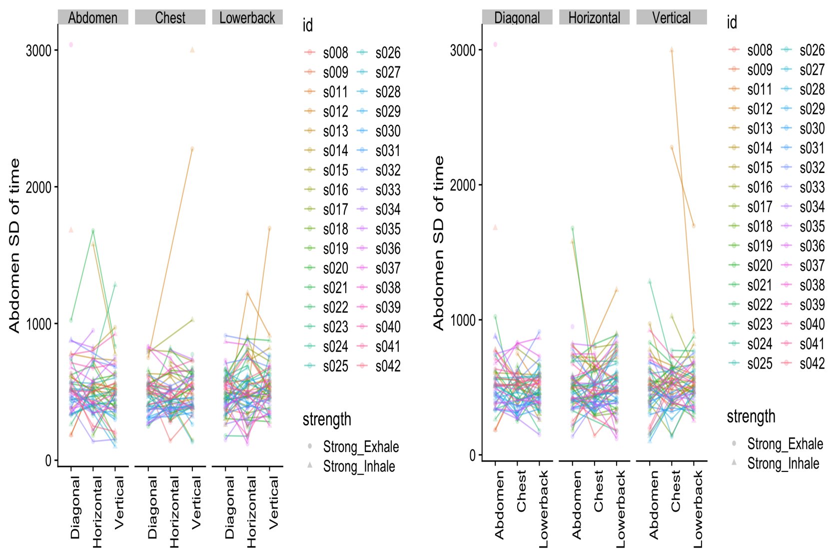


(a) By position



(b) By shape

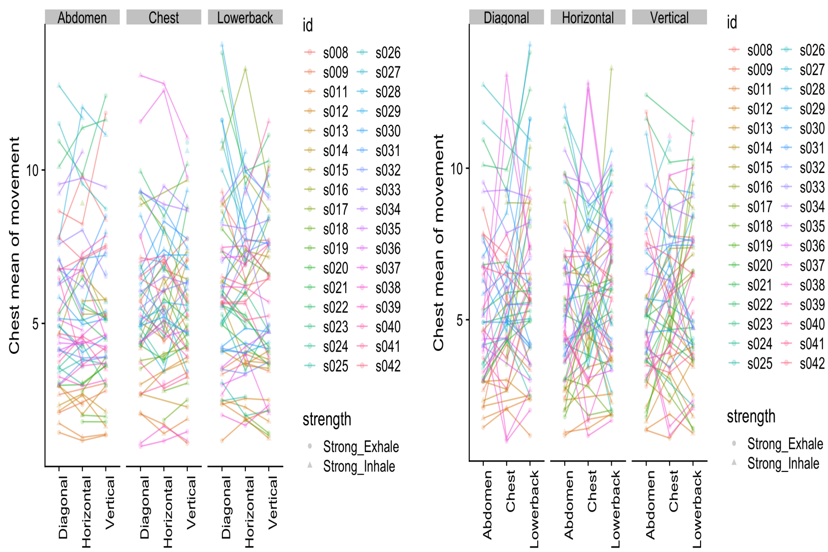
Figure A.15: Abdomen, SD movement



(a) By position

(b) By shape

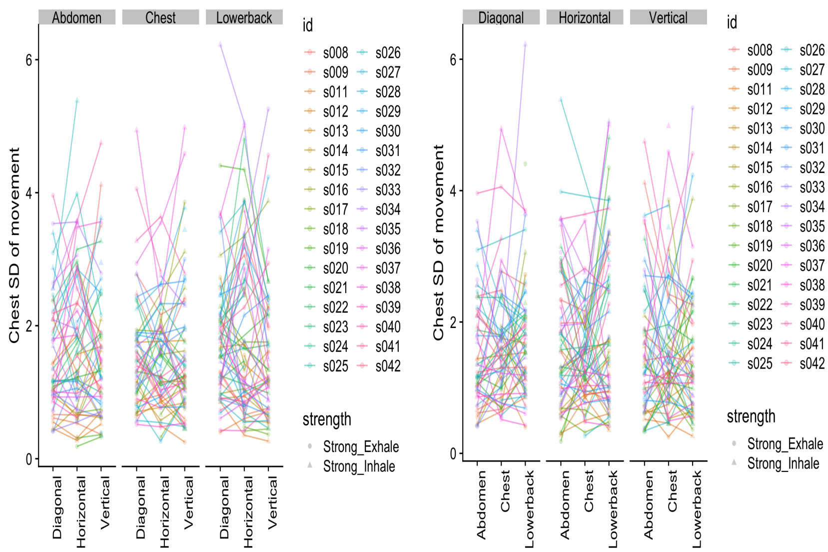
Figure A.16: Abdomen, SD time



(a) By position

(b) By shape

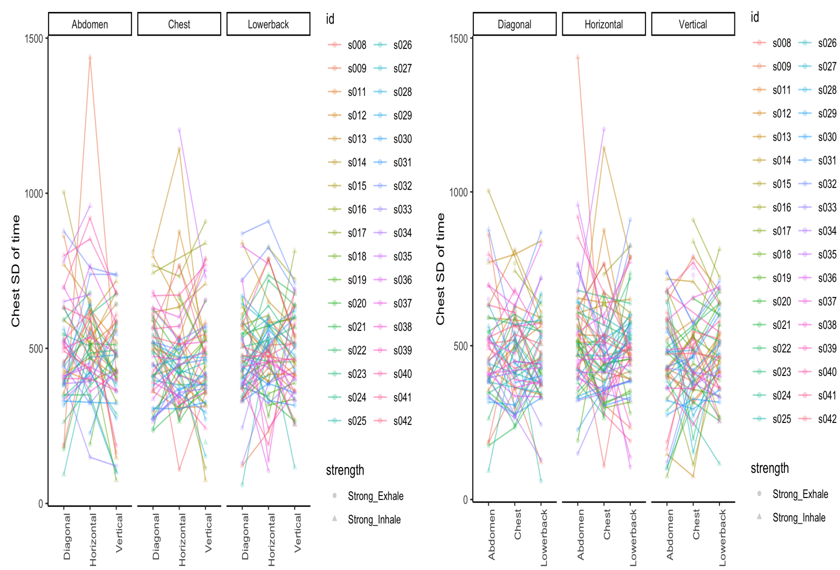
Figure A.17: Chest, mean movement



(a) By position

(b) By shape

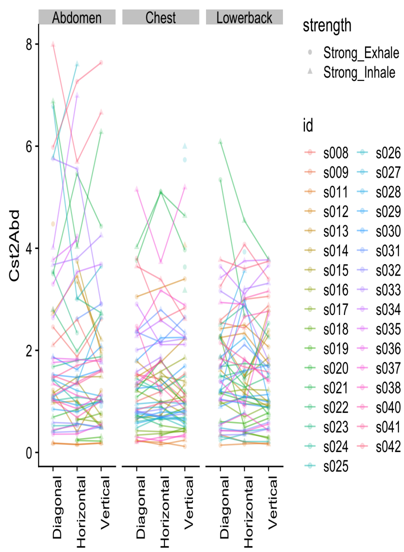
Figure A.18: Chest, SD movement



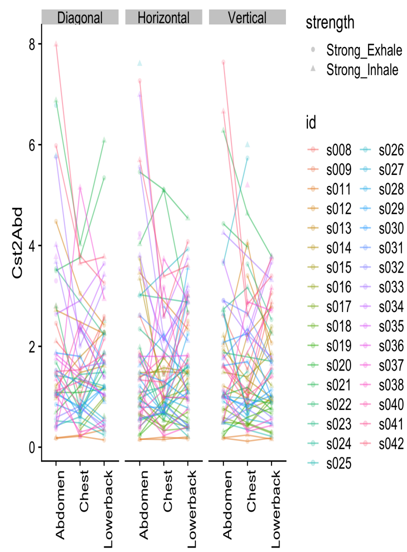
(a) By position

(b) By shape

Figure A.19: Chest, SD time

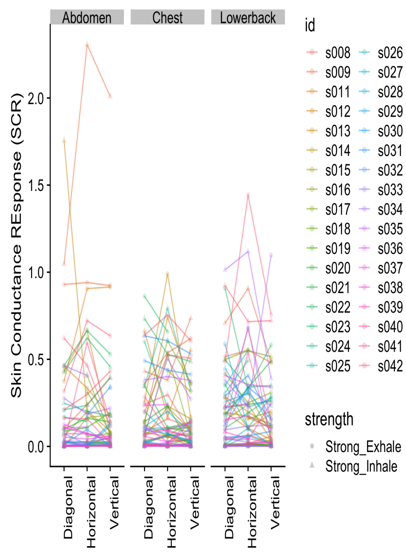


(a) By position

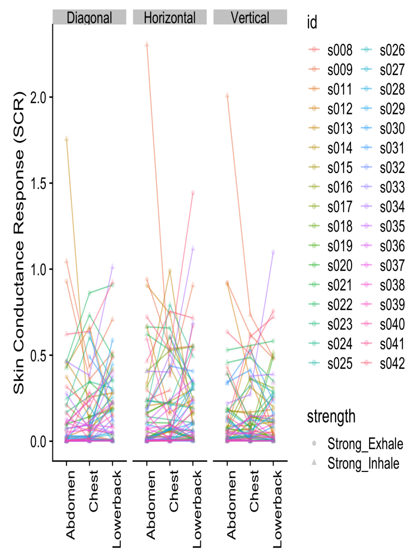


(b) By shape

Figure A.20: Chest movement to abdomen movement ratio

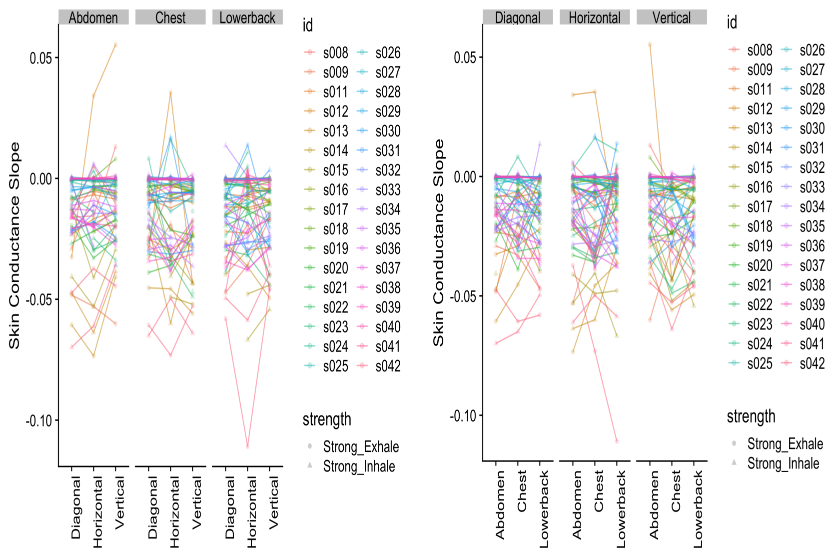


(a) By position



(b) By shape

Figure A.21: Skin conductance response



(a) By position

(b) By shape

Figure A.22: Skin conductance slope

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