PIV: Placement, Pattern, and Personalization of an Inconspicuous Vibrotactile Breathing Pacer

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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 a 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 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.

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CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; • **Computer systems organization** → *Sensors and actuators*; • **Hardware** → *PCB design and layout*; *Sensors and actuators*;

Additional Key Words and Phrases: Haptic, emotion, emotion regulation, wearable, EDA, skin conductance response, respiration, affect, vibrotactile, slow-paced breathing

ACM Reference format:
Pardis Miri, Robert Flory, Andero Uusberg, Heather Culbertson, Richard H. Harvey, Agata Kelman, Davis Erik Peper, James J. Gross, Katherine Isbister, and Keith Marzullo. 2020. PIV: Placement, Pattern, and Personalization of an Inconspicuous Vibrotactile Breathing Pacer. *ACM Trans. Comput.-Hum. Interact.* 27, 1, Article 5 (January 2020), 44 pages.
https://doi.org/10.1145/3365107

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1073-0516/2020/01-ART5 $15.00
https://doi.org/10.1145/3365107

1 INTRODUCTION

Slow-paced breathing has been shown to reduce perceived stress and physiological arousal [16, 52, 69], 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 study, 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 [7], 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 [6] or use the Breathe app [14] 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.*

During high arousal negative affective states (for example experiencing anxiety or anger), cognitive abilities diminish [32, 64], which may constrain us to apply unhelpful affect regulation strategies such as suppression, surface acting, visual avoidance, and distraction. These strategies are often called unhelpful because even though they help in the short term, applying them comes at a cost in the long run. For example surface acting can lead to job burnout, depression, and insomnia, and suppression can lead to cardiovascular issues. [23, 27, 31]

A central question is whether technology might be used to facilitate this reduction of high arousal negative affect in a context-appropriate way. To reduce high arousal negative affect, slow paced breathing is an effective strategy, which can change affect [35, 57]. But, it is hard to do in the heat of the moment. Therefore, a technology that can be used to facilitate slow-paced breathing in a social setting seems to be a reasonable solution.[1]

[1]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 article, we focus on the use case suggested above: the use of vibrotactile technology to inconspicuously interact with the user.

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.

Given the small amount of work published on the design of effective vibrotactile breathing pacers and with us being motivated by scenarios similar to above, we (1) theorized about the design of an effective breathing pacer, (2) built a personalizable and inconspicuous vibrotactile (PIV), a high-fidelity wearable breathing pacer prototype, (3) designed a personalization procedure, and (4) conducted an exploratory study to decide where the pacer should be placed on the body and what type of pacing pattern is effective.

Our study examines the consequences of different choices one can make in designing a vibrotactile breathing pacer. To describe these choices, we first introduce 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 BPM). 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 (Figure 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 (Figure 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.

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 × 3 shapes × 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 × pattern × order effect was most effective, we produced covariance pattern models with a heterogeneous compound symmetric error structure for each DV. We

This use case is an important one: as we describe in Section 2, many commercial devices appearing on the market that unobtrusively help regulate emotions use vibrotactile technology.

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 7.

Contributions. This article contributes the following: (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 article is about PIV placement, pattern, and personalization.

A strength of our contribution comes from the interdisciplinarity of our team. Included in 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 [53, 54].

2 RELATED WORK

There is a considerable design and development work currently taking place in vibrotactile interventions for assisting with emotion regulation.

We use the framework in Miri et al. [53, 54] for exploring this broader set of projects and products. Miri's model is motivated by Gross's process model [30]. We first describe the framework, and then in Section 2.4, use it to discuss projects similar to ours.

This framework defines three types of haptic interventions for emotion regulation: *cueing*, which directs someone toward an emotion 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 of haptic intervention reflects a different way for the user to interact with the device. Two projects 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.

2.1 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 [4], Spire Stone [7], and Vitali Sports Bra [8]. 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 that the user possesses was 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 [63]. There are some promising results that are useful in narrow situations [7, 59]. 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 do not know how they compare with a person's own ability to detect rising emotions in the context of, say, a tense meeting. For the purpose of PIV, we rely on the user's own abilities to detect rising emotions, but we can benefit from advances in cueing interventions.

2.2 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 2.3.) 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[2] [34].

Implicit interventions are intriguing because they place few cognitive demands on the user. Examples of projects that used implicit involvement include Doppel [9] and EmotionCheck [19]. 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 [24].

A third example of the use of an implicit involvement intervention is Haptic Creature [72]. This was a furry vibrotactile toy, about the size of a cat, that used 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.[3] Haptic Chair [60] 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 [59]. This is a clever example of emotion detection in a specialized setting.

Breeze [25] 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),

[2]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 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.

[3]Lief Patch also implemented a vibrotactile breathing pacer, but we have no information on the haptic pattern outside of it being "gentle" [3]. Lacking information, we don't discuss its utility as a breathing pacer.

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 [74] used tactile (but not vibrotactile) haptics. It consisted of a small rubber bag that inflated and deflated. The user rested their hand on 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 HRV and breathing rate, but not as measured by self-reported measures.

2.3 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. We have found only one project that uses feedback intervention, namely Lief, which used feedback intervention based on a set of 3-minute breathing exercises that can affect HRV.

2.4 PIV in Relation to Other Devices and Projects

PIV uses explicit involvement intervention. 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 [16, 52, 69].

Table 1 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 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 [33, 40, 49]. 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 [39] 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 1. 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 BPM [41]. 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.

Table 1. List of Vibrotactile Devices Used of Anxiety Reduction

	(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 [19]	intervention	implicit involvement	anxiety reduction	no	yes	somewhat	wrist	no	no
Haptic Creature [72]	intervention	implicit involvement	anxiety reduction	no	no	no	NA	no	no
Haptic Chair [60]	sensing & intervention	explicit involvement	anxiety reduction	yes	no	no	back	no	no
Breeze [25]	intervention	explicit involvement	anxiety reduction	yes	yes	somewhat	chest	no	no
Breathe With Touch [74]	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

3 MEASURES AND MODELS USED IN THIS ARTICLE

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. The goal of this section is to make it easier to comprehend the results in Section 7.

3.1 Emotion Regulation Model

Our work is inspired in part by the model of emotion regulation by James Gross [29, 30]. 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).

3.2 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 PA and NA using two separate axes. Doing so addresses the evidence that suggested individuals can experience mixed emotional states, such as guilty pleasure [10, 37, 46, 48].

Kron [43, 44] 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 facial motor activity as measured by electromyographic (EMG) activity 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 [43, 44].

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.

3.3 Linear Mixed Model and Covariance Pattern Model

Linear mixed models (LMMs) 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 LMM 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 we have, which may not hold true in all situations.

This model is appropriate to use when reporting how much of the variability of each personalization parameter is explainable by the body placement and the individual differences. We used this model to report the findings in Section 7.1.

Covariance pattern model, on the other hand, is appropriate to analyze the dependent variables of self-reported and physiological measures in our study because it does not make the compound symmetry assumptions.

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, and so on. 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. Given the number of IV in our dataset, using a heterogeneous compound symmetric error structure was appropriate.

The unstructured error structure can take a very long time to converge when the number of conditions is too high and when some DVs have missing measurements. We found this to be the case, and so we used the covariance pattern model with a heterogeneous compound symmetric error structure, which converges much more 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, we started 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.

3.4 EDA and Continuous Decomposition Analysis

EDA refers to the phenomena of the variation of the electrical properties of the skin in response to sweat secretion [24]. 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 1 and the red circled areas of the purple curve in the lower part of Figure 6(c)).

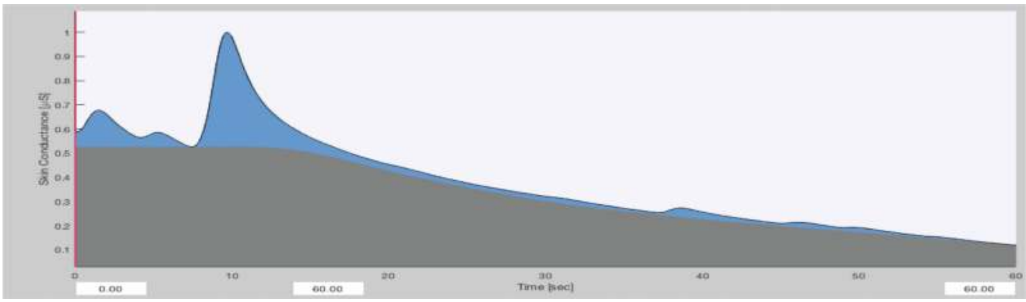

Fig. 1. Skin conductance from one of our trials as displayed by the Ledalab analysis software. The blue area indicates the phasic component of the signal, and the gray area represents the tonic component.

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 [13, 22]. This technique, however, can be limiting in the case of closely superposing SCRs [28, 45]. The issue of superposing responses motivated us to use other methods that offer a more precise assessments of the SCR amplitude.

Continuous decomposition analysis (CDA) [11, 12] 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 1). This method is useful especially in situations with high phasic activity. The tonic activity gives basic level of skin conductance (SC) level and varies, depending on the individual, between 2 and 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 [17]. In this study, we used this method to analyze the phasic component of the SC signal. More specifically, we used the Matlab-based LedaLab software [2] 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 [21, 42, 47].

4 THE DESIGN OF THE BREATHING PACER

In designing the breathing pacer, we adopted the following 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.

4.1 Using Haptic Intervention

There are several advantages in using vibration in affect regulation interventions. They include the following: (1) vibrations engage the largest organ of the body, which is not prone to rapid decay of short-term sensory memory [18]; (2) relative to vision and hearing, the spatial resolving power of the skin is poorer than the ear's but better than the eye's [49]; (3) vibrotactile signals are simple, personal, and subtle, making them attractive for use in technological aids [26] especially when other channels including visual and auditory are overloaded or unreliable [38, 65]; (4) due to the lack of decay of short-term sensory memory, vibrotactile signals works well for learning; (5) passive haptic learning (PHL) allows people to learn muscle memory through vibration stimuli while devoting little to no attention to the stimulus [68]; (6) vibrotactile signals are private, whereas visual and auditory cues are not. This reduces the stigma of using therapeutic device, which is an important barrier; (7) vibrotactile signals can be annoying but they can also be pleasant if designed correctly. For example, Morrison et al. [55] suggest that on the trunk of a body, constant vibration is unpleasant, but vibration that varies in magnitude or location is pleasant.

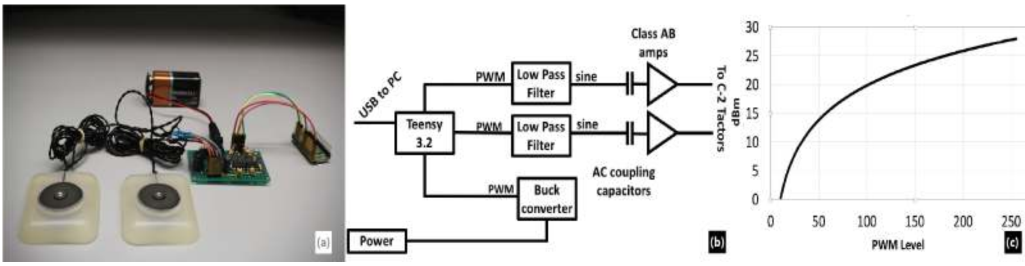

Fig. 2. PIV device (a); PIV circuit board design (b); C-2 power in terms of PWM levels (c).

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) [5], 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 [1] 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 100 kHz) 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 [58], 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 2(c) shows this relation, with power expressed in terms of dBm (decibels with a reference power of 1 milliwatt).[4] The maximum power in this scale is 27.6 dBm. In the result section, we reported the amplitude values of personalized haptic shapes in units of PWM level.

4.2 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) [40]. 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

[4]Perception also depends on the efficiency of the C-2 tactor, which is not taken into account in Figure 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 $dBm(\text{PWM}) = 10\log_{10}(((2.5 * \text{PWM}/255)^2/10) * 1{,}000) = 20\log_{10}\text{PWM} - 20.172$.

Fig. 3. C-2 tactor chest placement (a); abdomen placement (b); lower back placement (c); frequency - amplitude representations of the three shapes (d).

in social settings. In addition, the PIV tactors should be located in a place that is effective in pacing breathing [15, 56]. 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 [51], since one often looks at a wrist-mounted device by bending the head down.

4.2.1 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 ourselves (the authors and research assistants (RAs)), we all preferred to have two symmetrically placed tactors at least 2 to 3 inches from the midline. This is consistent with advice from our authors 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.

4.2.2 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 3(a)–(c). These body locations were chosen due to their importance in breathing training taught by biofeedback practices as well as professional singers.

—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 [62]. 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 [41]. 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 [50] and so this spot should be sufficiently sensitive to be useful.

In addition, the lower back is an area that is considered in breathing practices in specific populations, such as singers. Professional singers also learn breathing exercises by focusing on four areas of the lower body that can expand while inhaling (waist, midriff, lower abdominals, and lower back) [36].

—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 do not contradict the results of [40]. 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 and 8, and our chest sites are their sites 10 and 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.

4.3 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 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.

4.3.1 Pacing Shapes. The biofeedback practitioners guided us in choosing the shape we used in this study. The shape is reminiscent of the sound of breathing. Figure 4 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 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.

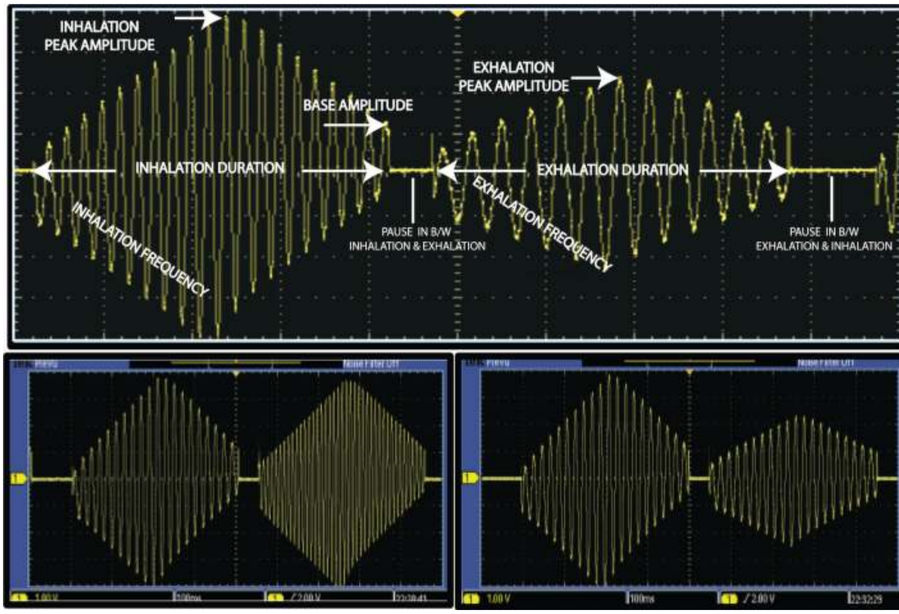

Fig. 4. A horizontal pattern with order = strong exhale on the top; A vertical pattern with order = strong inhale on bottom left; A vertical pattern with order = strong inhale on bottom right. All these three breathing patterns are captured with an oscilloscope. The *x* axis represents time and the y axis represents PWM level.

4.4 Being Personalizable

Given a pattern, the pacer needs to be personalized for the participant. One part of the personalization process involves finding their BPM and *br*. As we observed in Section 2.4, the goal is for the user to practice effortless, uniform slow-paced breathing that is within the range of 4.5 to 9 BPM [41]. 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 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 6.2 and Algorithm 1. We assessed whether there is variability across subjects in these parameters in Section 7.

4.5 Being Usable at Any Place and Time

In our use case scenario, the situations that can create anxiety can arise at unpredictable times. This unpredictability of such situations suggests a wearable haptic pacer that it is always available and usable even when the user is involved in other activities.

4.5.1 PIV Hardware and Software Design. 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 V; as such, it not appropriate for a wearable. The Macaron approach [66] 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 V circuit board that uses a Class

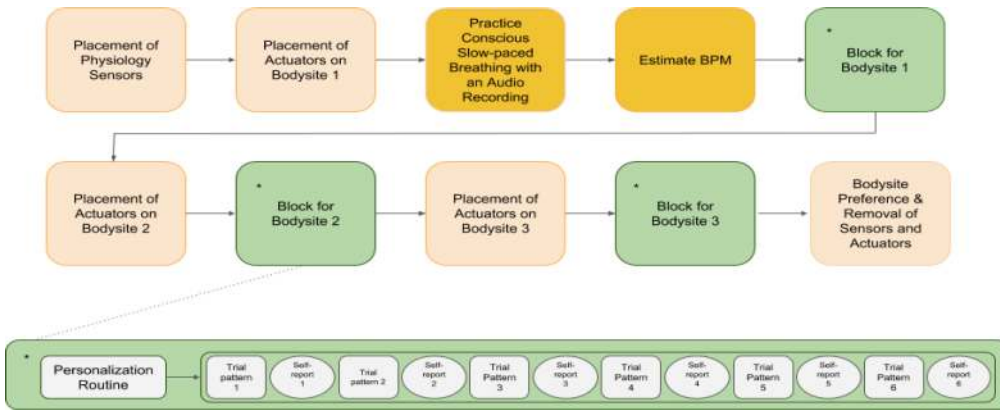

Fig. 5. Experimental protocol for each participant. The beige boxes are the actions that involve the RA working with the participant on experimental setup and pacer placement. The gold boxes are actions with the RA in the control room and the participant alone in the experimental room. The green boxes, exploded in the bottom, include the vibrotactile personalization routine for that placement followed by six randomized pairs of trials and self-reported responses.

AB amplifier[5] to produce a clean sine wave. This board drives two C-2 actuators simultaneously (see Figure 5, upper right) and is powered by a battery or a 9 V 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 experimenter 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 RESEARCH QUESTIONS

We used a lab-based no-stressor approach to investigate pattern and placement as a function of PIV experience and efficacy.[6]

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 [16, 41, 52, 69]. Hence, we would prefer

[5]We used On Semiconductor L272M amplifiers.
[6]For the purposes of practicality, we did not introduce a stressor into this study. Our findings, such as the importance of personalization, the limitations of amplitude-based shapes, and the effect of placement on chest to abdominal breathing ratios, hold as long as the user is successfully able to synchronize with the pacer in the presence of certain stressor types and magnitudes.

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 personalizing of the vibrotactile pattern for each body site? See Section 7.1.
(2) How do the choices of body site and breathing vibrotactile pattern influence participant affect as well as their ability to attend to the pacer, to differentiate the cues for inhaling and exhaling, and to synchronize breathing with the pacer? See Section 7.3.
(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 7.4.

6 EXPERIMENT

A total of 36 volunteers (14 female and 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 onsite 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[7] to collect, with a sampling rate of 256 Hz, 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.

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.

[7] http://thoughttechnology.com/.

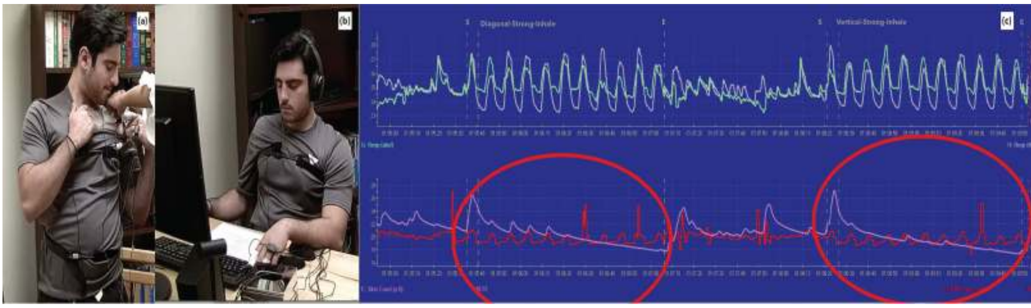

Fig. 6. C-2 tactor placement on the chest (a); participant performing paced-breathing during a trial (b); physiology measurements of the participant during two trials (c). The top graph shows the breathing curves: the teal curve is for the abdomen and the gray curve for the chest. The lower graph shows the pulse rate (red) and SC (purple).

6.1 Experimental Protocol

The protocol is shown in Figure 5. It had a three factor within-subjects design. The factors were placement (chest, abdomen, and lower back), shape (vertical, horizontal, and diagonal), and order (strong inhale and 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 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 6(a) and (b)). When attaching the tactors to a 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 Bose 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 5 minute recording that led them through a mindful, slow paced-breathing exercise. The participant was asked to practice these breathing techniques for 2 minutes while listening to text from [20] 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 [41]. The *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 6.2 and the pseudocode is presented in Appendix D 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; and (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 to 100 with the seven 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 to 100, with 0 labeled as not at all and 100 labeled as extremely.

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.

6.2 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 D. The goal of this routine is to determine the six points in frequency—amplitude space shown in Figure 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.[8] These parameters were used as follows (see Figure 3(d)):

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

Table 2. Descriptive Statistics of Personalization Parameters

Param	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]

- 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 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 [41]. 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).

7 RESULTS AND DISCUSSION

In this section, we will be answering the research questions specified in Section 5.

7.1 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 2. These differences can be seen in Figure 7. 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} (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 LMM with body site as the fixed effect and id as the random effect.[9] And, we used a

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

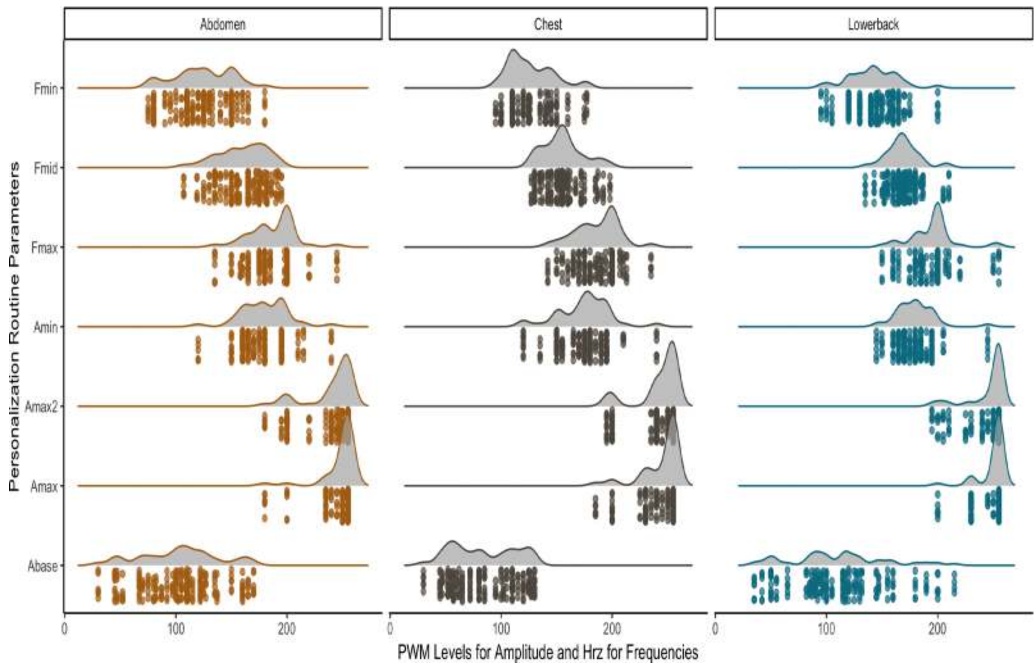

Fig. 7. Distributions of each personalization parameter (both frequencies and amplitudes) on three body sites. The top three lines refer to frequencies and the remaining four refer to amplitudes. In the case of frequencies, the *x*-axis is measured in Hz; in the case of amplitudes, the *x*-axis is PWM 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.

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).[10] We found that all seven parameters differed significantly between body sites. Table 3 summarizes the results.

Comparing the last two columns in Table 3, it is readily apparent that the variance due to individual differences is at least 4–5 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.

7.2 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 A.1. Then, for each of the seven DVs of interest, 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 with Bonferroni correction. The decisions about which effects to report were based on the results of this second model with p values being smaller than 0.0071 considered as significant. Then, for each of

[10] This is the formula that we used in R to perform this test: tab_model(model.fit, show.std = “std2,” p.val = “kr,” show.adj.icc = TRUE, show.df = TRUE).

Table 3. Sources of Variance on Calibration Parameters

Param	$F(2, 610)$	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%

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, $p < 0.0001$.

Table 4. Descriptive Statistic on Self-Reported Measures

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]

the pairwise comparisons, we made an additional correction (divided p by number of pairwise comparisons).

The main effect results are listed in Tables 5–7 and Appendix C. The seven DVs of interest are Differentiate, Synchronize, PA–NA, Mean_cst_movement, Mean_abd_movement, Ch:Ab ratio, and CDA.SCR.[11] We used the two DVs Attend and SC_slope as manipulation checks: in both cases, we expected that participants could attend because of personalization, and that SC_slope would be negative). For the remaining four DVs, SD_abd_movement, SD_abd_time, SD_cst_movement, and SD_cst_time, we note their correlation with high movement.

7.3 Pacer Experience: Self-Reported Measures

The second question was how the choices of body site and breathing vibrotactile pattern influenced participant self-reported measures. The self-reported measures were positive and negative affect as well as ability to attend to the pacer, to differentiate the cues for inhaling and exhaling, and to synchronize breathing with the pacer.

7.3.1 Descriptive Analysis. The descriptive statistics for self-reported measures are shown in Table 4, Figures 8 and 9. The range of possible values for all five measures was $[0, 100]$. For synchronize, attend, and differentiate, higher values indicated more difficulty in performing that action. High PA values indicated high positive affect, and high NA values indicated high negative affect.

[11]These measures will be introduced in Sections 7.4.1, 7.4.2, and 7.3.

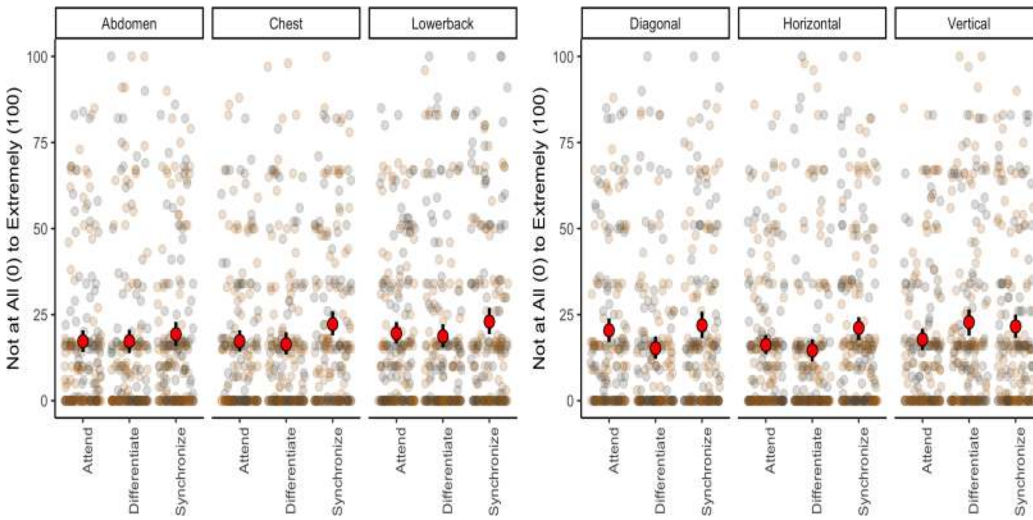

Fig. 8. Descriptive statistics of the self-reported measures of attend, differentiate, and synchronize. Note that the higher the *y* axis value, the harder it was to attend, differentiate, or synchronize with a pattern. See caption of Figure 7 for explanation of diagram.

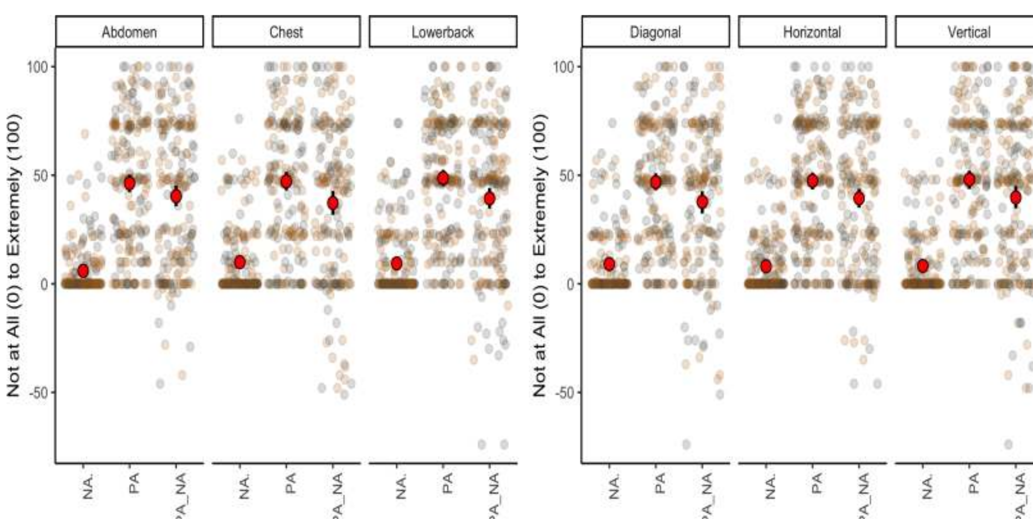

Fig. 9. Descriptive statistics of the self-reported measures of Positive Affect (PA, Negative Affect (NA), and the difference between PA and NA. Higher *y* axis indicates more extreme reports of PA, NA, and PA − NA. See caption of Figure 7 for explanation of diagram.

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 8 and 9). 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.

It requires some care to understand the self-reported NA values. We observed that some participants did not use the NA slider at all, and instead reduced their self-reported PA value to indicate

Table 5. Significant Results for Differentiate, Synchronize, and PA − NA Measures

Predictors	DV	Cohen's d	Mean Diff	Std. Error	$pr(>\|z\|)$
Shape:Vertical vs. Diagonal	Differentiate	0.31*	9.093	2.169	<0.0001
Shape:Vertical vs. Horizontal	Differentiate	0.32	9.287	2.104	<0.0001

The Cohen's d values suggest substantial shift between the two mean distributions. Adjusted for three pairwise comparisons, the value is significant at 0.0035. See Figure 17 for the visualization of the effect.

that they were not feeling as positive as before about a pattern. Thus, we created a summary measure of valence by subtracting the NA value from the PA value (PA − NA).

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.

7.3.2 Model Summary. To present the results, we reported in Table 5 the significant results of the three DVs of differentiate, synchronize, and PA − NA. Synchronize and PA − NA are not included as a DV in the table because we failed to find evidence that the model could explain the variability of that dependent variables. Finding that the PA − NA measure could not be explained by any combination of the fixed parameters led us to believe that participants had no preference for any pattern or body site.

Table 5 shows two significant results with regards to differentiation. 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 reported in Table 5 (and illustrated by the left graph of Figure 16 in Appendix C) suggest that, for differentiate, the mean for vertical shapes is approximately 30% of a standard deviation shifted from the means for the other two shapes. This represents 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 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 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.

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 ($\chi^2 = 0.30$, $df = 2$, $p = 0.850$) 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.

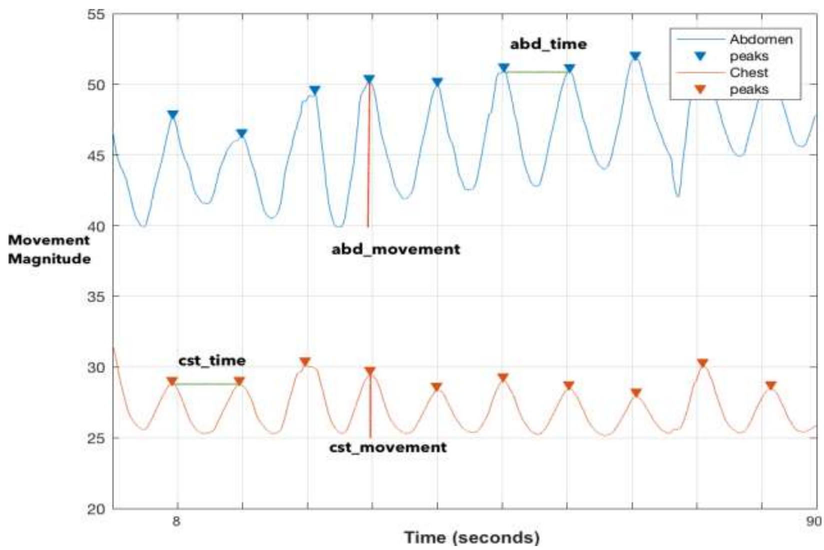

Fig. 10. Breathing waves from Subject ID 18, with abdomen placement, vertical shape, and strong inhale.

7.4 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 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 10 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 1 and the purple curve in the lower part of Figure 6(c) are examples of SC signals collected during a trial from Subject 21.[12]

7.4.1 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 (Figure 10). 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 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.

[12] As noted in Section 6, SC and breathing data was collected via a Thought Technology system with a sampling rate of 256Hz.

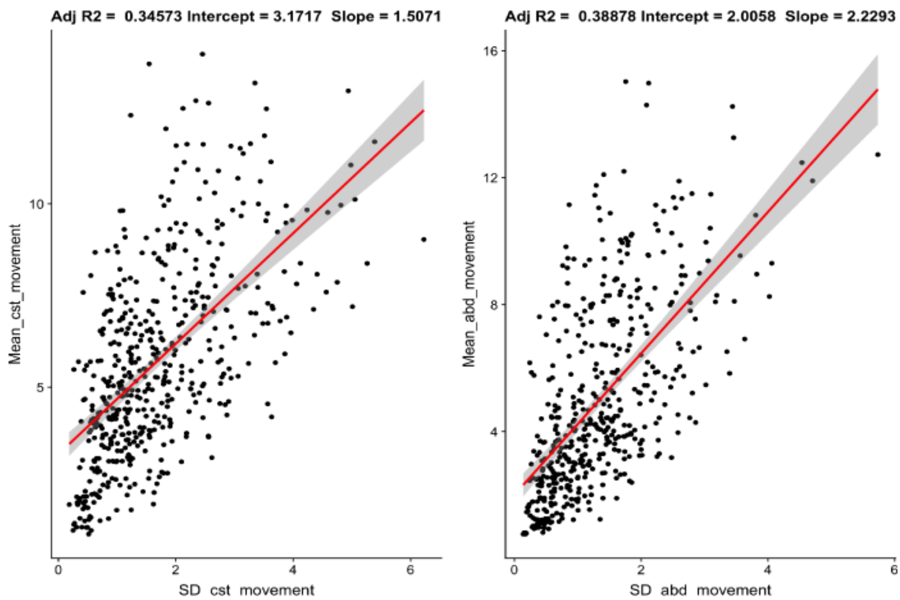

Fig. 11. Linear regression lines suggest that an increase in the mean of chest or abdomen movement results in an increase in the irregularity of the chest or abdominal breath depths.

Table 6. Significant Results for Mean_abd_movement, Mean_cst_movement, and Ch:Ab Ratio

Predictors	DV	Cohen's d	Mean Diff	Std. Error	$pr(>\|z\|)$
Order:Strong_Inhale vs. Strong_Exhale	Mean_cst_movement	0.13	0.429	0.125	0.001
Placement:Abdomen vs. Lowerback	Mean_cst_movement	0.21	− 0.525	0.156	0.002
Placement:Abdomen vs. Lowerback	Mean_abd_movement	0.23	− 0.617	0.12	0.009
Placement:Abdomen-Chest	Mean_abd_movement	0.33	0.36	0.112	< 0.0001
Placement:Abdomen vs. Lowerback	Ch:Ab ratio	0.25	0.17	0.084	0.131
Placement:Abdomen vs. Chest	Ch:Ab ratio	0.34	0.334	0.084	< 0.0001

The Cohen's d values suggest substantial shift between the two mean distributions. Adjusted for three pairwise comparisons, the p value is significant at 0.0035. See Figures 16 and 17 for the visualization of the effect.

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 [16, 41, 52, 69].

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 correlation matrix of these breathing measures are presented in Figure 15 of Appendix B. The results suggested that the mean of the chest and abdomen movement are highly correlated with the standard deviation of chest and abdomen movement, but not with the standard deviation of chest and abdomen times. Figure 11 shows the relation between the SD and the mean of movement for both the chest and abdomen: the higher the depth of the breathing, the higher the depth irregularity and the more difficult the paced breathing.

Table 6 and Figures 16 and the right graph of 17 in Appendix C show our findings. Specifically:

—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

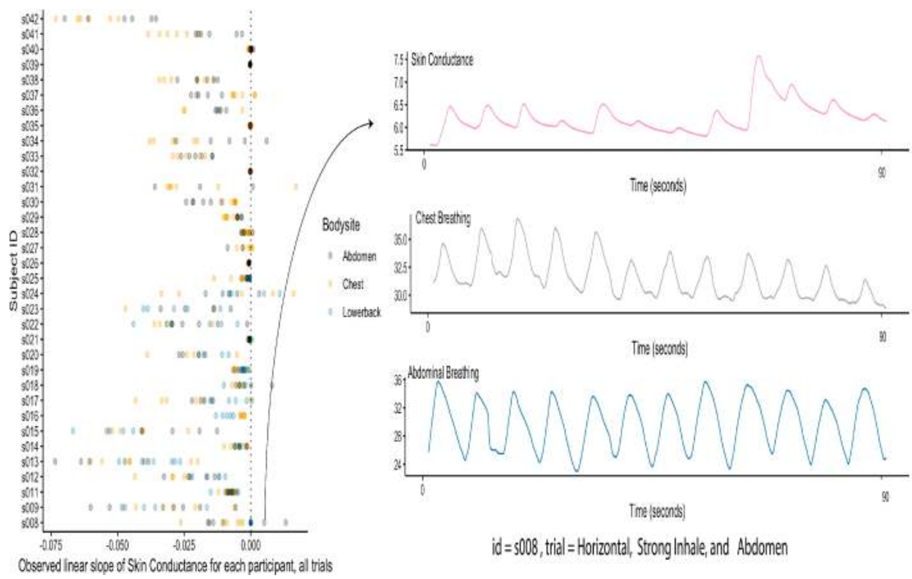

Fig. 12. A negative slope of the linear regression for SC indicated a calming effect for that trial (image on the left). There were 30 trials in which the slope was greater than zero. The image on the right illustrates one of such trial (Subject ID 8, placement = abdomen, shape = horizontal, order = strong inhale).

exhale. Given that the Cohen's d for both of these DVs is around 0.13, we consider these as negligible effects, yet worth further exploring in future studies.

—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 ($d = 0.23$) or abdomen ($d = 0.33$). These results suggest that when tactors are moved to the abdomen, the amount of chest and abdomen breathing both decrease, but 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.

Together, these points suggest that a strong exhale pattern and placing the tactors on the abdomen are good choices for our future studies.

7.4.2 SC Measures. For most trials of paced breathing, the SC signal dropped during the trial. Examples are shown in Figure 1 and in purple in the lower part of Figure 6(c). Recall that a dropping SC signal is associated with reduced sympathetic nervous system arousal. As a manipulation check, 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 12), 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 12, which illustrates the SC and breathing waves for a trial by Subject ID 8 (placement = abdomen, shape = horizontal, and 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 CDA.SCR using the CDA method implemented in Ledalab software. We found that when the vibrotactile pattern is vertical as compared to horizontal, CDA.SCR was significantly

Table 7. Significant Results for Skin Conductance Response (CDA.SCR)

Predictors	DV	Cohen's d	Mean Diff	Std. Error	$pr(>\|z\|)$
Shape:Vertical vs. Horizontal	CDA.SCR	0.15	−0.038	0.012	0.003

Adjusted for three pairwise comparisons, the p value is significant at 0.0035. See Figure 17 for the visualization of the effect.

reduced, which indicates less tonic activity. In other words, it appears that less arousal was observed when the tactors played vertical shapes. The effect size, however, is very small ($d = 0.15$), and so we do not take this result into much consideration. Table 7 and the center graph of Figure 17 in Appendix C summarize this result.

8 DISCUSSION

8.1 Preferred Choices of Body Site and Pattern

The analysis of the breathing signals 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. We also observed 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.

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 measure of 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. As described in Appendices E.5 and E.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 vs. 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 tradeoffs 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 SCR, then abdomen is more preferred than the lower back.

8.2 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 [25] 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 (Table 1), 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 [70]). 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 vs. 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 [9, 19]. 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 [16, 52, 69]. 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 [9] 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.

9 CONCLUSION

This article described a study on the design, pattern, and placement of a PIV breathing pacer. 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 toward 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.

Based on the physiology measures analyses, we think that the abdomen is an appropriate choice for placing the pacer tactors. With regards to the breathing pattern, after incorporating breathing and SC signals analysis, we concluded that the depth of the breathing has an effect on how smoothly a user breathes: deeper breaths result in larger depth-wise irregularity. Therefore, we think it is wise to use body placement with that does not result in too strong chest or abdominal breathing depth. 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 could not provide higher amplitudes.

Several researchers have observed that vibration is effective for eliciting higher arousal (and often unpleasant) emotions [67, 71, 73]. 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.

APPENDICES

A 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.

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 13(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

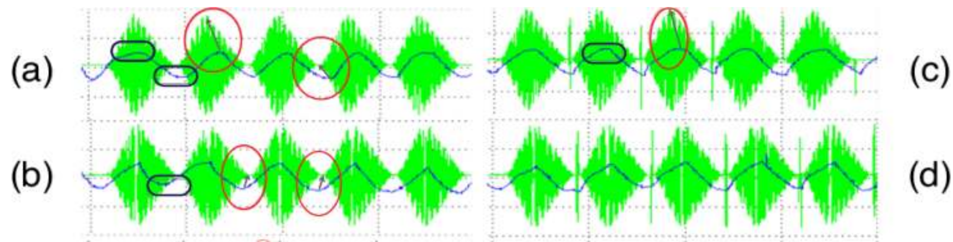

Fig. 13. Accelerometer data showing a user's breathing signal (shown in blue) overlayed with the haptic pacing pattern waveform (shown in green) the user was pacing with. The *x* axis represents time and the *y* axis represents PWM level. The breathing signal and the haptic pattern were not in phase, 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.

wave and the haptic wave were not in phase, as noted in the circles. The reason for this delay is explainable: [61] 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 13(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 13(c)). This also worked well: as can be seen, he deliberately began to inhale at the correct times. Figure 13(d) shows the results of using a pacer with both the pause and the pulse.

A biofeedback practitioner on our team, 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.

A.1 Inclusion and Exclusion

In total, we excluded 78 of the 648 trials (12%) 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 14 shows these trials. On the left, we present the 22 trials whose measured BPM are outside of the range of 5–9 BPM[13] On the right, we show two of these problematic trials. The top trial shows

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

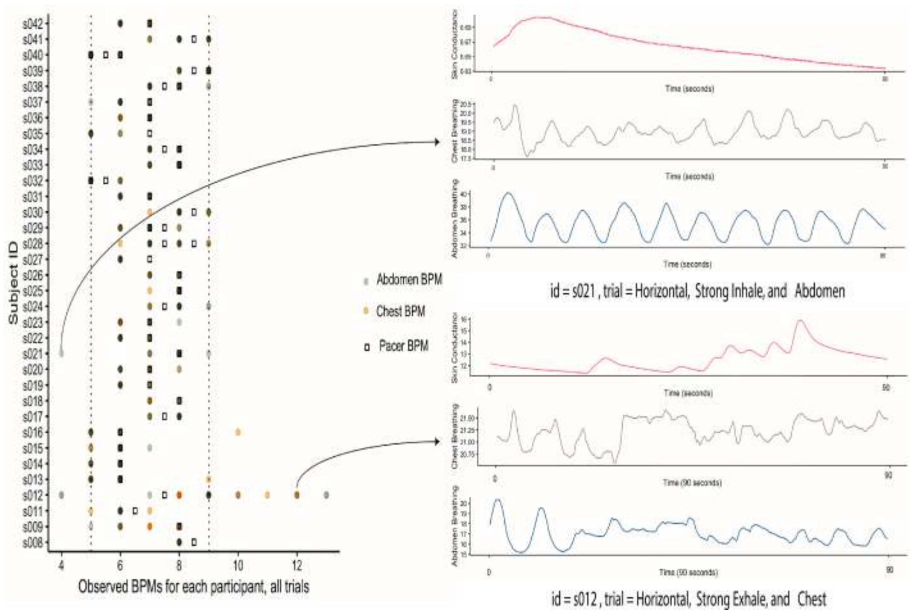

Fig. 14. Left: the pacer's BPM (unfilled squares) and approximate measured BPM (colored squares) for all the trials. Right: two of the 22 trials that lie outside of the range of 5–9 BPM. See discussion in article.

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 do not 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 do not 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 than most. The bounds we chose that triggered further inspection are as follows:

— mean_abd_movement > 12
— sd_abd_movement > 3.5
— sd_abd_time > 1,000
— mean_cst_movement > 14
— sd_cst_movement > 19
— sd_cst_time > 1,000

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:

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	Vertical, 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. These cases are as follows:

DV	Subject ID	Placements	SD from mean
abd_std_dev	s027	Chest vs. lower back	−3.01
cst_sd_movement_log	s019	Abdomen vs. lower back	−3.75
abd_mean_movement	s037	Abdomen vs. lower back	3.34
abd_mean_movement	s022	Abdomen vs. chest	−4.17
abd_mean_movement	s019	Chest vs. lower back	3.26
PA − NA	s028	Abdomen vs. chest	3.71
Synchronize	s028	Abdomen vs. chest	−3.24
CDA.SCR	s009	Abdomen vs. chest	3.63

B BREATHING MEASURES CORRELATIONS

In this section, we present the correlation matrix of the breathing measures that we investigated in this study. Note that the largest correlations are between Mean_cst_movement and SD_cst_movement, as well as between Mean_abd_movement and SD_abd_movement. That is, deeper breaths are correlated with more variance in the depths of the breaths.

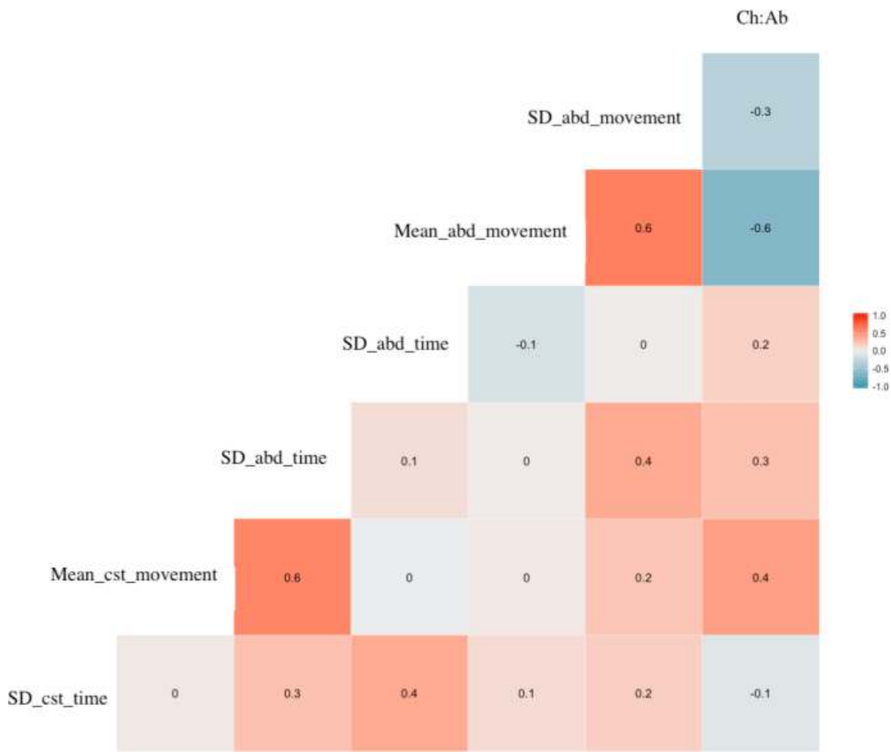

Fig. 15. Correlation matrix of all breathing measures. We concluded that the mean of the chest and abdomen movement are highly correlated with the standard deviation of chest and abdomen movement, but not with the standard deviation of chest and abdomen times.

C MAIN EFFECTS OF THE DEPENDENT VARIABLES

In this section, we present the visualizations of the main effects listed in Tables 5, 6, and 7. Table 5 is shown in the left graph of Figure 17, Table 6 is shown in Figure 16 and the right graph of Figure 17, and Table 7 is shown in the center graph of Figure 17.

D PERSONALIZATION ROUTINE: PSEUDOCODE

In this section, we present the personalization routine as pseudocode. The personalization routine involves several agents: the two RAs (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 E.

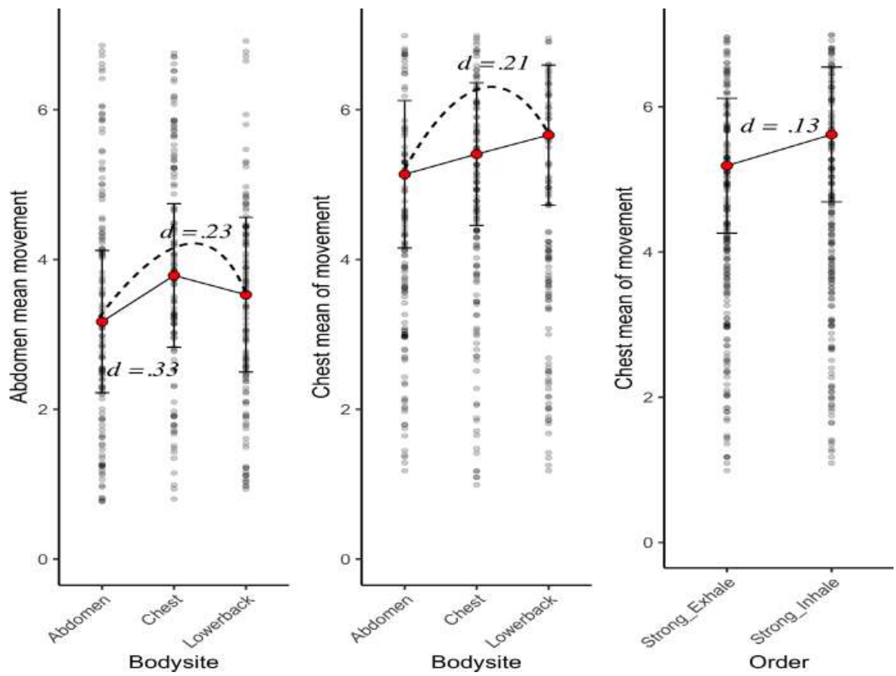

Fig. 16. Main effects of the abdomen and chest mean movements with effect sizes.

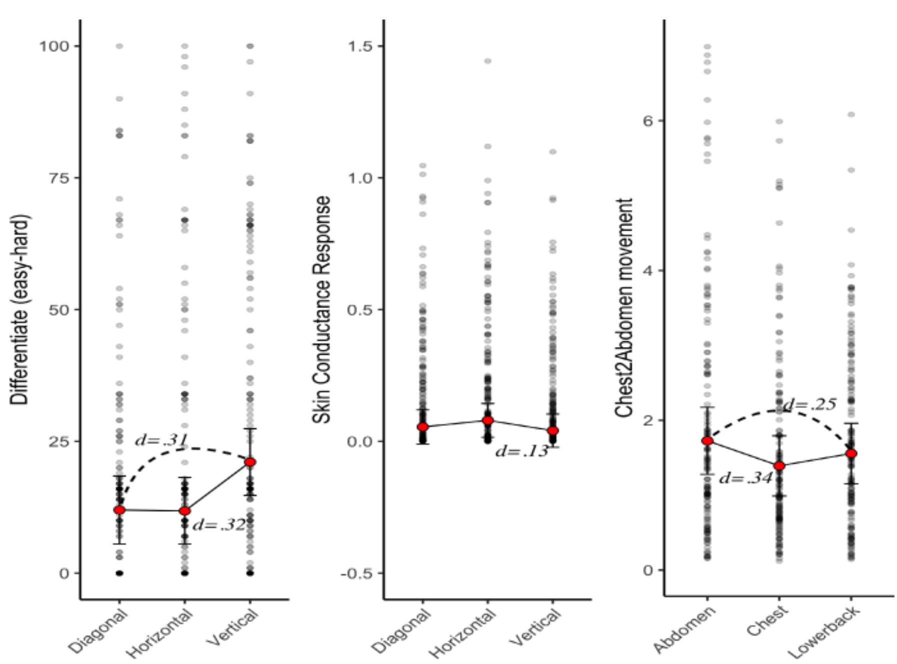

Fig. 17. Main effects of the Differentiate, Skin Conductance Response (CDA.SCR), and the mean of chest to abdomen ratio of breathing.

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 ← 300 *// delay between inhale and exhale*
  Ex2InDelay ← 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*

  Frq // frequency of default pattern
  Amp // peak amplitude of default pattern

  BPM ← 7.5 *// number of breaths per minute*
  BR ← 1 *// ratio of inhale to exhale duration*
end global variables

E PERSONALIZATION ROUTINE: SCRIPT

This section contains the script that the 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.

E.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 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

ALGORITHM 1: Personalization Routine: Functions.

```
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) ∧ (strength = inhale) then
        pattern ← [F_max, A_max2, F_min, A_max2, A_base, BPM, BR]
    else if (shape = horizontal) ∧ (strength = exhale) then
        pattern ← [F_min, A_max2, F_max, A_max2, A_base, BPM, BR]
    else if (shape = vertical) ∧ (strength = inhale) then
        pattern ← [F_mid, A_max, F_mid, A_min, A_base, BPM, BR]
    else if (shape = vertical) ∧ (strength = exhale) then
        pattern ← [F_mid, A_min, F_max, A_max, A_base, BPM, BR]
    else if (shape = diagonal) ∧ (strength = inhale) then
        pattern ← [F_max, A_max2, F_mid, A_min, A_base, BPM, BR]
    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
```

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?

E.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.

ALGORITHM 1: Personalization routine: Procedures (1).

```
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
    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
    until participant barely notices pattern
    A_hi ← Amp
    stopPattern()
    Amp ← A_low + 55
    repeat
        Amp ← Amp − 5
        playPattern(NULL, NULL, continuously)
        wait 8 seconds
    until participant can no longer notice pattern
    A_low ← Amp
    stopPattern()
    A_base ← (A_low + A_hi)/2 + 20
end procedure
```

E.3 Find $\mathbf{F_{min}}$

- 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.

ALGORITHM 1: Personalization routine: Procedures (2).

```
 95: procedure FINE TUNE HORIZONTAL PATTERN
 96:     BPM ← participant's estimated breaths per minute
 97:     playPattern(horizontal, exhale, continuously)
 98:     Experimenter repeatedly asks participant how the pattern is
 99:       perceived and adjusts F_min, A_max , and F_max accordingly
100:     repeat
101:         with probability .5
102:                 playPattern(horizontal, inhale, continuously)
103:             or playPattern(horizontal, exhale, continuously)
104:         end with
105:     until participant correctly detects which of the two waves is stronger 3 times in
     a row
106:     stopPattern()
107:     playPattern(horizontal, exhale, continuously)
108:     Experimenter asks participant to breath with the pattern
109:     wait 4 breaths
110:     Experimenter asks participant about any issues they have with
111:       the pattern, and adjusts F_min, A_max, F_max, BPM and BB accordingly
112:     stopPattern()
113: end procedure
114:
115: procedure FINE TUNE VERTICAL PATTERN
116:     BPM ← participant's estimated breaths per minute
117:     playPattern(vertical, exhale, continuously)
118:     Experimenter repeatedly asks participant how the pattern is
119:       perceived and adjusts F_min, A_max , and F_max accordingly
120:     repeat
121:         with probability .5
122:                 playPattern(vertical, inhale, continuously)
123:             or playPattern(vertical, exhale, continuously)
124:         end with
125:     until participant correctly detects which of the two waves is stronger 3 times in
     a row
126:     stopPattern()
127:     playPattern(vertical, exhale, continuously)
128:     Experimenter asks participant to breath with the pattern
129:     wait 4 breaths
130:     Experimenter asks participant about any issues they have with
131:       the pattern, and adjusts F_min, A_max, F_max, BPM and BB accordingly
132:     stopPattern()
133: end procedure
```

E.4 Find 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.

E.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?

E.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?

E.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.

F 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.

REFERENCES

[1] 2018. *Engineering Acoustics, Inc. C-2*. Retrieved August 31, 2018 from https://www.eaiinfo.com/product/c2.

[2] 2018. *LedaLab*. Retrieved August 31, 2018 from http://www.ledalab.de/.

[3] 2018. *Lief Patch*. Retrieved August 31, 2018 from https://www.youtube.com/watch?v=aclzen-GGTE.

[4] 2018. *Lief Therapeutics*. Retrieved August 31, 2018 from https://getlief.com.

[5] 2018. *Linear Resonant Actuators, Precision Microdrives Inc*. Retrieved August 31, 2018 from https://www.precisionmicrodrives.com/vibration-motors/linear-resonant-actuators-lras/.

[6] 2018. *Paced-breathing App*. Retrieved August 31, 2018 from https://groups.google.com/forum/#!forum/paced-breathing.

[7] 2018. *Spire Stone*. Retrieved August 31, 2018 from https://spire.io/pages/stone.

[8] 2018. *Vitali Sports Bra*. Retrieved August 31, 2018 from https://vitaliwear.com.

[9] Ruben T. Azevedo, Nell Bennett, Andreas Bilicki, Jack Hooper, Fotini Markopoulou, and Manos Tsakiris. 2017. The calming effect of a new wearable device during the anticipation of public speech. *Scientific Reports* 7, 1 (2017), 2285. DOI: https://doi.org/10.1038/s41598-017-02274-2

[10] Lisa Feldman Barrett and James A. Russell. 1999. The structure of current affect: Controversies and emerging consensus. *Current Directions in Psychological Science* 8, 1 (1999), 10–14.

[11] Mathias Benedek and Christian Kaernbach. 2010. A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods* 190, 1 (2010), 80–91. DOI: https://doi.org/10.1016/j.jneumeth.2010.04.028

[12] Mathias Benedek and Christian Kaernbach. 2010. Decomposition of skin conductance data by means of nonnegative deconvolution. *Psychophysiology* 47, 4 (2010), 647–658.

[13] Wolfram Boucsein. 2012. *Electrodermal Activity*. Springer Science & Business Media.

[14] Breathe App. [n.d.]. Retrieved June 6, 2019 from https://support.apple.com/en-us/HT206999.

[15] Jeremy D. Brown, R. Brent Gillespie, Duane Gardner, and Emmanuel A. Gansallo. 2012. Co-location of force and action improves identification of force-displacement features. In *Proceedings of the Haptics Symposium (HAPTICS'12)*. IEEE, 187–193.

[16] Volker Busch, Walter Magerl, Uwe Kern, Joachim Haas, Göran Hajak, and Peter Eichhammer. 2012. The effect of deep and slow breathing on pain perception, autonomic activity, and mood processing - an experimental study. *Pain Medicine* 13, 2 (2012), 215–228. DOI: https://doi.org/10.1111/j.1526-4637.2011.01243.x

[17] John T. Cacioppo, Louis G. Tassinary, and Gary Berntson. 2007. *Handbook of Psychophysiology*. Cambridge University Press.

[18] Helen J. Chatterjee and Leonie Hannan. 2015. *Engaging the Senses: Object-based Learning in Higher Education*. Ashgate Publishing Ltd.

[19] Jean Costa, Alexander T. Adams, Malte F. Jung, François Guimbetiere, and Tanzeem Choudhury. 2016. EmotionCheck: Leveraging bodily signals and false feedback to regulate our emotions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 758–769. DOI: https://doi.org/10.1145/2971648.2971752

[20] Michelle G. Craske and David H. Barlow. 2007. *Mastery of Your Anxiety and Panic: Workbook for Primary Care Settings (Treatments That Work)*. Oxford University Press.

[21] David Driscoll, Daniel Tranel, and Steven W. Anderson. 2009. The effects of voluntary regulation of positive and negative emotion on psychophysiological responsiveness. *International Journal of Psychophysiology* 72, 1 (2009), 61–66. DOI: https://doi.org/10.1016/j.ijpsycho.2008.03.012

[22] Robert Edelberg. 1977. Relation of electrical properties of skin to structure and physiologic state. *Journal of Investigative Dermatology* 69, 3 (1977), 324–327.

[23] Eli J. Finkel, Erica B. Slotter, Laura B. Luchies, Gregory M. Walton, and James J. Gross. 2013. A brief intervention to promote conflict reappraisal preserves marital quality over time. *Psychological Science* 24, 8 (2013), 1595–1601.

[24] Don C. Fowles, Margaret J. Christie, Robert Edelberg, William W. Grings, David T. Lykken, and Peter H. Venables. 1981. Publication recommendations for electrodermal measurements. *Psychophysiology* 18, 3 (1981), 232–239. DOI: https://doi.org/10.1111/j.1469-8986.2012.01384.x

[25] Jérémy Frey, May Grabli, Ronit Slyper, and Jessica R. Cauchard. 2018. Breeze: Sharing biofeedback through wearable technologies. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI'18)*. ACM, New York, NY, Article 645, 12 pages. DOI: https://doi.org/10.1145/3173574.3174219

[26] Francine Gemperle, Nathan Ota, and Dan Siewiorek. 2001. Design of a wearable tactile display. In *Proceedings of 5th International Symposium on Wearable Computers*. IEEE, 5–12. DOI: https://doi.org/10.1109/ISWC.2001.962082

[27] Alicia A. Grandey and Allison S. Gabriel. 2015. Emotional labor at a crossroads: Where do we go from here? *Annual Review of Organizational Psychology and Organizational Behavior* 2, 1 (2015), 323–349.

[28] William W. Grings and Anne M. Schell. 1969. Magnitude of electrodermal response to a standard stimulus as a function of intensity and proximity of a prior stimulus. *Journal of Comparative and Physiological Psychology* 67, 1 (1969), 77. DOI: https://doi.org/10.1037/h0026651

[29] James J. Gross. 2014. *Handbook of Emotion Regulation* (2nd ed.). Guilford publications, Berlin, New York.

[30] James J. Gross. 2015. Emotion regulation: Current status and future prospects. *Psychological Inquiry* 26, 1 (2015), 1–26. DOI: https://doi.org/10.1080/1047840X.2014.940781

[31] James J. Gross and Oliver P. John. 2003. Individual differences in two emotion regulation processes: Implications for affect, relationships, and well-being. *Journal of Personality and Social Psychology* 85, 2 (2003), 348.

[32] James J. Gross and Robert W. Levenson. 1995. Emotion elicitation using films. *Cognition & Emotion* 9, 1 (1995), 87–108.

[33] Eric Gunther and Sile O'Modhrain. 2003. Cutaneous grooves: Composing for the sense of touch. *Journal of New Music Research* 32, 4 (2003), 369–381. DOI: https://doi.org/10.1076/jnmr.32.4.369.18856

[34] Anett Gyurak, James J. Gross, and Amit Etkin. 2011. Explicit and implicit emotion regulation: A dual-process framework. *Cognition and Emotion* 25, 3 (2011), 400–412. DOI: https://doi.org/10.1080/02699931.2010.544160

[35] Lori Haase, Nate J. Thom, Akanksha Shukla, Paul W. Davenport, Alan N. Simmons, Elizabeth A. Stanley, Martin P. Paulus, and Douglas C. Johnson. 2014. Mindfulness-based training attenuates insula response to an aversive interoceptive challenge. *Social Cognitive and Affective Neuroscience* 11, 1 (2014), 182–190.

[36] Karen Hall. 2014. *So You Want to Sing Music Theater: A Guide for Professionals*, Vol. 1. Scarecrow Press.

[37] Christopher L. Heavey, Noelle L. Lefforge, Leiszle Lapping-Carr, and Russell T. Hurlburt. 2017. Mixed emotions: Toward a phenomenology of blended and multiple feelings. *Emotion Review* 9, 2 (2017), 105–110.

[38] A. Kron, M. Pilkiw, J. Banaei, A. Goldstein, and A. K. Anderson. 2015. Are valence and arousal separable in emotional experience?. *Emotion* 15, 1 (2015), 35.

[39] Idin Karuei and Karen E. MacLean. 2015. Susceptibility to periodic vibrotactile guidance of human cadence. In *Proceedings of the IEEE Haptics Symposium*. IEEE, 141–146.

[40] Idin Karuei, Karen E. MacLean, Zoltan Foley-Fisher, Russell MacKenzie, Sebastian Koch, and Mohamed El-Zohairy. 2011. Detecting vibrations across the body in mobile contexts. In *Proceedings of the 2011 CHI Conference on Human Factors in Computing Systems*. ACM, 141–146.

[41] Inna Z. Khazan. 2013. *The Clinical Handbook of Biofeedback: A Step-by-Step Guide for Training and Practice with Mindfulness*. John Wiley & Sons.

[42] Sang Hee Kim and Stephan Hamann. 2012. The effect of cognitive reappraisal on physiological reactivity and emotional memory. *International Journal of Psychophysiology* 83, 3 (2012), 348–356. DOI: https://doi.org/10.1016/j.ijpsycho.2011.12.001

[43] Assaf Kron, Ariel Goldstein, Daniel Hyuk-Joon Lee, Katherine Gardhouse, and Adam Keith Anderson. 2013. How are you feeling? Revisiting the quantification of emotional qualia. *Psychological Science* 24, 8 (2013), 1503–1511. DOI: https://doi.org/10.1177/0956797613475456

[44] Assaf Kron, Maryna Pilkiw, Jasmin Banaei, Ariel Goldstein, and Adam Keith Anderson. 2015. Are valence and arousal separable in emotional experience? *Emotion* 15, 1 (2015), 35. DOI: https://doi.org/10.1037/a0038474

[45] M. Kunimoto, K. Kirnö, M. Elam, T. Karlsson, and B. G. Wallin. 1992. Non-linearity of skin resistance response to intraneural electrical stimulation of sudomotor nerves. *Acta Physiologica Scandinavica* 146, 3 (1992), 385–392. DOI: https://doi.org/10.1111/j.1748-1716.1992.tb09433.x

[46] Peter Kuppens, Francis Tuerlinckx, James A Russell, and Lisa Feldman Barrett. 2013. The relation between valence and arousal in subjective experience. *Psychological Bulletin* 139, 4 (2013), 917.

[47] Peter J. Lang, Mark K. Greenwald, Margaret M. Bradley, and Alfons O. Hamm. 1993. Looking at pictures: Affective, facial, visceral, and behavioral reactions. *Psychophysiology* 30, 3 (1993), 261–273.

[48] Jeff T. Larsen and A. Peter McGraw. 2011. Further evidence for mixed emotions. *Journal of Personality and Social Psychology* 100, 6 (2011), 1095. DOI: https://doi.org/10.1037/a0021846

[49] Pablo Enrique Paredes, Nur Al-Huda Hamdan, Dav Clark, Carrie Cai, Wendy Ju, and James A. Landay. 2017. Evaluating in-car movements in the design of mindful commute interventions: exploratory study. *Journal of Medical Internet Research* 19, 12 (2017), e372.

[50] Susan J. Lederman and Roberta L. Klatzky. 2009. Haptic perception: A tutorial. *Attention, Perception, & Psychophysics* 71, 7 (2009), 1439–1459. DOI: https://doi.org/10.3758/APP.71.7.1439

[51] Fang Lin, Sriranjani Parthasarathy, Susan J. Taylor, Deborah Pucci, Ronald W. Hendrix, and Mohsen Makhsous. 2006. Effect of different sitting postures on lung capacity, expiratory flow, and lumbar lordosis. *Archives of Physical Medicine and Rehabilitation* 87, 4 (April 2006), 504–509. DOI: https://doi.org/10.1016/j.apmr.2005.11.031

[52] Kevin D. McCaul, Sheldon Solomon, and David S. Holmes. 1979. Effects of paced respiration and expectations on physiological and psychological responses to threat. *Journal of Personality and Social Psychology* 37, 4 (1979), 564. DOI: https://doi.org/10.1037/0022-3514.37.4.564

[53] Pardis Miri, Andero Uusberg, Heather Culbertson, Robert Flory, Helen Uusberg, James J. Gross, Keith Marzullo, and Katherine Isbister. 2018. *Emotion Regulation in the Wild: The WEHAB Approach*. Technical Report. University of California, Santa Cruz. Retrieved from https://www.soe.ucsc.edu/sites/default/files/technical-reports/UCSC-SOE-18-04.pdf.

[54] Pardis Miri, Andero Uusberg, Heather Culbertson, Robert Flory, Helen Uusberg, James J. Gross, Keith Marzullo, and Katherine Isbister. 2018. Emotion regulation in the wild: Introducing WEHAB system architecture. In *Proceedings of the Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, LBW021.

[55] Ann Morrison, Cristina Manresa-Yee, and Walther Jensen. 2018. Sensations on the body: Varying duration, overlap, ratios and placement on dynamic vibrotactile patterns. In *Proceedings of the XIX International Conference on Human Computer Interaction*. ACM, 6.

[56] L. Narici, I. Modena, Reinier-Jacques Opsomer, V. Pizzella, G. L. Romani, G. Torrioli, R. Traversa, and P. M. Rossini. 1991. Neuromagnetic somatosensory homunculus: A non-invasive approach in humans. *Neuroscience Letters* 121, 1–2 (1991), 51–54.

[57] Meike Pappens, Omer Van den Bergh, Steven De Peuter, Johan Bresseleers, Debora Vansteenwegen, and Ilse Van Diest. 2010. Defense reactions to interoceptive threats: A comparison between loaded breathing and aversive picture viewing. *Biological Psychology* 84, 1 (2010), 98–103.

[58] Pablo Enrique Paredes, Nur Al-Huda Hamdan, Dav Clark, Carrie Cai, Wendy Ju, and James A. Landay. 2017. Evaluating in-car movements in the design of mindful commute interventions: Exploratory study. *Journal of Medical Internet Research* 19, 12 (2017), e372. DOI: https://doi.org/10.2196/jmir.6983

[59] Pablo E. Paredes, Francisco Ordonez, Wendy Ju, and James A. Landay. 2018. Fast & furious: Detecting stress with a car steering wheel. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI'18)*. ACM, New York, NY. DOI: https://doi.org/10.1145/3173574.3174219

[60] Pablo E. Paredes, Yijun Zhou, Nur Al-Huda Hamdan, Stephane Balters, Elizabeth Murnane, Wendy Ju, and James A Landay. 2018. Just breathe: In-car interventions for guided slow breathing. In *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1 (2018). DOI: https://doi.org/10.1145/3191760

[61] Gunhyuk Park and Seungmoon Choi. 2011. Perceptual space of amplitude-modulated vibrotactile stimuli. In *Proceedings of the World Haptics Conference (WHC'11)*. IEEE, 59–64. DOI: https://doi.org/10.1109/WHC.2011.5945462

[62] Erik Peper, Annette Booiman, I-Mei Lin, Richard Harvey, and Jasmine Mitose. 2016. Abdominal SEMG feedback for diaphragmatic breathing: A methodological note. *Biofeedback* 44, 1 (2016), 42–49. DOI: https://doi.org/10.5298/1081-5937-44.1.03

[63] R. W. Picard. 2010. Affective computing: From laughter to IEEE. *IEEE Transactions on Affective Computing* 1, 1 (January 2010), 11–17. DOI: https://doi.org/10.1109/T-AFFC.2010.10

[64] Jane M. Richards and James J. Gross. 2000. Emotion regulation and memory: The cognitive costs of keeping one's cool. *Journal of Personality and Social Psychology* 79, 3 (2000), 410.

[65] A. H. Rupert and R. E. Gadolin. 1993. *Motion and Spatial Disorientation Systems: Special Research Capabilities*. Technical Report. DTIC Document. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a265155.pdf.

[66] Oliver Schneider. [n.d.]. *Macaronkit: USB-powered Mono Audio Amplifier*. Retrieved August 31, 2018 http://www.instructables.com/id/MacaronKit-USB-Powered-Mono-Audio-Amplifier.

[67] Hasti Seifi and Karon E. Maclean. 2013. A first look at individuals' affective ratings of vibrations. In *Proceedings of the 2013 World Haptics Conference (WHC'13)*. IEEE, 605–610.

[68] Caitlyn E. Seim, David Quigley, and Thad E. Starner. 2014. Passive haptic learning of typing skills facilitated by wearable computers. In *Proceedings of the CHI'14 Extended Abstracts on Human Factors in Computing Systems*. ACM, 2203–2208.

[69] Mikołaj Tytus Szulczewski and Andrzej Rynkiewicz. 2018. The effects of breathing at a frequency of 0.1 Hz on affective state, the cardiovascular system, and adequacy of ventilation. *Psychophysiology* 55, 12 (2018), e13221. DOI: https://doi.org/10.1111/psyp.13221

[70] Ana Tajadura-Jiménez, Aleksander Väljamäe, and Daniel Västfjäll. 2008. Self-representation in mediated environments: The experience of emotions modulated by auditory-vibrotactile heartbeat. *CyberPsychology & Behavior* 11, 1 (2008), 33–38. DOI: https://doi.org/10.1089/cpb.2007.0002

[71] Graham Wilson and Stephen A. Brewster. 2017. Multi-moji: Combining thermal, vibrotactile & visual stimuli to expand the affective range of feedback. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 1743–1755.

[72] S. Yohanan and K. E. MacLean. 2011. Design and assessment of the Haptic Creature's affect display. In *Proceedings of the 2011 6th ACM/IEEE International Conference on Human-Robot Interaction (HRI'11)*. 473–480. DOI: https://doi.org/10.1145/1957656.1957820

[73] Yongjae Yoo, Taekbeom Yoo, Jihyun Kong, and Seungmoon Choi. 2015. Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope. In *Proceedings of theWorld Haptics Conference (WHC'15)*. IEEE, 235–240.

[74] Bin Yu, Loe Feijs, Mathias Funk, and Jun Hu. 2015. Breathe with touch: A tactile interface for breathing assistance system. In *Proceedings of the15th IFIP TC 13 International Conference on Human-Computer Interaction — INTERACT 2015 - Volume 9298*. Springer-Verlag, Berlin, 45–52. DOI: https://doi.org/10.1007/978-3-319-22698-9_4

Received December 2018; revised July 2019; accepted September 2019